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**Grand Canyon Monitoring and Research Center Triennial Budget and Work Plan Prospectus—Fiscal Years 2018–2020**

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Prepared by

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Introduction

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

**Work Plan Prospectus**

**FY18/19/20**

This document is a compilation of likely and potential projects proposed to be conducted in fiscal years 2018 (FY18), 2019 (FY19), and 2020 (FY20) by the U.S. Geological Survey Grand Canyon Monitoring and Research Center (GCMRC) and its cooperators. This document also includes budget summary tables for each proposed project, with cost estimates by project element as well as comprehensive budget tables for each year of the workplan, with all projects and elements included. A summary budget table that includes budget estimates by project and year is included as Appendix 2 at the end of the work plan.

The purpose of this document is to continue the discussion with stakeholders, partner agencies, and cooperators about the monitoring and research priorities that will guide work activities in support of implementation of the Long-Term Experimental and Management Plan (LTEMP) and to meet the scientific information needs of the Glen Canyon Dam Adaptive Management Program (GCDAMP) during the next three years. In addition, this document provides full drafts of proposed workplan projects intended for review and comment by DOI, the Science Advisors Program, tribes, the Budget Ad Hoc Group (BAHG), Technical Work Group (TWG), and other stakeholders. We recognize that the suspension of Federal Advisory Committee Act (FACA) activities per the May 5, 2017 memo from DOI precludes review by the BAHG, TWG, and other stakeholders. Each project description includes a list of investigators, a project summary, background information, descriptions of proposed work, expected products to result from the project, references, and a detailed budget. A number of formal and informal meetings, conference calls, and discussions concerning the FY2018-20 Triennial Work Plan (TWP) have occurred to date including in-person meetings with the tribal representatives, conference calls with the BAHG, and TWG meetings in January and April. The verbal and written feedback received by GCMRC thus far has been informative and helpful as individual investigators worked to develop the ideas shared in the extended abstracts (April 7, 2017 draft of the TWP) into full proposals. Several stakeholders suggested revising the project numbering scheme employed for the April draft of the TWP, which identified projects by letter, to avoid confusion with Reclamation’s portion of the budget which also identified projects by letter. We were unable to implement that revision for this draft (May 2017) of the TWP, but will work with Reclamation to develop a project identification system that avoids duplication between the Reclamation and GCMRC portions of the TWP.

This document identifies likely and potential projects to be funded in FY18-20. The primary funding source for these activities will be the GCDAMP. Approximately $8.8 million in GCDAMP funding is anticipated to be available to support GCMRC activities in FY18. Funding levels for FY19 and FY20 are projected to increase by 1% per year due to anticipated annual changes in the Consumer Price Index. A major budgetary challenge for the FY2018-20 Work Plan is the projected increase in overhead rates for GCMRC due to increased facilities costs associated with a new building. Although delayed for several years, we expect to move into this yet-to-be-built facility in summer 2018 at which time GCMRC’s lease costs will increase considerably. Current projections of overhead rates for funds expended by GCMRC are 16% in FY18 and 26% in FY19 and FY20. GCMRC’s overhead rates for funds transferred to outside entities will remain at 3% for partner agencies and cooperators and 0% for other USGS science centers although each of these entities typically charge their own overhead rates on funds they expend.

The total cost of all potential projects presently identified by GCMRC for consideration as FY18 work activities to be funded by the GCDAMP is approximately $10.5 million. In FY18, GCMRC anticipates applying approximately $130,000 in supplemental funding already received from the Bureau of Reclamation to support monitoring of Lake Powell reservoir water quality to fund activities identified in Project Element E.1. Projected costs of proposed projects in FY19 are $11.7 million and $11.8 million in FY20. Additional funding to support proposed work beyond anticipated funding levels have yet to be identified.

Recognizing the need to reduce project costs from levels identified in the April 7, 2017 draft, GCMRC investigators were directed to prioritize projects and elements focusing first on LTEMP implementation. Criteria identified included whether or not the proposed work was necessary to trigger an experiment, for monitoring an ecosystem response, to inform experimental off-ramps, or for context in interpreting responses to experiments. Compliance with the Biological Opinion and National Historic Preservation Act were also priorities. Next level criteria included whether or not the proposed work was duplicative, at the appropriate level of effort, included tribal coordination as appropriate, was efficient logistically, and was the proposal of high quality. Feedback received from stakeholders and others during previously mentioned interactions also proved helpful guidance for identifying areas for budget reductions. Despite this guidance and feedback, we struggled to reduce budget estimates for many projects in this draft of the TWP such that projected costs exceed anticipated funding by a considerable margin.

To reduce the budget to within anticipated funding levels, it is essential to work with partner agencies, cooperators, and stakeholders as appropriate to identify monitoring and research priorities. GCMRC will also work to identify strategies for reducing the costs of specific projects including working with partner agencies and cooperators to eliminate areas of overlap and redundancy and ensure that proposed levels of work do not exceed what is necessary to meet the information needs of decision makers and the GCDAMP and for LTEMP implementation. It will not be possible to fund all proposed project elements, therefore GCMRC requests feedback regarding which elements are of most interest to stakeholders. In addition, we seek input on prioritizing unfunded elements that should be conducted in the event additional resources become available. We look forward to constructive discussions with partner agencies, cooperators, and stakeholders as appropriate as we work to finalize this Work Plan.

In June, GCMRC will release a third draft of the proposed TWP which will include final project proposals revised in response to feedback and comments received on this document. The third draft of the proposed TWP will also include an extended discussion about how the workplan is responsive to the guidance and suggestions provided by the BAHG, TWG, and Science Advisors as well as how it implements the Science Plan for the LTEMP.

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

# 1. Investigators

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# 2. Project Summary

The primary linkage between Glen Canyon Dam operations and the characteristics of the physical, biological, and cultural resources of the Colorado River ecosystem (CRe) downstream from Glen Canyon Dam is through the stage, discharge, water quality, and sediment transport of the Colorado River. This project makes and interprets the basic measurements of these parameters at locations throughout the CRe. The data collected by this project are used to implement the High Flow Experiment (HFE) Protocol (i.e., trigger and design HFE hydrographs), to evaluate the reach-scale sand mass-balance response to the HFE Protocol (U.S. Department of the Interior, 2011; Grams and others, 2015), and to evaluate the downstream effects of releases conducted under the Long-Term Experimental and Management Plan Environmental Impact Statement (LTEMP) EIS (U.S. Department of the Interior, 2016a, b). The data collected by this project are also required by the other physical, ecological, and socio-cultural projects funded by the Glen Canyon Dam Adaptive Management Program (GCDAMP). Most of the project funds support basic data collection at U.S. Geological Survey (USGS) gaging stations, with only a small amount of project funds supporting interpretation of basic data. The funds requested under this proposal cover only ~70% of the costs required to operate and interpret data at the network of USGS gaging stations used by this project; other funding for this network is provided to the USGS Arizona Water Science Center from USGS headquarters, the Bureau of Land Management, and the Arizona Department of Environmental Quality (AZDEQ).

This project is designed to provide measurements of stage (i.e., water elevation), discharge (i.e., streamflow), water quality, and suspended sediment at sufficiently high temporal resolutions (~15-minute) to resolve changes in these parameters and to allow accurate determination of suspended-sediment loads for use in sediment budgeting. The proposed monitoring under this project will be very similar to that conducted over the last 5-10 years. The 3 elements of this project are as follows:

**1. Stream gaging:** This element partially funds the collection, serving, and interpretation of continuous 15-minute measurements of stage and discharge on the main-stem Colorado River at USGS streamflow gaging stations located at river miles (RM) 0, 30, 61, 87, 166, and 225, and at gaging stations on the major tributaries and in a representative subset of the smaller, and formerly ungaged, tributaries.

**2. Water quality:** This element funds the collection, serving, and interpretation of continuous 15-minute measurements of water temperature, specific conductance (a measure of salinity), turbidity, and dissolved oxygen at the above-mentioned six main-stem Colorado River gaging stations, as well as continuous measurements of water temperature at additional stations on the Colorado River and in the major tributaries. In addition, this element provides a small amount of funding toward the logistics required to collect samples for water-chemistry analyses (including nutrients) at gaging stations on the Colorado River.

**3. Sediment transport and budgeting:** This element funds the collection, serving, and interpretation of continuous 15-minute measurements and also episodic measurements of suspended sediment and bed sediment at the above-mentioned gaging stations on the Colorado River and its tributaries. The continuous suspended-sediment measurements at the 6 main-stem Colorado River gaging stations, and the episodic suspended-sediment measurements in the tributaries are used in the construction of mass-balance sand budgets. These budgets inform scientists and managers on the effects of dam operations on the sand mass balance in the CRe between Lees Ferry and Lake Mead (divided into 6 reaches). Increases in the sand mass balance in a reach indicate an increase in the amount of sand in that reach and therefore an increase in the amount of sand available for sandbar deposition during HFEs, whereas decreases in the sand mass balance in a reach indicate a net loss of sand from that reach.

All measurements made by this project are made using standard USGS and other peer-reviewed techniques. All of these measurements can be plotted and/or downloaded at: <https://www.gcmrc.gov/discharge_qw_sediment/> or <https://cida.usgs.gov/gcmrc/discharge_qw_sediment/>. Plots of continuous parameters can be made in time-series or duration-curve formats. In addition, the user-interactive mass-balance sand budgets for the six CRe reaches are available at this website (Sibley and others, 2015).

In addition to the collection and serving of the basic streamflow, water-quality, and sediment-transport data, time is spent in this project interpreting the data and reporting on the results and interpretations in peer-reviewed articles in the areas of hydrology, water quality, and sediment transport. The interpretive papers published by this project are designed to address key questions relevant to river management, especially to management in the GCDAMP. To date, this ongoing project has published over 80 peer-reviewed journal articles, books, proceedings articles, and USGS reports, a full listing of which are available at: [https://www.usgs.gov/centers/sbsc/science/fluvial-river-sediment-dynamics?qt-science\_center\_objects=1 - qt-science\_center\_objects](https://www.usgs.gov/centers/sbsc/science/fluvial-river-sediment-dynamics?qt-science_center_objects=1#qt-science_center_objects). This website also provides urls to download these publications.

**3. Background**

Systematic measurements of streamflow and water quality, including suspended-sediment concentration, in the CRe began with installation of the Lees Ferry gaging station (USGS gaging station 09380000, Colorado River at Lees Ferry, AZ) in May 1921 (Howard, 1947; Topping and others, 2003). During much of the 20th century, daily measurements of suspended-sediment concentration and water temperature, and episodic measurements of other water-quality parameters, were made by the USGS at multiple gaging stations in the CRe and on key tributaries. This intensive period of measurements ended in the early 1970s (Andrews, 1991; Topping and others, 2000a). Concern about the effects of the operation of Glen Canyon Dam on the CRe resulted in a new emphasis on scientific measurements and modeling of water quality and sediment transport beginning in the early 1980s (National Research Council, 1996). The results of these studies have been published in numerous USGS reports and journal articles, and ultimately resulted in the current form of the proposed project described herein.

The operation of Glen Canyon Dam controls the CRe because it is the dominant controller of river stage, discharge, and water quality, and is a primary regulator of sediment transport, erosion, and deposition (Topping and others, 2000, 2003; Rubin and Topping, 2001, 2008; Gloss and others, 2005). Water temperature, salinity, dissolved oxygen, and water chemistry at the foot of the dam are determined by the physical and chemical characteristics of the reservoir water at the penstock and/or jet-tube elevations on the upstream face of the dam (Vernieu and others, 2005). Because the amount of water supplied by downstream tributaries is small and large floods on these tributaries are infrequent, dam operations largely determine stage, discharge, and key water-quality parameters (water temperature and salinity) throughout the CRe (Wiele and Smith, 1996; Wiele and Griffin, 1998; Voichick and Wright, 2007; Voichick, 2008; Wright and others, 2009; Voichick and Topping, 2010). In addition, because sediment transport in the CRe is controlled by both changes in discharge and changes in bed-sediment grain size (Rubin and Topping, 2001, 2008), and because dam operations control discharge, the operation of Glen Canyon Dam acts as a primary regulator of sediment transport in the CRe. As dam operations regulate the amount of sediment in the water column (i.e., suspended sediment), and because suspended sediment largely determines turbidity (Voichick and Topping, 2014), dam operations therefore influence downstream turbidity in the CRe. Finally, because dam operations largely determine water temperature and also influence turbidity, other downstream water-quality parameters regulated by water temperature and turbidity are also affected by dam operations, e.g., dissolved oxygen at locations far downstream from the dam (e.g., Hall and others, 2015) (dissolved oxygen is generally negatively related to water temperature, turbidity, and suspended-sediment concentration, e.g., data at: <https://www.gcmrc.gov/discharge_qw_sediment/>).

Suspended sediment is an important water quality parameter in the CRe for several reasons. First, deposition and/or erosion of the eddy sandbars and channel-margin deposits important to many biological, cultural, and recreational resources are directly controlled by the transport of sand (Gloss and others, 2005). Because the amount of sand transported as bedload is much smaller (typically <5%) than the amount of sand transported in suspension at moderate and higher dam releases (Rubin and others, 2001), the rate of deposition and/or erosion of eddy sandbars and channel-margin deposits is related by mass conservation to spatial gradients in the suspended-sand flux (after Exner, 1920, 1925). By theory (Grams and others, 2013) and experiments (Schmidt and others, 1993), eddy-sandbar deposition is most efficient when the flux of suspended sand is the highest in the main channel of the river. Because suspended-sand flux is the depth-integrated product of suspended-sand concentration and water discharge, maximum main-channel sand flux occurs when the concentration of suspended sand is the highest (determined by the water discharge, bed-sand grain-size distribution, and areal amount of sand on the bed, e.g., Topping and others, 2007) and the velocity is the highest (i.e., at higher discharge). Under this condition, the convergence (i.e., negative spatial gradient) in the sand flux between the main channel and the riverbank in an eddy is the largest, leading to the greatest sand deposition rates in an eddy (Topping and others, 2010; Grams and others, 2013). Therefore, by the physics that control eddy-sandbar deposition, eddy sandbars are built most effectively when the discharge is high and the amount of finer sand in a reach is maximized (Schmidt and Grams, 2011). Thus, effective management of eddy sandbars (and associated resources) in different reaches of the Colorado River requires managers to know when the amount of finer sand in those specific reaches is enriched so that artificial controlled floods (now known as HFEs) can be released from the dam (Wright and others, 2005, 2008; Topping and others, 2010).

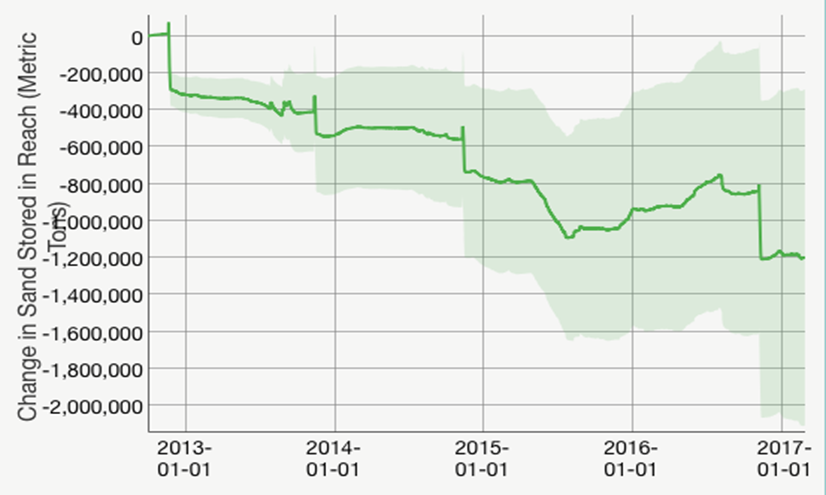
The second major reason as to why suspended sediment is an important water quality parameter is that it largely determines turbidity, and therefore influences the aquatic and fish ecology of the river (Voichick and others, 2016). The endemic fishes of the CRe evolved in a highly turbid river (Gloss and Coggins, 2005). Turbidity is primarily determined by the concentration of suspended silt and clay and, to a lesser degree, suspended sand (Voichick and Topping, 2014). Because closure of Glen Canyon Dam cutoff the upstream supply of silt and clay, the post-dam Colorado River in Marble and Grand Canyons is much less turbid than ever occurred naturally (Voichick and Topping, 2014). Although on average turbidity increases in a stepwise fashion in the downstream direction (at the mouths of the Paria and Little Colorado rivers), the Colorado River in the CRe is now moderately to highly turbid only during periods of tributary flooding (Voichick and Topping, 2014).

The transport of suspended sediment in the CRe is controlled by both the discharge released from the dam and the episodic tributary resupply of sand, silt, and clay (Topping and others, 2000b). By cutting off the majority of the sediment formerly supplied to the Colorado River in Marble and Grand canyons, closure of Glen Canyon Dam in 1963 reduced the upstream supply of sand, silt and clay at the upstream boundary of Grand Canyon National Park to ~5% of its pre-dam amount, and reduced the upstream supply of sand at this location to ~6% of its pre-dam amount (Topping and others, 2000a). Although other tributaries downstream from the dam do episodically supply sediment and sometimes in large amounts (Griffiths and others, 2015, in press), the majority of silt and clay supplied to the CRe is now supplied by the Little Colorado River and the majority of the sand supplied to the CRe is now supplied by the Paria River (U.S. Geological Survey, 2017). Although the Little Colorado River was historically an important supplier of sand, recent analyses of suspended-sediment data from the Little Colorado River indicate that the amount of sand supplied from this river has decreased substantially over time and may still be decreasing into the future (Dean and Topping, in prep; all 1949-2016 sand-transport data available at <https://www.gcmrc.gov/discharge_qw_sediment/>). At most flows, silt- and clay-sized sediment has negligible interaction with the bed sediment by Rouse mechanics (e.g., McLean, 1992). Consequently, silt and clay is transported as washload and is quickly transported downstream in the Colorado River following resupply during tributary floods. In contrast, because of the strong interaction between the suspended sand and the bed sediment, the changes in bed-sand grain size associated with the tributary resupply of sand exert a strong and longer-lasting control on the downstream transport of sand (Rubin and Topping, 2001, 2008; Topping and others, 2010). The fining of the bed sand in the Colorado River immediately following a tributary flood and the daily increases in discharge caused by dam operations can both cause similar magnitudes of increase in suspended-sand concentration of 100% to over 1,000% (U.S. Geological Survey, 2017).

This finding – that sand transport in the post-dam Colorado River was essentially co-equally regulated by changes in discharge and changes in bed-sand grain size – refuted key aspects of the 1995 Glen Canyon Dam Environmental Impact Statement (U.S. Department of the Interior, 1995). That 1995 document assumed that suspended-sand transport was regulated only by changes in discharge (Rubin and others, 2002). At moderate and higher dam releases, the residence time of tributary-supplied sand in the CRe is much shorter than assumed in the 1995 EIS (Topping and others, 2000b; Rubin and others, 2002; Wright and others, 2005). The 1995 EIS assumed that multi-year accumulations of tributary-supplied sand in the CRe could be utilized for sandbar rebuilding during rare HFEs. However, the evidence has shown that this is not a viable sand-management strategy (Rubin and others, 2002; Wright and others, 2005). Because both discharge and bed-sand grain size exert strong controls on sand transport, and because a multi-year residence time of tributary-supplied sand cannot be assumed, continuous suspended-sediment measurements were thus required to evaluate the effects of dam operations on sediment transport in the CRe, and thus required by managers to know when sufficient sand was available to conduct an HFE (Wright and others, 2005; Wright and Kennedy, 2011; Grams and others, 2015).

Through any given river cross section, the transport of sediment is regulated by the physical interaction of the flow with the local channel geometry and by the grain-size distribution of the bed sediment (Rubin and Topping, 2001, 2008; Topping and others, 2007). Thus, at a constant discharge (i.e., dam release), the downstream transport of sediment will vary as a function of longitudinal differences in channel geometry and bed-sediment grain size (Topping and others, 2000b). Channel geometry is not constant in the longitudinal direction along the Colorado River and bed-sediment grain size varies longitudinally because, after resupply by tributaries, sediment travels downstream in the Colorado River as elongating sediment waves (Topping and others, 2000b). These conditions lead to longitudinally nonuniform sediment transport in the CRe, even under conditions of constant discharge, e.g., during high-flow experiments (HFEs) or equalization releases. Sediment transport does not necessarily monotonically increase in the downstream direction under constant discharge, even when the discharge is high (Topping and others, 2010). For example, during the 2011 equalization releases, sand transport at the Colorado River above Diamond Creek gaging station was less than that at upstream gaging stations, leading to net deposition of sand in the West-central Grand Canyon reach of the Colorado River (between river miles 166 and 225) even though sand was eroded from all upstream reaches during these high-discharge releases (U.S. Geological Survey, 2017). Because of the always present, but temporally varying, longitudinal nonuniformity in sediment transport in the Colorado River, continuous sediment-transport measurements are required at locations bracketing key reaches of interest in order to document how dam operations affect sediment resources in the CRe (Wright and others, 2005).

The longitudinal nonuniformity in sediment transport, and specifically in sand transport, leads to the condition in the CRe where, during discrete time periods, sand gets deposited in long reaches while it gets eroded from other long reaches. Thus, it is incorrect to ever assume that the CRe as a whole, or even Marble or Grand canyons as a whole, undergo similar changes in the mass of sand stored in these long river segments. Furthermore, it is incorrect to assume that changes in sand mass get more positive progressively farther downstream in the CRe. For example, during the post-2012 period of the HFE Protocol (U.S. Department of the Interior, 2011; Grams and others, 2015), the two long reaches of the CRe that have generally experienced erosion of sand are not at the upstream end of the CRe, but rather are the Eastern Grand Canyon reach (river miles 61-88) immediately downstream from the Little Colorado River and the West-Central Grand Canyon reach (river miles 166-225) (**Figure** 1, U.S. Geological Survey, 2017).



**Figure 1.** Measured change in sand mass in the West-central Grand Canyon Reach of the Colorado River in the CRe (river miles 166-225) during 10-1-2012 through 3-1-2017. Given the uncertainty (light green region) in this continuous mass-balance sand budget, this reach has lost between 290,000 and 2,100,000 metric tons of sand during this period. Plot from this project's website (U.S. Geological Survey, 2017).

In addition, although HFEs invariably erode large amounts of sand from the CRe in the process of building higher-elevation sandbars (Rubin and others, 2002; Wright and others, 2005), this erosion is not uniformly distributed longitudinally along the CRe, with long segments of the CRe actually gaining sand during HFEs. Even though net erosion of sand occurred in other reaches during the 2012, 2013, and 2014 HFEs, net deposition of sand occurred during these HFEs in the Lower Marble Canyon reach (river miles 30-61) and the East-Central Grand Canyon reach (river miles 88-166) (U.S. Geological Survey, 2017). The spatial patterns of erosion and deposition of sand were somewhat different during the 2008 and 2016 HFEs. In the 2008 HFE, net erosion of sand occurred in all reaches except the East- and West Central Grand Canyon reaches (river miles 88-166 and 166-225), both of which experienced net sand deposition (U.S. Geological Survey, 2017). In the 2016 HFE, net erosion of sand occurred in all reaches except the East-Central Grand Canyon reach (U.S. Geological Survey, 2017).

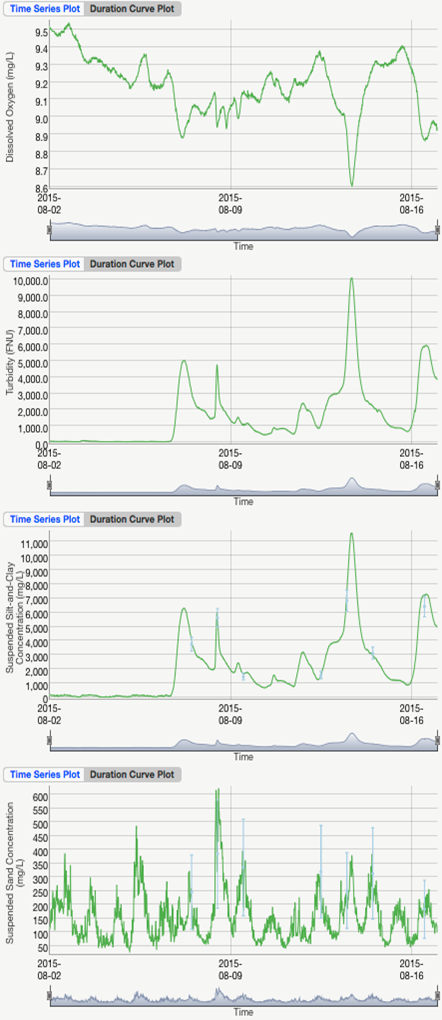
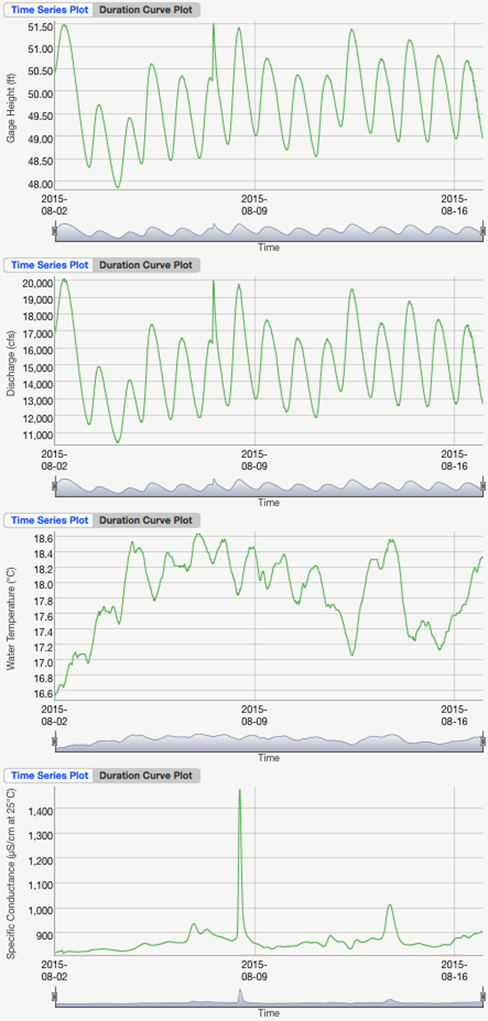
Monitoring of changes in the sand resources in the CRe therefore requires a strategy where the CRe is divided into key reaches on the partial basis of the locations of major tributaries that affect the sediment supply and potentially the water quality of the CRe. This is the strategy that has been used in this project since it began in the early 2000s. Therefore, in this ongoing project, the CRe was divided into seven monitoring reaches bracketed by USGS gaging stations (described later in this proposal). At each of these six gaging stations, stage, discharge, water temperature, specific conductance, dissolved oxygen, and turbidity are measured continuously at 15-minute intervals. At the downstream five of these stations in Marble and Grand canyons, suspended-silt-and-clay concentration, suspended-sand concentration, and suspended-sand grain size are also measured at 15-minute intervals. These sediment-transport data are used to compute the estimates of sediment loads that are, in turn, used in the six user-interactive mass-balance sand budgets served on this project's website (Sibley and others, 2015). These sand budgets are used to evaluate the near-realtime continuous effects of dam operations (including special LTEMP releases for trout management and invertebrates) on sand resources throughout the CRe, and used in the design and evaluation of HFEs.

Research on the Colorado and on other rivers has shown that, to be meaningful, measurements of stage, discharge, water temperature, specific conductance, turbidity, dissolved oxygen, and suspended sediment must be made at temporal intervals shorter than those over which these parameters vary. Owing to the effects of dam operations and tributary floods, substantial changes in all of these parameters occur at times over timescales less than 1 hour (**Figure 2**, Wiele and Smith, 1996; Wiele and Griffin, 1998; Topping and others, 2000b, 2003, 2010; Voichick and Wright, 2007; Voichick, 2008; Wright and others, 2009; Voichick and Topping, 2010, 2014; U.S. Geological Survey, 2017). This ongoing project was therefore designed to provide measurements of stage, discharge, water quality, and suspended sediment at sufficiently high temporal resolutions (~15-minutes) to capture the variability in these parameters, and in the case of suspended sediment, calculate accurate sediment loads. Collection of such data at 15-minute intervals is the USGS standard. Months to years of data collected at this resolution easily fit on modern dataloggers, result in no additional processing time in the office, and result in no additional financial cost to the project.

# 4. Proposed Work

The work proposed herein is for the continuation of an ongoing project (approved by the GCDAMP Technical Work Group as core monitoring in 2007) to collect, serve, and interpret stage, discharge, water-quality (temperature, specific conductance, turbidity, dissolved oxygen), and sediment-transport data at stations located on the Colorado River in the CRe and on key tributaries. In addition, we propose to continue the web-based construction, serving, and analysis of the continuous mass-balance sand budgets used to evaluate the effects of dam operations on sand storage in the CRe. A map showing the locations at which data are collected/utilized by this project is at: <https://www.gcmrc.gov/discharge_qw_sediment/stations/GCDAMP>; note that the GCDAMP does not fund the data collection at all of the stations on this map. A map showing the extents of the mass-balance sand budgets is at: <https://www.gcmrc.gov/discharge_qw_sediment/reaches/GCDAMP>. Selection of the locations of the stations at which data are collected by this project was largely based on the need to resolve longitudinal differences in sediment storage in key river segments that bracket major tributaries. Elsewhere, data-collection station locations were established to support other GCDAMP-funded projects or to reoccupy former USGS gaging stations.

The data collected by this project will be used to evaluate the near-realtime effects of all LTEMP dam releases on water elevation (stage), discharge, water quality, sediment transport, and sediment storage in the CRe (U.S. Department of the Interior, 2016a, b). The continuous mass-balance sand budgets provide the measurement-based "ground-truthing" of the Sand Mass Balance Index (SMBI) developed in Appendix E of the LTEMP EIS (U.S. Department of the Interior, 2016a). Higher values of the SMBI in the LTEMP EIS were taken as indicators of increased sand storage in the CRe, with increases in sand storage indicating an increase in the sand available to be deposited in sandbars during HFEs. In addition, the sediment-transport data and mass-balance sand budgets are used under the HFE Protocol (U.S. Department of the Interior, 2011; Grams and others, 2015) to work collaboratively with the Bureau of Reclamation to trigger HFEs, design the hydrograph of HFEs, and evaluate the effects of HFEs on sand storage in the CRe.



**Figure 2.**  Plots of 15-minute gage height (i.e., stage, water elevation), water discharge, water temperature, specific conductance, turbidity, dissolved oxygen, suspended-silt-and-clay concentration, and suspended-sand concentration for the two-week period 8-2-2015 through 8-16-2015 at the Colorado River above Diamond Creek gaging station. Light blue dots with 95%-confidence-level error bars indicate episodically measured silt and clay concentrations and sand concentrations (from physical suspended-sediment samples) used to verify the two-frequency acoustical suspended-sediment measurements. Variability in each of these parameters over this two-week period arises from the interaction of dam operations with tributary floods. Plots from this project's website (U.S. Geological Survey, 2017).

All data collected by this project are served and can be downloaded at this project's website at: <https://www.gcmrc.gov/discharge_qw_sediment/> or <https://cida.usgs.gov/gcmrc/discharge_qw_sediment/>. At this website, the user can construct plots in time-series or duration-curve format. In addition, the user can construct interactive plots of the mass-balance sand budgets for the six CRe reaches for any time period for which data exist. The development of this website and its associated database by the collaboration between this project and the USGS Office of Water Information (formerly the Center for Integrated Data Analytics) was the most significant product from this project funded under the FY2013-14 GCDAMP workplan. A brief description of the design of the database and website is provided by Sibley and others (2015). The USGS Office of Water Information (OWI) is the leader within the USGS in database and website design. Collaboration with the OWI resulted in a major leap forward in serving data in a user friendly and interactive way, something that had proven problematic for the Grand Canyon Monitoring and Research Center (GCMRC) to do on its own in previous funding cycles. The tools developed in collaboration with the OWI allow anyone to plot data and construct mass-balance sand budgets for any time period in any reach of the CRe on demand.

A small part of the funding requested under each project element is for the continued maintenance and minor improvement of the database and website by the OWI in Middleton, WI. A minor part of this goes to the housing and secure backup of the servers on which the database and website are located; these servers are physically located at the USGS Earth Resources Observation and Science (EROS) Center near Sioux Falls, SD. In addition to simply maintaining the website during FY 2018-20, we plan to optimize plotting speed, add links to publications, and add metadata.

The USGS-GCMRC personnel on this project are: David Topping (Research Hydrologist and project chief), Ron Griffiths (Hydrologist and deputy project chief), David Dean (Research Hydrologist), Nick Voichick (Hydrologist and water quality specialist), Tom Sabol (Hydrologist and laboratory manager), and three part-time student laboratory technicians. With the exception of the laboratory technicians, all personnel with salary funded by this project receive a substantial part of their salary from other funding sources outside of the GCDAMP.

The measurements of this project are used by all other projects funded by the GCDAMP and are therefore integral to the success of all other projects funded by the GCDAMP. In particular, this project maintains close collaborative ties to Project B (Grams and others, *Sandbar and Sediment Storage Monitoring and Research*). The external collaborations funded through this project are with three USGS cooperators: the Arizona Water Science Center, the Utah Water Science Center, and the Office of Water Information. In addition, academic collaborations (not funded through this project) exist between this project and researchers at Arizona State University, Utah State University, Northern Arizona University, and the University of California–Santa Cruz.

The work proposed herein is segregated into three project elements as described below.

**4.1 Project Elements**

***Project Element A.1, Stream gaging***

This element partially funds the continued collection, serving, and interpretation of continuous 15-minute stage and discharge data at gaging stations on the Colorado River and on key tributaries. All measurements of stage and discharge, and all calculations of discharge are made using standard USGS methods. This element provides partial to full funding for these measurements at five gaging stations on the Colorado River at river miles 30, 61, 87, 166, and 225 (Griffiths and others, 2012). In addition, this element provides partial to full funding for these measurements at: two gaging stations on the Paria River; four gaging stations on the Little Colorado River and in its important sediment-supplying tributary Moenkopi Wash; one gaging station each on Kanab and Havasu creeks; and at eight stations in a representative sub-sample of the previously ungaged lesser tributaries to Glen, Marble, and Grand canyons (Griffiths and others, 2014, 2015, in press). Of the gaging stations at which stage and discharge measurements are utilized by this project, the only two stations that receive no GCDAMP funds are: Colorado River at Lees Ferry, AZ, and Moenkopi Wash at Moenkopi, AZ. The costs of operating a gaging station for stage and discharge varies substantially between stations. Of the stations funded by this element, the most expensive is the Colorado River above Diamond Creek near Peach Springs, AZ, gaging station at river mile 225. This station requires ~$22,000 gross per year to operate. In contrast, each of the stations on the lesser tributaries and half of the stations in the Little Colorado River basin require only ~$1,200 gross per year to operate. Even though the Colorado River above Diamond Creek is the most expensive gaging station operated by this project, it is an extremely important station to maintain. In addition to providing key information on the status of the western part of the CRe, it is the gaging station used to measure the ongoing amount of Colorado River sediment filling Lake Mead (a byproduct of the work funded under Project Element A.3).

In addition to the collection and serving of stage and discharge data at gaging stations, work proposed under this element will also focus on interpreting these data. During the FY 2018-20 period, this interpretive work will focus on completing publications on four topics. First, a major publication will be completed that describes the 1920s-present hydrology of the Paria River and the implications of hydrologic variability/change on the Paria River for sand management in the CRe. The Paria River is the single largest and geographically most important supplier of sand to the Colorado River in the CRe, and current management of sediment in the CRe using HFEs depends on the sand supply from the Paria River (U.S. Department of the Interior, 2011, 2016 a, b). Thus, because changes in the hydrology of the Paria River directly result in changes in the sand supply of the Paria River, this publication will be of great importance to river managers. Second, a publication will be completed that uses stream-gaging data funded by this element in the Little Colorado River and Moenkopi Wash to evaluate the decrease in sand transport in the Little Colorado River. Third, a publication will be completed that uses the stream-gaging data funded by this element to evaluate how the flood history of the Little Colorado River has affected the native fish habitat in the lowermost part of this river. Finally and fourth, a publication will be completed using the stream-gaging data funded by this element in the main-stem Colorado River to evaluate the effects of all LTEMP­­ flows on sediment transport and storage in the Colorado River.

***Project Element A.2, Water quality***

This element fully funds the continued collection, serving, and interpretation of continuous 15-minute measurements of water temperature, specific conductance, turbidity, and dissolved oxygen. This element also funds episodic measurements of specific conductance associated with suspended-sediment samples collected in tributaries (these measurements are intrinsic to the laboratory methods for processing the suspended-sediment samples and therefore cost nothing). In addition, this element provides a small amount of the logistical support required to make non-GCDAMP-funded water-chemistry measurements in the Colorado River (including some of the measurements of nutrients used by proposed Project E). All water-quality measurements are made using standard USGS methods. Under this element 15-minute measurements of water temperature, specific conductance, turbidity, and dissolved oxygen are made using YSI multi-parameter sondes in the Colorado River at the gaging stations located at river miles 30, 61, 87, 166, and 225. See Voichick and Wright (2007), Voichick (2008), and Voichick and Topping (2010, 2014) for detailed descriptions of these sondes and measurements. In addition, 15-minute measurements of water temperature are made at three additional stations on the Colorado River and at stations near the mouths of the Paria and Little Colorado rivers, and Kanab and Havasu creeks.

***Project Element A.3, Sediment transport and budgeting***

This element fully funds the continued collection, serving, and interpretation of continuous 15-minute measurements and also episodic measurements of suspended and bed sediment. All measurements funded under this element are made using standard USGS and other peer-reviewed methods. Under this element, continuous two-frequency acoustical suspended-sediment measurements (calibrated and verified using conventional physical suspended-sediment measurements) are made in the Colorado River at the gaging stations located at river miles 30, 61, 87, 166, and 225 using the method of Topping and Wright (2016). In addition to informing river management in the GCDAMP, this acoustical method is now being used to also inform river managers of sediment transport at locations in the Upper Colorado River basin and in the Rio Grande basin (Dean and others, 2016; Topping and others, 2016). Errors in the conventional suspended-sediment measurements are calculated using the methods of Topping and others (2011) and Sabol and Topping (2013); errors in the acoustical measurements are documented in Topping and Wright (2016). In addition to these measurements on the main-stem Colorado River, episodic suspended-sediment measurements are made at the tributary gaging stations funded under project element 1. These measurements are used in conjunction with models (after Topping, 1997) to determine the near-realtime sediment inputs from the Paria and Little Colorado rivers. On the other tributaries, these measurements are used to document the sand, silt, and clay supply from the other major and lesser tributaries and to refine the long-term estimates of the importance of these other tributaries for supplying sediment to the Colorado River. Most of the sediment work on tributaries utilizes automatic samplers and has a large payoff in information for relatively low cost.

In addition to the collection of the sediment-transport data, this element fully funds the web-based construction and analysis of continuous mass-balance sand budgets for the CRe using the continuous suspended-sediment measurements on the Colorado River and the episodic suspended-sediment measurements on the tributaries. These sand budgets have been proven to be an accurate indicator of the change in the amount of sand stored in the Colorado River. In two independent comparisons with sand budgets developed using the channel-mapping data of Project B (*Grams and others*), these continuous mass-balance sand budgets have agreed with the topographic-based sand budgets of Project A within an acceptable range of uncertainty. These comparisons were conducted between 2009 and 2012 in the Lower Marble Canyon reach (river miles 30-61) and between 2011 and 2014 in the Eastern Grand Canyon reach (river miles 61-87). Therefore, the continuous mass-balance sand budgets allow managers to accurately track changes in the amount of sand (with uncertainty) in different reaches of the CRe on an ongoing, near-realtime basis (daily to monthly as needed), and therefore allow managers to continuously evaluate the effects of any flow released from the dam (LTEMP or otherwise) on the sand resources in the CRe on monthly or shorter timescales. Furthermore, these sand budgets provide the "ground truth" for the Sand Mass-balance Index used to evaluate different flow alternatives in the LTEMP EIS (U.S. Department of the Interior, 2016a, b).

In addition to having great utility in evaluating the effects of LTEMP dam releases on the CRe, these mass-balance sand budgets are used in collaboration with the Bureau of Reclamation to trigger, plan, and evaluate HFEs (U.S. Department of the Interior, 2011; Grams and others, 2015). HFEs are triggered and designed on the basis of the Paria-supplied sand that accumulates in Marble Canyon during fall and spring implementation windows (U.S. Department of the Interior, 2011). This process involves using many suspended-sediment samples collected in the Paria River (quickly processed through the GCMRC sediment laboratory) in combination with discharge data (funded under Project Element A.1) and initial model estimates (after Topping, 1997) to determine the near-realtime continuous sand supply from the Paria River. The Bureau of Reclamation then uses this information, along with information on planned dam releases, as input to the sand-routing model of Wright and others (2010). As more suspended-sediment measurements get processed through the laboratory (work funded by this element), the uncertainty is reduced in the estimates of the Paria River sand supply, and additional model runs are made by the Bureau of Reclamation. As time progresses, the Bureau of Reclamation's model-predictions of sand retention in Marble Canyon are compared against the actual measured sand retention in the continuous mass-balance sand budgets funded under this project element. Because the predictions of the sand-routing model of Wright and others (2010) may be biased, this comparison allows evidence-based redesign of each planned HFE hydrograph. Finally, after the completion of each HFE, these sand budgets allow quick post-facto evaluation of the longitudinal effects of each HFE on the sand resources in the CRe.

In addition to the collection and serving of the sediment-transport data and construction of the continuous mass-balance sand budgets, work proposed under this element will also focus on interpreting these data. During the FY 2018-20 period, this interpretive work will focus on completing publications on three topics. First, a major publication will be completed that links the hydrology and geomorphology of the Paria River to the amount of sand supplied by the Paria River to the Colorado River. Second, a publication will be completed that documents the causes of the long-term decreases in and likely future magnitude of the amount of sand supplied by the Little Colorado River to the Colorado River. In addition, this paper will directly address how changes in sediment transport in the Little Colorado River have affected the habitat for native fish in the lower Little Colorado River, and how future changes in sediment transport may continue to alter this habitat. Third, a publication will be completed that uses all data collected by this project to evaluate how LTEMP dam releases have affected sand resources during 2018-20.

**4.2 Deliverables**

Deliverables from this project fall into two categories: serving of data and publication of interpretive products. Perhaps the most important deliverable from this project during FY 2018-20 will be the continued serving of all data collected and/or utilized by this project, including the continuous mass-balance sand budgets, at: <https://www.gcmrc.gov/discharge_qw_sediment/> or <https://cida.usgs.gov/gcmrc/discharge_qw_sediment/>. In addition, multiple interpretive journal articles and top-tier USGS reports will be published, including on the following topics:

* + Analysis of Paria River hydrology 1920s-present with implications for long-term sediment management in the CRe (*lead author Topping*)
  + Geomorphology, hydraulic geometry, and sediment transport in the Paria River (*lead author Topping*)
  + Sediment transport and geomorphic change in the Little Colorado River, with implications for aquatic and riparian habitat in the lower Little Colorado River (*lead author Dean*)
  + Initial evaluation of LTEMP flows on sediment storage in the CRe (*lead author Griffiths*)

In addition to these major publications, additional data reports and interpretive reports will be published by project personnel and USGS cooperators. Among these additional reports form USGS cooperators will be a USGS report describing the flood history of the lowermost Little Colorado River, and the implications of this flood history for maintenance of native fish habitat.

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# Budget

Owing to efficiencies in conducting the work funded under this ongoing project, and to the diversification of the salary burden to projects on other rivers funded by non-GCDAMP sources, the annual net (i.e., before overhead) budget proposed for this project during the FY2018-20 period is ~10% less than that requested during the FY2015-17 period. Although the proposed budget is sufficient to cover annual monitoring and research (including during standard HFEs), supplemental funding may be requested from the Bureau of Reclamation's experimental fund to conduct additional monitoring and research during special LTEMP flow experiments (e.g., extended-duration HFEs).







Project B. Sandbar and Sediment Storage Monitoring and Research

1. **Investigators**

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Robert Tusso, Hydrologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

Robert Ross, Hydrologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

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John C. Schmidt, Professor, Utah State University

1. **Project Summary**

The purposes of this project are to a) track the effects of individual high-flow experiments (HFEs) on sandbars, b) monitor the cumulative effect of successive HFEs and intervening operations on sandbars and sand conservation, and c) investigate the interactions between dam operations, sand transport, and eddy sandbar dynamics.

The sand deposits on the bed and banks of the Colorado River in Glen, Marble, and Grand Canyons are directly affected by the operations of Glen Canyon Dam. Depending on the relative magnitudes of dam releases and tributary sediment inputs, sand either accumulates or is eroded from the bed of the river. When evaluated over long river segments, sand is evacuated from the river bed during sustained periods of high dam-releases (Topping and others, 2000; Grams and others, 2015) and sand accumulates during periods of average dam-releases and substantial tributary sediment inputs (Grams, 2013; Grams and others, 2013). Sandbars along the river banks above average base flow (about 8,000 ft3/s) also change in response to dam operations, but in a different pattern, because they are not always inundated and because they comprise a small fraction of the sand in the system (Hazel and others, 2006; Grams and others, 2013). These deposits aggrade significantly during HFEs that exceed powerplant capacity (Schmidt and Grams, 2011) and, to a lesser extent, during powerplant capacity flows (Hazel and others, 2006). These deposits typically erode during normal powerplant operations between HFEs (Hazel and others, 2010).

One of the stated goals in the Record of Decision (ROD) for the recently completed Long-Term Experimental and Management Plan (LTEMP) (U.S. Department of the Interior, 2016) is to "increase and retain fine sediment volume, area, and distribution...for ecological, cultural, and recreational purposes." Expectations of improved sandbar building and conservation of sediment were among the criteria used in the selection of the preferred alternative. One of the central components of the selected alternative is the continued implementation of HFEs for building sandbars. The LTEMP extends the program initiated with the *Environmental Assessment for Development and Implementation of a Protocol for High-Flow Experimental Releases from Glen Canyon Dam* (HFE Protocol)which asked the question*,* "Can sandbar building during HFEs exceed sandbar erosion during periods between HFEs, such that sandbar size can be increased and maintained over several years?" In other words, does the volume of sand aggraded into eddies and onto sandbars during controlled floods exceed the volume eroded from sandbars during intervening dam operations? Additional, condition-dependent experiments are included in the preferred alternative that have objectives related to sandbar building and sediment conservation. Project B includes elements that are designed to evaluate whether the sediment-related goals of the LTEMP are met, provide the information that is needed to proceed with or abort LTEMP experimental activities, and evaluate the effectiveness of implemented experiments.

Thus, one of the most important objectives of Project B is to monitor the changes in sandbars over many years, including a period that contains several controlled floods, in order to compile the information required to answer the fundamental question of the HFE Protocol. The monitoring program described here continues the program implemented in previous work plans and is based on annual measurements of sandbars, using conventional topographic surveys supplemented with daily measurements of sandbar change using ‘remote cameras’ that autonomously and repeatedly take photographs. These annual measurements and daily photographs are included in Project Element B.1. This project element also includes work to more efficiently conduct quantitative analyses of the remote camera images. Because these long-term monitoring sites represent only a small proportion of the total number of sandbars in Marble and Grand Canyons, this project also includes periodic measurements of nearly all sandbars within individual 50 to 130 km river segments.

Another critical piece of information needed to evaluate the outcome of the HFE Protocol and the LTEMP will be the change in total sand storage in long river segments. HFEs build sandbars by redistributing sand from the low-elevation portion of the channel to sandbars in eddies and on the banks. The sand available for bar building is the sand that is in storage along the channel bed, which is the sum of the sand contributed by the most recent tributary inputs, all the sand that has accumulated during the decades since Glen Canyon Dam was completed, and any sand that remains from the pre-dam era. The goal of the HFE protocol is to accomplish sandbar building by mobilizing only the quantity of sand most recently contributed by the Paria River. Some of the mobilized sand is deposited in eddies where it maintains and builds eddy sandbars. Some of the sand is eventually transported downstream to Lake Mead reservoir. The most efficient floods for the purposes of sandbar building are those that maximize eddy sandbar aggradation yet minimize the amount of sand transported far downstream, thus minimizing losses to sand storage. Dam operations between HFEs also transport sand downstream, causing decreases in sand storage.

The trends in sand storage along the channel bed combined with trends in exposed sandbars will provide the necessary context on which to base future decisions about dam operations and other potential management options. If sand storage is maintained or increased, we expect the response to future HFEs to be similar to or better than that observed following recent HFEs. In contrast, depleted conditions of fine sediment in the active channel are potentially irreversible and threaten the long-term ability to maintain eddy sandbars. These long-term trends are measured in Project Element B.2, which includes one “channel mapping” campaign to map changes in sand storage in both Lower Marble Canyon and Eastern Grand Canyon in 2019. Because these segments have been mapped previously and because mapping efficiency has increased, we are able to map longer river segments in a single river trip than previously. These data will be used to provide long-term (8 to 10 year) assessments of sandbar and sand storage change for these segments and a robust evaluation of 7 years of implementation of the HFE Protocol.

This project also includes two research components, a support component, and one experimental component. The first research component is Project Element B.3, which is a modeling project that will produce flow models that predict the inundation extent and flow velocities for dam operations and HFEs in Marble Canyon and improve capabilities for predicting sandbar response to dam operations. Project Element B.4 is a research project that will investigate river channel adjustment and redistribution of reservoir delta sediments on the Colorado River within the Colorado River ecosystem (CRe) between Diamond Creek and the western boundary of Grand Canyon National Park. Project Element B.5 includes work to improve the control network in support of this and other work plan projects. Project Element B.6 describes studies that will be conducted to monitor and evaluate the condition-dependent experiments that affect sandbars and sediment resources. This project element also includes description of proposed laboratory experiments to address the same suite of questions as the condition-dependent experimental HFEs are designed to test.

1. **Background**

The changes to the flow regime and sediment supply associated with completion of Glen Canyon Dam (Topping and others, 2000) caused deep scour and armoring of the river bed between the dam and Lees Ferry, 25 km downstream (Pemberton, 1976; Williams and Wolman, 1984; Grams and others, 2007). Downstream from Lees Ferry in Marble and Grand Canyons, the debris fans at tributary mouths result in a different channel configuration and different style of response to the upstream dam. The boulder and cobble deposits that form rapids have been largely stable (Magirl and others, 2005), while areas of the bed covered by fine sediment have been eroded, and many eddy sandbars are much smaller than they once were (Schmidt and others, 2004; Wright and others, 2005). Because systematic measurements of fine-sediment thickness have not yet been made, the total volume of fine sediment present (or eroded) is not known.

Sandbars are one component of the total sediment budget for the Colorado River. The sediment budget, or sediment mass balance, is simply the accounting by mass (or volume) of all sediment entering and exiting any segment of a river. This budget may be expressed as:

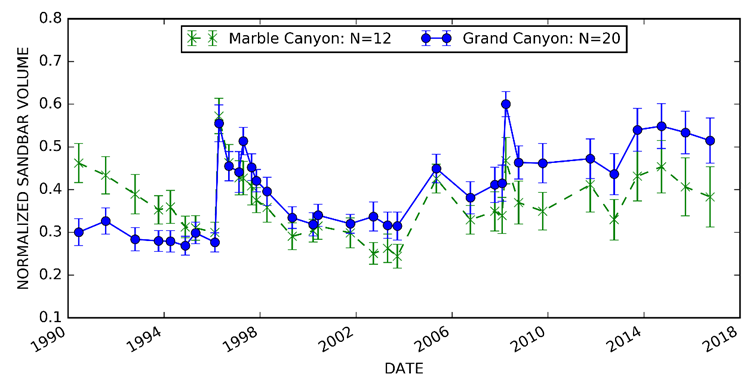
, (1)

where is the sum of all inputs, is the sum of all outputs, and is the net change in the sediment deposits that occurs within that segment of river. When inputs exceed outputs, sediment accumulation occurs; when outputs exceed inputs, sediment evacuation occurs. To provide greater spatial resolution, equation (1) can be partitioned by the elevation zone in which occurs. Sand stored low in the active channel () is always underwater and sand stored higher in the active channel () is only occasionally inundated. Thus,

(2)

We use “low” to refer to fine-sediment deposits below the stage associated with the 8,000 ft3/s discharge and “high” to refer to fine-sediment deposits above the 8,000 ft3/s stage. The low-elevation deposits are always underwater except during the trough of some flow fluctuations; these deposits consist of the lower parts of eddy sandbars and patches of sand on the river bed. These low-elevation deposits are relevant to aquatic habitat and are the source for sand remobilized during HFEs. The high-elevation fine-sediment deposits are alternately inundated and exposed, depending on the flow regime. These deposits are used as camping beaches, support riparian vegetation, and support other upland resources.

Annual monitoring of high-elevation deposits has been conducted systematically since 1990. These data clearly demonstrate the role of dam operations, primarily HFEs, in causing changes in sandbar size (Fig. 1). Each HFE has resulted in deposition and there has been erosion in each of the periods between HFEs (Hazel and others, 2010; Schmidt and Grams, 2011; Mueller and others, 2014). HFEs conducted within the HFE Protocol since 2012 have resulted in sustained, but not progressive, increases in sandbar area. Additionally, vegetation has established on portions of sandbars in many parts of the river corridor since the beginning of monitoring (Sankey and others, 2015; Mueller and others, 2016), which may stabilize new HFE deposits so that the area available for sandbar building is reduced during subsequent HFEs.



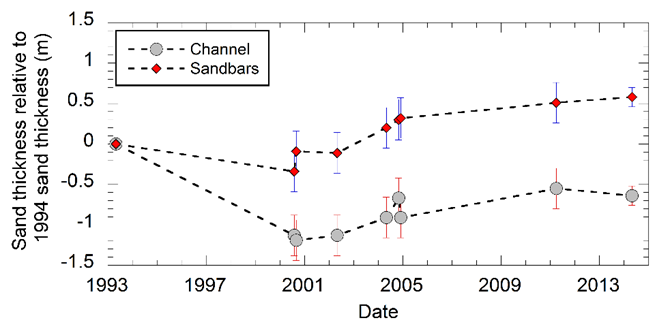
**Figure 1.** Sandbar size from 1990 to October 2016 (preliminary data provided by Joseph E. Hazel, Jr.). N is the number of sites in those respective reaches. The sandbar volume is normalized to the maximum expected volume for each site.

Low- and high-elevation deposits are coupled through processes of streamflow erosion and deposition, wind erosion and deposition, and mass failure. This coupling means that changes in will affect both low- and high-elevation sediment. Although HFEs are scheduled based on the quantity of recent sand inputs from the Paria River, both those inputs and residual sand are mobilized to elevate sand concentrations. Recent investigations of the geochemistry of sand deposited during HFEs indicates that between 20 and 80 percent of the sand within HFE deposits is likely derived from the Paria River (Chapman and others, 2016), with the remainder derived from pre-dam sediment along the channel and its margins. Thus, a substantial proportion of the sand deposited during HFEs may be derived from pre-dam sediment stored in eddies and the riverbed. Because higher concentrations of sand in suspension will result in greater rates of deposition during HFEs (Wiele and others, 1999), decreases in background sand storage – unless they are offset by tributary sediment inputs – will likely lead to diminished capacity to achieve one of the central LTEMP goals of rebuilding and maintaining sandbars using HFEs. Therefore, predictions about the long-term fate of sandbars must be based on understanding long-term trends in , including both . For these reasons, all sandbar research and monitoring is designed around this concept of the sediment budget.

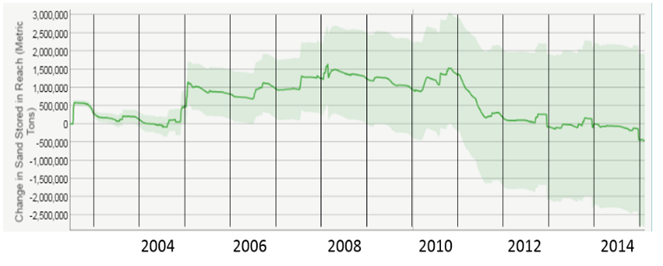
The measurements of suspended sediment made in Project A track the inputs and outputs (*I* and *O* in equation (1) and are used to calculate for the sediment budget reaches[[1]](#footnote-2). This approach tracks the accumulation of tributary inputs that is essential for implementation of the HFE Protocol. However, this calculation does not distinguish between low- and high-elevation deposits, so results cannot be used to evaluate changes in sandbar size, campsite area, sand available for plant colonization, or other changes of recreational or ecological significance. Uncertainty in the measurements of sediment flux also accumulate with time, limiting the utility of those measurements for tracking long-term trends.

Previous studies analyzing repeat topographic measurements of the channel, eddies, and sandbars have found that 90 percent or more of the changes in sand volume occur at low-elevation and the high-elevation sandbars comprise only about 10 percent or less of the fine sediment in the system (Hazel and others, 2006). These studies have also found that computed for short study reaches yielded different values than computed as the difference between sand inflows measured at gaging stations using equation (1). This discrepancy stems from the inability to correctly extrapolate measurements from the short reaches to larger spatial scales because changes in bed topography are highly localized and spatially variable (Grams and others, 2013). These findings demonstrate that determining whether sediment storage in each storage environment – at low and high elevations and in the channel and eddy – is increasing, decreasing, or stable, requires repeat measurements of sand storage in every storage environment throughout the long sediment budgeting reaches.

Such measurements have been made in various sand-budgeting segments since 2009 and repeat maps for the segment between river mile (RM) 30 and RM 61 (Lower Marble Canyon) and the segment between RM 61 and RM 87 (Eastern Grand Canyon) both capture large spatial variability in erosion and deposition that allow robust calculation of the evacuation of sand that occurred during the period of high releases in summer 2011 (Grams and others, 2015). These measurements also show an overall loss of high-elevation sand in Lower Marble Canyon and a slight increase in high-elevation sand in Eastern Grand Canyon.

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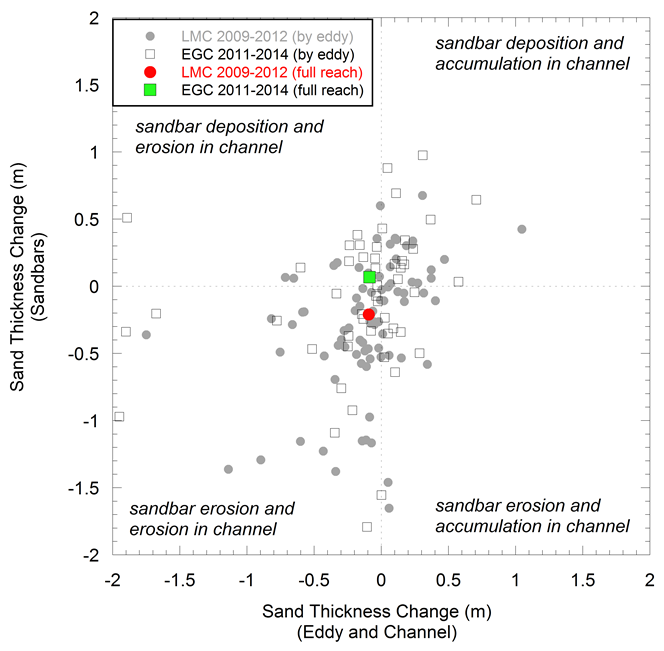
**Figure 2.** Change in mean bed elevation between 1993 and 2011 for a 4-km segment between RM 63 and RM 65 in Eastern Grand Canyon. The changes between 2011 and 2014 are based on measurements made throughout all of Eastern Grand Canyon and have less uncertainty. Uncertainty is a smaller fraction of the change in this example than in Fig. 3, because this figure shows larger changes over a longer time period.



**Figure 3.** Sand budget for August 2002 to December 2014 for Eastern Grand Canyon. The sand budget computed by the difference in sand transport at the upstream and downstream ends of the reach is shown by the solid line with the shaded region indicating uncertainty bounds.

As the period of repeat measurement of the bed and sandbars lengthens, the value of those measurements and the importance of the interpretations will increase. Figure 2 shows changes in bed elevation for a 4-km reach between RM 63 and RM 65 between 1993 and 2014. For the period between 2002 and 2014, these data show changes that are consistent with the flux-based sand budget but have much less uncertainty than the flux-based measurements (Fig. 3) whose uncertainty accumulates with time.

Figure 4 illustrates how these measurements will be interpreted and how they may be used to guide management decisions. This plot shows sand thickness change in sandbars () against sand thickness change in the eddy and channel (), using all of the data collected in Lower Marble Canyon (changes between 2009 and 2012) and Eastern Grand Canyon (changes between 2011 and 2014). The measurements for individual eddies show a general tendency for the low and high elevation deposits to change similarly, but there are many eddies for which the low and high elevation deposits change in opposing directions. Averaged for all of Lower Marble Canyon, there was erosion of both low- and high-elevation deposits. On average in Eastern Grand Canyon, there was erosion of low-elevation deposits and slight deposition of high-elevation deposits. If sustained over long periods, these changes would have significant management implications. Sandbar deposition accompanied with accumulation in the channel would indicate that sandbar building and sediment conservation goals are likely being met and, furthermore, that sand supply would likely support increases in HFE frequency and/or duration. Sandbar erosion accompanied with sand accumulation in the channel would also indicate that despite adequate sand supply, sandbar maintenance goals are not being met. This would suggest some change in operations might be required to achieve different results. Sandbar deposition accompanied by erosion in the channel is expected to occur over short periods (such as during HFEs) as sand is transferred from low to high elevation. However, continuation of this pattern over long periods would indicate that sandbars are being built at the expense of progressive depletion from the channel. In this case, reductions in HFE frequency and duration or other changes to operations might be considered. The “worst case” scenario is sandbar erosion accompanied by erosion in the channel. This is also expected to occur over short time periods, but over long periods would likely indicate that available sand supply is insufficient to support sandbar maintenance without changes in dam operations or other management actions.



**Figure 4.** Change in high-elevation sand (sandbars) as a function of change in low-elevation sand (eddy and channel) based on repeat measurements in Lower Marble Canyon (LMC) and Eastern Grand Canyon (EGC). The data points “by eddy” show changes tabulated for each eddy within the respective segments. The colored “full reach” points show the average of all changes for each segment. Changes are in average “thickness” of sand. An average thickness change of just 0.5 m over a 50-km reach equates to over 4 million metric tons of sand.

1. **Proposed Work**

**4.1. Project Elements**

***Project Element B.1. Sandbar monitoring using topographic surveys and remote cameras***

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Keith Kohl, Surveyor, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

Robert Ross, Hydrologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

Graduate Student, Northern Arizona University

***Project Description***

The primary purposes of the sandbar monitoring project are to track the individual and cumulative effects of HFEs and intervening dam operations on sandbars and campsites in the CRe. In addition, this project will evaluate how sandbar size and shape; 1) affect the bar-building response of HFEs, and 2) affect bar erosion following HFEs.

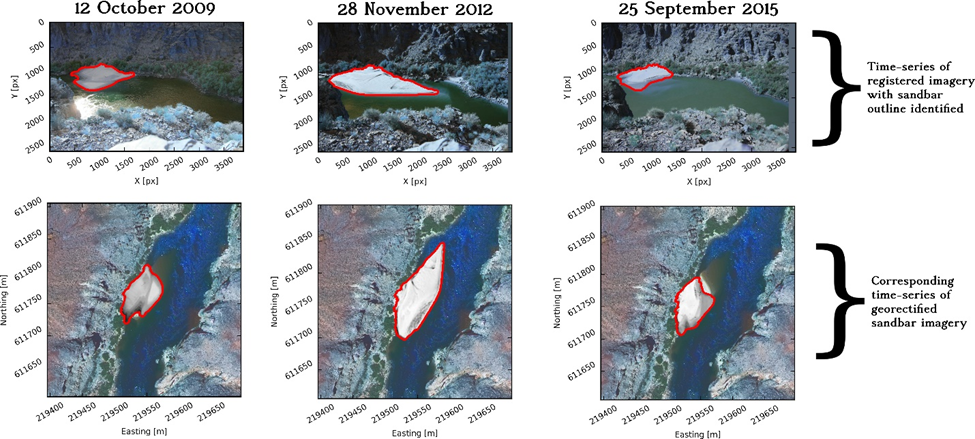
A subset of all sandbars and campsites located throughout the CRe will continue to be monitored annually using conventional ground-based topographic surveys. These surveys will contribute to the long-term sandbar time-series, maintained by Northern Arizona University, which is the longest, most accurate, and complete dataset describing the state of sandbars in the CRe. The monitoring program, initiated in 1990, includes surveys at 47 sites, which provides measurements of sandbar area and volume above the stage associated with a discharge of 8,000 ft3/s. Methods for these surveys are described by Hazel and others (2008; 2010) and Kaplinski and others (2009; 2014). These annual surveys are supplemented by photographs of 42 sites, taken several times per day, using autonomous remote digital-camera systems (Bogle and others, 2012). These images make it possible to record the effects of changes in flow at a temporal precision that cannot be resolved by the annual topographic measurements. The FY2015–17 work plan included a project that evaluated using images collected from hand-held and pole mounted digital cameras for surveying sandbars. The project demonstrated that the method can be applied to surveying sandbars, but does not provide a time or cost savings over the traditional methods. Therefore, we do not propose a change in monitoring methods for this work plan.

The monitoring metrics of sandbar volume and area are related to campsite area (Hazel and others, 2010), but are not a direct measurement of campsite size. Two supplementary monitoring efforts are, therefore, included in this project to track changes in campsite size that are related to changes in sandbar topography and/or change in the extent of vegetation cover. The first of these project components is annual measurements of campsite area at 32 of the 47 sandbar monitoring sites conducted on the annual sandbar-monitoring trip. The second component is observations and photographs for a collection of approximately 40 of the most popular recreational camping beaches between Lees Ferry and Diamond Creek. These observations are made by Grand Canyon River Guides through the “Adopt-a-Beach” program.

During the FY2015-17 work plan, techniques were developed and tested for using the remote camera images to 1) compute sandbar area; 2) estimate sandbar face slope in the region of flow fluctuations; and 3) estimate sandbar volumes from digital elevation models (DEMs) of entire sandbars from photographs taken during the recession phase of an HFE. During the next work plan, we propose to move beyond this ‘proof-of-concept’ phase into a robust monitoring technique that will be implemented at 10 to 15 of the existing network of 45 sites to reliably provide 1) monthly time-series of sandbar areas and face slopes, and 2) sandbar volume immediately after HFEs.

A monthly time-series of sandbar area and shoreface slope measurements will provide crucial and otherwise unobtainable information about the retention of sand in bars in the months following HFEs as well as in response to equalization flows and other proposed flows. Sandbar volume estimates derived from measurements made immediately following HFEs will provide the necessary data to quantify and understand the HFE response of a given sandbar, and a set of sandbars collectively. Furthermore, the greater temporal resolution of the sandbar time-series will allow for a more robust quantification of sandbar erosion rates following HFEs. This will be a major advance over present qualitative (visual) assessments of sandbar responses to HFEs, and will be vital to model validation in Project Element B.3.

There are three major aspects to computing a time-series of sandbar area measurements from a series of oblique photographs at a site. First, the image must be georectified (Fig. 5), which is the process of creating a planform-perspective image in a projected coordinate system. Second, the sandbar must be segmented from the image, which is the process of identifying the entire outline of the sandbar. Third, relationships must be established between the area of a sandbar at a given time (i.e., at a specific flow stage), and that at a reference flow stage (8,000 ft3/s), for comparative purposes.



**Figure 5.** Time-series of registered oblique (top row) and corresponding georectified (bottom row) imagery. The red perimeters of the bar have been found using a semi-automated procedure.

To facilitate data processing and analysis, we intend to develop software that will be linked to a database that will streamline the entire processing workflow. This workflow includes image uploading, keeping track of image metadata and derived data from images, implementing methods for image registration, georectification, segmentation, extraction of waterline contours, area and slope estimation, post-flood DEM construction and sandbar volume estimation. This software will serve as the ‘one-stop’ sandbar-monitoring tool that will store data in formats that can easily be served on the existing sandbar-monitoring website and data repository at www.gcmrc.gov.

***Outcomes and Products***

* Update on sandbar area and volume and campsite area based on monitoring from the previous year.
* Annual monitoring data made available on website within six months following data collection.
* Adopt-a-Beach photography to be served on website on an annual basis.
* Remote camera images showing effects of HFEs made available on website within two months following data collection.
* Remote camera image georectifications, sandbar area and slope time-series, and post-HFE sandbar volumes, for at least 13 sites, also served on sandbar website.
* Report and/or journal article describing remote camera image processing methods and results.

***Project Element B.2. Bathymetric and topographic mapping for monitoring long-term trends in sediment storage***

Paul Grams, Research Hydrologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

Daniel Buscombe, Research Professor, Northern Arizona University\

Matt Kaplinski, Research Associate, Northern Arizona University

Joseph E. Hazel, Jr., Research Associate, Northern Arizona University

Robert Tusso, Hydrologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

Keith Kohl, Surveyor, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

David Topping, Research Hydrologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

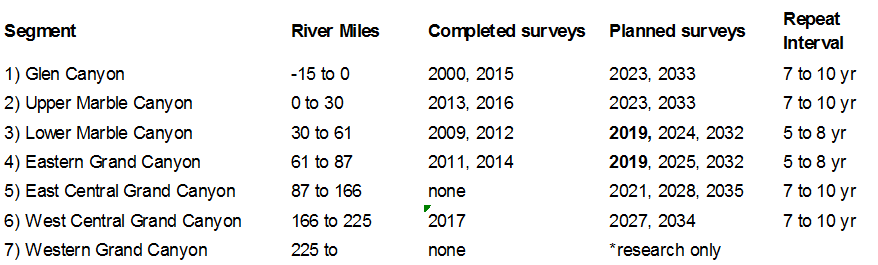
Graduate Student, Northern Arizona University

***Project Description***

LTEMP objectives for fine sediment are focused on the condition of sandbars. The purpose of the HFE protocol embedded in the LTEMP is to maintain and build sandbars using high flow releases that are timed to coincide with periods of sand supply from tributaries (Wright and Kennedy, 2011). The success of this approach is predicated on the existence of sand within the channel for rebuilding sandbars. The primary purpose of Project Element B.2 is to track trends in sandbar conditions and sand storage over the time scale of the HFE protocol and the LTEMP and thereby provide a robust measure of whether or not that supply of sand necessary for building sandbars is increasing, decreasing, or stable (Wright and others, 2008). This project monitors changes in sand storage by location, providing spatially explicit quantification of changes in the channel, eddies and sandbars. The results from this project will be used to evaluate the outcome of the flow regime adopted in the LTEMP with respect to sandbar building and sand conservation. The measurements of sand storage in the channel are critical, because that information will be needed to explain the observed trends in sandbar area and volume. This information will be needed to determine whether HFEs should be conducted more frequently or less frequently than prescribed in the LTEMP ROD and will be needed to assess whether the implemented flow regime alone is sufficient to achieve sediment-related goals, or whether additional management actions should be considered.

The sampling design used in this project is based on our current understanding of sediment dynamics, the locations of stream-gaging stations, and the timeframe of the LTEMP. The CRe is divided into seven segments based on the location of the streamflow and sediment gages (Table 1). For each of the five segments between Lees Ferry and Diamond Creek, flux-based sand budgets are computed at 15-min. intervals (see Project A). In using these same segment boundaries for long-term sandbar and sand-storage monitoring, we are able to correlate changes that occur in the channel, eddies, and on sandbars with the measurements of sand transport. Within each of these segments, it is necessary to measure approximately 50 to 70 percent of the channel and eddies, based on the findings of Grams and others (2013) and Grams and others (2015). Because about 90 percent of the sand that is available for redistribution by dam operations is submerged (Hazel and others, 2006), the monitoring method must include measurements of sediment on the bed of the river in eddies and pools. Bed sediment data collection will combine multibeam and singlebeam sonars, coupled with conventional topographic surveys for areas above the water surface. These methods have been described by Hazel and others (2008; 2010) and Kaplinski and others (2009; 2014; 2017). The data will result in high-resolution digital elevation models of the mapped segments for each mapping effort (e.g. Kaplinski and others, 2017).

The proposed schedule for completing repeat maps for each segment is based on the major milestones in the high-flow experimental protocol and the LTEMP. These milestones are; 1) 10 years of implementing the HFE protocol, 2) 10 years after LTEMP implementation when a major evaluation is required, and 3) 20 years after LTEMP implementation. The assessment of the first 10 years of the HFE protocol will be based on repeat maps of lower Marble Canyon and Eastern Grand Canyon that will be collected in this work plan. Upper Marble Canyon is not included in this assessment in an effort to limit mapping frequency to one data collection effort in this 3-year work plan to provide the flexibility that will be required to implement the contingency studies to evaluate the effects of LTEMP experimental flows (see Project Element B.6). The 10-year assessment of LTEMP will be provided by repeat maps of upper Marble Canyon, lower Marble Canyon, and Eastern Grand Canyon conducted between 2023 and 2025. Repeat maps of West Central Grand Canyon and East Central Grand Canyon will be completed in 2027 and 2028, respectively, to provide interim evaluations of the effects of LTEMP operations on those segments. The final assessment of LTEMP will be based on repeat maps of all segments conducted between 2032 and 2036.



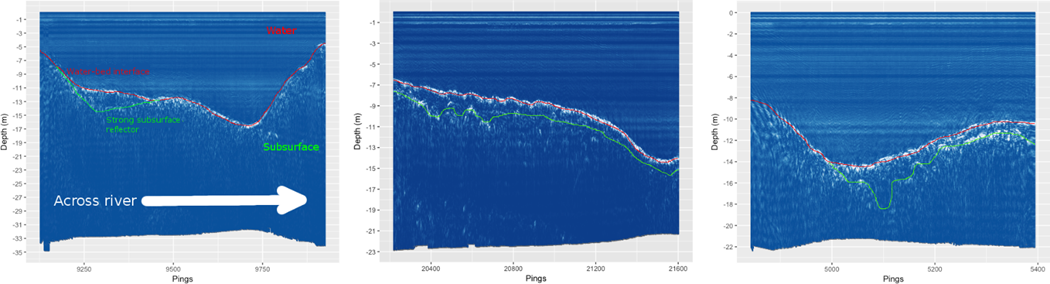
**Table 1.** Proposed schedule of channel mapping efforts for this work plan through the period of the LTEMP.

Efforts are focused on Marble Canyon and eastern Grand Canyon, because these segments are believed to have the greatest risk of sediment deficit and because sandbar volume gains in the HFE period have not been as large in Marble Canyon as in downstream segments. However, exclusive focus on Marble Canyon does not fully address sediment-related GCDAMP and LTEMP goals, which include all river segments in the CRe. For these reasons, an initial map of West Central Grand Canyon was completed in April 2017. We propose completing an initial map of East Central Grand Canyon in FY 2021, which will require control work in the current work plan (see Project Element B.5).

Upon completion of a repeat map of a segment, the maps (DEMs) will be compared to compute the net change in the volume of sediment within the segment. These computations will distinguish between fine and coarse sediment using recently developed acoustic sediment classification algorithms (Buscombe and others, 2014a, b), between sediment stored in the channel and eddies, and between sediment at high- and low-elevation. The resulting maps of bed sediment substrates are as highly resolved as the bathymetric maps and will be used for habitat classifications in other projects.

A secondary purpose of this project is to develop estimates of the total mass and volume of sand storage. Information on the volume of sand stored within the channel bed is valuable for three primary reasons. First, understanding the dynamics of sandbars in eddies requires information on the sand replenishment potential from the adjacent eddy and channel, which in turn necessitates information on the thickness of sand deposits in those areas. Second, only through estimating the total sand storage in the system can we evaluate the long-term importance of observed net changes in sand storage by repeat channel mapping and sediment flux monitoring (Project A). Third, the sediment routing model used to design HFEs requires information on the active layer sand thickness on the channel bed. Currently, in lieu of better information, this was set to 0.5 m, and the model was calibrated to this estimate (Wright and others, 2010). This simplification limits the predictive capacity of the model.

During the FY2015-17 work-plan, techniques for sub-surface imaging of the riverbed and estimation of sand thickness were developed and data were collected in Upper Marble Canyon and West Central Grand Canyon with a frequency-modulated (CHIRP) echosounder system, which provides up to 10 m of subsurface penetration through sand (Fig. 6).



**Figure 6.** Example cross-sections from CHIRP sonar surveys. Red line is sediment-water interface. Green line is interpreted as the lower boundary of sand deposit. Sand thickness varies 0 - 5 m in these examples. The presence or absence of sand in areas with no strong subsurface reflector (green line) will be determined by analysis of multibeam-derived surface sediment maps.

In this work plan, we propose to use the same sub-bottom profiler to collect similar data in Lower Marble Canyon and Eastern Grand Canyon. These data and the data previously collected will be interpreted to provide sand thickness estimates for all areas mapped. Sediment classification maps (Buscombe and others, 2014a, b), rectified echograms from sidescan sonar (Buscombe and others, 2015; Buscombe, 2017), and bed sediment images from the eyeball system (Buscombe, 2013) will be used to aid interpretation of the CHIRP data. To provide estimates of sand thickness in areas of the bed not mapped with the CHIRP sonar, we will develop relationships between sand thickness and a suite of variables derived from the more spatially extensive channel mapping data products (principally, bathymetry, surface sediment maps) as well as channel geometry, geological and hydraulic characteristics. For Marble Canyon, we will compare maps of sand thickness and sediment texture to the output of the two-dimensional hydraulic model developed in Project Element B.3. We expect correlations between sand thickness and flow velocity, and that other important explanatory variables are likely to be surface sand-grain-size, proximity to a debris fan (coarse sediment input), and pool depth-width scaling.

By the end of FY20, this project element will produce estimates, with uncertainties, of total in-channel sand storage along 146 miles of river (RM 0 - 30, RM 30 - 87, and RM 166 - 225), which comprises 65 % of the monitored channel between Lees Ferry and Diamond Creek. These data will be a crucial component of ongoing studies into developing mechanistic explanations for sandbar dynamics during HFEs and during flows associated with ordinary dam operations.

During the FY2015-17 work plan, we collected several sets of high-quality measurements of migrating submerged dune fields at the Colorado River stream gage above Diamond Creek. We used these data to develop a probabilistic model that relates bedload flux to discharge, suspended sand flux and grain size (Ashley and others, 2016) for the purpose of reducing uncertainty in the measurements of sand flux made in Project A. Under Project B for FY18-20, we propose to apply that model to additional gaging sites. Data necessary to extend the model will be collected at the gaging stations at RM 30, RM 61, and RM 87 during the 2019 channel mapping campaign. Data will also be collected on Project A gage-station maintenance trips to avoid added logistics costs.

This project element will result in development of a generalized model that predicts instantaneous bedload flux from measured discharge and suspended sediment flux and grain size, calibrated to each of the five gaging stations between RM 30 and RM 225. Model outputs will be incorporated into the existing sediment monitoring pages on www.gcmrc.gov, for quasi real-time bedload estimates. These improved total load (bedload plus suspended load) estimates will allow for more accurate tracking of changes in sediment storage and for designing HFEs.

***Outcomes and Products***

* Report and maps for RM 166 to 225 (mapped in 2017) (*lead author Kaplinski*).
* Report/journal article on geomorphic changes in Lower Marble Canyon and Eastern Grand Canyon describing effects of HFE Protocol on sandbars and sand storage, 2009-2019 (*lead author Grams*).
* Estimates, with uncertainties, of total in-channel sand storage along 146 miles of river (RM 0 - 30, RM 30 - 87, and RM 166 - 225), which comprises 65 % of the monitored channel between Lees Ferry and Diamond Creek.
* Report/journal article on development of CHIRP sonar-derived sand thickness measurements, and estimates of total sand storage (*lead author Buscombe*).
* A generalized model that predicts instantaneous bedload flux from measured discharge and suspended sediment flux and grain size, calibrated to each of the five gage sites between RM 30 and RM 224
* Report/journal article on bedload measurements, model development, and application to several gaging station sites for estimates of total load transport (*lead author Buscombe*).

#### Project Element B.3. Characterization and predictive modeling of sandbar response at local and reach scales

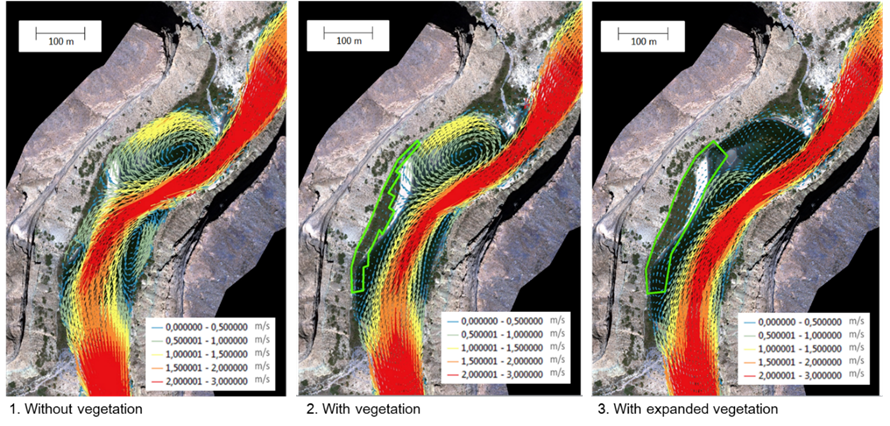
Erich Mueller, Research Hydrologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

Paul Grams, Research Hydrologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

Alan Kasprak, Research Geologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

***Project Description***

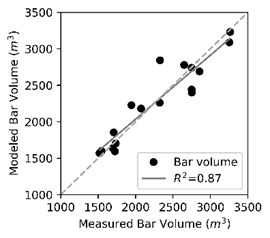
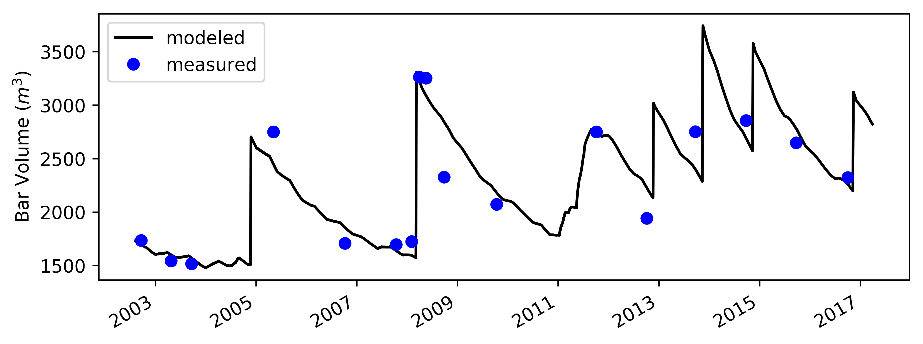
The purpose of sandbar modeling is to improve capabilities for predicting sandbar response to dam operations, including HFEs. In the FY2015-17 work plan, progress was made on identifying groupings (classes) of sandbar responses and developing a simple physics-based, numerical [or analytical?] model for predicting sandbar response to dam operations based on site characteristics, streamflow, and sediment supply. We propose to continue development and validation of that numerical [or analytical?] model in conjunction with hydraulic and physical modeling during FY2018-20. We will use bathymetry and near-channel topography collected during previous channel mapping trips in Marble Canyon between 2009 and 2016, along with upland topography collected by the 2013 aerial overflight data, to produce two-dimensional (i.e., depth-averaged) numerical [or analytical?] flow models. These models will predict flow depth, velocity, and inundation extent (modeled or “virtual” shorelines) from low flows (i.e., < 8,000 ft3/s) up to the historic flood of record (210,000 ft3/s). Combined with a recently-developed two-dimensional numerical [or analytical?] flow model for Glen Canyon, this work will enable near-continuous predictions of inundation extents and river channel hydraulics (e.g. Fig. 7) important to riparian vegetation diversity (Project C), aeolian transport of sand (Project D), aquatic ecology (Project F), and fish habitat variability (Projects G, H, and I) throughout Glen Canyon and Marble Canyon.



**Figure 7.** Changes in flow hydraulics during a flood at the Buckfarm (RM 41) sandbar modeled using Delft3d. 1) Without vegetation; 2) with the observed vegetation; and 3) with expanded vegetation (outlined in green).

A hydraulic model for Marble Canyon will allow us to quantitatively address a primary management question at large spatial scales: *Are differences in sandbar response to HFEs and other dam operations driven by local flow hydraulics, or more strongly linked to flow and sediment supply boundary conditions, and how does that vary between eddies?* In FY2015-17 we classified sandbar responses to HFEs [?] based on geomorphic setting using a Principal Components Analysis (PCA) and demonstrated that there are predictable differences in bar response (Mueller and others, 2016). The hydraulic modeling will allow us to directly link these differences to the flow hydraulics that control bar sedimentation. We hypothesize that eddies with higher velocities and stronger flow recirculation patterns typical of more narrow reaches tend to be more dynamic and thus potentially more responsive to different flow scenarios and HFE frequency. In lower velocity settings, vegetation encroachment stabilizes sandbar deposits and long-term bar trajectory is more strongly related to the cumulative flow history that may successively increase vegetated bar elevation. This project element will be collaborative with Project C to better understand the feedbacks between vegetation encroachment on sandbar dynamics (Fig. 7), and how that influences the riparian species guilds associated with different hydraulic environments and inundation frequencies.

Evaluating bar response to different flow release scenarios under LTEMP requires a modeling element to couple eddy hydraulics and measured suspended sediment concentration, discharge, and grain size (Project A) to predict sandbar area and volume change. Thus, a primary objective of this research is to use the two-dimensional streamflow model to better parameterize a physics-based model of individual bar response that incorporates the continuous flow and sediment transport data from Project A. The hydraulic model will enable us to provide mechanistic explanations for bar responses to suspended sediment concentration, inundation depth (flood magnitude) and flood duration, as well as shed light on observed site-specific differences in eddy velocity (“exchange rates”) and the episodic versus gradual erosion processes that control the spatial variability in bar response. Model predictions can be validated using the sandbar area and volume data sets (Fig. 8) but these validation data sets are at much coarser resolution than the 15-minute model predictions and often do not capture the changes in sandbar form to shorter-term flow release volumes. As a result, we will use results from the remote camera study (Project Element B.1) to link daily changes in bar area to the sub-daily predictions of the model. One of the great difficulties in understanding long-term bar behavior, especially between controlled floods, is quantifying both episodic and gradual sandbar erosion processes at different sites. Quantifying changes in bar area from the remote cameras will allow us to develop an empirically based erosion equation for different sites. Once a suitable model is developed for a given site or group of sites, synthetic flow scenarios can be used to predict likely spatial and temporal differences in bar response. By using empirically constrained eddy exchange rates and erosion rates, the model will be a significant advancement over previous modeling attempts. Combined with the PCA analysis of sandbar groups (Mueller and others, 2016), we can develop predictions of potential short-term or long-term bar response for sites with differing degrees of bar dynamism and vegetation encroachment.



**Figure 8.** Modeled sandbar volume for the Group-1 bars of Mueller and others (2016), a composite of nine geomorphically similar bars, based on the flow and sediment gaging record at the 30-mile gage 2002 to present.

***Outcomes and Products***

* A two-dimensional hydraulic model, with spatially explicit results, including mapped depth, velocity, and inundation extent (shorelines) for different flow magnitudes.
* Report or journal article on variability of flow hydraulics at the site and reach scale, and linkages to riparian vegetation, using results from the two-dimensional hydraulic model (*lead author Kasprak*)
* Report or journal article on the physics-based sandbar volume model that couples the streamflow and sediment transport measurements of Project A with the survey and remote camera sandbar monitoring data of Project B.1. (*lead author Mueller*)

***Project Element B.4. Research Study: Bank erosion, bed sedimentation, and channel change in the Colorado River arm of the Lake Mead delta in Grand Canyon***

Erich Mueller, Research Hydrologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

Paul Grams, Research Hydrologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

Daniel Buscombe, Research Professor, Northern Arizona University

Ed Schenk, Physical Scientist, Grand Canyon National Park

John C. Schmidt, Professor, Utah State University

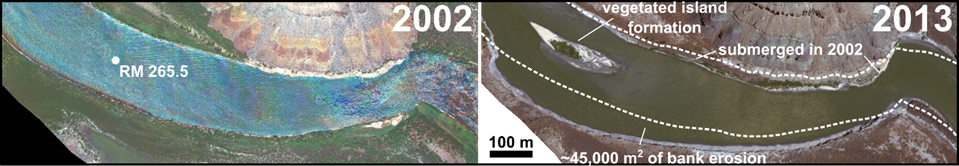
***Project Description***

Erosion of sediment from high banks and subsequent remobilization in the Colorado River arm of the Lake Mead delta presents significant navigation and habitat management issues in the western part of Grand Canyon. All large reservoirs trap incoming sediment, and post-dam sedimentation in Lake Mead has been periodically studied since the completion of Hoover Dam in 1935 (Twitchell and others, 1999, 2004). Current and projected decline in water supply and total allocation of Colorado River water would suggest that Lake Mead and Lake Powell are likely to stay well below full pool for the foreseeable future, converting the upstream parts of these reservoirs to riverine segments that are rapidly evolving and redistributing sediment from upper to parts of the delta. Thus, river-reservoir system management must consider the physical and geochemical effects of erosion and redistribution of this legacy sediment.

Currently, little is known about the magnitude to which channel aggradation and widening is occurring, or the processes associated with those changes. The primary objectives of this research are to; *1) quantify the rates and spatial patterns of lateral incision and bank erosion of former reservoir sediment in the now riverine segment of the Lake Mead delta;* and *2) link transient river channel change and bed aggradation to increased sediment supply from banks and lateral channel migration*. We hypothesize that bank erosion rates have increased in recent years as a result of reservoir drawdown and bed incision, and that following initial channel incision, rapid bluff erosion causes bed aggradation and channel widening which may promote further bluff erosion. As bluff erosion progresses and the incised river valley widens, we may expect a decrease in sediment supply and a stabilization of the channel planform inset within the delta deposits with vegetation eventually stabilizing bars. Whether, and how often, this cycle repeats itself depends on the downstream base level control and the frequency incision events associated with changes in reservoir level and knickpoint migration. This sequence of incision, widening, and stabilization has been described for a number of degrading river systems (Simon and Rinaldi, 2006).

The upstream end of Lake Mead that is within Grand Canyon National Park is the final segment for many Grand Canyon river trips, is the centerpiece of river running operations by the Hualapai tribe, and is inherently within the purview of the GCDAMP, being a segment of the Grand Canyon and one that now affords a river-running experience. This section of the Colorado River in Grand Canyon is perhaps the busiest section of the river, in terms of boat traffic, in the National Park. It is increasingly difficult for the Hualapai tribe to maintain docks for their upstream fleet, and bed aggradation often causes boat beaching and difficulty accessing the Pearce Ferry boat ramp. The delta deposits also inhibit natural campground development because there are few beaches adjacent to the steep banks. Furthermore, Lake Mead has a self-sustaining population of endangered razorback sucker (*Xyrauchen texanus*) that must use this segment of river to migrate between the reservoir and riverine environments. Thus, erosion of reservoir sediment and subsequent remobilization in the Colorado River arm of the Lake Mead delta presents significant navigation and habitat management issues in the western part of Grand Canyon.

The sediments of the Lake Mead delta extend upstream to approximately the location of Separation Rapid in Grand Canyon, about 40 river miles upstream from Pearce Ferry. Since 2000, Lake Mead water levels have declined approximately 40 meters. The Colorado River has subsequently incised through newly exposed delta sediments, persistently eroding tall banks of fine-grained lake and delta deposits (Fig. 9). Erosion of these banks delivers sediment to the river resulting in ever-shifting sandbars throughout much of the lower river corridor between Separation Rapid and Pearce Ferry. Downstream from Pearce Ferry, the Colorado River flows over a ledge of poorly consolidated bedrock (Pearce Ferry rapids) because the path of the incised channel does not follow its pre-reservoir course. This ledge (knickpoint) creates a significant navigation hazard and may also affect native fish migration from the reservoir upstream to the Colorado River in Grand Canyon. Additionally, this bedrock ledge provides the downstream base-level for the incising section of the lower Colorado River in Grand Canyon National Park, and thus plays an important role in regulating incision and sediment evacuation from upstream reaches.



**Figure 9.** Example of bank erosion and mid-channel bar formation between 2002 and 2013 for an approximately 1 km long reach between river miles 265 and 266. Dashed white line shows 2002 shoreline.

In order to address the primary research questions above, we intend to study channel response to reservoir drawdown along the Colorado River arm of the Lake Mead delta in collaboration with the National Park Service (NPS). Preliminary surveys of bank topography were collected in collaboration with Ed Schenk of the NPS during the 2016 HFE. In addition, we will work with the Hualapai tribe to develop a plan to study issues associated with river bed sedimentation and bank erosion in reaches critical for boat navigation. In the first part of our analysis, we propose to use available remote sensing data sets and repeat topographic surveys to document historical changes in bank and river channel morphology. The second part of our analysis will include short field data collection trips, in conjunction with LiDAR surveys of banks, to map changes in the subaqueous channel morphology. The shifting sandbars of the Colorado River where it flows through Lake Mead delta sediments presents a considerable navigational hazard. This is an extremely challenging environment for bathymetric mapping because of very shallow and highly turbid water, which precludes many sonar and image-based methods. We will use a very low draft, wide-angle, dual- LiDAR- sonar system specially designed for swath mapping in shallow water, collecting swath data up to 10 times the water depth and LiDAR topography of sediment banks up to 100 m away. We will work with the Hualapai Tribe and NPS to create a baseline map of the channel thalweg and other navigable parts of the channel and, if possible, document thalweg migration rates. We will also explore other remote sensing technologies that may allow for more continuous documentation of thalweg and sandbar migration patterns. Because similar issues exist upstream along the deltas of the Colorado and San Juan arms of Lake Powell, this research project also could provide guidance for management of other large reservoirs in the Colorado River basin.

***Outcomes and Products***

* Report/journal article on bank erosion, bed sedimentation, and channel change of the Colorado River area of the Lake Mead delta.

#### Project Element B.5. Control network and survey support

Keith Kohl, Surveyor, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

***Project Description***

The overarching goal of this project element is to develop a sound process for establishing, maintaining, and verifying survey control in support of long-term monitoring within the CRe. The work will ensurethat spatial data collected in support of GCMRC projects are accurately referenced and precisely defined and can be reliably compared with past and future datasets within Geographical Information Systems (GIS). This compatibility requires referencing the monitoring data to a common, well-defined geospatial datum and quantifying accuracy of all subsequent spatial data sets. The reliability of the positions within the datum provides the confidence to quantify and reduce uncertainty within each dataset; improving the confidence in future GIS analyses and on the management decisions relying on those conclusions. Referencing the datum defined by the National Spatial Reference System (NSRS) allows us to add new measurements into a nationwide published geodetic framework and sustains comparable high-accuracy positions throughout the entire CRe.

Toward this end, GCMRC requires a control network and survey procedures that will yield reliable and consistent results now, while allowing for advances in theory and technology in the future. Importantly, the procedures must withstand changes in personnel that will inevitably occur over the life of the CRe monitoring programs. The control network is a set of monumented and documented reference marks that exist along the river corridor and on the rim together with the collection of observations that determine the relative and absolute positions of those points. These stations serve as the basis for referencing all ground- and air-based monitoring observations. Currently, the control network includes more than 9,000 Global Navigation Satellite System (GNSS observations) and more than 4,000 optical observations that determine the precise location of more than 1,200 stations along the river corridor and on the canyon rim. This project includes work in three broad categories: 1) building the control network, 2) direct support of research and monitoring activities, and 3) storage and archival of the control database.

An accurate geodetic control network is required to support nearly every GCMRC monitoring project including sandbars, sediment storage, archeological site and vegetation monitoring and projects that use system-wide airborne remote sensing. The remote sensing work is particularly dependent on control operations, without which image data could not be compared accurately with ground-based measurements. Geodetic control is essential to enable comparison among data sets collected by different methods and ensures that spatially referenced observations are repeatable.

Combining conventional measurements (which reference gravity) with GNSS measurements (which reference a geocentric ellipsoid) requires the reduction of field measurements to the ellipse. Variations of mass density will affect local gravity, deflection of the vertical, zenith angle measurements, and height determination. High-resolution geoid models set out to define these relationships. Identifying these interactions within the CRe is critical since diverse methods are used to determine positions, including remotely sensed lidar, imagery, and sonar along with conventional total-station and GNSS.

***Building the Control Network***

Primary tasks of completing the control network include making GNSS observations at new and existing benchmarks, and linking conventional total station traverses between the GNSS monuments to determine positions and heights. Seventy-seven percent of the river corridor from Glen Canyon Dam to Diamond Creek has a sufficient number of control points to support monitoring activities. The remaining 23% (about 80 km) will be addressed in this work plan and network adjustment results will be made available prior to the aerial and bathymetric collection planned for this budget cycle. GNSS data will be collected at NSRS stations along the rim, while simultaneously observing stations along the river corridor. GNSS derived stations will be interconnected with terrestrial control stations positioned with conventional total station measurements in locations where GNSS observations are not practical. The primarily focus of the surveys will be on establishing control between Bright Angel Creek (RM 88) and National Canyon (RM 166).

Data will be processed and the measurements adjusted following established procedures. Measurements, coordinates and error analysis will be published and archived as source coordinates for subsequent data collection.

***Support of Research and Monitoring Projects***

The scope of this survey-support project-element is to assist other GCMRC projects with survey knowledge, consistent survey practices, control infrastructure and equipment as need arises. The major projects that require survey support in 2018–2020 are Streamflow, Water Quality, and Sediment Transport and Budgeting (Project A), Sandbar and Sediment Storage (Project B), Riparian Vegetation (Project C), Geomorphic Effects of Dam Operations (Project D), Geospatial Science and Technology (Project K), and Remote Sensing Overflight (Project L).

The sandbar and sediment storage project-elements collectively rely on the accurate positions of hundreds of monuments to link measurements and validate equipment setup and calibration. The topographic and bathymetric surfaces share the same datum and reference the same monuments and coordinates as the remotely sensed data. The control network also supports accuracy assessments by determining the positions of well-defined points from independent sources of higher accuracy providing means to assess positional accuracy of data, maps, and products as expressed in FGDC Part 3 “National Standard for Spatial Data Accuracy”.

***Storage, Archiving, and Documentation of the Control Network Database***

Coordinates, datum descriptions, and accuracy results are provided in a format compatible with Federal Geographic Data Committee (FGDC) delivery standards. GNSS base stations are published (blue-booked) within the National Geodetic Survey Integrated Database (NGSIDB). The control network data are stored in a GIS database that is linked to gcmrc.gov. The survey staff works with GIS staff to maintain and update the database as needed.

***Outcomes and Products***

* Control network adjustment for lower Marble Canyon and eastern Grand Canyon (contributes to product in Project Element B.2).
* Report/ article on combining GNSS observations and historical leveling data for more accurate elevations and updated geoid models 1923 to 2017.
* Collect, process, adjust and publish geodetic control data for the remaining areas of the CRe, including Bright Angel Creek to National Canyon. Results will be used as constraints for aerial imagery and channel mapping efforts of 2020.
* Updates to the National Geodetic Survey Integrated Database (NGSIDB) of all available Height Modernization and benchmark stations used for GNSS overflight reference.
* Updated database with results of the entire CRe geodetic control network.

***Project Element B.6. Sandbar response to differences in HFE magnitude and duration***

Paul Grams, Research Hydrologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

Daniel Buscombe, Research Professor, Northern Arizona University

Erich Mueller, Research Hydrologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

Matt Kaplinski, Research Associate, Northern Arizona University

Joseph E. Hazel, Jr., Research Associate, Northern Arizona University

***Project Description***

The LTEMP EIS and ROD includes two experimental activities designed to improve sandbar and sediment resources (extended duration HFEs and proactive HFEs) and one experimental activity that may cause increased sandbar erosion (trout management flows). Additionally, sediment-triggered HFEs implemented following the protocol that is extended in the LTEMP ROD could be any magnitude between 31,500 ft3/s and 45,000 ft3/s. Although there is no explicit identification of the need to compare the results of different magnitude HFEs in the LTEMP ROD, we expect that evaluation of the effects of low-magnitude HFEs (<34,000 ft3/s) compared with the effects of high-magnitude HFEs (>40,000 ft3/s) will be of interest. The primary purpose of this project element is to collect and analyze the data that will be necessary to evaluate the effects of any of those flow experiments if and when they occur. Because the timing of those experiments is condition dependent and because uncontrollable factors, such as antecedent sandbar condition and sand supply, inevitably present challenges to interpreting the results of large-scale field experiments, this project element also includes a laboratory experimental study that is designed to address the same questions that motivate the experiments outlined in the LTEMP. The budget for this project element is separate from the rest of the Project B elements (see Section &), because we propose this work be funded from either the annual experimental fund or a contingency fund established to support research and monitoring in support of condition-dependent experiments. The field components would only occur when the experiments occur and evaluation of those experiments is required.

*Extended duration HFEs*

As defined in the LTEMP ROD, extended duration HFEs are restricted to implementation in the fall sand accounting period and would be triggered according to the same criterion used for other sediment-triggered HFEs -- that the sand mass balance for the fall sand accounting-period (July 1 – December 1) remain positive through HFE implementation based on model projections. The original HFE protocol allows for HFE duration of up to 96 hours with a peak magnitude of 45,000 ft3/s. The extended duration HFEs may be 144, 192, or 250 hours in duration; however, the first test of an extended duration HFE is limited to 192 hours. Extending HFE duration is based on the hypothesis that, under conditions of enriched sand supply, longer duration HFEs will maintain elevated suspended sand concentrations for longer than the duration of a 96-hour HFE, resulting in more deposition and larger sandbars.

The key information needed to evaluate the effects of extended duration HFEs on sediment resources will be (1) measurements of suspended sand concentration during each entire HFE, (2) measurements of sandbar size before and after the extended duration HFE, and (3) daily observations of sandbar dynamics during the HFE. The measurements of suspended sand concentration will be used to determine if sand concentrations remain elevated throughout the extended HFE or if sand supply becomes depleted and concentrations decline. The basis for evaluating the effects of extended duration HFEs on sandbar deposition will be by comparison with measurements of deposition for other HFEs. Images from the remote cameras will be used for a qualitative comparison at all sites and a quantitative comparison at some sites (see project element B.1). However, pre- and post-HFE topographic surveys are required for a quantitative comparison with measurements made before and after the 1996, 2004, and 2008 HFEs. Because the extended duration HFEs are limited to the fall accounting period, data collected in the fall sandbar-monitoring trip, which occurs annually in early October, will be used as the pre-HFE sandbar measurement, which saves logistical costs. One additional sandbar-monitoring trip will be required following the extended duration HFE. The focus of the pre- and post-HFE study will be on deposition above the 8,000 ft3/s stage. Therefore, the surveys will be for sandbar topography only and do not require bathymetry. Additional information will be gained by conducting daily surveys during the extended duration HFE at two locations. These surveys will allow for comparison between observed sandbar deposition rates and main-channel suspended sand concentrations. Finally, we will compare observed changes in sandbar volume to predictions based on site-specific sandbar modeling (Element B. 3) to evaluate the predictive capability of the modeling approach.

*Proactive HFEs*

Proactive HFEs are defined in the LTEMP EIS and ROD as releases of up to 45,000 ft3/s and up to 24-hour duration that would occur in spring (April – June) in advance of scheduled equalization flows. The intended purpose of proactive HFEs is to create sand deposits above the expected stage of equalization flows, such that those deposits would not be subject to erosion during the equalization flows. Evaluation of the effectiveness of the proactive HFEs, therefore, requires (1) measurements of sandbar deposition by proactive HFEs followed by (2) measurements of erosion of the deposited sandbars through and immediately following the period of summer equalization flows. This would require surveys of sandbar topography immediately following the proactive HFE and following the equalization flows. Images from remote cameras already in place would be used to monitor the portions of sandbars exposed above water during the equalization flows (see project element B.1). The post-equalization flow survey would be accomplished on the annual sandbar-monitoring trip in early October. The post-HFE survey would require one additional survey trip. If dam releases were less than about 16,000 ft3/s during the survey, this could be accomplished with topography only. If releases were higher, bathymetric measurements would be required to enable surveying the entire sandbar above the 8,000 ft3/s stage. Surveying the sandbar down to the 8,000 ft3/s stage is required for the purposes of comparison with other surveys.

*Trout management flows*

Trout management flows are described in the LTEMP EIS and ROD as repeated cycles of flow fluctuations between high flows of approximately 20,000 ft3/s and low flows of 8,000 ft3/s or lower. The high-flow component would last for between two and seven days with the low-flow component lasting for less than 24 hours. These flows are expected to cause increased rates of sandbar erosion. The requirement for monitoring sandbar response would depend on the expected number of fluctuation cycles in a given TMF event. If a TMF event consists of only a few cycles, the increased amount of erosion compared to normal fluctuations would likely be small and difficult to measure. Under this scenario, observations from existing remote cameras will be used to determine if sandbar erosion rates are affected by these flows, particularly at the sites where georectification allows for daily to weekly calculation of area and, potentially, bar volume change. In contrast, if a TMF event consists of many fluctuation cycles, the expected additional erosion might require additional sandbar surveys to quantify sandbar change at all sites.

*Low-magnitude HFE*

A low-magnitude HFE would occur according to the HFE protocol either when there is insufficient sand for a larger-magnitude HFE, or if there is insufficient capacity to release more than that amount of water with the combined capacity of the powerplant and the bypass tubes. We define a low-magnitude HFE as a release that is between the powerplant capacity of 31,500 ft3/s and 34,000 ft3/s. Because sandbar response to a low-magnitude HFE could be very different from the response to a high-magnitude HFEs, quantification of the magnitude of this difference would be useful for planning purposes. If the low-magnitude HFE occurred in the fall, monitoring the response would require one additional post-HFE sandbar survey trip, using the regular monitoring trip as the pre-HFE condition. If the low-magnitude HFE occurred in the spring, two additional sandbar survey trips would be required.

*Physical modeling of bar response to HFE hydrograph scenarios*

One of the challenges faced in implementation of the HFE protocol is a lack of information for predicting sandbar response to HFEs of different magnitude, duration, or hydrograph shape. Because the HFE variations that would occur in the context of the LTEMP are condition dependent, it is not clear when or if those tests will occur. Moreover, the LTEMP does not include experiments to evaluate if/how variation in HFE magnitude or hydrograph shape (ramp rates) may affect sandbar responses to HFEs. Furthermore, lack of controlled conditions in the field coupled with the expense of collecting detailed field measurements around each HFE makes it difficult to address questions about the effect of hydrograph characteristics on sandbar response based on field data alone. In fact, some questions might be almost impossible to address without the ability to control discharge and sediment supply systematically across a range of values as in a laboratory setting.

The purpose of this project element is to investigate the effects of hydrograph shape on sandbar deposition and erosion with a set of laboratory flume experiments. Laboratory experimentation will allow us to explore HFE hydrograph design options in terms of peak flow (below, at, or above power plant capacity), hydrograph asymmetry (up- and down-ramp rates), and duration, in order evaluate how these variables affect sandbar deposition and erosion. The results will allow us, for example, to assess what combination of these three would maximize the volume and minimize the slope of subaerial (immediately post-flood) sandbars. The proposed work will investigate the immediate post-flood sandbar volume and slope under a very large range of experimental flows that will mimic various HFE hydrograph scenarios.

A short pilot study was conducted in 2016 at St. Anthony Falls Hydraulic Laboratory, Minneapolis, MN, whereby it was demonstrated that a flow constriction could be made that created an eddy sandbar, and that flows could be adjusted to manipulate the bar. Laboratory conditions were designed using a 3-D hydraulic model (Alvarez and others, 2017). We propose to build on the success of these pilot experiments with a full experimental program to study, in isolation, the effects of flow magnitude, duration and asymmetry (upramp and downramp rates) on sandbars, in order to test the following hypotheses:

*1) Flow duration is the biggest lever on total sandbar deposition*; *2) Flow magnitude is the biggest lever on sandbar elevation*; and *3) Slower downramp rates during the recession limb of an HFE result in gentler sandbar slopes.*

To conduct these experiments, a debris fan and eddy complex will be created within the flume and the channel bed will be filled with sand. First, a series of experiments will establish the time scales required for bars to reach equilibrium under different flow magnitudes (low, medium and high). This will be necessary to establish the length of the “long duration” flows, and to scale the medium and short duration flows accordingly. Then, another series of experiments will be conducted whereby three flow variables are independently varied, namely duration ('pulse' and 'surge'), magnitude ('large' and 'small') and hydrograph symmetry ('symmetric', 'flood-dominated', 'ebb-dominated'). During the experiments, sand will be fed in above the constriction at a constant rate. During each experiment, detailed measurements of the evolution of the sandbar will be made, to assess the effect of each flow treatment on overall sandbar slope and volume, sandbar elevation, and slopes and volumes above different flow levels.

***Outcomes and Products***

* Report or journal article describing laboratory experimental methods and results, with a synthesis of relative importance of flow duration, magnitude and hydrograph shape on sandbar volume and slope.
* Report or journal article describing field data and effects of extended/proactive HFEs, should they occur.

**4.2 Deliverables**

See “Outcomes and Products” listed by project element, above.

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1. **Budget**







1. **Experimental Project Budget**

Proposed budgets for funding from the annual experimental fund or a contingency fund established to support research and monitoring of extended duration or proactive HFE experiments were they to occur in FY2018-20. Funds would cover costs associated with additional logistics, field personnel, and data processing. Reporting would be covered by existing projects. Some work will be conducted as part of planned annual monitoring trips. The costs for those trips is included in the project budget, not the HFE experimental budget. The budget for the proposed laboratory experiments is the annual cost each year for a 3-year project.







Project C. Riparian Vegetation Monitoring and **Research**

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1. **Project Summary**

This project seeks to monitor riparian vegetation response to dam operations in order to determine if the Long-Term Experimental and Management Plan (LTEMP) resource goals for riparian vegetation are being met (Elements 1 and 2), leverage the data created by riparian vegetation monitoring to address gaps related to predicting the responses of vegetation to LTEMP experimental flows (Element 3), support the implementation of experimental vegetation treatments directed by the Long-Term Experimental and Management Plan Record of Decision (LTEMP ROD, Element 4), and record decadal-scale Colorado River ecosystem change (Element 5).

Monitoring the state of riparian vegetation along the mainstem is ongoing and critical for understanding the effects of dam operations on riparian vegetation and associated resources. Ultimately, monitoring assesses if riparian vegetation is being maintained “in various stages of maturity, such that they are diverse, healthy, productive, self-sustaining, and ecologically appropriate” and assesses if dam operations under the new ROD have the expected result of “more native plant community cover, higher native plant diversity, a lower ratio of native to nonnative plants, less arrowweed, and more wetland,” (Vanderkooi and others, 2017). This project utilizes annual field measurements (Element 1) and digital imagery (Element 2) for integrated monitoring of changes in vegetation at river segment (for example Glen Canyon, Marble Canyon, etc.) and system-wide scales. Included in monitoring are: a 5-year assessment of vegetation change (Element 1); analyzing a new system-wide remote sensing vegetation classification, providing a system-wide assessment of tamarisk beetle defoliation from 2009-2013, and analyzing the sand/vegetation turnover dynamism (Element 2). Each of these elements provides an assessment of the status of plant communities identified as being of interest or concern by stakeholders.

Element 3 proposes to utilize existing vegetation and flow data to examine the influence of dam operations and other environmental variables on riparian vegetation distribution and other knowledge gaps regarding vegetation response. A recent knowledge assessment that was conducted to identify the current understanding of how vegetation responds to dam operations elucidated uncertainties regarding how experimental flows will impact vegetation complexity, functional diversity, and species composition. We plan to address some of these uncertainties by creating predictive models of vegetation responses to LTEMP flow scenarios based on the vegetation monitoring and remote-sensing products outlined above (and described below). These predicted outcomes will be generated across multiple spatial scales in order to better understand how experimental flows are impacting the integrity of riparian vegetation. The results of this work will help predict vegetation response to flow experiments outlined in the LTEMP, help assess if the LTEMP management goals for vegetation are advancing, and inform the parameters in which vegetation management will be most successful.

As stated in the LTEMP ROD, NPS and tribal partners will coordinate with Grand Canyon Monitoring and Research Center (GCMRC) to conduct targeted vegetation removal and plantings, including “control of nonnative plant species and revegetation with native species (U.S. Department of Interior, 2016).” Project element 4 will help address information needs and management design required for the successful implementation of this required vegetation management. As outlined in the LTEMP ROD, the NPS, Tribes, and other stakeholders seek to preserve sand resources, camp sites, and archeological sites through vegetation removals and support the integrity of the riparian ecosystem by planting native species. The long-term success of planting efforts will depend on matching genetically suitable plant material to specific sites varying in substrate stability and existing vegetation. Monitoring of post-removal vegetation trajectories could identify how successional processes interact with dam operations to reverse riparian vegetation expansion and determine the long-term preservation of these sites, as well as to prioritize needs for future interventions on a site-by-site basis. These sites will encompass only a small portion of the riparian corridor and will have different goals and locations from the monitoring outlined in Element 1, so this work cannot replace ongoing monitoring efforts throughout the Colorado River ecosystem (CRe).

A final element of the project (Element 5) proposes to conduct decadal-scale vegetation monitoring based on continuation of efforts during the previous workplan to replicate historical photographs. This element will create a baseline visual record of mainstem ecological status, which can be analyzed now and in the future.

1. **Background**

Riparian vegetation is strongly influenced by seasonal and interannual discharge, such that changes to the flow regime alter the plant species that can reproduce and survive (Naiman and Decamps, 1997; Rood and others, 2003). Changes in discharge fundamentally change the structure and function of the associated riparian vegetation, whether that change is from a natural to a regulated flow regime or among differing regulated flow regimes (Greet and others, 2011; Lytle and Poff, 2004; Rood and others, 2003; Shafroth and others, 2002; Stromberg, 2001). Flow experiments designed to influence fish, foodbase, or sediment will therefore have a collateral influence on riparian vegetation, even if vegetation is not removed in the process as of flooding and drought can alter the structure and types of vegetation (Greet and others, 2011; Lytle and Poff, 2004). Since riparian plants have different societal, biological, and physical values (e.g., tall shade trees vs. thorny herbs), changes to the amount and types of vegetation impact the quality of wildlife habitat (Merritt and Bateman, 2012; Ralston, 2005), influence sediment deposition and retention (Dean and Schmidt, 2011; Manners and others, 2014), affect the experience of visitors (Ralston, 2005; Stewart and others, 2003), and influence ecological integrity in general (Bailey and others, 2001; Richardson and others, 2007; Stromberg and others, 2012). Thus, changes to dam operations as part of the LTEMP ROD will alter riparian vegetation and affect the following resource goals:

* *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.
* *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*.*
* *Recreational Experience*. Maintain and improve the quality of recreational experiences for the users of the Colorado River Ecosystem.
* *Tribal Resources*. Maintain the diverse values and resources of traditionally associated Tribes along the Colorado River corridor through Glen, Marble, and Grand Canyons.

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 or not the resource goals for riparian vegetation are being met. Since riparian vegetation in the CRe is layered and complex (for example, >300 different species ranging from annual species that are only a few centimeters tall to hundred year old trees over 20m tall), it is best practice to monitor on both annual and decadal-scale time scales to observe both rapid changes due to high flow experiments (HFE’s) (for example shifts in wetland communities) and tree growth and mortality. It is also important to monitor locations along the entire length of the corridor, since riparian vegetation changes with distance downstream (Palmquist and others, *in review*). The different floristic communities located along the river may not respond similarly to dam operations, so conclusions based on data from one end of the canyon (for example, Marble Canyon) cannot be applied to another part of the canyon (for example, western Grand Canyon).

1. **Proposed Work**

**4.1. Project Elements**

***Project Element C.1. Ground-based riparian vegetation monitoring***

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This project element is annual ground-based monitoring conducted at the species level. Ground-based monitoring is particularly useful for studying the entire suite of plant species that occur in the riparian area, including forbs, grasses, and shrubs. The current monitoring protocol began in 2013 and has been continued annually since then (Palmquist and others, *in revision*). The primary purpose of this monitoring project is to annually quantify the composition and cover of riparian vegetation in order to determine the status of native vegetation throughout the experimental flows planned for the next 20 years, such that the vegetation is, “diverse, healthy, productive, self-sustaining, and ecologically appropriate” (U.S. Department of Interior, 2016). These data can additionally be used to assess vegetation characteristics that affect recreational experience (e.g., is there an increase in thorny vegetation on sandbars?) and potentially inform wildlife habitat quality and availability. Particularly, this element aims to:

1. Annually sample and summarize the status (composition and cover) of native and non-native vascular plant species within the riparian zone of the Colorado River from Glen Canyon Dam and to 240 river miles downstream of Lees Ferry.
2. At 5-year intervals, assess change in vegetation composition and cover in the riparian zone, as related to geomorphic setting and dam operations, particularly flow regime.
3. Collect data in a manner that can be used by multiple stakeholders and is compatible with the basin-wide monitoring programs overseen by the National Park Service’s Northern Colorado Plateau Network Inventory and Monitoring program.

This project element is independent of, but complementary to, the experimental vegetation management work that is being planned by NPS and tribal stakeholder and will also require a separate monitoring approach to assess management success. The experimental vegetation management that is planned will only affect a small portion of the river corridor (approximately <1%), so it is necessary to continue monitoring the riparian corridor as a whole in order to assess if goals for this resource are being met with the new flows.

Ground-based riparian monitoring utilizes both stratified random sampling and sites that are revisited each year. The combination of a random sample design and a revisit design allows us to understand changes that are occurring along the whole length of the mainstem by sampling a relatively small portion of the area. The random sample dataset encompasses approximately 70 to 90 sample sites each year distributed among channel margins, debris fans, and sandbars between river miles -15.5 and 240, in order to gain a broad-scale understanding of how riparian vegetation responds to dam operations across multiple habitats and in all reaches. The dataset based on annual site revisits is collected on annually surveyed sandbars (see project B.1) and is intended to provide information on how vegetation is impacting sand deposition and retention, as well as how the changing physical processes of sandbars influence vegetation encroachment.

Collaborations with the Northern Colorado Plateau Network Inventory and Monitoring program will continue. This group currently monitors riparian vegetation along the Yampa River, the Green River, and the upper Colorado River. This collaboration focuses on coordinating data collection methods and techniques with the ultimate goal of being able to conduct basin-wide analyses of riparian vegetation change using our combined datasets. This collaboration also fosters communication and positive relationships with the National Park Service and the riparian ecology scientific community.

Five years of data using the current monitoring protocol will be available after the 2017 field season, which is a reasonable time frame to begin assessing the status and trends of riparian vegetation in the CRe. This project element will include a summary of data collected from 2013 through 2017 with a particular focus on the state of riparian vegetation at the beginning of the new ROD. It will also include an assessment of interannual variation and how often riparian vegetation should be sampled to sufficiently track its status and trends (i.e., power analysis). This summary is expected to be used as a baseline against which future change due to any implemented management flows (spring high flow experiments, trout management flows, etc.) can be assessed. It may also indicate the current trajectory of riparian vegetation, e.g., if non-native species are increasing or decreasing and where or if sandbars support higher amounts of vegetation than other geomorphic features.

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

Joel Sankey, Research Geologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

Laura Durning, Research Specialist Sr., Northern Arizona University

Recently, landscape-scale remote sensing of riparian vegetation has been successfully used by GCMRC scientists to investigate several important contemporary environmental issues in the CRe. Specifically we have: 1) within specific reaches quantified long-term changes in total riparian vegetation as a function of dam release patterns (discharge from the dam) and regional climate (Sankey and others, 2015), 2) classified and mapped the composition of total riparian vegetation by vegetation species and associations (Bedford and others, *in prep*; Durning and others, *in prep*; Ralston and others, 2008), and 3) mapped non-native invasive tamarisk vegetation impacted by herbivory by the introduced tamarisk beetle using 2009, 2013 imagery and airborne lidar (Bedford and others, *in prep*; Sankey and others, 2016). This project element will continue to leverage those successful applications of landscape-scale remote sensing of riparian vegetation to:

1. Analyze mapped species and associations for how the composition of woody riparian vegetation varies spatially throughout the entire river corridor and how species have changed across the decades captured in digital imagery;
2. Quantify where and how much turnover between bare sand and riparian vegetation occurs due to erosion, deposition, establishment, and mortality within the stages of the riparian zone currently inundated by controlled floods (HFEs) and other flow fluctuations; and
3. Detect where repeat tamarisk beetle herbivory events and tamarisk mortality are occurring in the river corridor using interannual satellite imagery.

In (i) we will focus on interpreting the vegetation classification which is currently in production during FY17 by the riparian vegetation remote sensing project (Durning and others, *in prep*) using the 2013 multispectral image mosaic of the river corridor from Glen Canyon Dam to Lake Mead (Durning and others, 2016). We will also complete a change detection of that most recent riparian vegetation classification with the previously produced classification of Ralston and others (2008), based on multispectral imagery acquired in 2002. With the change detection analysis we will, for the first time, be able to synoptically assess corridor-wide vegetation shifts at the species and community levels for woody, long-lived species. We will better understand vegetation succession that has occurred during that past 2 decades, including transitions from herbaceous (in general) to woody species that may be contributing to factors like bank stabilization, channel narrowing, and campsite encroachment. In (ii) we will use total vegetation classifications and other remote sensing based landcover data (e.g., water and sand classifications; see data published with Sankey and others, 2015) to analyze the amount of turnover or ‘dynamism’ that has occurred between riparian vegetation and bare sand within the active river channel using imagery acquired by overflights of the canyon in 2002, 2009, and 2013. Sankey and others (2015) determined that short duration controlled floods (HFEs) in general do not keep vegetation from expanding onto bare sand habitat, but a synoptic river-corridor wide assessment of sand-vegetation turnover has not been completed. A full assessment will identify inundation zones of riparian interest and geomorphic landform units where turnover does in fact currently occur as well as the magnitude of turnover. In (iii) we will use interannual time series of World View satellite imagery to detect beetle-impacted tamarisk mapped with imagery from 2013 by Bedford and others (*in prep*) that have subsequently experienced repeat beetle herbivory events and eventual mortality. This work will focus on specific reaches of the river where the canyon is wide enough to be suitable for satellite image analysis.

***Project Element C.3. Vegetation responses to LTEMP flow scenarios***

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Emily Palmquist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

Predictive models of riparian vegetation change in response to proposed LTEMP flow scenarios can inform stakeholders about the potential influences of 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 and flow data integrated with flow-response vegetation guilds to examine the influence of LTEMP flow scenarios on species distributions and potential community change. The modeling done for the EIS 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 much better understanding of how LTEMP flows will change vegetation. We will test these predictions based on responses observed in long-term monitoring data to a wealth of hydrological and geomorphological factors.

Models of how the flow regime impacts the distribution and composition of riparian vegetation are also useful for developing successful experimental vegetation treatments (Stromberg, 2001). Ecological rehabilitation is expensive and time consuming, so an understanding of what environmental factors are influencing the growth and survival of different species is imperative to increasing chances of a successful treatment. For example, if the goal of vegetation treatment is to increase the cover of native plant species, it is valuable to know if the current composition of species is largely due to flow regime or other environmental factors, such as shade, soil composition, temperature, or precipitation. If the latter has a stronger influence on riparian vegetation composition, then treatment design should primarily focus on planting in areas that have the correct temperature, light availability, and sand: silt ratio. If the former has a stronger influence, then the placement of plantings in relation to the river is a much more important consideration, and may require some creative solutions to supporting vegetation that struggles with the given flow regime. The objectives of this project element then are to use existing data to:

1. Determine which environmental stressors have the strongest effect on species composition and location and at what scale,
2. Develop predictive models of how LTEMP flows will alter vegetation that provide a much better understanding than the simple models developed for the EIS,
3. Use that knowledge to support the design of vegetation treatments.

Numerous vegetation datasets have been collected over the past two decades in the CRe, which can be used to develop and test these models. Remotely sensed imagery, plot-based monitoring and functional trait data have culminated in a number of synthetic analyses during the previous work plan, including changes in the cover and structure of vegetation (Sankey and others, 2015), state and transition models of vegetation change (Ralston and others, 2014), flow-response guilds (Merritt and others, 2010; Sarr and others, *in prep*), and mechanistic links between plant functional traits and inundation (McCoy-Sulentic and others, 2017a; McCoy-Sulentic and others, 2017b). These data and analyses provide a robust framework for developing predictive vegetation models, which hitherto have been overly simplistic and have not incorporated the many complexities that influence riparian vegetation. That simplicity reduced the usefulness of the models, and incorporating as much of the data as we have available to us will greatly improve our predictive power and help understand the mechanisms underlying vegetation community assembly. These more complex models will allow us to model how sediment accumulation and loss on sandbars interacts with vegetation and how environmental variables differentially influence vegetation in the changing setting of LTEMP dam operations. No previous modeling efforts have been able to tackle these topics, due to limitations to model complexity. These models will also support the design of successful vegetation treatments by identifying the primary limiting factors for riparian vegetation establishment and predicting the influence of experimental flows (trout management flows, macroinvertebrate production flows, etc.) on riparian vegetation (Webb and others, 2014).

We propose to use hierarchical Bayesian modeling to generate these models (Webb and others, 2014). Briefly, hierarchical Bayesian models can be used to couple empirical statistical analysis with process-based, theoretical models of systems derived from quantitative review of literature and expert opinion. The “hierarchical” aspect of this analysis includes the ability to incorporate ecological processes functioning at varying scales, which is ideal for the CRe in which both temporal (HFEs, seasonal, and daily variation) and spatial (reach, sand bar-eddy complex, micro-elevation) variation in ecological processes is structured in clear hierarchies. The “Bayesian” aspect of this analysis incorporates prior information derived from process-based models that improves predictive ability and, critically, is designed for predicting future outcomes and associated uncertainty under simulated conditions. To generate alternative dam operations, we will draw from the current ROD to predict if the planned operations for the next 20 years will result in a departure from the goals for riparian vegetation on sandbars, for wildlife habitat, and as it relates to vegetation management.

Depending on the timing and availability of data generated as a part of element C.4 (see below), genetic and plasticity (ability to change its growth and shape in response to the environment) data from key riparian plant species may be incorporated into the final models. Genetic diversity and plasticity can factor strongly into the resilience and resistance of vegetation treatments and ecosystems to environmental change, but is as yet an understudied component of the CRe. If we are able to incorporate these data into the models, we should be able to examine the roles that these factors play in mediating plant and vegetation responses to variation in flows.

***Project Element C.4. Vegetation management decision support***

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The current LTEMP ROD (U.S. Department of Interior, 2016) includes a number of vegetation treatment actions to be conducted on NPS managed lands, in consultation with tribal partners and GCMRC. These experimental activities are expected to include (1) control of nonnative plant species, (2) development of native plant materials, (3) replanting native plant species, (4) removal of vegetation encroaching on campsites, and (5) management to assist with cultural site preservation. The GCMRC will work with the NPS and tribal partners to:

1. Develop a repeatable process that managers can use to quantify restoration goals and achievements and identify an initial set of experimental sites and treatments that will balance desired outcomes with information gain,
2. Provide information on appropriate transfer zones for native plant materials,
3. Assist with monitoring plan and protocol development.

Success of vegetation treatments that incorporate native plantings are likely to depend in large part on the availability and use of genetically suitable native plant materials (Durka and others, 2017; Grady and others, 2011; Pluess and others, 2016). The genetic make-up of planted materials affects how well individuals grow and survive in a treatment location and has cascading effects on the ecological integrity of the riparian system (Crutsinger and others, 2014; Grady and others, 2011; Whitham and others, 2012). Transfer zones based on existing genetic structure and morphological characteristics, which indicate where restoration stock should come from, are now considered “best practices” for determining ecologically appropriate source populations that balance local-adaptation, genetic diversity, and ecosystem services (Durka and others, 2017; Jørgensen and others, 2016; Williams and others, 2014). The LTEMP Scientific Monitoring Plan indicates that one aspect of the experimental vegetation treatments will include “establishing sources of native plants” (Vanderkooi and others, 2017), illustrating the importance of this step in the management process. The NPS restoration approaches use local materials in rehabilitation treatments in order to retain locally adapted genotypes and conserve unique local populations. However, the extent and parameters of what “local” means in the CRe and in riparian systems in general is unknown. GCMRC will work with the NPS and tribal partners to identify appropriate planting material of several focal native species to be grown in greenhouses for use in experimental revegetation treatments. This collaboration can also be extended to assisting with choosing appropriate locations for vegetation management and designing planting plans, as needed. We intend to seek outside funding to supplement genetic data with greenhouse experiments conducted in cooperation with the Restoration Assessment and Monitoring Program for the Southwest (RAMPS, <http://nau.edu/Merriam-Powell/RAMPS/>), and in consultation with tribal resource managers and federal partners. These experiments would be aimed at understanding variation in important traits associated with drought and inundation tolerances, competitive ability and other factors to help develop protocols for plant materials development that will maximize the effectiveness of revegetation treatments.

Targeted monitoring (separate from Element 1) will be necessary in order to properly assess the efficacy and secondary consequences of experimental vegetation treatments. Protocols may vary depending upon treatment type, but are likely to include assessments of plant regrowth and plant community changes in removal treatments, plant growth and survival in native plantings, and associated changes in the physical environment such as sand fluxes. GCMRC will develop protocols that are necessary to assess whether treatments are deemed effective based on desired outcomes defined by NPS and tribal partners.

Lastly, these collaborations and assessment can be used to develop a flexible decision support tool to provide managers (tribal resource managers, federal partners) with treatment recommendations given information on target locations and desired outcomes. Recommendations will provide a range of success probabilities given hydrological settings, flow levels, timing of treatments, focal species and native plant material sources (genotypes or cultivars). The decision support tool will be tested using a range of preliminary and simulated data, with the intent of populating the tool with experimental data as they are obtained. This tool will utilize an existing platform currently under development by RAMPS.

***Project Element C.5. Systemwide decadal-scale vegetation change monitoring***

Helen Fairley, Social Scientist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

The limited time depth of currently available vegetation monitoring data limits our ability to interpret vegetation changes in the CRe over decadal temporal scales. The replication and analysis of historical photographs provides a very powerful, cost-efficient, and “user-friendly” means of extending the currently available monitoring record farther back in time. High-quality replications of historical images have been successfully and effectively used by previous researchers to document landscape changes throughout the world (Webb and others, 2010) including desert and riparian vegetation in the Grand Canyon river corridor (Turner and Karpiscak, 1980; Webb, 1996) and in other riparian corridors throughout the American Southwest (e.g., Turner and others, 2003; Webb and others, 2007). More recently, this technique has been used to document significant increases in woody riparian vegetation and other significant riparian vegetation changes occurring within Grand Canyon between the early 1990s and 2010s (Scott and others, *in review;* Webb and others, 2011). This project element will extend the currently available record of vegetation change in the Colorado river corridor between river miles -15.5 and 240 through acquiring replications of photographs taken during several past expeditions on the Colorado River (e.g., 1923 U.S. Geological Survey expedition, 1940 Norm Nevills expedition, 1973 Weeden survey.)

Through collecting high-resolution and precisely replicated historical images, we will not only be able to document long-term changes throughout the riparian zone, but we will simultaneously be creating a baseline visual record at the start of the 20-year LTEMP period that documents the current condition of riparian vegetation throughout the river corridor. These images can be matched at the conclusion of the LTEMP period to document how conditions changed over the course of this 20-year-long experimental plan. A secondary benefit of acquiring these ground-level photographs will be to serve as an independent means of ground-truthing and illustrating vegetation conditions in the riparian zone in support of the ground-based monitoring and remotely sensed analyses being proposed under elements 1 and 2 of this project. Specifically, element C.5 aims to:

1. Precisely replicate historical images taken during past river expeditions using modern, high resolution digital technologies and to systematically analyze pair sets of images for changes in riparian species distribution, growth and abundance.
2. Develop a system-wide visual record of current riparian vegetation and campsite conditions that can serve as a baseline record for future photographic comparisons at the end of LTEMP period.
3. Provide an adjunct source of site-specific, ground-based information on riparian vegetation that is readily accessible to non-scientists and can support and supplement other kinds of monitoring data being collected under elements 1, 2, and 3.

This project element will build upon historical photo replication efforts initiated through a pilot study in the FY15-17 work plan, but this element will be specifically targeted at developing a system-wide visual record of riparian conditions at the start of the LTEMP period. This record can be used to monitor changes retroactively as well as into the future. We anticipate acquiring hundreds of replicated images over the duration of this three year work effort. Each paired set of images will be systematically analyzed for presence and abundance of common riparian species. The images will be annotated in the field to document where vegetation has persisted or changed through time, as well as any obvious changes in geomorphic setting and substrates that may affect species composition. The photographic replication work will be conducted in association with other vegetation monitoring work and/or with other scientific research, administrative or tribal monitoring trips whose schedules are compatible with the logistical requirements of this monitoring effort. All photographs and associated documentation will be digitized and archived with the U.S. Geological Survey (USGS) Southwest Repeat Photography Collection housed at the USGS Campus in Flagstaff, Arizona. These data will be made available online for use by other researchers in the future.

**4.2. Deliverables**

**Element C.1**: Annual data on plant species presence and cover from river mile -15.5 to 240, peer-reviewed publication on the status and trends of riparian vegetation from 2013 through 2017.

**Element C. 2**: Peer-reviewed journal manuscripts describing (i) the aerial image-based vegetation classification, (ii) riparian vegetation and sand dynamism, and (iii) satellite image analysis of tamarisk phenology and beetle impacts.

**Element C.3**: Peer-reviewed journal manuscript describing the relative influences of environmental pressures, including flow regime, on the composition and location of riparian vegetation. Recommendations of what environmental factors need to be considered in the design of vegetation treatments.

**Element C.4**: Guidance on the selection of vegetation treatment locations, recommended transfer zones for native plant propagation and planting, monitoring support, and general vegetation treatment assistance as new needs are identified. Decision support tool for treatment recommendations.

**Element C.5**: 60-80 replications of historical photos between river mile -15 to 240 will be collected each year, with analyses of vegetation change between paired sets.Peer-reviewed journal article in FY2020 will describes conditions at start of LTEMP and changes observed since 1923.

***Unfunded Project Element. Marsh community changes***

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Marshes are regionally rare vegetation communities that have attracted considerable interest from diverse stakeholders associated with the Grand Canyon. Marsh cover increased in the Grand Canyon following construction of the Glen Canyon Dam: the increase in baseflows and reduction in flood frequency created moderately inundated silty and sandy substrates ideal for a wide range of marsh species (Stevens and others, 1995). The postdam period may be divided into two distinct periods of different reservoir release patterns: (1) the period between 1963 and 1991 when power-plant operations involved unrestricted hydro-peaking and when long-duration floods occurred between 1983 and 1986 and (2) the period after 1991 when the range of daily hydro-peaking was restricted and when short-duration controlled floods occurred in 1996, 2004, 2008, 2012, 2013, 2014, and 2016 (Bureau of Reclamation, 1996; Schmidt and Grams, 2011). Marsh vegetation communities were mapped and categorized by Stevens and others (1995) in 1991, the end of the first distinct period of release patterns. At that time, marshes had increased from 0.09 to 25 hectares due to the preceding increase in baseflows and reduction in flood frequency. It is currently unknown how the second time period, characterized by reduced hydropeaking, has altered marsh habitat. Vegetation studies conducted during the interim flows of the early 1990’s indicated this unique habitat was drying up (Kearsley and Ayers, 1996), and recent observations suggest that marshes have changed in species composition and have been replaced by xeric phreatophyte vegetation, for example tamarisk (*Tamarix* spp.) and mesquite (*Prosopis glandulosa*).

Given the expectation that the new LTEMP operations will support more wetland vegetation than other alternatives (U.S. Department of Interior, 2016), stakeholder interest in marsh vegetation, and observed reductions in its extent within the Grand Canyon, we propose to conduct a reassessment of species composition and extent of marsh vegetation. We will use both remote sensing and ground-based monitoring data, as was done in Stevens and others (1995). Additionally, environmental niche models of dominant marsh species will be used to estimate impacts of future flow scenarios. The overall objectives of the project element are to:

1. Identify how total marsh area has changed (i.e., increased, decreased, or remained stable) since the completion of the Stevens and others, (1995) study;
2. Identify whether and how species composition in the marshes has changed, and if so, in what ways during the same time frame as (i)
3. Determine the state of marsh habitats at the beginning of the new LTEMP operations to be able to assess if Alternative D does, in fact, support more marsh vegetation at the end of the record of decision.

Remote sensing analysis of changes in marsh coverage will utilize data from recent riparian vegetation classification and change detection conducted by GCMRC (Bedford and others, *in prep*; Durning and others, 2016; Durning and others, *in prep*; Sankey and others, 2015; Sankey and others, 2016) to estimate temporal trends in marsh cover, frequency and patchiness. Stevens and others (1995) reported that as of 1991, there were “253 fluvial wet marshes (cattail/reed and horseweed/Bermuda grass) and 850 dry marshes (horsetail/willow) that occupied 25.0 ha (1%) of the 363 km mainstream riparian corridor between Lees Ferry and Diamond Creek”. We plan to use more recent remote sensing data to update the census of wet and dry marshes and determine how their spatial extent, patchiness and frequency by river reach (*sensu* Stevens and others, 1995) have changed. Remote sensing data will primarily be the corridor-wide multispectral imagery and vegetation classifications from 2002 and 2013 overflights (Durning and others, *in prep*; Ralston and others, 2008), though we will also consider using aerial imagery from 2004, 2005, and 2009 multispectral datasets (see Sankey and others, 2015). Vegetation classifications completed with 2002 and 2013 imagery include a wetland class which we will use as a proxy for the wet marsh category mapped by Stevens and others (1995). Thus we will determine where wet marshes mapped in 1991 are not similarly mapped as the remotely sensed wetland class in 2002 and/or 2013. We will determined where and why areas might exist that were mapped as the wetland class in 2002 and/or 2013 but not similarly mapped as wet marsh in 1991. We will also summarize what the composition of wet and dry marshes mapped in 1991 was as of the 2002 and 2013 vegetation classifications.

In order to characterize changes in the composition of marsh communities, we will resample species composition and cover at the locations in Stevens and others (1995) coincident with the annual riparian vegetation monitoring trips (Element 1). Using indicator species defined by Stevens and others (1995), we will assess changes in the composition and relative cover of four different marsh vegetation associations (clonal wet marsh (cattail/reed), nonclonal wet marsh (horseweed/Bermuda-grass), woody phreatophyte (tamarisk/arrowweed), and dry marsh (horsetail/willow)).

Utilizing environmental niche models developed from the retrospective vegetation analysis (previous workplan), we will model responses of individual species, marsh associations, and total marsh vegetation to alternative flow scenarios. These environmental niche models will define the breadth of river stage conditions that are viable for individual species.

**Deliverables**: Peer-reviewed journal manuscript that describes marsh community changes since the 1992 ROD and Stevens and others (1995).

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1. **Budget**







Project D. Geomorphic Effects of Dam Operations and Vegetation Management for Dunefields, Terraces, and Archaeological Sites

1. **Investigators**

Joel Sankey, Research Geologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center, and others (see each project element below for specific lead investigator and collaborators)

1. **Project Summary**

The operation of Glen Canyon Dam for hydropower generation since 1963 has fundamentally altered the flow regime of the Colorado River in Grand Canyon, and has largely eliminated pre-dam low flows (i.e., below 5,000 ft3/s) that historically exposed large areas of bare sand (U.S. Department of the Interior, 2016a; Kasprak and others, *in prep*). At the same time, the combination of elevated low flows with the elimination of large, regularly-occurring spring floods in excess of 70,000 ft3/s has led to widespread riparian vegetation encroachment along the Colorado River, further reducing the extent of bare sand (U.S. Department of the Interior, 2016a, Sankey and others, 2015). The reduction in bare sand and 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 supply of sediment exposed to wind transport from the active river channel (e.g., sandbars) to the adjoining landscape (U.S. Department of Interior, 2016a; Draut, 2012; East and others, 2016). Many archaeological sites and other evidence of past human activity are now subject to accelerated degradation due to reductions in wind-blown sediment resupply 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 resources goal for 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. The increased riverine supply of sediment, in conjunction with targeted riparian vegetation removal, is expected to result in the resupply of more wind-blown sediment to archaeological sites and dunefields, depending on site-specific riparian vegetation and geomorphic conditions (Sankey and others, *in prep*). At the same time, HFEs can also directly erode some river sediment deposits containing cultural resources, particularly large terraces in the Glen Canyon reach (U.S. Department of Interior, 2016a).

This project quantifies the geomorphic effects of ongoing and experimental dam operations, as well as the geomorphic effects of riparian vegetation expansion and management, focusing on effects to the supply of wind-blown sediment to cultural sites, dunefields, and terraces. The ongoing and experimental dam operations of interest are those that will be undertaken under the LTEMP ROD during the next 20 years. The data and analyses will allow the GCDAMP to objectively evaluate whether and how these non-flow and flow actions affect cultural resources, vegetation, and sediment dynamics, and how they ultimately affect the long term preservation of cultural resources and other culturally-valued and ecologically important landscape elements located within the river corridor downstream of Glen Canyon Dam.

1. **Background**

The LTEMP EIS relied on a series of conceptual and numerical models to evaluate the likely responses of resources to a suite of proposed alternatives for operating Glen Canyon Dam over the next 20 years. The models incorporated past scientific learning and produced generalized predictions about how resource conditions would potentially change under each alternative. The model-based analyses predicted that Alternative D, the alternative ultimately selected for implementation in the LTEMP ROD, would result in modest benefits for cultural resources by improving sediment conditions that help to stabilize and preserve archaeological sites in situ, while also benefiting natural processes, campsites, riparian vegetation, hydropower, endangered fish, and other resources valued by modern society.

Over the past decade, GCMRC scientists have developed and refined methods for tracking trends and quantifying rates, amounts, and sources of geomorphic change affecting cultural resources in the Colorado River ecosystem (CRe). Over the next three years, we propose to apply a suite of these methods to evaluate whether the predictions of resource improvement are born out over the next 20 years (U.S. Department of Interior, 2016a, b). Specifically, we will evaluate whether changes in operations improve sediment supply to cultural resources and the associated terraces and dunefields in which these sites are embedded, and whether such changes in turn result in a reduction of erosion rates and improved preservation of the physical attributes that are necessary to maintain site integrity under the National Historical Preservation Act.

The LTEMP ROD (subsection 6.4) also identifies vegetation management as a non-flow action that will be used to assist with cultural site protection. Specifically, the NPS will work with tribal partners and GCMRC to remove woody riparian vegetation at individual sites to increase the amount of river sand that is transported by wind and deposited on adjacent sand dunes, terraces, and archaeological sites contained therein. In this project, we propose to apply our scientific expertise on the geomorphic effects of dam operations to: (i) provide decision support assistance to the NPS and Tribes to plan and design vegetation removal treatments during FY18, and (ii) quantify the outcome of the experimental vegetation removal treatments when they are implemented beginning in FY19. We will quantify the outcome of the vegetation treatments as part of our ongoing program for monitoring the effects of dam operations on the geomorphic condition of archaeological sites which we have implemented in Project 4 (of the FY15-17 workplan).

The LTEMP EIS identifies river terraces, specifically in the Glen Canyon NRA reach, as being vulnerable to erosion and degradation from controlled floods (HFEs) which are otherwise intended to distribute sediment throughout the river downstream of the Paria(also see Grams and others, 2007). In this project, we will assist NPS and tribal stakeholders in quantifying the effects of dam operations on the erosion of terraces and other river sediment deposits by determining erosion rates during the approximately two decades since the implementation of the previous ROD (U.S. Department of Interior, 1996) with river flow regime of episodic controlled floods and restricted hydropeaking, through the current ROD. We will use new methods developed from our research in Project 4 (FY15-17 workplan; Kasprak and others, 2017) as well as methods from our ongoing program for monitoring the effects of dam operations on the geomorphic condition of archaeological sites implemented in Project 4.

This project is founded on more than two decades of research and monitoring in the CRE. Previous research has demonstrated that throughout Grand Canyon, numerous terraces and dunefields, and the cultural resources contained therein, are subject to degradation from erosion processes and visitor impacts. Past studies have also demonstrated that the effects of dam operations have accelerated and exacerbated the rates of erosion affecting these areas. Furthermore, research has shown that the areas containing many cultural resource sites have become disconnected from the active river channel due to the combination of riparian vegetation encroachment and alterations in flow downstream of Glen Canyon Dam, which historically supplied sediment (e.g., during floods) and also exposed that sediment for transport (e.g., during low flows; East and others, 2016). Terraces and dunefields are a substantial component of sediment resources in the ecosystem, in addition to containing widespread evidence of past human activity in the ecosystem (e.g., archaeological sites; U.S. Department of the Interior, 2016a). Thus, the ongoing loss of these upper-elevation sediment deposits is contributing to the loss of all sediment-dependent resources in the CRe, including cultural sites. In some places, for example at the large terraces in the Glen Canyon reach of the Colorado River, sediment transport between the active channel and upland areas occurs primarily through fluvial and mass failure processes; here, HFEs have resulted in erosion of terraces, mainly from the draw-down effect and change in pore pressure gradient after flood water recession exposes saturated terrace banks, which then shed material into the river channel. In other cases, sediment connectivity exists via aeolian transport of sand from sandbars to dunefields. In both situations, the deposition or erosion of sediment in the terraces and dunefields can have direct impacts on buried or exposed archaeological sites situated on these surfaces, and can also have indirect impacts such as offsetting rates of erosion from natural processes in the surrounding landscape (U.S. Department of the Interior, 2016a). These impacts are in turn interpreted by NPS and tribal resource managers as being either beneficial or deleterious to the cultural resources in question. Purely from the standpoint of the sediment resource, erosion obviously reduces the abundance of sediment while increased deposition increases the abundance of sediment. In addition to the work described above that is directly responsive to management planned per the LTEMP ROD and Long-Term Experimental and Management Plan Final Environmental Impact Statement FEIS (U.S., Department of the Interior, 2016a,b), this project aims to quantify the influence of dam operations and vegetation encroachment on the areal extent of sand available for sandbar and dunefield maintenance over the 241-mile reach from Glen Canyon Dam to Diamond Creek. A short, 16-mile proof-of-concept reach of Marble Canyon was previously evaluated in Project 4 by Kasprak and others, *in prep*. This pilot study quantified the individual and additive effects of hydrology and vegetation on sediment connectivity.

Each of these projects elements are discussed in further detail below.

1. **Proposed Work**

### 4.1. Project Elements

#### Project Element D.1. Geomorphic effects of dam operations and vegetation management

Joel Sankey, Research Geologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

Helen Fairley, Social Scientist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

Jen Dierker, Archaeologist, National Park Service, Grand Canyon National Park

Ellen Brennan, Cultural Programs Manager, National Park Service, Grand Canyon National Park

This project element will use the plan for monitoring the geomorphic condition of archaeological sites that we implemented in Project 4 (FY15-17 workplan) to quantify changes in the physical condition of archaeological sites, surrounding landscapes, and their sand supply. We will then use the data to assess the possible causal relationships through which (i) dam operations, (ii) natural processes, and (iii) vegetation management conducted by NPS and tribes per the LTEMP ROD affect these quantified changes in physical condition. Monitoring will focus on quantifying changes in physical condition, including effects to archaeological site-specific attributes that are important to maintaining site integrity, using methods we have previously developed and implemented for geomorphic change detection (e.g., lidar, structure-from-motion, total station; Kasprak and others, 2017; Collins and others, 2008, 2009, 2012, 2014, 2016; East and others, 2016; Wheaton and others, 2013). Geomorphic change detection will employ the new morphological sediment budgeting tools we developed in Project 4 to quantify the role of individual geomorphic processes (fluvial, alluvial, colluvial, and aeolian) driving change at sites (Kasprak and others, 2017). We also propose to use sediment tracer experiments to quantify the degree of sediment connectivity between sandbars and dunefields at individual sites over annual timescales (Dukes and others, in review). Monitoring during this workplan will not entail any additional site classification work (i.e., we will not be updating the aeolian classification presented in East and others, 2016). However, the archaeological site classification data collected during Project 4 will be used to draw inferences about the relative roles of dam operations (including experimental flows), natural processes, and vegetation management in driving geomorphic change at sites, and also for selecting treatment and control sites for evaluating the effects of vegetation removal (East and others, 2016).

During FY18 we plan to specifically assist the NPS and tribes to select sites and design experimental vegetation removal treatments to increase sediment connectivity between sandbars and archaeological sites. We have already identified several locations where previous monitoring provides a clear rationale for conducting vegetation removal, and we propose to use this and new information as necessary to help the NPS and tribes develop experimental test cases to be implemented in FY19 and then quantitatively evaluate the effects of these treatments. Specific to vegetation management, a hypothesis of this project element is that removal of woody riparian vegetation at selected locations can significantly increase aeolian (or also flood-transported?) deposition of Colorado River sand at individual source-bordering dunefields and archaeological sites. Evaluation of vegetation removal treatments and site geomorphic condition will focus on locations where the deposition of sand is perceived by resource managers (i.e., NPS and Native American Tribes) as having the potential to positively impact the preservation of cultural resources (i.e., archaeological sites) and possibly other sediment-dependent resources (e.g., culturally important plants). We will use existing archaeological site-specific baseline data from our monitoring program and collect new monitoring data as necessary for this work.

#### Project Element D.2. Contemporary changes at terraces and other river sediment deposits

Joel Sankey, Research Geologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

Brian Harmon, Archaeologist, National Park Service, Glen Canyon

Paul Grams, Supervisory Hydrologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

Helen Fairley, Social Scientist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

This project element will determine recent erosion rates of terraces and other pre-dam river sediment deposits in Glen, Marble, and Grand Canyons and evaluate their relationships to dam operations (e.g., HFEs). In Glen Canyon National Recreation Area (GLCA) this will involve collaboration with GLCA archaeology staff who have asked GCMRC to assist with:

1. identifying terrace deposits most likely to contain buried cultural materials that are at risk from flow-related erosion and
2. quantifying how terraces are changing due to bank and gully erosion, and
3. completing site-specific geomorphic change detection before and after future HFEs.

The first two components of the collaboration with GLCA will be to (1) map the existing terraces and other pre-dam river sediment deposits and (2) update the assessment of dam-related geomorphic changes in Glen Canyon published by Grams and others (2007). That previous study quantified the rate and pattern of bed incision and bank adjustment between 1956 and 2000. We will employ post-2000 remote sensing imagery, topography, bathymetry, and flow (inundation) modelling, as well as additional field-based terrace and vegetation mapping in order to update the assessment and then deliver the datasets to GLCA archaeology staff. This will result in a collaborative evaluation of recent (post-2000) changes to Glen Canyon’s terraces, shorelines, and riparian vegetation that are relevant for the GLCA archaeology staff’s goals of preserving cultural resources and archaeological sites. This work will be completed in FY18.

The third component of the collaboration with GLCA will be to use survey and remote sensing techniques to quantify geomorphic changes associated with HFEs in FY18-20. GLCA archaeology staff will identify site-specific monitoring locations and GCMRC will assist and also train the GLCA archaeology staff to collect imagery and topographic data using ground and UAS-based photogrammetry (structure-from-motion) as well as lidar. GCMRC will process the data and perform geomorphic change detection and will then deliver the derivative datasets to the GLCA staff. GLCA and GCMRC will collaborate to interpret, summarize, and report on the monitoring results. This work will be conducted in all three years of the workplan.

In Glen, Marble, and Grand Canyon we will also implement the new software utility published by Kasprak and others (2017), which determines site-scale sediment budgets and the relative contributions of individual sediment transport processes including fluvial, alluvial, colluvial, and aeolian transport in driving geomorphic changes. We will then use the output from the sediment budget analysis to evaluate how erosion rates of terrace and other pre-dam river sediment deposit geomorphic changes vary in relation to dam operations on a reach-scale basis. We will use 1-m resolution digital topography acquired from aerial overflights in 2002, 2009, and 2013 to estimate rates and patterns of geomorphic changes relative to dam operations. This will also include developing a web-mapping framework, hosted by GCMRC, to allow public online use of the software utility to visualize geomorphic changes at user-selected locations in Glen, Marble, and Grand Canyons. This work will be completed in FY18 and FY19.

#### Project Element D.3. Effects of dam operations and vegetation on the areal extent of bare sand

Joel Sankey, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

This element will synthesize data from Projects B, C, and D to quantify the influence of Glen Canyon Dam discharge and vegetation encroachment on altering the areal extent of bare sand available for fluvial and aeolian transport from Glen Canyon Dam to Diamond Creek. This research will be completed over a two-year period beginning in FY18 and concluding in FY19.

For a 16-mile study reach (from RM 46 to RM 62) where both data on the extent of sand and vegetation are available from this project and the channel mapping project, Kasprak and others (*in prep*) found that hydrologic alteration reduced the amount of bare sand by 14% following closure of Glen Canyon Dam, vegetation encroachment reduced sand extent by 20%, and the additive effect of altered hydrology and vegetation resulted in a 27% reduction in bare sand area between the pre- and post-dam periods. Kasprak and others (*in prep*) also found that at present, approximately 10% of the total area of unvegetated sand is located above the maximum stage reached by HFEs, and roughly 50% of the total bare sand area is located above the contemporary low-flow stage, with the remaining 50% being inundated nearly continuously. Importantly, however, the individual and additive effects of hydrologic alteration and vegetation encroachment on the areal extent of bare sand, and their subsequent role in interrupting fluvial-hillslope sediment connectivity and the maintenance of river-derived sand deposits in upland landscapes, remain unknown outside of this 16-mile study reach, which may or may not be representative of conditions throughout Grand Canyon.

With the anticipated channel bed mapping (Project B) and riparian vegetation mapping (Project C) in this work plan, continuous maps of bare sand and vegetation extent will be available from Glen Canyon Dam to Diamond Creek. Project Element D.3 seeks to extend the 16-mile proof-of-concept work done by Kasprak and others (*in prep*) to quantify the role of hydrologic alteration and vegetation encroachment on bare sand extent continuously along this entire 241 mile reach. The results of this analysis will evaluate the degree of to which bare sand alteration results from Glen Canyon Dam operations and how this relationship may vary longitudinally along the CRe. This work will also provide a corridor-wide framework for quantifying the effects of proposed flow regimes and vegetation removal efforts on the extent of sand available for building sandbars, maintaining existing campsites, and promoting fluvial-hillslope sediment connectivity for the preservation of cultural resources.

***Project Element D.4 Cultural resources synthesis to inform Historic Preservation Plan***

Helen Fairley, U.S. Geological Survey, Grand Canyon Monitoring and Research Center, in collaboration with PA signatories

Reclamation and GCDAMP stakeholders who are signatories to the new Section 106 Programmatic Agreement for Cultural Resources (PA) have identified the need for a synthesis of the results of past monitoring, research, and mitigation adverse effects, and other impacts to cultural resources in the CRe. This synthesis is needed 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 historic properties affected by dam operations.

This project will involve assembling, reviewing, evaluating and synthesizing all past monitoring, research, and mitigation projects and associated data collected by NPS archaeologists, GCMRC contractors, tribal cooperators, and U.S. Geological Survey (USGS) scientists related to cultural resources within the Area of Potential Effect from dam operations over the past three decades (early 1980s through 2017). The GCMRC’s cultural program manager (Helen Fairley) is well-positioned to develop this knowledge synthesis, having previously evaluated or analyzed the available monitoring and research data related to this topic and having previously read most, if not all, reports that have been generated about this subject, including reports on previous mitigation activities, over the past three decades.

The synthesis will include a management summary table for all identified historic properties within the Area of Potential Effect from dam operations, including Traditional Cultural Properties, for which publicly accessible information is available. For each individual property, the table will include a summary of documented impacts to each resource (including impacts from GCDAMP-related activities), previous actions (monitoring, research, and/or mitigation) undertaken at each property, long-term management goals for the property (to the extent that they have been established), and citations for all the extant reports that reference each specific property.

In developing this synthesis, GCMRC’s cultural program manager (Helen Fairley) will work closely with the PA signatories, agency personnel, and AMP stakeholders to ensure that all relevant sources of information are included in the synthesis and to identify specific issues and sub-topics that tribes, other AMP stakeholders, and agency personnel feel are important to consider. GCMRC’s cultural program manager also will consult with the wider archaeological and geo-archaeological research community to ensure that the resulting synthesis is well-founded, objective, and thorough in its evaluation and synthesis of currently available data.

Once the initial synthesis has been completed in FY18, ,GCMRC’s cultural program manager will initiate an analysis of the hundreds of photographs that have been assembled over the previous 2+ decades of monitoring cultural resources in the CRe, to extract as much information as possible about the processes affecting historic properties in the CRe and to assess their utility for future monitoring purposes. This analysis of the legacy photograph collection was previously recommended by a scientific review panel in 2007 (Kintigh and others, 2007), but as of 2016, no progress on completing this analysis has been made. GCMRC’s cultural program manager will collaborate with NPS archaeologists and Tribes to ensure that this analysis meets the needs and interests of the Section 106 compliance program, as well as information needs of the GCDAMP. Qualitative analysis methods developed in collaboration with the PA signatories will be used. The resulting data and report will provide additional baseline information about the causes and processes affecting cultural resources in the CRe to help inform future decisions and priority-setting activities under the new PA

### Deliverables

**Element D.1.:** Vegetation removal treatment and site geomorphic condition monitoring reports to NPS, Tribes (and all stakeholders), and a journal publication that describes the results of the initial experimental treatments approximately 2 years into post-treatment monitoring. Published datasets.

**Element D.2.:** A USGS report that updates the Grams and others (2007) study and describes changes in Glen Canyon. A report that describes erosion rates and patterns determined from change detection at terraces and river sediment deposits in Marble and Grand Canyons. Published datasets.

**Element D.3.:** A USGS Scientific Investigations Report detailing results of bare sand analyses from Glen Canyon Dam to Diamond Creek; Published datasets and a software utility for estimating the effect of proposed flow regimes and vegetation removal efforts on areal extent of bare sand.

**Element D.4.:** A peer-reviewed report synthesizing past monitoring, research and mitigation work performed at historic properties within the Area of Potential Effects from dam operations and a second report synthesizing the changes and impacts that have been recorded in 20+ years of monitoring photographs taken at cultural resource sites in the CRe.

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1. **Budget**







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

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1. **Project Summary**

The temperature of, and nutrient concentrations in, the outflow from Lake Powell are two important controls on invertebrate and fish communities, as well as on overall ecosystem productivity in the Colorado River ecosystem (CRe). Ecosystem temperature and nutrient dynamics can influence both species 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). In the CRe, temperature and nutrients are likely to directly drive trends in all aquatic resources identified by the Long-Term Experimental and Management Plan (LTEMP, U.S. Department of Interior, 2016a), as well as affecting vegetation colonization on sandbars, and thus potentially affecting the beach resource. The 2016 fisheries protocol evaluation panel (PEP) identified potential changes in Lake Powell outflow as one of the most important emerging issues and recommended more study of nutrients throughout the CRe (Casper and others, 2016). In addition, the degree to which temperature constrains growth and reproduction of native fish in the CRe has long been recognized (Gorman and VanHoosen, 2000; Robinson and Childs, 2001) as has the potential threat for invasions by nonnative warm-water species that are prevalent in other parts of the Colorado River Basin (Tyus and Saunders, 2000). The desire to manage temperatures in the CRe has led to recommendations for potential flow alterations (e.g., low summer flows) and evaluations of potential infrastructure alterations (e.g., temperature control devices, retrofitting of jet tubes) discussed within the LTEMP Biological Opinion (U.S. Department of Interior, 2016b). However, there is also a growing appreciation for the important interactions between temperature and food availability in ultimately determining fish responses to temperature management (Dodrill and others, 2016). For example, increases in growth rates of fish at optimal temperatures could be cut short if nutrient turnover is not sufficient to augment the aquatic foodbase to the degree that the energetic demands of fish are met, but nutrient turnover is itself affected by water temperature. Historical data from Wahweap suggest that epilimnetic releases from Lake Powell not only are warmer than releases from deeper in the lake, but are likely to deliver lower concentrations of nutrients to the CRe because phosphorus concentrations are lower in the epilimnion of the lake than in deeper waters (Vernieu, 2009). A decline in nutrients from the dam could lead to declines in the aquatic foodbase, irrespective of increasing temperatures.

Our understanding of basic patterns of nutrient availability in the CRe, and their significance, is poor, however, even as there is growing recognition of their potential importance. While both nitrogen and phosphorus are known to be important limiting nutrients in freshwater ecosystems, exceptionally high nitrogen to phosphorus ratios in the CRe suggest that phosphorus is most limiting in this system. Thus, the majority of the work proposed here focuses on better characterizing phosphorus bioavailability and cycling in the river. Phosphorous (specifically soluble reactive phosphorous - SRP) is required by the primary producers (i.e., algae) that serve as the foundation of the aquatic foodbase. Preliminary data suggest that declines in SRP availability over the last five years have propagated through the entire aquatic food web, constraining rates of primary production, invertebrate production, and ultimately suppressing the recruitment of rainbow trout (*Oncorhynchus mykiss*) at Lees Ferry and the condition of adult humpback chub (*Gila cypha*) near the Little Colorado River (LCR) confluence (Yackulic, 2017). In addition, rainbow trout recruitment since 2001 (when the detection limit for monitoring SRP was lowered to allow for tracking of trends) can be better explained statistically by models that include variables for SRP concentration and the number of trout already in the system, than by models that include only flow variables, such as the model used to predict rainbow trout recruitment for the LTEMP. Most phosphorous in the CRe is likely to be either bound to carbonates in fine sediments (Elser and others, 1996; Wildman and Hering, 2011) or locked up in biomass (including vegetation, invertebrates, and fish). High flows under the LTEMP, especially HFEs that redistribute sediments and uproot aquatic vegetation and bury it in sediment, have the potential to redistribute phosphorous and alter rates of exchanges with the water column.

Given the importance of nutrients and temperature as drivers of the aquatic ecosystem, it is important to understand their spatio-temporal patterns both because they may be altered by management actions considered in the LTEMP, and because they may provide essential context for interpreting responses to flow experiments. Given the potential importance of nutrients and temperature in driving CRe dynamics, we propose monitoring, research and modelling to: 1) understand the factors that drive variation in nutrients and temperature in the outflow from Lake Powell, 2) identify processes outside of Lake Powell that drive spatial and temporal variation in nutrients and temperature throughout the CRe, and 3) establish quantitative and mechanistic links among these ecosystem drivers, primary production, and higher trophic levels.

A number of physical and biogeochemical processes in Lake Powell affect the nutrient concentration of dam releases, however, we lack a good quantitative understanding of the relative importance of these different reservoir processes in determining variation in nutrient concentrations in Lake Powell’s outflow. More generally, the high uncertainty concerning drivers of water quality in Lake Powell’s outflow was highlighted in the recent knowledge assessment conducted by the Technical Work Group of the Glen Canyon Dam Adaptive Management Program, in which this category consistently had the highest uncertainty (Braun, 2017). This lack of understanding impedes our ability to predict how various actions discussed in the LTEMP Biological Opinion (e.g., retrofitting the dam to draw waters from different reservoir depths) will affect the CRe, or to predict how effects from environmental factors (e.g., prolonged drought) on GCDAMP priority resources such as rainbow trout and humpback chub may override impacts from experimental flows associated with the LTEMP. Furthermore, the August 2016 fisheries PEP recommended additional study of reservoir dynamics as a priority emerging issue, with specific emphasis on a better understanding of temperature and nutrients including the potential impacts of releases from the meta- and epilimnetic regions of the reservoir and increasing influence of quagga mussel (*Dreissena bugensis*) on nutrients and temperature conditions. For these reasons, we propose renewed study of Lake Powell in FY2018-20 that expands upon the current monitoring efforts conducted under the Interagency Agreement R13PG40028 between the Bureau of Reclamation and GCMRC. Currently, we are assessing historical data to identify unmet needs and redundancies in current monitoring, assessing the evidence for various hypotheses about the drivers of temperature and nutrient patterns, and determining priorities for research. As we move through the FY2018-20 work period, we will integrate learning from analyses of historical data, improved monitoring, and research projects to develop quantitative methods to predict nutrient concentrations in the Lake Powell outflow under various scenarios of change and management options.

Travelling downriver from Glen Canyon Dam, both temperature and nutrients change in response to various processes. A dense network of stream gaging stations in Grand Canyon provides information on temperature at fine temporal resolutions (Project A) and a temperature model exists to predict downriver temperature (Wright and others, 2008). This model was used to predict responses of downriver native fish populations and invasive warm water non-native fish species to management alternatives in the LTEMP. Although the Wright et al. (2008) temperature model was a valuable tool for EIS modeling efforts, it has important limitations. For example, Wright and others (2008) clearly acknowledge that their model overestimates temperatures in downriver reaches during fall low flow months by as much as 2 °C, however, this assumption does not appear to have been acknowledged in LTEMP modelling of downriver temperatures. We are currently modifying Wright’s model and propose to finish this work in FY2018. These modifications are expected to improve downriver predictions.

In contrast to our detailed understanding of temperature, we lack even a basic understanding of gross patterns in nutrient concentrations and their variation over time and along the river, especially patterns in SRP availability in the Colorado River downstream of Lees Ferry. While continuous nutrient monitoring at Lees Ferry shows a strong correspondence between nutrient availability in the reservoir outflow and in the Lees Ferry reach, there are very few measurements of nutrients downstream of the Paria River inflow, with no measurements of SRP routinely made. While the dam releases contribute substantially more discharge than all tributary inputs combined, tributaries like the Paria River and the LCR are the major sources of sediment and labile organic matter inputs to the Colorado River and can drive riverine suspended sediment dynamics independent of total river discharge (Topping and others, 2007; Ulseth, 2012), and nutrient loads may vary in part with suspended sediment loads. Indirect evidence suggests that reservoir inputs may dominate nutrient concentrations in the upper parts of the CRe, but other factors may become more important downriver. For example, as nutrient concentrations in Lake Powell declined during 2014, Colorado River invertebrate and fish populations between Glen Canyon Dam and Lees Ferry and near the LCR confluence declined dramatically. However, in more downriver portions of the CRe, the catch of humpback chub, especially juvenile life stages, was higher in 2014 than in prior years. This suggests either that nutrient limitation is currently not a controlling factor in the lower half of the CRe (see hypotheses H5, H6, and H8 in Project G), or that there are unaccounted sources of nutrients in the lower CRe. These unaccounted sources of nutrients in the lower CRe could consist of tributary inputs, release of geologically bound P under different environmental conditions, or elevated mineralization with higher temperature and/or organic matter inputs (see hypothesis H7 in Project G).

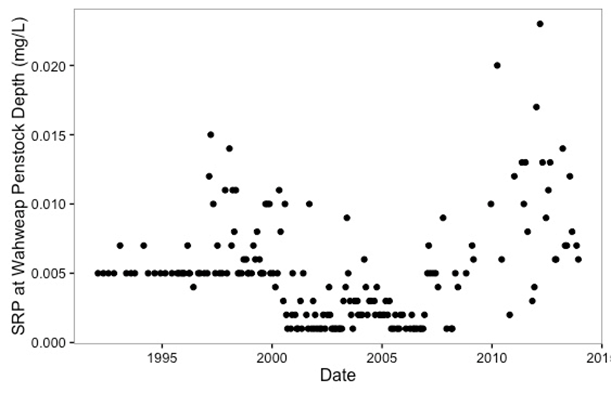
To address these critical management uncertainties, we propose a multi-pronged approach that aims to better understand processes affecting temperature and nutrient availability in Lake Powell outflows, to measure and improve predictions of spatial and temporal patterns in nutrients and temperature within the CRe, and to further investigate links between these drivers and Colorado River food webs.

1. **Background**

***Factors affecting nutrients in Lake Powell outflow***

Reservoirs behind dams are often sinks for biologically relevant nutrients like nitrogen and silica (Harrison and others, 2012; Harrison and others, 2009). With respect to phosphorous, individual reservoirs can either be sinks or sources of phosphorus depending on their individual characteristics (Powers and others, 2015,), however they often retain phosphorus and contribute to significant reductions in the downstream transport of phosphorus at the global scale (Maavara, 2015; Maavara and others, 2015). Historical data suggests Lake Powell is functioning as a net phosphorous sink given higher concentrations of phosphorous in the reservoir inflows than in the outflow (Vernieu, 2009). In particular, Lake Powell outflows often have very low concentrations of SRP, the form of phosphorous that is used most readily by the primary producers that form the basis of foodwebs in both Lake Powell and the CRe. While concentrations of SRP are always relatively low (mean of 5 µg L-1 in the water exiting Glen Canyon Dam), they have also varied substantially through time (factor of three variation in SRP concentration within a single season between 2012 and 2016 alone, Vernieu, 2009). In addition, the recent knowledge assessment conducted by the Technical Work Group of the Glen Canyon Dam Adaptive Management Program highlighted the drivers of temporal variation in nutrient concentrations in Lake Powell as one of the largest uncertainties within the CRe (Braun, 2017).

Nutrients have been monitored at penstock depth 2.4 kilometers upstream of Lake Powell since the early 1990s, however the detection limit for key nutrients (e.g., SRP) was relatively high until 2001, and thus temporal patterns in the 1990s are partially obscured. Following changes in detection, the degree of temporal variation in nutrients like SRP became much clearer. In a broad sense, SRP has been relatively high during two periods (the late 1990s and 2008-2014), and currently appears to be trending towards the extremely low concentrations more typical of the early to mid-2000s (Figure 1). Past efforts to understand and predict water quality in the outflow from Lake Powell has focused on other attributes (e.g., predicting water temperature with a two dimensional hydrodynamic and water quality model, CE-QUAL-W2, Williams, 2007), with much less focus on understanding temporal patterns in nutrients like SRP. Given recent findings that SRP may be a key driver of ecosystem productivity in the CRe, there is a need to more closely examine historical data including data from elsewhere in Lake Powell and estimates of SRP loading that can be derived from historical measurements along the Green, Colorado and San Juan Rivers. Analyses of these data should help us test some very broad hypotheses concerning drivers of temporal variation of SRP in Lake Powell.



**Figure 1.** Concentrations of SRP versus date. All data are from the penstock depth at Wahweap and were taken from the Lake Powell historical water quality dataset (Vernieu, 2009). Note the change in analysis detection limit that occurred in 2001.

The Colorado and San Juan Rivers deliver large amounts of total phosphorous to Lake Powell, however, much of this phosphorous is bound to fine sediments and is deposited in the deltaic sediments. As the elevation of Lake Powell drops, these deltaic sediments can become repeatedly exposed and reinundated. It has been hypothesized (**H1**) that inundation of these sediments may lead to surges of SRP flowing out of the deltas into Lake Powell (Wildman and Hering, 2011). Such surges potentially result in advection of the SRP toward the dam and eventually in elevated SRP in Lake Powell outflow. This scenario is more likely to occur during winter and early spring when there is less biological uptake of SRP within the lake and inflow waters tend to flow under the Lake Powell epilimnion. This hypothesis suggests that the interaction of season, low lake elevation, and high inflows should lead to increased SRP in lake waters, leading to increased SRP discharge at Glen Canyon Dam. However an alternative hypothesis (**H2**) is that high inflow nutrient loading itself may bring high concentrations of SRP into Lake Powell (i.e., that low lake elevation may not be necessary for surges of SRP). Distinguishing between these hypotheses is important for predicting how climate, water policy (e.g., the 2007 Interim Guidelines), or both may affect overall phosphorous cycles in Lake Powell.

The waters of Lake Powell vary in density, both over time and with depth. Waters with different densities sink to different depths within the lake, resulting in density stratification. Lake inflows also vary in density over time. The interaction between the density of inflows and existing density stratification in Lake Powell determines the depth at which inflows enter the Lake Powell water column. Water temperature and salinity are the primary factors determining water density, and both the density of the inflowing water and the density stratification within the reservoir change through time. We hypothesize (**H3**) that SRP rich waters which end up closer to the surface are less likely to contribute to increased SRP in the outflow, both because the SRP is more likely to be taken up by primary producers in the light-saturated surface waters (epilimnion) of the Lake Powell ecosystem and because primary producers will elevate pH in these upper waters, leading to increased rates of co-precipitation of SRP with calcium carbonate. Given the long residence time of water in Lake Powell (2-3 years) and its horizontal and vertical mixing dynamics, we also hypothesize (**H4**) that SRP concentrations in Lake Powell outflow may reflect inflow conditions over many years and not just the single prior year. Lastly, we hypothesize (**H5**) that an important factor affecting SRP concentrations in the lake and its outflow over the last few years, and in the future, may be the continued establishment of quagga mussels in the lake. The mussels may increase both temperature and dissolved nutrients by filtering phytoplankton and zooplankton from the water column. This specific hypothesis, **H5**, and the more general need to integrate our understanding of Lake Powell nutrient dynamics with our understanding of the CRe were identified as a priority by the 2016 fisheries PEP.

While wwe expect that SRP concentrations in Lake Powell outflows have historically been primarily driven by the magnitude and seasonal timing of inflows, the amount of exposed deltaic sediments and the interactions of inflows with existing reservoir stratification (i.e., **H1-H4**) and may increasingly be affected by quagga mussels (**H5**). We also hypothesize that dam operations and potential infrastructure changes can change SRP concentrations in Lake Powell outflows. In particular, we hypothesize (**H6**) that drawing water through the jet tubes (either during HFEs or if retrofitting of jet tubes is pursued after the feasibility study dictated by the LTEMP EIS and associated Biological Opinion) could elevate riverine SRP concentrations in dam outflows. This effect would arise because of the higher concentrations of phosphorus found in the lake’s hypolimnion (the stratum of dense water that develops below the typical mixing depth for a reservoir). In addition, past work suggests some support for hypothesis (**H7**) that dam operations, such as high flow events, can lead to substantially mixing of stratified layers within Lake Powell. For example, Hueftle and Stevens (2001) showed that the 1996 spring high flow experiment (HFE) diminished hypoxia in the hypolimnion as far as 100 km up-lake from Glen Canyon Dam while also resulting in high salinity, high dissolved oxygen concentrations, and damped fluctuations in dissolved oxygen and pH in the dam tailwater (Hueftle and Stevens, 2001). Nutrient data collected four days before and two days after the 1996 spring HFE showed drops in phosphorus concentration at both the penstock and river outlet works (Hueftle and Stevens, 2001), although the magnitude of this drop is difficult to determine given the detection limit of the analyses used at that time. Monitoring during the 2008 HFE also showed elevated dissolved oxygen concentrations immediately downstream of the dam (at maximum 120% of saturation), but relatively minimal effects on the structure of the water column up-lake of the dam (Vernieu, 2010). Still, this study only considered water temperature, specific conductance, and dissolved oxygen, but not nutrients. Lastly, the amount of water stored in Lake Powell is also clearly a factor in determining temperature and nutrients in the outflow so long as the depth from which the penstock pull is fixed. There tends to be more phosphorus in the colder hypolimnion than in the warmer epilimnion, but the relationship between water level and outflow phosphorus concentrations is not straightforward in the historical dataset suggesting the importance of other drivers like inflow, quagga mussels, and sediment deltaic dynamics.

***Factors affecting spatio-temporal variation in temperature and nutrients in the CRe.***

Spatio-temporal variation in temperature in the Colorado River downstream from Glen Canyon Dam is well understood and primarily driven by the temperature of Lake Powell outflows, air temperature, and discharge. Wright et al. (2008) developed a model for predicting water temperature given these drivers in the CRe and this model does an excellent job of predicting temperatures with one important exception. The model overestimates temperatures in downriver reaches during fall low flow months by as much as 2 °C. One factor contributing to this overestimation is that the model assumes linear warming, when exponential warming (in the form y= a-b\*exp (-x)) would be expected based on physics. We hypothesize (**H8**) that replacing the assumption of linear warming with an assumption of exponential warming will lessen or eliminate the bias in the Wright et al. (2008), leading to better predictions of water temperature to predict both native fish responses and potential for invasion and establishment by nonnative warm-water fish.

In contrast to our understanding of spatio-temporal patterns in temperature, our understanding of patterns in nutrients, especially phosphorous and SRP in the CRe is extremely poor. Long-term data on nitrate spanning decades and extending prior to closure of Glen Canyon Dam is available at the Grand Canyon gage near Phantom Ranch, and other nutrients are measured occasionally at the Grand Canyon gages near both Bright Angel and Diamond Creeks as well as in some tributaries (U.S. Geological Survey, 2004). Still, SRP has only been measured downstream of Lees Ferry in a few instances (Parnell and others, 1999). SRP concentrations in the Colorado River at Lees Ferry have been regularly measured and generally track measurements taken in the draft intake tubes in Glen Canyon Dam (e.g. water from one of the dam penstocks that is actively being used at the time of sampling), as well as at penstock depth in Lake Powell near the dam (e.g. at the Wahweap sampling station). While the large number of estimates at or near detection limits complicates analysis (Figure 1), preliminary analysis suggests that, on average, SRP measurements taken at Lees Ferry differ from measurements in the dam’s draft intake tubes by approximately the amount that is required for observed rates of gross primary productivity in Lees Ferry (i.e., 1 µg L-1 drop in SRP concentration assuming average gross primary productivity of 5 g O2 m-2 d-1). Importantly, the average drop is similar in magnitude to the current detection limit, suggesting that measurements of SRP below detection limit indicate severe phosphorous limitation within this reach, let alone at downstream reaches.

As we move downstream of Lees Ferry, a number of processes could potentially modify nutrient cycling, leading to either increases or decreases in SRP. We hypothesize (**H9**) that primary producers will generally remove SRP as water moves longitudinally with greatest losses in the most productive reaches during the day, when turbidity is low. Downstream of the LCR confluence, especially when the LCR is at baseflow, we also hypothesize (**H10**) that SRP concentrations may decline due to co-precipitation of phosphorous with bicarbonate. This geologic sink for phosphorus has been shown to have a strong influence on phosphorus availability in Arizona streams and can be regulated by rates of primary production and associated effects on pH (Corman and others, 2015, 2016). On other hand, the LCR may serve as a source of SRP at times, particularly when flows are elevated. Storm events that constitute just weeks to months on an annual hydrograph can be responsible for a large fraction of nutrient loading across a variety of stream and river ecosystems (Martin and Harrison, 2011) including in desert systems (Jones and others, 1997). Prior work suggests that the LCR should not contribute substantially to the phosphorus budget of the CRe when at base flow (Moody and Muehlbauer, unpublished data,), however, we hypothesize (**H11**) that flood waters originating in the Paria River and LCR watersheds are a significant source of nutrients, including phosphorous to the CRe. The size of the LCR watershed, and the nutrient intensive human activities and volcanic substrates within it suggest it has the greatest potential to be a nutrient source during storms. Still, given the important role of the Paria River in riverine sediment budgets, it could also contribute significantly. In addition, we hypothesize (**H12**) that run-off after forest fires may, at times, provide significant inputs of nutrients, including phosphorous, to the CRe. In particular, large forest fires, such as the recent fire in the Shinumo Creek watershed, have the potential to input significant amounts of phosphorous.

Dam operations may also play an important role in spatio-temporal patterns of phosphorous. For example, just as the deltaic sediments in Lake Powell inlets may contribute phosphorous to the water column when they are periodically dried and then wetted, we also hypothesize (**H13**) that portions of the river bed that dry during months of lower maximum flows may contribute SRP to the river when they are re-inundated during months of higher maximum flows. In particular, we expect that varial zones (e.g. zones that are only periodically inundated with water) that are high in organic matter and/or silts and clays could be significant sources of bioavailable phosphorous. We also hypothesize (**H14**)that high flows events (HFEs) may play an important role in scouring and burying vegetation, and that the phosphorous in the buried vegetation may later return to the aquatic ecosystem (Parnell and others, 1999). This mechanism may be particularly important in the western portion of the CRe, where there are few other sources of bioavailable phosphorous and where sediment deposition is frequent during HFEs. Alternatively, variation in water levels may lead to less stable backwater habitat and lower rates of nutrient recycling and availability (**H14b**). In the CRe, backwaters were found to have more organic matter and have higher water residence times during the 2008 September and October steady flows than during times when discharge fluctuated on a daily basis (Behn and others, 2010).

***Quantitative links among temperature, nutrients, primary production, and higher trophic levels.***

Temperature is known to be an important lever on fish bioenergetics, condition and population dynamics in the CRe, however its effects on primary and secondary production are less well understood. For many of the native fish in the CRe, including humpback chub, temperatures above ~12 °C are necessary for growth in length, and temperatures above 15 °C are required for reproduction (Gorman and VanHoosen, 2000; Marsh, 1985). Once these thresholds are exceeded, however, other factors may become important. For example, growth of subadult humpback chub in the LCR does not peak at the warmest time of the year, rather it is greatest when food availability is high during March through May (Dzul and others, 2016). In the CRe, turbidity has an approximately equal role to temperature in explaining the growth of juvenile (Yackulic and others, In Review) and sub-adult humpback chub (Dzul and others, 2016). With respect to rainbow trout, we might expect warming to have a neutral to positive effects on rainbow trout if food were plentiful (well fed rainbow trout should have a temperature preference around 16 °C,), however, recent bioenergetics modelling of the upper CRe (Glen and Marble Canyon reaches) suggests that if the aquatic foodbase is unchanged, warming will have negative effects on rainbow trout (Dodrill and others, 2016). Further downstream at Diamond Creek, the aquatic foodbase is also unlikely to peak with river temperatures since primary production is limited by the highly turbid conditions that occur concomitantly with summertime temperature peaks (Hall and others, 2015). Still, preliminary modeling efforts suggest that seasonal patterns in gross primary productivity (GPP) rates differ from site to site such that the combined effects of nutrients and temperature on fish could vary considerably by location. Taken together, this evidence suggests a need to better understand the drivers of primary and secondary production in the CRe, so as to better understand how different scenarios of warming and are likely to benefit, or harm, key aquatic resources identified by the LTEMP EIS, including humpback chub and rainbow trout. In other words, we hypothesize (**H15**) that the impacts of changes in temperature on the aquatic ecosystem in the CRe will depend crucially on the state of the aquatic foodbase.

Although aquatic ecosystems are frequently nutrient limited and reservoirs often deplete nutrients, there has been surprisingly little study of how reservoir-induced biogeochemical changes affect downstream riverine ecosystems (Poff and Zimmerman, 2010). In the CRe, we hypothesize (**H16**) that nutrients, in particular SRP, are important drivers of overall ecosystem productivity, especially in the upstream portion of the CRe (i.e., from Glen Canyon Dam downstream to the confluence of the LCR). One reason why **H16** has not received more attention in the past, is that variation in SRP has often coincided with unusual dam releases (e.g., SRP began to increase in 2007 – 2008 coincident with the 2008 Spring HFE, and over the past 16 years, SRP was highest in 2011 and 2012 corresponding to 2011 equalization flows). These releases have led to a number of hypotheses including the hypothesis (**H17a**) that spring HFEs stimulate the aquatic foodbase and rainbow trout production, the hypothesis (**H17b**) that higher stability of flows stimulates the aquatic foodbase and rainbow trout production, and the hypothesis (**H17c**) that higher volume of flows adds habitat that stimulates the aquatic foodbase and rainbow trout production. Modelling of alternative management strategies as part of the LTEMP acknowledged uncertainty in **H17a-c**, but did not consider the potential importance of nutrients (**H16**). Importantly, these hypotheses are not mutually exclusive, and there is good corroborating evidence suggesting the important role of spring HFEs in favoring insect over non-insect taxa (**H17a**,Cross and others, 2013) and of more stable flows leading to increased rainbow trout growth (**H17b**, Korman and Campana, 2009).

Recent analyses by GCMRC support a potentially important role for **H16—**that nutrients are an important driver of ecosystem productivity (Deemer and others, unpublished data[[2]](#footnote-3); Yackulic, 2017).In Lees Ferry, SRP concentration is correlated with invertebrate drift rates and appears to be linked to rainbow trout recruitment rates. In addition, SRP availability is the single best statistical predictor of rainbow trout recruitment over the last 16 years, and a rainbow trout recruitment statistical model that includes just two predictor variables – the number of adults already in the system in the spring and SRP concentrations – can explain 73% of the variation in recruitment. For comparison, the best statistical prediction model using the number of adults already in the system and various flow metrics representing **H17a-c**, explains 48% of the variation in recruitment. In addition to the impacts of nutrients on overall ecosystem productivity, periods of nutrient limitation may also have played a role in the dramatic shifts in the composition of aquatic vegetation community over the last few decades, particularly in the Colorado River in Glen Canyon, where other factors like turbidity play less of a role in limiting gross primary production and shaping aquatic vegetation communities. We hypothesize (**H18**) that during periods of low SRP concentrations in the water column, aquatic algal and plant species that can access phosphorous outside of the water column (e.g., rooted macrophytes) will be favored over species that primarily draw nutrients from the water column (e.g., Cladophora).

Downriver from Lees Ferry, near the Little Colorado River, we also see recent evidence supporting **H16**.Since 2012, we have monitored various biological variables near the LCR confluence. SRP concentrations measured at penstock depth in Lake Powell are highly correlated with these biological variables, which include seasonal estimates of primary production, invertebrate drift biomass, and the condition of adults of the three large-bodied native fish species (flannelmouth sucker (*Catostomus latipinnis*), bluehead sucker (*Catostomus discobolus*), and humpback chub). Furthermore, there have been a ~50% declines in rates of spawning of humpback chub in the last two years, coincident with declines in adult fish condition, potentially driven by declining SRP. The effects of declines in aquatic foodbase on juvenile humpback chub are less clear and expected to be one emphasis of analyses being undertaken as part of Project G, however, we have some expectation that there may be two broad patterns of fish response to periods of food shortage that transcend humpback chub. Specifically, we hypothesize (**H19**) that fish species and life stages that are well-adapted to persist through periods of food shortage (e.g., adult native fish) will have slower growth, drops in condition, and declines in reproductive output, but will not experience increased mortality, while fish species (e.g., rainbow trout) and life stages (i.e., juvenile native fish) with less fat reserves relative to their metabolic rate will respond more quickly with increased mortality.

While recent work shows a strong link between nutrient concentrations at the Lake Powell penstock depth and ecosystem productivity in the upper part of the CRe, it is unknown how far downstream Lake Powell exerts a dominant influence on riverine nutrient budgets because of the many processes that may be depleting or augmenting SRP concentrations (**H9-H14**). In addition, the downriver CRe has more allochthonous inputs, which leads to the hypothesis (**H20**) that autochthony plays a lesser role (and thus temporal variation in nutrients may not be as strong a driver) in the lower half of CRe. **H20** was not supported by previous foodbase work throughout the CRe (Cross and others, 2013), which found that diatoms continue to be a significant portion of aquatic insect diets at downriver study locations and the insects remain an important part of fish diets. Interestingly, while most components of the aquatic ecosystem appeared to decline in 2014 in the upper part of the CRe, there is some evidence that humpback chub in the lower part of the CRe (i.e., downstream of Havasu Creek) did very well in 2014. If nutrients are an important ecosystem driver throughout the CRe (i.e., **H16** is more supported than **H20**), then some mechanism must have led to higher SRP in the lower part of the CRe (**H9-H14**), either decreased uptake or increased inputs or both. Alternatively, we might hypothesize (**H21**) that fish densities are so low that SRP does not yet limit population responses. Under **H21**, humpback chub may respond primarily to increases in temperature alone so long as their own densities remain low, however, at some point food limitation must matter (**H15**) so the long-term prospects for large populations of humpback chub would seem to be not be as promising without increases in primary and second production.

It would not be surprising if humpback chub numbers are currently food-limited near the LCR, and recruitment limited in western Grand Canyon, because of the interactions of temperature and geography. Near the LCR, temperatures in the CRe only need to be warm enough to allow for growth of juveniles because spawning occurs in the LCR. There is some evidence that the portion of the humpback chub population in the Colorado River near the LCR can be recruitment-limited over shorter time scales (1-3 years), but during the recent decline may have been more food-limited. If humpback chub reproduction in the lower CRe occurs within the Colorado River, then temperatures rarely exceed the necessary physiological thresholds leading to recruitment-limitation. Importantly, however, warming temperatures, especially if they occur without increases in the foodbase, may simply replace the recruitment limitation with a food limitation. If this is the case, we would expect the carrying capacity of a humpback chub population in the western CRe to be substantially lower than that of the population near the LCR.

The large uncertainty surrounding basic patterns in nutrients in the CRe, combined with the potential importance of nutrients as ecosystem drivers throughout the CRe, suggests the need for additional monitoring of nutrients (Project E.2) and more study of the foodbase in the lower half of the CRe (Project F). Given current trends in humpback chub (Project G) and rainbow trout (Project H), potentially driven by declining SRP, there is also need for more work studying how temperature and nutrients affect ecosystem metabolism (i.e., gross primary production and respiration) and how changes in metabolism affect insect and fish production. The 2016 fisheries PEP also identified the need to study how various trophic levels will respond to future conditions, especially the potential for warmer temperature combined with lower nutrients. The following sections illustrate how we will address these needs.

**4. Proposed Work**

**4.1. Project Elements**

***Project Element E.1. Identifying patterns and drivers of nutrient outflow from Lake Powell***

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***Project Description***

This project element aims to capitalize and expand upon a large volume of historical nutrient data that has been collected in Lake Powell, within the draft intake tubes of Glen Canyon Dam, and at Lees Ferry. Given the important links between phosphorus availability and native fish condition, the ultimate goal of the proposed work is to better ascertain the dominant controls on phosphorus export from the river outlet works and phosphorus fate in the Colorado River in Glen Canyon. Historical data from the Lake Powell water quality monitoring program have already been used for a number of important purposes including the development of a working CE-QUAL-W2 model and the description of long term trends in stratification and associated oxygen dynamics (Vernieu, 2009). Still, there has been relatively little effort to describe nutrient dynamics within the reservoir aside from some early work demonstrating the important role of advection in the system (Gloss and others, 1980) and some recent work to show the composition of various phosphorus fractions in inlet deltaic sediments (Wildman and Hering, 2011). Here we propose a combination of data analysis and experimental work to examine the importance of several potentially important drivers of Lake Powell phosphorus export. By discerning mechanistic controls on phosphorus export from Lake Powell, the insights gained from this work could provide managers with forecasts of future nutrient conditions downstream of Glen Canyon Dam as well as potential tools for altering downstream nutrient concentrations via flow modifications.

***Objectives***

1. Characterize the relative importance of deltaic sediments, tributary nutrient concentrations, and quagga mussel establishment in governing Lake Powell’s phosphorus budget.
2. Describe seasonal effects on phosphorus availability and mixing.
3. Investigate the potential for experimental flows to alter the nutrient concentrations in the water discharged from Glen Canyon Dam.

***Methods***

*Assessing the Role of Deltaic Sediments, Quagga Mussels, and Nutrient Loading from Lake Powell’s Major Tributaries in Lake Powell Phosphorus Dynamics*

This sub-element will estimate the fate of nutrient loading to Lake Powell’s inlets using the USGS program LOADEST in combination with data on historic discharge and nutrient concentrations (records generally exist from 1990-2000) from the National Water Information System (NWIS) stations: Green River at Green River, Colorado River near Cisco Utah, and San Juan River at Bluff (U.S. Geological Survey, 2004). Modeled riverine nutrient loading for this decade will be compared to nutrient measurements in the Lake Powell dataset (the historical dataset has measurements of nutrient concentrations in surface and bottom waters at >20 sampling stations as well as at penstock depth at the Wahweap forebay station) to look for an advective signal of riverine nutrient loading. Seasonality will be taken into strong consideration given the likelihood that wintertime nutrient loading is a more important factor determining outlet release concentrations. Together with information about Lake Powell’s surface elevation (and associated modeling to identify large deltaic sediment inundation events), and quagga mussel establishment data, these data sources will help us better identify the most important processes controlling phosphorus availability in Lake Powell and Glen Canyon Dam releases and will also inform the development of future sampling and experimental plans.

*Seasonal Effects on P Availability and Mixing*

Riverine inflows to Lake Powell and associated nutrients are generally advected towards the dam as an interflow or underflow (depending on the density of the inflow relative to the density stratification in the lake, Gloss and others, 1980). The historical dataset has measured nutrient concentrations in surface and bottom waters at >20 sampling stations as well as at penstock depth at the Wahweap forebay station. While this information provides critical insight into Lake Powell nutrient patterns and dynamics, the limited depth resolution makes it difficult to understand how phosphorus may be advected (or cycled) within the interflow. We will begin more highly resolved sampling in the vertical direction at the Wahweap station to better capture these patterns (4-12 additional depths to be determined after initial sampling at 15 depths) and will run SRP analyses using methods with detection limits <1 µg L-1. We will also install conductivity and thermistor strings to capture stratification and mixing data at one site near the dam and at one site near the plunge zone (where inflowing river water mixes with the reservoir). Finally, we will examine historical data collected in the major Lake Powell inlets (Colorado River and San Juan River) to look for a pH-dependent decoupling between riverine phosphorus loading and summertime chlorophyll a concentrations. Depending on our findings, additional experimental assays will be conducted to look at the role of carbonate precipitation.

*Quantifying the Effects of Experimental Flows on Phosphorus Downstream of Glen Canyon Dam*

The potential for experimental flows to modify downstream nutrient regimes will be examined by conducting targeted nutrient sampling before, during, and after experimental flows. Targeted profiling in Lake Powell at Wahweap and grab sampling from the Colorado River at Lees Ferry will be conducted at least twice prior to experimental flow, twice during experimental flow, and twice post experimental flow to better quantify the effects of flow regime on reservoir and outlet chemistry. Thermistor string data will also be examined for changes in physical stratification as well as nutrient dynamics.

***Project Element E.2. Temperature and nutrients in the CRe – patterns, drivers, and improved predictions***

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Charles Yackulic, Research Statistician, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

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Theodore Kennedy, Research Biologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

***Project Description***

This project element aims to characterize spatial and temporal patterns in Colorado River temperatures and 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. To more accurately predict downstream river temperatures in the CRe, an existing model for forecasting river temperatures downstream from the dam will be modified to better predict measured downstream temperatures. To begin characterizing the CRe nutrient budget, the concentrations of various nutrient species will be measured over diel, storm-based, and seasonal timescales and longitudinally in the Colorado River between Glen Canyon Dam and western Grand Canyon. Nutrient cycling dynamics will also be examined via sediment coring, alkaline phosphatase assays, and potential carbonate precipitation assays conducted across space and time to understand the potential role of changing water levels in phosphorus cycling, the bio-availability of phosphorus in the river and the role that carbonate precipitation may be playing in removing phosphorus from the water column.

***Objectives***

1. Modify previous models for predicting CRe temperatures to reflect exponential (rather than linear) warming.
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).
3. Assess the potential role of several ecosystem processes likely to control phosphorus availability:
4. co-precipitation of phosphorus with calcium carbonate
5. release of phosphorus due to drying and re-wetting of sediments or backwater mineralization
6. mobilization of phosphorus into the river due to watershed forest fires.

***Methods***

*Modeling River Temperatures in the CRe*

Historically, water temperatures near the Little Colorado River (LCR) confluence have been too low to allow for reproduction by native fish such as the humpback chub, instead water temperature has mainly influenced fish growth and condition (Dzul and others, 2016; Yackulic and others, 2014). This phenomenon has occurred even in ‘warm’ years (e.g., 2005) in which water temperatures increased by 3-4 °C degrees in summer in response to declining Lake Powell levels. Further downstream, warmer than average years may actually provide for conditions that allow for mainstem reproduction of humpback chub, which is significant given that mainstem reproduction or a second spawning population would be an important step towards humpback chub recovery. As such, predicting reproductive responses of the humpback chub population near the Little Colorado River (LCR) and in western Grand Canyon to management alternatives was a high priority in the LTEMP EIS. We propose to develop an improved temperature model for the Colorado River ecosystem (CRe) based on exponential (rather than linear) warming with increasing distance from Glen Canyon dam to Lake Mead. This model will parse out the influence of air temperature, discharge, and reservoir levels (i.e., discharge temperature) on downstream temperatures based on conditions from the past several decades as well as anticipated future conditions. Water temperature predictions can be used to improve humpback chub reproduction models, but also improve our understanding of how the CRe may change at the ecosystem level in a future warmer and drier climate. This improved model will increase our preparedness to anticipate and respond to future changes in other aspects of the ecosystem including the food base, nutrient availability, the rainbow trout sport fishery, and native and non-native fish distributions.

*Characterizing Spatial and Temporal Patterns in Nutrient Availability*

Longitudinal sampling will be conducted during each of the four seasons (spring, summer, fall, winter) at 15 sampling sites in the mainstem Colorado River spread relatively evenly between Glen Canyon Dam and Diamond Creek. Sample timing will be carefully determined based on the results of diel (24-hour) sampling-- if there is a diel pattern in nutrient availability as has been observed in other systems then we will standardize sampling by time of day. This longitudinal sampling will be compared with longitudinal measurements of both chlorophyll a and ecosystem metabolism (described in Project Element E.3). We will also place refrigerated ISCO samplers (automatic samplers) in the mainstem Colorado River, Paria River, and LCR to capture potential nutrient pulses during storm events. To better estimate tributary contribution to mainstem nutrient concentrations, ISCOs will be placed in pairs: one in the mainstem Colorado River directly upstream of the tributary and one in the tributary of interest. Our plan is to target the Paria River and LCR given that they contribute the majority of tributary discharge between Lake Powell and Lake Mead, but if longitudinal sampling suggests that other tributaries may be important with respect to nutrients we will adjust our plans accordingly.

*Assessing Phosphorus Bioavailability and Co-precipitation Potentials*

While soluble reactive phosphorus 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 (chemical form, fraction, or “species”) of phosphorus entering the river and not just its total concentration. We will conduct alkaline phosphatase assays to assess the bioavailability of aquatic phosphorus concentrations and the organic matter mineralization sources of bioavailable phosphorus. This will be done at the Moab branch of the U.S. Geological Survey Southwest Biological Science Center. Briefly, the method involves adding a substrate with a fluorescent label to each water sample. Fluorescence is then related to the breakdown of the substrate by phosphatase enzymes and thus provides phosphatase enzyme activity rates. Enzyme assays will be conducted on samples collected longitudinally in the river as well as selected samples from storm-based collections. We will also conduct co-precipitation potential assays on these same samples to determine the relative importance of calcium carbonate precipitation as a phosphorus sink in the river. This will be done by collecting paired water samples and adding NaOH to one sample while leaving the other at ambient pH. We will then compare phosphorus concentrations in the ambient versus basic sample. In addition to riverine sites, we will conduct co-precipitation potential assays along a longitudinal transect in Lake Powell to assess the importance of this mechanism for phosphorus sequestration in the reservoir.

*Characterizing the Role of Water Level Fluctuations for Potential Riverine P Availability and Primary Production*

We will collect nine sediment cores from each of the following habitat types along the CRe: varial zone inundated daily, varial zone inundated seasonally, varial zone inundated high flow. In each of these zones, we will select three sites along the river’s main channel, three sites in backwater habitats, and three sites located near tamarisk trees experiencing beetle herbivory. Cores will be subsampled by depth and analyzed for biologically-relevant nutrients. If funds become available, we will also follow up on a USGS study of basal resources in backwaters (Behn and others, 2010) by comparing rates of primary production and phosphorus availability in Colorado River backwaters experiencing daily water level fluctuations with those above Lake Powell where water levels are more constant on a daily basis.

*Assessing the Potential Role of Forest Fire in Enhancing Aquatic Nutrient Availability*

Large fires in the Colorado River watershed are expected to increase the transport of bioavailable nutrients into the river, particularly phosphorus. Such fire-induced increases in nutrient availability may be reflected in the chemistry of macroinvertebrate tissue such that samples from downstream of a tributary watershed that experienced a large fire would have higher phosphorus content than samples collected upstream. To assess the potential that fires can supplement Colorado River ecosystems with nutrients, we will analyze the total phosphorus content of emergent aquatic insects collected along the Colorado River via light trap both upstream and downstream of Shinumo Creek from 2013 to 2015. The sample allows a BACI-based analysis (before, after, control, experiment) where we can compare total phosphorus content in insects upstream and downstream of Shinumo Creek both before and after the 2014 wildfire.

***Project Element E.3. Linking temperature and nutrients to metabolism and higher trophic levels***

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Michael Yard, Fish Biologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

***Project Description***

This project element aims to link information about patterns in riverine nutrients and temperature (gained in Project Elements E.1 and E.2) with information on whole ecosystem responses. Experimental methods will be employed to better understand the patterns and controls on aquatic vegetation structure, primary production (e.g., ecosystem metabolism), and secondary production (e.g., aquatic insects). The resulting improved understanding of the lowermost trophic levels in the CRe food web will be used to develop ecosystem models that link temperature and nutrients to ecologically relevant aspects of the aquatic foodbase (e.g., composition and biomass production aquatic vegetation and insects) and ultimately to fish composition and abundance.

***Objectives***

1. Develop and apply methods for surveying aquatic vegetation in the Lees Ferry reach of the CRe with the goal of establishing a cost-effective monitoring scheme.
2. Determine drivers of ecosystem metabolism (including primary production and respiration) throughout the CRe.
3. Simulate the potential ecosystem impacts of changes in temperature and nutrients using artificial stream experiments.
4. Develop ecosystem models linking temperature, nutrients and various trophic levels.

***Methods***

*Aquatic Vegetation Surveys in Lees Ferry*

Anglers and scientists alike recognize the dramatic changes that have occurred in the composition and abundance of submerged aquatic vegetation in the Lees Ferry tailwater over the last 1-2 decades. Understanding the drivers of these changes, such as the relative importance of flow, dissolved nutrients, and temperature, as well as the current distribution of different vegetation types, requires a relatively cheap surveying method that can easily be repeated at least once each year. During the FY2015-17 workplan we made several advances toward developing a protocol for low-cost surveys of submerged vegetation in the Lees Ferry reach. We developed a new HD underwater video camera system for geolocated video observations of the bed, and used these observations to 1) observe vegetation types at the genus or species level, as well as the depth and substrate they are growing at/on; and 2) develop a high-resolution vegetation mapping system based on acoustic backscatter measured by multibeam sonar (Buscombe and others, In Review). Using backscatter data collected during the 2014 HFE, we have developed a substrate classification for the 15-mile reach from Glen Canyon Dam to Lees Ferry. Video surveys of selected reaches were also collected in December 2014, October 2015, and August 2016. During these surveys, a low-cost sidescan sonar on a Humminbird fishfinder was used to collect backscatter data and automated data processing techniques were developed for distinguishing between hard/rough and soft/smooth substrates based on the form of echoes received by the sonar (Buscombe, 2017). Work to relate these echo parameters to vegetation presence/absence is showing much promise. In the present workplan we propose to use the video and Humminbird sonar systems to carry out aquatic vegetation surveys on a seasonal-annual basis. Trips lasting 2-5 days will require just a single boat. The video is required for making detailed, smaller scale species-composition surveys of selected reaches. We will develop a semi-automated genus/species-level vegetation mapping system based on the collected video. This will be used to assess annual-decadal scale changes in species composition, including invasive weeds. The sonar system will be used for developing large-scale (15-mile) substrate maps that indicate the presence/absence of vegetation, which will be used for detecting annual-decadal scale changes in vegetation distribution and abundance.

*Ecosystem metabolism*

Primary production in rivers can be estimated from diel patterns of dissolved oxygen. Long-term dissolved oxygen data are available at six sites throughout the Grand Canyon and can be analyzed to yield time-series of primary production. Previously, data from one site, Diamond Creek, was analyzed using semi-mechanistic models to determine drivers of gross primary production (Hall and others, 2015). We propose to extend this type of analysis to the other long-term sites, and consider additional drivers, especially nutrients, in our statistical analyses of the oxygen data. The quality of inferences from these analyses will be improved by undertaking a series of measurements to better calibrate our estimates of ecosystem respiration and gas exchange rates. We will also compare estimates from these sites to continuous longitudinal profiles of chlorophyll concentrations to better understand variation in primary production throughout the whole CRe. These measurements will be taken as part of river trips by other projects and may potentially include samples taken by citizen scientists. Longitudinal chlorophyll profiles will be compared to longitudinal measurements of nutrients and additional short-term dissolved oxygen deployments to estimate primary production will be employed if warranted. Estimates of primary production will also be compared to data from other higher trophic levels using ecosystem models.

*Artificial streams*

Understanding how water quality conditions, invertebrate assemblages, and, in turn, native and non-native fish populations respond to future changes in nutrient stoichiometry and water temperature downriver of Glen Canyon dam is one of the biggest management uncertainties associated with dam operations. Historical data from Lake Powell suggest that declines in Lake Powell water levels will result in warmer, nutrient-poor water from the reservoirs’ epilimnion becoming entrained in the penstocks and being discharged downstream (Vernieu, 2009). It is highly possible that summer water temperatures downriver of the dam in Lees Ferry will reach 20 °C or higher (Dibble, unpublished data), so being able to anticipate and plan for such future conditions will improve our ability to manage the rainbow trout sport fishery and native and non-native fish populations throughout the CRe. Here, we propose to use artificial stream experiments to determine how primary producers, invertebrates, and fish respond to variation in water temperature, nutrient availability, and nutrient ratios (N:P) within the current ranges of variation coming from Glen Canyon dam and under scenarios based on potential future conditions in a warmer and drier climate.

Artificial stream experiments will be conducted by building a floating research laboratory that uses Colorado River water and can be deployed at the Lees Ferry boat ramp or motored upstream to various reaches of Glen Canyon. We envision building this project in phases, where each step will be used to inform methods in the next phase. 1) We will use information from historical Lake Powell water quality data (Vernieu, 2009) and nutrient modeling efforts described in Project E.1 to develop a range of nitrogen and phosphorus (SRP) concentrations to be expected under baseline and future warming scenarios; 2) Measure the response of two key invertebrate species in the Colorado River (midges and blackflies) to nutrient concentration and temperature scenarios developed in phase 1, focusing on changes in invertebrate biomass, size, and quality; 3) Develop diets based on prey information gained in phase 2 to examine physiological responses of native and non-native fish species to change in diet quality or quantity; and 4) Revise bioenergetics models for trout and develop models for other species that account for potential future changes in invertebrate biomass, size, and quality, and in turn, fish size and condition. This floating research facility is a first step toward being able to measure the response of biota to simulated future field conditions using actual CRe water. As a benefit, this artificial stream facility will be built to withstand river travel so it can be used in future work plans to answer questions related to water quality and biota in the unique conditions encountered downstream.

*Ecosystem models*

Walters and others (2000) developed a computer-based ecosystem model of immense heuristic value,which helped to identify gaps in monitoring of the CRe at that time and provide basic screeningof policy ideas. Over the last 17 years, we have improved monitoring and developedunderstanding of various components of the CRe through more focused modelling. For example,our understanding of humpback chub population dynamics has improved considerably followingadoption of mark-recapture studies first in the LCR first and later in the nearby Colorado River andassociated modelling efforts (Coggins and Walters, 2009; Yackulic and others, 2014). Similarly,foodbase studies have improved our understanding of trophic interactions (Cross and others, 2013) and led to development of methods for monitoring primary production and invertebratedrift and emergence (Hall and others, 2015; Kennedy and others, 2014). The goal of this projectis to develop models of more modest scope than Walters and others (2000) work, but with abroader focus than recent work that has focused on one (or at most two) trophic levels, or in thecase of food web modelling, were mostly descriptive (rather than predictive). This broadening ofscope is essential for answering questions about the roles of temperature and nutrients inecosystem dynamics, for better understanding dynamic trophic linkages, and for integratingvarious diverse sources of data (fish studies, invertebrate studies, primary production estimates,nutrient measurements, etc.) to address hypotheses detailed above, especially hypotheses H16-H21. Broadening the scope of our models should also help us to make better predictions undernovel conditions (including a better understanding of uncertainty and gaps in our knowledge). Inparticular, while the models used to make predictions for the LTEMP EIS were a step in theright direction, they were narrow in their treatment of drivers and representation of ecosystemprocesses. As such they were more suited for predictions within the range of historically observed conditions(i.e., in the Colorado River near the LCR for temperatures between 8 and 16 °C), than for someof the conditions outside these ranges (e.g., 20 °C near the LCR).

**4.2. Deliverables**

This work will result in multiple peer-reviewed publications as well as data to support potential management actions by the resource management agencies. Information will be provided in the form of oral and written presentations to the GCDAMP at annual reporting meetings.

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1. **Budget**







Project F. Aquatic Invertebrate Ecology

1. **Investigators**

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1. **Project Summary**

A primary focus of the food base group over the next three years is continuation of long-term monitoring that is needed to evaluate progress toward resource goals identified in the Long Term Experimental and Management Plan (LTEMP). Specifically, we will continue monitoring Colorado River invertebrate drift in Glen and Marble Canyons, which now represent datasets spanning 10 and 6 years, respectively. We will also continue the citizen science light trapping of emergent aquatic insects throughout Marble and Grand Canyons, as well as sticky and light trap monitoring of these insects in Glen Canyon, now in their 6th and 4th years, respectively. All of these long-term monitoring projects provide important baseline information that will be used to determine how the aquatic food base responds to LTEMP flow experiments such as Macroinvertebrate Production Flows. Aquatic insect emergence is a fundamental natural process in rivers, and thus these monitoring data will also directly inform progress towards the LTEMP goal for *Natural Processes*. These food base monitoring data will also provide essential context in support of other LTEMP goals including *Humpback Chub*, the *Rainbow Trout Fishery*, *Other Native Fish*, *Nonnative Invasive Species*, and *Recreational Experience*.

We will also evaluate ecosystem responses to Macroinvertebrate Production Flows and other LTEMP flow experiments by initiating drift and benthic monitoring at new sites in the Colorado River throughout Glen, Marble, and Grand Canyons during twice annual food base river trips. Most of these new monitoring sites will be adjacent to tributaries, and at the peaks and troughs of midge abundance identified in citizen science emergence monitoring data (e.g., Lees Ferry, Nankoweep, Bright Angel, Tapeats, etc.). Additionally, as part of food base river trips we will continue field experiments on aquatic insect egg-laying that were initiated in 2016.

In support of the LTEMP goal for *Humpback Chub*, we will characterize the quantity and quality of the prey base in the Colorado River at the Little Colorado River confluence and in western Grand Canyon (see Project G). Drift and emergence monitoring will be used to determine the quantity of prey available at these locations. We will characterize the quality of prey using lipid analysis and ecological stoichiometery (the ratio of carbon, nitrogen, and phosphorus in prey). We will quantify humpback chub feeding habits for one year (2018) at these locations using non-lethal gastric lavage. These data on humpback chub feeding habits and the quality and quantity of prey will be integrated using bioenergetics models, which explicitly account for the effect that water temperature and food availability have on fish physiology. We will also conduct drift and emergence monitoring at sites in the Colorado River downstream of Diamond Creek, where very little is known about the condition of the aquatic food base, and where humpback chub and razorback sucker populations are expanding.

We will also support the LTEMP goal for *Humpback Chub* by monitoring the food base in Colorado River tributaries where humpback chub occur. Specifically, we will collaborate with the U.S. Fish and Wildlife Service to monitor the aquatic food base in the Little Colorado River during their spring and fall humpback chub monitoring trips (see Project G). In collaboration with the National Park Service, we will continue food web research in Bright Angel Creek, and initiate new food web studies at Havasu Creek and Shinumo Creek, locations where humpback chub have been translocated or are proposed for translocation once conditions such as food base availability are suitable.

Research into terrestrial-aquatic linkages will be carried out by our group in support of LTEMP goals for *Natural Processes* and *Tribal Resources*. The main thrust of this research is a new collaboration with tribal resource trips to monitor bird and bat activity in the Colorado River ecosystem. This effort will test the hypothesis that bat and bird abundance is correlated with the 3-fold variation in midge abundance among sites in Marble and Grand Canyon identified in Kennedy and others’ *Bioscience* paper (2016). As part of these terrestrial-aquatic linkage studies, we will also continue to partially support the PhD research of Arizona State University graduate student Christina Lupoli that describes the relative importance of aquatic vs. terrestrial prey to birds, bats, lizards, and rodents (note that Arizona State University covers half of Lupoli’s tuition and stipend through a fellowship). This research will identify the extent to which aquatic insect emergence affects the broader Colorado River ecosystem, and whether changes in aquatic insect abundance owing to Macroinvertebrate Production Flows have ecological effects that cascade (i.e., ramify) out of the River itself.

In support of the LTEMP goal for *Nonnative Invasive Species* we will initiate new benthic monitoring to track the expansion of quagga mussels into the Colorado River in Glen, Marble, and Grand Canyons. Quagga mussels began appearing in Glen Canyon in 2013, and their downstream progression is only being tracked by sparse, ad-hoc, and anecdotal efforts. We will develop a scientifically-robust monitoring program for quagga mussels that will include benthic sampling in potential quagga habitats. Quagga mussel monitoring will occur during biannual food base river trips.

To identify whether there is a causal link between fall High Flow Experiments (HFEs) and recent deterioration of the food base, we will conduct new research, predominantly in Glen Canyon, on smaller-scale habitat effects on the food base. We will advance learning regarding potential negative effects of fall HFEs on the food base by: 1) tracking algae and invertebrate response to mechanical scrubbing of rocks and loosening cobbles at different times of year (i.e., spring vs. fall), which mimic HFE scouring of benthic substrates, 2) exploring lateral variation in invertebrate drift along channel cross sections and across flow conditions, and 3) synthesizing what is known about potential declines in *Gammarus* populations from the 1980s to present. We will also conduct new research into brown trout feeding habits, prey selection, and bioenergetics in Glen Canyon to determine whether brown trout population increases in this reach are related to recent deterioration of the prey base. These topics were identified as important research needs in the 2017 Food Base Knowledge Assessment.

1. **Background**

The primary focus of food base research and monitoring at GCMRC over the past decade has been on the broad-scale characterization of aquatic food webs in the Colorado River in Glen, Marble, and Grand Canyons. The recent culmination of this research has been illuminating, because of the strong links that were identified between flow management, the aquatic food base, and the growth, condition, and stability of fish populations. Synoptic food web studies conducted by the food base group demonstrated that the growth, condition, and abundance of rainbow trout in Glen Canyon and native fishes in Grand Canyon was limited by the scarcity of high quality invertebrate prey (Cross and others, 2013; Kennedy and others, 2013). These food web studies demonstrated that low aquatic insect diversity was contributing to food limitation of fishes in the Colorado River, because larger-bodied, higher-quality invertebrates in the mayfly, stonefly, and caddisfly groups (“EPT,” from their collective Order names: Ephemeroptera, Plecoptera, and Trichoptera, respectively) are conspicuously absent (Dodrill and others, 2016; Kennedy and others, 2016). Using multiple lines of evidence, the food base group demonstrated that load-following flows released from Glen Canyon Dam were contributing to the absence of EPT taxa from the Colorado River and constraining the abundance of midges by causing mortality of aquatic insect eggs laid along unstable river shorelines (Kennedy and others, 2016). Conclusions from this study informed the design of the LTEMP experimental Macroinvertebrate Production Flows, which will be tested as part of implementation of the LTEMP selected alternative.

In addition to these persistent structural deficiencies in Colorado River food webs (i.e., low insect diversity, no EPT), the existing food base has been deteriorating since at least 2013. This deterioration is evident across multiple metrics (i.e., invertebrate drift, light traps) and across sites spanning the entire Colorado River ecosystem (<https://www.usbr.gov/uc/rm/amp/twg/mtgs/17jan26/AR19_Kennedy.pdf>). For example, citizen science aquatic insect emergence monitoring shows a ~60% decline in the abundance of adult midges throughout Marble and Grand Canyon from 2012 to 2015 (data for 2016 are not yet available). Similarly, invertebrate drift concentrations at the Little Colorado River confluence declined by ~50% between 2012 and 2016. This food base deterioration has occurred coincident with a sequence of fall HFEs beginning in 2012. Although a causal link between fall HFEs and the deteriorating food base has not been demonstrated with high confidence, this pattern nonetheless stands in stark contrast to the dramatically improving food base condition observed after the 2008 spring HFE (Cross and others, 2013). Significantly, recent declines in the condition (plumpness) of humpback chub near the Little Colorado River confluence, and declines in the number of spawning humpback chub entering the Little Colorado River in spring, are highly correlated with the deteriorating Colorado River food base (<https://www.usbr.gov/uc/rm/amp/twg/mtgs/17jan26/AR20_Yackulic.pdf>). Additionally, declines in the condition of rainbow trout in Glen Canyon are correlated with declines in invertebrate drift from that location. Owing to the system-wide deterioration of the food base and concomitant declines in the condition of native and desired non-native fish species, the 2017 Food Base Knowledge Assessment group rated the current status and trends of the Food Base as being of Significant Concern (<http://gcdamp.com/index.php?title=2017_Knowledge_Assessment>).

While Knowledge Assessment groups were asked to evaluate numerous management actions, the Food Base group felt that those related to HFEs and Macroinvertebrate Production Flows had the greatest potential for improving the food base and the condition of desired fish populations. Given the apparent negative response of the food base to a sequence of four fall HFEs from 2012-2016, and the contrasting strong positive response of the food base to the 2008 spring HFE, the working group suggested that testing a spring HFE was a logical next step in the adaptive management process, assuming that managing for a healthy and productive food base was a priority. Additionally, if food base diversity is important, the working group suggested testing Macroinvertebrate Production Flows as a potential means for increasing the overall baseline abundance and diversity of the food base. In light of the multiple years of food base deterioration and associated declines in the health of native and desired non-native fish populations, the timing may be ripe for experimentation with spring HFEs and Macroinvertebrate Production Flows to potentially improve this condition.

Continued testing of High Flow Experiments is a prominent component of the LTEMP selected alternative. In support of continued learning regarding ecosystem effects of fall HFEs, the Food Base Knowledge Assessment group developed a package of new research and monitoring that will identify whether a causal link exists between the recent deterioration of the food base and the November timing of these experiments (see Project F.4). Although existing monitoring data indicate a correlation between multiple fall HFEs and the deteriorating food base, these data are inherently observational. Thus, the further HFE-related research described herein is intended to provide additional, more rigorous experimental information with respect to the underlying mechanisms controlling Colorado River aquatic food base response to HFEs.

Macroinvertebrate Production Flows are intended to improve the health and abundance of the aquatic food base and are also a prominent component of the selected alternative. These experimental flows will involve releasing stable and low flows every weekend during periods of peak aquatic insect egg laying (May-August). Releasing low flows every weekend should ensure that eggs laid on weekends remain wetted and are never subject to desiccation prior to hatching, which typically occurs after days-to-weeks of incubation (Merritt et al. 2008, Statzner and Beche 2010). This resource management strategy should minimize impacts to hydropower production while substantially improving the quality of substrates available for aquatic insect egg-laying and rearing. It is certainly possible that multiple stressors (i.e., altered flow, temperature, and sediment regimes) are responsible for the near-complete absence of EPT taxa from the Colorado River ecosystem, and that mitigating one of these stressors (i.e., flow-related egg mortality) via Macroinvertebrate Production Flows will not facilitate re-colonization by EPT taxa. However, even in the absence of successful re-colonization by EPT taxa from tributaries within Grand Canyon or elsewhere, it is hypothesized that Macroinvertebrate Production Flows will still improve the condition and health of the food base and desired fish populations by increasing midge production (Kennedy and others, 2016). Project F includes expanded food base monitoring and research designed to track food base and ecosystem responses to this flow experiment.

High Flow Experiments, Macroinvertebrate Production Flows, and the other flow experiments in the selected alternative are intended to aid progress toward the 11 resource goals described in the LTEMP. The aquatic ecology research and food base monitoring described in Project F will be used to evaluate progress towards two of these resource goals—*Natural Processes* and *Nonnative Invasive Species*. Additionally, research and monitoring described in Project F will provide essential context on the aquatic food base that will inform progress towards other LTEMP resource goals including *Humpback Chub*, *Other Native Fish*, *Recreational Experience*, and the *Rainbow Trout Fishery*. Project F also includes new research into terrestrial-aquatic linkages that will be done in collaboration with tribal resource trips and will inform progress towards the LTEMP goal for *Tribal Resources*.

1. **Proposed Work**

### 4.1. Project Elements

#### Project F.1, Influence of dam operations on the food base

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This project element focuses on identifying links between Glen Canyon Dam (GCD) operations and the downstream aquatic food base. The main thrust of this element is the citizen science monitoring of emergent aquatic insects, where river guides, education groups, private boaters, and other citizen scientists deploy a simple light trap each night in camp to collect samples of adult aquatic insects that have emerged from the Colorado River downstream of GCD. At the conclusion of their river trip, citizen scientists return samples to GCMRC for processing. Laboratory processing includes counting and identifying aquatic insects to family or genus whereas terrestrial insects are identified to order or family. For around 20% of samples, aquatic insect specimens are archived at GCMRC. In January 2017, GCMRC established a memorandum of understanding with Museum of Northern Arizona and Grand Canyon National Park that allows the transfer of terrestrial insect specimens to the Museum of Northern Arizona for identification and archiving. The Museum of Northern Arizona is providing this service at no cost. This citizen science monitoring has been ongoing since 2012 and has yielded useful insights into the role that dam operations may be playing in the health of the aquatic food base in the Colorado River ecosystem downstream of GCD (Kennedy and others, 2016; Metcalf and others, 2016). Citizen science monitoring of aquatic insects will be an important line of evidence used to evaluate the effectiveness of Macroinvertebrate Production Flows and other LTEMP flow experiments.

We will also monitor invertebrate drift (#/m3 and g/m3), benthic invertebrate densities (#/m2 or g/m2), and quantify egg-laying of aquatic insects in the Colorado River throughout Marble and Grand Canyons during two monitoring river trips per year (spring and fall). This type of strategic monitoring of drift and benthic densities throughout Marble and Grand Canyon will complement more spatially and temporally extensive citizen science monitoring, and will provide another line of evidence for evaluating food base response to LTEMP flow experiments. Additionally, as part of these monitoring trips we will quantify egg laying at the peaks and troughs of midge abundance identified by Kennedy and others (2016) to determine whether Macroinvertebrate Production Flows are increasing survival of aquatic insect eggs at the troughs, as hypothesized.

#### Project F.2, Aquatic food base status and use by native fishes in Marble and Grand Canyons

#### Ted Kennedy, Research Ecologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

#### Charles Yackulic, Research Statistician, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

#### Mike Yard, Research Fisheries Biologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

#### Kim Dibble, Research Fisheries Biologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

Recent deterioration of the aquatic food base in Marble Canyon and Grand Canyon and associated declines in the condition (plumpness) and number of spawning humpback chub at the Little Colorado River confluence highlight the fundamental role that the aquatic food base plays in the health of native fish populations. This project element is focused on quantifying the feeding habits of humpback chub and characterizing both the *quantity* and *quality* of the food base available to humpback chub and other native fishes. Sampling locations will include near the Little Colorado River confluence (JCM), in western Grand Canyon at a new juvenile chub monitoring site (JCM-west), and downstream of Diamond Creek where humpback chub and razorback sucker catch rates are increasing. Humpback chub feeding habits in the Colorado River were last quantified in 2008 at the Little Colorado River confluence as part of synoptic food web studies (Cross and others, 2013). We will quantify humpback chub feeding habits in spring, summer, and fall of 2018 (one year only) using gastric lavage (Stone, 2004). We will compare and contrast the feeding habits of humpback chub at the Little Colorado River confluence with humpback chub in western Grand Canyon. Additionally, we will use these data to identify whether the feeding habits of humpback chub at the Little Colorado River confluence have changed over time (Cross and others, 2013; Valdez and Ryel, 1995).

At each of these humpback chub monitoring locations, we will characterize the *quantity* of prey available by measuring invertebrate drift and insect emergence using light traps and sticky traps. We will also characterize the *quality* of the prey base at humpback chub monitoring locations using nutrient stoichiometry and lipid analysis. Nutrient stoichiometry involves calculating the ratio of different essential elements in prey and predator; carbon is a source of energy whereas nitrogen is a major component of muscle and phosphorus is essential to growth (Sterner and Elser, 2002). The ratio of carbon:nitrogen (C:N) in fish is generally around 5:1 while the ratio of carbon:phosphorus (C:P) is around 40:1 (Sterner and Elser, 2002). Invertebrates with elemental ratios similar to those in fish are high-quality prey, because these prey support fish growth and can be readily converted into new fish tissue and biomass. In contrast, invertebrates that have more carbon and less nitrogen and phosphorus (i.e., larger C:N and C:P ratios) compared to fish provide energy needed for fish movement and metabolism, but consumption of these low-quality prey creates an elemental imbalance for fish such that these prey do not readily support growth and development of new fish tissues (Elser and others, 2003). Fatty acids, a class of lipid, are major components of the storage fats in fish tissue. Fatty acids are incorporated into fish tissue in patterns reflective of diet and can be used to estimate the relative contribution of different prey to fish growth (Happel and others, 2015; Parrish, 1999; Parrish and others, 2015). We will quantify elemental ratios (i.e., C:N:P) and lipid class analysis of invertebrate prey to determine whether there are substantial differences in the *quantity* or *quality* of invertebrate prey among humpback chub monitoring sites (i.e., near the Little Colorado River, western Grand Canyon, downstream of Diamond Creek). Additionally, we will analyze elemental ratios and lipid classes of surrogate native fishes at each of these sites (e.g., speckled dace, bluehead sucker) using non-lethal muscle plugs to identify whether the *quality* of prey may be a factor influencing differences in humpback chub population abundance and growth in the Colorado River in eastern vs. western Grand Canyon.

Data on the quantity and quality of the food base and humpback chub feeding habits will be integrated using a bioenergetics approach (e.g., Dodrill and others, 2016) to determine levels of consumption (a proxy for how favorable conditions are for growth) at both the Little Colorado River confluence and western Grand Canyon. Use of bioenergetics models will be essential to interpreting these food base data in relation to growth potential for humpback chub across distant sites, because these bioenergetics models explicitly account for the influence of water temperature on fish metabolism (Petersen and Paukert, 2005).

#### Project F.3, Terrestrial-aquatic linkages

Ted Kennedy, Research Ecologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

Carol Fritzinger, Citizen science liaison, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

Christina Lupoli, Graduate student, Arizona State University, School of Life Science

John Sabo, Professor, Arizona State University, School of Life Science

Insect emergence is a fundamental natural process in streams and rivers. Emerging adult aquatic insects are a key prey item for Colorado River fish populations (Cross and others, 2013; Dodrill and others, 2016), and aquatic insects that successfully emerge from rivers are often the primary prey for terrestrial wildlife including birds, bats, lizards, and rodents (Nakano and Murakami, 2001; Sabo and Power, 2002). Citizen science light trapping is characterizing insect emergence throughout Grand Canyon. In this project element, we will leverage that large dataset to determine the extent to which terrestrial food webs in Grand Canyon are dependent on emerging insects as prey.

We will collaborate with tribal resource trips, educational trips, and other citizen scientists to quantify bat and bird activity throughout Grand Canyon. We will work with tribal participants and river guides to devise a simple and effective protocol for monitoring bat activity and species composition using acoustic monitoring devices (<https://www.wildlifeacoustics.com/>). The bat activity monitors we will use run on a tablet computer and can identify bats to species based on their calls. This bat monitoring application features an interactive display that allows the user to see, in real-time, the species and numbers of bats that are active during monitoring. The tablet records all this information as a sound file that will be downloaded to a computer at GCMRC once the river trip has concluded. We will also collaborate with tribal resource trips and river guides to develop protocols for quantifying abundance and activity of swallows, swifts, and other types of birds that may be dependent on emergent insects as prey. Protocols for bird monitoring might involve a trained observer making a categorical estimate of swallow and swift abundance along the river (i.e., 0 = no swallows visible, 1 = up to 10 swallows visible, 2 = up to 100 swallows visible, 3 = up to 1000 swallows visible, 4 = more than 1000 swallows visible). These observations of bird activity could be made in camp (e.g., at dawn and dusk while in camp) and/or while tribal trips are underway (e.g., once per hour while boating). Exact protocols for citizen science monitoring of bat and bird activity will be determined at a later date and in collaboration with tribes. Data on bat and bird activity and species composition will be compared to spatial and temporal patterns of aquatic insect activity as measured by citizen science light trapping to determine the extent to which bats and birds are dependent on emergent insects from the Colorado River. Although these approaches for monitoring bats and birds may seem simple, they will yield data that is robust and powerful enough to detect whether bat and bird activity are correlated with the 3-fold differences in emergent insect abundance that exist throughout Grand Canyon (Kennedy and others, 2016). Importantly, baseline data on bat and bird activity will also be used to determine whether bat and bird activity increases in the future and in response to changes in aquatic insect emergence owing to Macroinvertebrate Production Flows or other LTEMP flow experiments.

As part of this project element, we will also continue to partially support the PhD research of Arizona State University graduate student Christina Lupoli describing linkages between emergent aquatic insects and terrestrial species such as birds, bats, and lizards that depend on emergent aquatic insects as prey. Funding for Ms. Lupoli’s stipend and tuition is jointly provided by Arizona State University (half) and GCMRC (half). GCMRC also supports this research by providing logistics and facilitating her participation on existing river trips. Now in its second year, Ms. Lupoli’s research involves use of stable isotope analysis to describe feeding relationships and identify the degree to which terrestrial wildlife along the Colorado River ecosystem are feeding on terrestrial vs. aquatic prey. This in-depth investigation of terrestrial food webs and the relative importance of aquatic prey will complement citizen science approaches to bat and bird monitoring described above. Collectively, these studies will identify whether changes in aquatic insect abundance owing to Macroinvertebrate Production Flows cascade out of the River itself.

#### Project F.4, Glen Canyon aquatic food base monitoring and research

Ted Kennedy, Research Ecologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

Tom Quigley, Ecologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

David Goodenough, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

This project element is a continuation of a monthly Glen Canyon monitoring program that has been ongoing for several years (10+ in the case of some invertebrate drift sites), representing a valuable long-term dataset for identifying status and changes in the aquatic food base. Specifically, as part of this monitoring program, we sample aquatic invertebrate drift at ten sites from GCD to the head of Badger Rapid (RMs -13.0, -11.0, -8.0, -4.9, -3.5, -2.1, 0, 1.7, 3.3, and 6.0), which allows us to understand and model changes in invertebrate drift over time and also in response to flow conditions such as riffles, pools, and tributary sediment inputs from the Paria River.

In addition to drift sampling, this monitoring program includes monthly sticky and light trap sampling of emergent adult aquatic insects that has been ongoing since 2013. In this workplan, we propose to sample at a reduced number of sites compared to in previous years, because statistical analysis indicates sampling effort could be reduced by ~50% without a significant loss in power. Accordingly, we will reduce effort to 17 sticky sites and 4 light trap sites approximately evenly-spaced from GCD to the head of Badger Rapid. This reduction in effort will lower costs and still allow us to identify patterns and trends in adult aquatic insect emergence throughout Glen Canyon and upper Marble Canyon over time and in space. Emergent insects are more easily sampled than drift and yet tend to respond proportionally to changes in benthic insect abundance owing to, for example, environmental conditions (Statzner and Resh, 1993). Continuing to sample aquatic insects using multiple methods that collect drifting or emergent life stages in Glen Canyon enables quantification of the drift-emergent insect relationship in the Colorado River ecosystem. This, in turn, allows us to continue to make strong predictions about the food base available to support Colorado River fish populations in Marble and Grand Canyons, where citizen science light trapping occurs but frequent measurements of invertebrate drift are infeasible.

This monitoring is carried out using published methods developed by the food base group (Baxter and others, 2017; Copp and others, 2014; Kennedy and others, 2013; Kennedy and others, 2014; Muelbauer and others, 2017; Smith and others, 2014). Due to the consistency in sampling methodologies, these data also allow us to compare aquatic food base conditions in Glen Canyon to those in Marble and Grand Canyon (see Project Elements F.1 and F.2). Finally, we will conduct new research, predominantly in Glen Canyon, to more mechanistically explore the effects of fall HFEs on the food base. The flow experiments outlined in LTEMP may directly or indirectly affect the composition of the aquatic food base in Glen Canyon (see Project Element F.1), which may have important implications for growth potential for both rainbow trout and brown trout. There are several mechanisms by which experimental flows could alter aquatic food base composition. For instance, HFEs may cause direct mortality due to dislodgment and displacement of specific insect taxa. Flow experiments could also have indirect effects on the aquatic food base, via creation or disturbance of specific habitats, such as macrophyte beds, which favor New Zealand mudsnails and tubificid worms. In turn, flow meditated shifts in the invertebrate community may benefit either rainbow trout or brown trout, depending on their prey utilization and selection.

To address these uncertainties, we will conduct manipulative experiments involving loosening cobbles and scrubbing rocks free of algae, detritus, and sediment to mimic HFE scouring of benthic substrates. These experiments will be carried out using a randomized block design of rock habitat patches, with scrubbing at different times of year so as to be representative of the effect of high flows occurring during different seasons. Rock habitat patches will be monitored for the response of algae and macroinvertebrates in scrubbed vs un-scrubbed, control patches. We will also carry out studies on lateral variation in macroinvertebrate drift across the river’s width at the monthly drift monitoring sites across a range of discharges, including during fall HFEs. These data will be used to assess whether macroinvertebrate drift dynamics vary as a result of HFE and other flow conditions. Lateral patterns in the drift may shift under different higher flows, potentially making this food base more or less available to drift feeding fish such as rainbow trout. This lateral drift sampling would occur pre-, during, and post-HFEs, as well as quarterly, at the same drift monitoring sites that are monitored monthly. For the lateral sampling, these sites would be sampled not just in the thalweg, but also in nearshore and shallower-channel habitats. Finally, related to fall HFEs and selected alternative flow management more generally, we will conduct a synthesis of known information on the long-term status and trends of *Gammarus* in Glen Canyon. *Gammarus* were once the primary food item for rainbow trout in this river segment and were thought to be very abundant (Leibfried and Blinn, 1987), but contemporary food base studies indicate their drift concentrations are fairly low, and *Gammarus* are secondary to midges in terms of rainbow trout bioenergetics (Cross and others, 2011; Dodrill and others, 2016). This synthesis would attempt to identify long-term changes in *Gammarus* densities in Glen Canyon, and also to correlate any changes to alterations to the flow regime, water temperatures, habitat, and trout densities.

#### Project F.5, Are undesirable shifts in the Glen Canyon prey base facilitating expansion of brown trout?

Mike Dodrill, Fisheries Biologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

Ted Kennedy, Research Ecologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

Mike Yard, Fisheries Biologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

The objectives of this project element are to 1) compare and contrast prey utilization and selection by rainbow trout and brown trout and 2) use this information on trout foraging ecology to model and predict how these two species will respond to changes in the physical template of Glen Canyon (e.g., increases in water temperature) and changes in the prey base (e.g., New Zealand mudsnails vs. aquatic insects).

This project element will utilize long-term invertebrate drift monitoring data to characterize the prey resources available to foraging rainbow trout and brown trout in Glen Canyon over time. This information on prey availability will be combined with diet data to contrast how these two salmonids utilize prey resources. Prior food web studies in Glen Canyon demonstrated that midges and black flies were key prey items for rainbow trout (Cross and others, 2011). Recent bioenergetics modeling (Dodrill and others, 2016) and prey selection analyses (Dodrill, unpublished data) also point to the importance of black flies and midges in fueling rainbow trout growth and condition. Less is known about the foraging ecology of brown trout in Glen Canyon, but preliminary diet data indicate brown trout utilize more benthic prey types compared to rainbow trout (i.e., brown trout appear to preferentially prey upon New Zealand mudsnails and *Gammarus*). Since around 2013 the food base in Glen Canyon has been dominated by New Zealand mudsnails and other types of benthic prey (e.g., tubificid worms, *Gammarus*), while aquatic insects have been exceedingly rare, potentially owing to repeated testing of fall HFEs that began in 2012. Thus, recent declines in the abundance of aquatic insects and a shift in the food base towards New Zealand mudsnails may actually be facilitating the expansion of brown trout populations in Glen Canyon. Additionally, these undesirable shifts in the prey base may be exacerbating the negative effects that intra-specific competition for aquatic insects are having on the health and condition of rainbow trout populations in Glen Canyon (Korman and others, 2017).

This project element will describe the trophic ecology of rainbow trout and brown trout, which contributes to broader ecosystem modeling goals described in Project E. Additionally, information on prey selection patterns and observed shifts in the food base composition will be used to estimate growth potential for brown trout vs. rainbow trout under different prey availability scenarios (i.e., a prey base dominated by aquatic insects, as observed in 2008-2010, compared to the current prey base dominated by New Zealand mudsnails). Bioenergetics models will also be used to forecast growth potential for brown trout and rainbow trout under the different water temperature scenarios that were used in LTEMP modeling. These types of mechanistic approaches have been successfully applied in past research to understand how the prey availability and water temperature determines the lifetime growth potential of rainbow trout (Dodrill and others, 2016). This project will build on those recent efforts and identify whether shifts in the prey base and/or changing water temperatures have the potential to favor brown trout over rainbow trout.

#### Project Element F.6, Quantifying the expansion of quagga mussels

Ted Kennedy, Research Ecologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

Morgan Ford, Ecologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

To quantify the progression of quagga mussels downstream of GCD into Grand Canyon, we will use both larval veliger sampling with plankton net-style methods, and adult mussel monitoring using artificial substrates (e.g., Hester-Dendy style) to collect samples throughout the Colorado River in Glen, Marble, and Grand Canyons twice per year as part of food base monitoring river trips. These methods are common for quagga monitoring throughout the US, and are used by the Bureau of Reclamation in the Lower Colorado River where mussels are well-established. The purpose of this monitoring is to test the conclusions drawn in a 2007 risk assessment (Kennedy, 2007), which predicted that quagga populations would become established only in low densities throughout the Colorado River in Grand Canyon due to the presence of high suspended sediment concentrations (i.e., low food quality) and many high-turbulence rapids that would kill larval quagga veligers. If these predictions turn out to underestimate the extent of quagga mussel invasion in Grand Canyon, this information will aid the National Park Service in designing potential control measures for this species.

#### Project Element F.7, Aquatic food base status and change in Grand Canyon tributaries

Ted Kennedy, Research Ecologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

Erin Abernethy, Ph.D. Student, Oregon State University

David Lytle, Professor, Oregon State University

Megan Daubert, Ecologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

Brian Healy, Fisheries Biologist, National Park Service, Grand Canyon National Park

Some of the work described in this project element consists of ongoing research and monitoring in Grand Canyon tributaries, while other aspects represent new research starts. First, we propose to continue monitoring the aquatic food base in the Little Colorado River, which has been ongoing since 2014. The large-scale food base research carried out in the Little Colorado River during the last workplan will be scaled back in this workplan by ~75%, to represent only the deployment of one sticky trap pole at the top and bottom of each of the three fishing reaches worked by each of the three camps (Boulders, Coyote, and Salt) that are accessed in April, May, September, and October by the U.S. Fish and Wildlife Service and in June by GCMRC fisheries staff. Unlike in previous years, these sticky traps will be deployed by these fisheries staff, rather than by food base researchers, to minimize costs while still yielding useful spatial and temporal monitoring data as part of an ongoing Little Colorado River food base monitoring program. Additionally, light traps will be deployed at the start and end of each trip by personnel at each camp, allowing comparison of light trap catches in the Little Colorado River over time, as well as with the larger citizen science monitoring effort described in Project Element F.1.

In collaboration with the National Park Service, we will also continue sampling the aquatic food base in Bright Angel Creek to better understand aquatic food base responses to trout removal. Our food base research in Bright Angel Creek has involved quarterly (September, January, April, June) sampling since 2016, and is intended to continue for at least one year after trout removal ceases. We structure our sampling to be consistent with a pre-removal study of invertebrate drift and benthic densities carried out by Whiting and others (2014), allowing us to compare food base conditions pre, during, and post-trout removal. We also deploy sticky traps and take drift and benthic samples at various distances (0, 400, 1000, 1600, and 3200 m) up Bright Angel Creek from its confluence with the main stem Colorado River, to better characterize spatial patterns in food base diversity and densities in the creek and to compare with similar datasets collected in other tributaries and the main stem.

New for this workplan, we propose to carry out aquatic food base research in Shinumo and Havasu Creeks, also in collaboration with the National Park Service. These creeks are sites of previous, ongoing, and future planned humpback chub translocations. Better characterizing spatial and temporal status and trends of the aquatic food base in these creeks will provide important information on the potential for translocation success and humpback chub population status changes in these creeks. Sampling methodologies in these creeks will be similar to those used in the Little Colorado River and Bright Angel Creek, but will be limited to only one or two sampling events per year in order to characterize annual, rather than seasonal, trends.

Finally, we propose a collaboration with Oregon State University PhD student Erin Abernethy and her advisor, Dr. David Lytle, to study the population genetics of aquatic insects in Grand Canyon tributaries. Abernethy’s role in this study is independently funded through her NSF Graduate Research Fellowship and by a USGS Graduate Research Improvement grant she and Dr. Jeff Muehlbauer were awarded to carry out this research. The focus of the project will be to sample common aquatic invertebrate species in tributaries throughout Grand Canyon and compare them using next-gen genetic sequencing tools that allow comparison of genetic similarity across populations. The results of this genetic analysis will allow us to determine the extent to which populations of common species in Grand Canyon tributaries are genetically distinct from one another, as well as the relative time (pre-history, pre-dam, or post-dam) during which any genetic differentiation occurred. Thus, these results will help us understand whether common insect species that are currently present in tributaries but absent from the main stem Colorado River in Grand Canyon may have dispersed more readily pre-dam, likely due to the presence of mixing populations in the main stem river, or whether tributary populations were always distinct, indicating that those species likely were not in the mainstem even pre-dam.

#### Project Element F.8, Patterns and controls of aquatic insect diversity in regulated rivers

Ted Kennedy, Research Ecologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

Anya Metcalfe, Ecologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

Scott Miller, Director, Utah State University/Bureau of Land Management, National Aquatic Monitoring Center BugLab

David Lytle, Professor, Oregon State University

Ryan McManamay, Research Scientist, Department of Energy, Oak Ridge National Laboratory

Daren Carlisle, Chief, U.S. Geological Survey, National Water Quality Assessment (NAWQA)

This project element describes work proposed outside of the Colorado River ecosystem in Grand Canyon. This workis not being submitted for funding by the GCDAMP, but we are providing the information here for reference because it relates directly to the goal of identifying links between dam operations and the quantity and quality of the aquatic food base. First, we propose to carry out additional studies on EPT taxa in the Davis, Parker, and Hoover Dam tailwaters in the lower Colorado River, to better understand how certain EPT species in these tailwaters seem to thrive and even become a recreational nuisance in spite of the high level of load-following fluctuations experienced in these river segments. We are seeking funding for this research from the lower Colorado River Multi-Species Conservation Plan, Department of Energy, and non-governmental sources. Second, we are seeking non-AMP funding to synthesize existing tailwater benthic data collected throughout the nation by the US EPA and the USGS NAWQA program. We will identify the role that dam operations play in the food base of regulated rivers by comparing EPT richness and abundance among tailwaters with an existing database of dam flow and operational metrics recently compiled by the DOE Oak Ridge National Lab (<http://nhaap.ornl.gov/>).

This research was proposed as a USGS Powell Center Working Group (<https://powellcenter.usgs.gov/>) that would fund the salary of a postdoctoral researcher for FY 2019. Our 2017 USGS Powell Center proposal was not funded, but we will revise and resubmit in 2018.

**4.2. Deliverables**

Project F will evaluate food web response to Macroinvertebrate Production Flows, High Flow Experiments, and other LTEMP flow experiments. In general, each of the eight project elements will result in one or more peer-reviewed journal articles and presentations at scientific meetings. These project elements describe cutting-edge work in applied aquatic ecology, and the outcome of several of these project elements will be the publication of papers in the highest-tier scientific journals.

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1. **Budget**



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

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1. **Project Summary**

Proposed research and monitoring activities associated with humpback chub (*Gila cypha*) are diverse and primarily guided by the LTEMP EIS and associated Biological Opinion (BiOp), including needs for information on conditions that could trigger non-flow management actions mandated by the BiOp. Proposed activities also seek to respond to recommendations made by the August 2016 Fisheries Protocol Evaluation Panel (PEP) including: 1) focusing on open models and vital rates (movement, growth, and survival), in addition to abundance, 2) improving the efficiency of humpback chub research, 3) considering additional, hypothesis-driven research into recent increases in the lower half of the Colorado River ecosystem (CRe), and 4) critically examining the effectiveness of translocation programs. Given the complexity of work done on humpback chub, we group these activities into three main groups: A) ongoing long-term studies (e.g., monitoring, population models), B) new or substantially altered research, and C) translocations and associated research, which we discuss in more detail below.

***Ongoing long-term studies***

1. Population modelling that integrates data from mark-recapture efforts in the Little Colorado River (LCR) and Colorado River will continue to be used to estimate abundances and vital rates (survival, growth and movement) of various size classes of humpback chub in different locations, evaluate whether the resulting estimates cross triggering thresholds for non-flow management actions mandated by the BiOp, provide context to observed trends, and improve our understanding of humpback chub population ecology. Specific priorities for this workplan include: a) integrating data from new forms of portable remote antennas, including shore-based single antennas in the LCR and portable remote antennas in the Colorado River that have only recently been incorporated into LCR and Colorado River monitoring of humpback chub; b) incorporating the presence and demographic effects of juvenile fish translocated above Chute Falls into population models, to assess translocation effectiveness; c) analyzing drivers of key population processes, especially drivers affecting humpback chub recruitment and outmigration rates; and d) developing new models to understand how food availability, intraspecific densities, and the asynchrony between food availability and temperatures in the CRe interact to affect humpback chub survival and growth.
2. Monitoring of humpback chub in the LCR in the spring and fall using two trips in each season will continue and use joint agency and tribal staffing. We also plan to explore whether use of additional gear types during fall trips could allow us to estimate fall juvenile abundances in a single, fall trip timed to avoid floods, potentially leading to similar quality data at lower costs and with a smaller footprint in the LCR.
3. We will continue monitoring of humpback chub in the Colorado River near its confluence with the LCR as part of the juvenile chub monitoring (JCM) project. This project will involve (a) a single trip per year to the LCR before the start of Southwest monsoon storm runoff to estimate juvenile recruitment and outmigration rates in relation to LCR storm discharge, and (b) three other trips per year – in April, July, and October (decreased from four trips in prior years) – to a fixed site in the Colorado River just downstream of the LCR confluence. The data from these trips permit estimates of juvenile growth, survival, and abundance in the mainstem, as well as abundances (including adult abundance) and vital rates of various size classes of humpback chub. We plan to slightly decrease the number of nights per Colorado River trip, but also increase the spatial extent of JCM study reach to river mile[[3]](#footnote-4) (RM) 63 to 66 with the goal of increasing the number of marks released and improving population estimates, while also minimizing negative impacts on the wilderness experience of visitors in GCNP. We also will incorporate portable remote passive integrated transponder (PIT) antennas into our sampling design.
4. In the short term, we will continue to maintain and operate the remote PIT-tag antenna array in the LCR, however this system is slowly degrading and is unlikely to remain functioning through 2020. Therefore, we are currently testing the effectiveness of a series of shore-based single antennas placed in locations that naturally cause fish to pass through restricted areas within the lower portion of LCR as a potential replacement. USGS and USFWS have already begun working on this replacement plan and we are optimistic that shore-based antennas can provide as good or better data at lower costs and with a smaller footprint in the LCR. We also propose to include contingency funding to remove the PIT tag antenna array currently in place when it ceases to provide useful data.
5. Annual sampling at known humpback chub aggregation sites will continue as directed by the BiOp. The primary objective of this annual trip will be to continue a long-term catch-per-unit-effort (CPUE) index that has been constructed since the early 1990s (Persons and others, 2017). If funding is available, we propose one additional sampling trip during the three year workplan (tentatively planned for 2019) focused on non-aggregation sites, fulfilling another conservation measure. In addition, if funding is available, we propose an annual seining trip. Seining in backwaters can be a cost-effective way to monitor both juvenile humpback chub and warm-water non-native species.

***New or substantially altered research***

1. Since 2009, mark-recapture studies around the LCR (i.e., the Near Shore Ecology study from 2009 to 2011 and the JCM study from 2012 onwards) have led to a much improved understanding of several drivers of humpback chub population dynamics in the LCR aggregation. Specifically, these studies have generateddata to estimate the relative importance of physical (temperature, turbidity) and biological (rainbow trout, foodbase, density dependence) factors (Dzul and others, 2016; Yackulic and others, In Review). In recent years, catches in more western aggregations have increased dramatically. However, current sampling is insufficient to adequately measure proposed drivers. Furthermore, the BiOp states a need to determine the drivers of aggregations. For these reasons we propose to establish a fixed site in the western Grand Canyon in which to establish JCM-type sampling (JCM-West) to determine if we can estimate vital rates and abundances (as opposed to catch statistics) with an eventual goal of identifying and estimating the relative impacts of drivers of population dynamics. We will also use this work to make comparisons of capture probability between JCM and JCM-West to determine how much of the variation in capture probability is due to environmental factors (temperature, turbidity) that could be controlled to provide better indices of abundance based on aggregation-type sampling. Analysis of JCM data suggests that temperature alone can explain ~50% of capture probability variation and leads to the expectation that each degree increase in temperature should lead to 35% greater catch (Yackulic and others, In Review). Understanding the external factors that can variation in capture probabilities potentially will allow us to better estimate abundances at various aggregation sites. This improvement addresses another BiOp need, to estimate abundances at aggregations other than the LCR. JCM-West sampling would occur as part of the same trips used for JCM because of the overlap in gear and personnel in order to minimize costs (field trips for the Rainbow Trout Natal Origins study and JCM study were combined logistically in previous workplans). In 2017, we are planning a pilot study to determine the best location for JCM-West sampling with three potential sites currently being considered (Havasu: - RM 158-167, Parashant: 198-205, and Pumpkin Spring: 210-217). In FY 18-20, we will choose one site and visit it three times a year (April, June/July and October).
2. If funding is available, handheld forward looking infrared radar (FLIR) cameras will be used to thermally image the Colorado River and identify warm springs within the mainstem that may be correlated with increased humpback chub catch rates. Thermal imaging cameras have been used to map groundwater inputs and temperature distributions in other Arizona streams and have been shown to be effective at identifying and mapping the extent of warm-water springs at river mile 30 within Grand Canyon. This relatively low-cost tool will allow identification of currently unknown warm water inputs within the Colorado River that may provide important thermal refuges for humpback chub.
3. We propose using humpback chub data collected from 2000 through the present along with existing high resolution habitat data from the LCR to better understand environmental characteristics associated with spawning of humpback chub. By linking incidence of ripe female humpback chub captures to specific locations and environmental variables within the LCR, we hope to gain a better understanding of where humpback chub spawn. This work will establish methodologies for linking environmental variables to existing long-term fish data so that the existing database is more useable for humpback chub conservation and management.

***Translocations and associated research***

1. We will coordinate with the Havasupai Nation and the National Park Service to investigate the feasibility of translocating humpback chub to areas upstream of Beaver Falls in Havasu Creek. If the Havasupai Nation is supportive, we will work with the tribe to conduct planning, implement surveys, and translocate and monitor translocated fish.
2. We will continue translocation of juvenile humpback chub to upstream of Chute Falls on an annual basis and to continue annual monitoring (LTEMP BiOp Conservation Measure).
3. We will investigate natal site imprinting in humpback chub to improve the translocation program. If humpback chub imprint on chemical cues of their natal stream as larvae, individuals translocated using current methods may not remain in the areas to which they are translocated – either downstream tributaries or mainstem aggregation sites – once they reach reproductive maturity. Many of these fish may instead attempt to return to their natal stream, which in this case will be the LCR, to spawn. Such a pattern of return for spawning in their natal stream will reduce the likelihood of establishing additional spawning populations to meet downlisting/delisting criteria. To test this hypothesis, quantify rates of return to the LCR through a rigorous analysis of existing data, accounting for survival and capture probabilities.. We will also test that imprinting occurs in the laboratory using captive reared humpback chub larvae, by measuring thyroid hormones known to be linked to olfactory imprinting. This information will then be used to evaluate new methods for conducting translocations, such as stocking ripe adult fish whose offspring will imprint on the new location rather than translocating juvenile fish that have already imprinted on the LCR.
4. If genetic analyses being conducted in FY17 suggest a need for follow up work and if funding is available, we propose additional study of humpback chub genetics.
5. **Background**

***Humpback chub that spawn in the Little Colorado River (LCR****)*

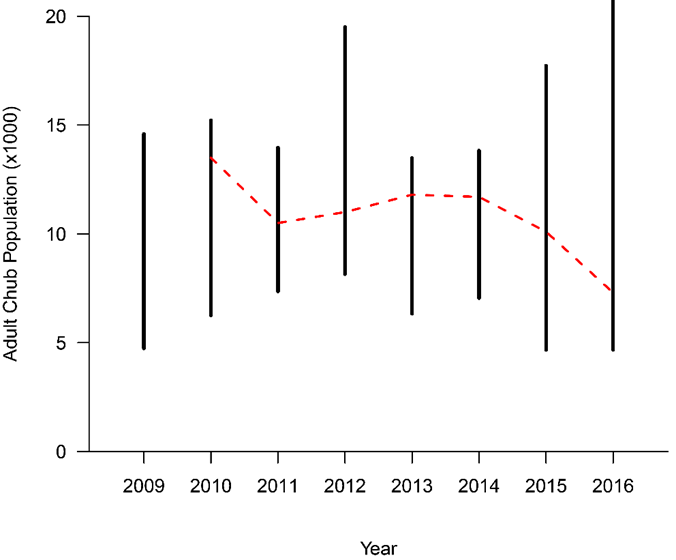
Since 2001, mark-recapture monitoring led by USFWS in the LCR has formed the backbone of monitoring for humpback chub that spawn in the LCR (Coggins and others, 2006; Van Haverbeke, 2013). Humpback chub have much higher capture probabilities in the LCR making it is easier to estimate spawning (spring) and resident (fall) adult abundances. The data from this mark-recapture monitoring provides information on conditions that could trigger non-flow management actions mandated by the BiOp, and provides a large amount of the data necessary to estimate total adult abundance, another important trigger variable identified in the BiOp. The data provided by this effort is necessary, but not sufficient, to estimate total adult abundances because humpback chub are skip-spawners (Pearson and others, 2015; Yackulic and others, 2014) and thus some portion of the adult population is not available for capture in (i.e., emigrates from and does not return to) the LCR in any given year. Estimating the total abundances with LCR-based data alone requires one of two assumptions: 1) that the probability that any given individual is present in the LCR in the fall or spring of a given year is independent of whether it was present in the prior spring or fall and 2) that survival and growth probabilities in the LCR and CRe are the same. Both assumptions are now known to be violated, with the first assumption grossly violated (Yackulic and others, 2014). The first assumption is implicit in any modelling approach that does incorporate temporary emigration or spatial location (i.e., CRe versus LCR,), and vviolation of this assumption can lead to negative bias in abundance estimates (Kendall and others, 1997) and the appearance of declines in total abundance that actually represent changes in the rate of spawning. If spawning rates decline and then increase, violation of this assumption should lead to unstable estimates of abundance as additional years of data are collected (i.e., retrospective bias; Coggins and others, 2009). Thus the complexity of the life history of humpback chub that spawn in the LCR necessitates that we also sample in the CRe and include spatial locations in our models so long as managers remain interested in total adult abundance as a triggering variable for various management actions under the BiOp.

Since 2009, mark-recapture studies in the Colorado River near its confluence with the LCR (i.e., the Near Shore Ecology study from 2009 to 2011 and the JCM study from 2012 onwards) have led to a much improved understanding of the population dynamics of humpback chub that spawn in the LCR. These studies have led to insights into how rainbow trout and environmental conditions affect the growth and survival of juvenile humpback chub (Dzul and others, 2016; Yackulic and others, In Review), allowing for better understanding of the likely consequences of different management alternatives (e.g., as examined in modelling carried out to support development of the LTEMP EIS), including different flows and mechanical removal. This work suggests that if there were consistently half as many rainbow trout near the LCR, we would expect approximately 25% more adult humpback chub at equilibrium (Yackulic and others, In Review). While this prediction of 25% more adult humpback chub is fairly insensitive to annual juvenile production in the LCR, the prediction of equilibrium abundance of adult humpback chub is extremely sensitive. If juvenile humpback chub production in the LCR is relatively high (e.g., 25,000 juveniles in July in the LCR), there may be no need to take action to reduce rainbow trout abundance in the CRe mainstem above the LCR confluence to maintain a population of humpback chub in the CRe mainstem greater than 5,000 adults over the long term. On the other hand, if juvenile humpback chub production in the LCR is relatively low (e.g., 15,000), reducing rainbow trout abundance in the CRe mainstem above the LCR confluence may be essential to maintain humpback chub populations in the CRe mainstem above 5,000 adults. Direct estimates of juvenile humpback chub production in the LCR over the last few years have been low (~14,000,), however, this covers a short time period and there has been extreme year to year variation (e.g., ~25,000 in 2015 followed by ~3,000 in 2016), necessitating additional study of juvenile humpback chub production.

Even if annual juvenile humpback chub production is low, it is highly unlikely that rainbow trout will drive humpback chub extinct in the absence of additional stressors (Yackulic and others, In Review). We note, however, there remains considerable uncertainty in this prediction given that halving rainbow trout abundance could lead to a wide range of responses from no appreciable increase in adult humpback chub to as much as a 59% increase in adult abundances (Yackulic and others, In Review). This uncertainty arises, in part, because rainbow trout abundance, temperature, and turbidity explain only 43% and 38% of the variation in juvenile humpback chub growth and survival, respectively, suggesting that our understanding of drivers of juvenile humpback chub dynamics is still not sufficient. Attempting to incorporate density-dependence (Yackulic and others, In Review) or drift densities (Dzul and others 2016, Yackulic, pers. obs.) as additional covariates in a regression context does not improve statistical prediction. However, it is possible that different structural assumptions (i.e., besides those implicit in a typical regression) could lead to improved understanding and predictive ability. In FY2018-20, we will focus on testing a series of hypotheses related to the interactions of juvenile humpback chub densities, food availability, and temperature on juvenile humpback chub growth and survival. In particular, we will test the hypothesis (**H1**) that temporal variation in food availability leads to temporal variation in the carrying-capacity of the CRe for juvenile humpback chub and that the interaction between this carrying capacity and actual densities plays an important role in determining humpback chub growth and survival. We will also seek to incorporate weight data directly into our models to test the hypothesis (**H2**) that humpback chub growth in terms of length and weight are asynchronous due to asynchrony in the CRe between temperature and food availability. Resolving **H1** and **H2**, will help to place negative effects of rainbow trout on humpback chub in their proper context, allowing us to better address a central management question in the CRe, to what degree is management of rainbow trout through trout management flows or mechanical removal necessary to maintain a healthy humpback chub population, or can flows or other dam management be used to improve the overall health of the ecosystem?

While primarily designed to inform questions about juvenile humpback chub in the mainstem Colorado River, the JCM program is also a mark-recapture study of larger size classes of humpback chub and provides data on triggering variables associated with the BiOp, and some of the data necessary to estimate total adult abundance. In addition, the JCM program includes invertebrate drift sampling (Project F) and weight measurements that allow for estimates of fish condition in the Colorado River. The information from these additional components played an essential role in triggering and guiding the response of scientists studying humpback chub, when LCR sampling in spring of 2015 indicated a decline in the abundance of spawning adults of ~ 40% from the prior year. A decline of this degree is difficult to reconcile with our understanding of adult humpback chub survival, as well as our expectation of continuing recruitment from sub-adult size classes (to be clear we expected rainbow trout to have lowered this rate, but not to zero). Initially, we wondered if the migration had been early and had been missed by sampling, however data from the LCR PIT-tag antenna array indicated that the timing of the spawning migration was the same as the year prior. Fortunately, we knew from invertebrate drift sampling that there had been far less food available in 2014 than in years prior, and that adult humpback chub condition had declined over this period (i.e., their fish condition factor – the ratio of the observed weight to the predicted weight based on length – had declined). This information, together with our knowledge that humpback chub exhibit skip-spawning (i.e., do not spawn every year; Yackulic and others, 2014) and that skipped-spawning is common when insufficient food is available (Rideout and Tomkiewicz, 2011), led us to urge caution in interpreting a decline in spawning adults as a decline in the adult population.

Specifically, we argued that the hypothesis (**H3**) that humpback chub are in poor condition and are spawning at a lower rate than in prior years was better supported by available data, then the alternative hypothesis (**H4**) that there had been a massive decline in the adult humpback chub population. Such a decline in adult survival could hypothetically have occurred in the mainstem (**H4a**) or in the LCR (**H4b**). The hypothesis (**H4b**) that humpback chub in the LCR had decreased survival during the fall of 2014 was based on observations of multiple fish species having difficulty breathing during a flood with unusually high sediment loads. The number of adult spawners remained low in 2016, however, adult humpback chub in the Colorado River remained skinny and integrated modelling of data from the mark-recapture studies in the LCR and JCM via a multistate model (Yackulic and others, 2014) continues to support the hypothesis of reduced humpback chub spawning rate (**H3**) over the hypothesis of a decline in adult humpback chub survival (**H4a, b**). However, since we have extremely low capture probabilities in the Colorado River, we cannot entirely rule out **H4** yet. Furthermore, the uncertainty in estimates of adult abundances has increased substantially over the last two years. Even if reduced food availability has not decreased adult humpback chub survival yet, it is possible that continuation of low invertebrate drift densities (see Project F) will eventually lead to declines in survival and/or decreased recruitment from smaller size classes. For these reasons, we see understanding the drivers of recent declines in the food base (both the role of nutrients, Project E, and the role of flows, Project F) as essential research alongside ongoing monitoring in the JCM program. Importantly, if only information from the LCR monitoring had been available in 2014 and 2015, and populations had been assumed to be well-mixed (i.e., the assumptions outlined above), we might now believe that were in the midst of a substantial decline (red line in Fig. 1) and would have no evidence suggesting a declining food base in the mainstem. In fact, it seems plausible that, in the absence of information collected by the JCM program, a reasonable person might have linked this hypothetical humpback chub decline to the large number of rainbow trout produced during the period 2008-2012. The reasonable person would then come to the management implication that the AMP needed to focus on removing non-natives near the LCR, rather than on better determining the effects and drivers of declining invertebrate production.

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**Figure 1.** Adult humpback chub abundance estimates (95% Confidence intervals in black) based on a multistate mark-recapture model that allows for skip-spawning, variation in skip-spawning in different year, and differential growth rates in the Little Colorado River (LCR) and Colorado River. The rate of spawning for both smaller (200-250 mm) and larger (250+ mm) humpback chub adults has declined by approximately 50% in 2015 and 2016 leading to greater uncertainty in population abundances, however, given the choice the model prefers the hypothesis of a decline in spawning over the hypothesis that adult survival has declined. A model that used only LCR data and assumed fish present in the LCR were a random sample of the population (assumptions that are now known to be grossly violated) would wrongly attribute the decline in spawning rate to a decline in adult survival and suggest a 40% decline in adult abundances over the last two years (red line).

***Humpback chub that do not spawn in the LCR***

Available data suggest that 2014 was a tale of two rivers. In Glen and Marble Canyons, both primary production and invertebrate drift were declining (likely due to declining SRP; Project E), leading to both declining condition in adult humpback chub and declining condition and abundances of juvenile humpback chub. In contrast, in the Grand Canyon reaches of the CRe, there was evidence of higher levels of juvenile humpback chub recruitment than had previously been observed (Young, pers. obs.). Temperatures at National Canyon (RM 167) and Diamond Creek (RM 225) in 2014 were comparable to temperatures observed in these locations during 2000 and 2005, the two other warmest years in the last twenty years, and it has long been hypothesized that cooler temperatures limit humpback chub recruitment. This untested hypothesis formed the basis for modelling of humpback chub aggregations, excluding the LCR aggregation, during the LTEMP process. Flows, nutrients, food, and interspecific interactions were assumed to be unimportant as factors affecting humpback chub abundance and recruitment, in part, because we had never put sufficient effort into studying drivers of humpback chub population dynamics at locations outside of the LCR aggregation.

It now seems highly unlikely that temperature alone is the primary determinant of humpback chub abundance and recruitment below the LCR confluence (and by proxy that the abundance of food matters near the LCR, but does not matter further downriver), given the direct effect warmer temperatures have on metabolism (and thus food requirements) – one of the few general truths in biology. We can think of at least four hypotheses to explain the “two rivers” contrast in 2014. Some of these hypotheses will be addressed through this project, and others which will be addressed more directly through Projects E and F. The first hypothesis (**H5**) is that humpback chub densities are still so low in Grand Canyon, in contrast to Glen and Marble Canyons, that food limitation is not yet an important factor in the Grand Canyon, but will become one if populations continue to recover – with implications for establishing a second population. The next hypothesis (**H6**) is that humpback chub in Grand Canyon are not as dependent on autochthonous production (i.e., diatoms in the river that require SRP and that in turn are the main food of the aquatic insects on which humpback chub feed), and thus are less affected by the amount of SRP in dam releases (see Project E). Alternatively, since we know very little about nutrients downstream of Lees Ferry, we might hypothesize (**H7**) that there were sources of SRP downstream of the Little Colorado River in 2014, such that autochtonous production did not decline as substantially in Grand Canyon as they did in Glen and Marble Canyons. There are myriad processes (tributary inflows, nutrient spiraling, etc.) that could explain such a spatial difference in SRP availability. In particular, a final hypothesis (**H8**) is that frequent HFEs over the last four years have exported large quantities of aquatic vegetation biomass (including a big pool of phosphorous within that biomass) and mineral phosphorus in sediment from the upper part of the CRe, into the lower part, providing a slow drip of SRP to the downriver ecosystem. Work in the 1990s suggested that HFEs can play an important role in establishing sand deposits as phosphorous hotspots (Parnell and others, 1999).

Distinguishing among these hypotheses to determine drivers of these humpback chub populations is difficult, in part, because there are no ongoing intensive studies of the food base, humpback chub, or other fish species in the lower half of the Colorado River. However, determining if the drivers of population dynamics near the LCR and in the western portions of the Grand Canyon are the same is vital for understanding the long-term viability of humpback chub downstream of Glen Canyon Dam. Knowing what the drivers of population dynamics in the lower half of the CRe are, and whether dynamics in this portion of the Colorado River and the near the LCR are synchronous is arguably more important to understanding risks of subpopulation extirpations within the CRe than knowing the amount of genetic exchange between the subpopulations near the LCR and in western Grand Canyon. Consideration of two scenarios illustrates this point. In scenario A, the two subpopulations have minimal exchange of individuals, but are highly synchronous (i.e., they decline and increase together), so the second population adds little demographic redundancy or resilience. In scenario B, exchange is more frequent, but subpopulation dynamics are highly asynchronous leading to an overall population with a much higher probability of long-term persistence with implications for down-listing of humpback chub. For these reasons, we propose establishment of a fixed juvenile chub study area in western Grand Canyon (JCM-west), using similar methodologies as the JCM near the LCR, to better understand the drivers of humpback chub populations at downstream locations.

Monitoring via the aggregation sampling project provides extensive sampling that provides useful information on length-frequency and catch statistics at a number of sites and we propose to continue this work (Persons and others, 2017). However, learning about drivers from only data (and parsing between hypotheses like **H5-H8**) is likely to be slow and estimating abundances will be very difficult. Nonetheless, the BiOp calls for a better understanding of drivers and estimates of abundances for aggregations other than the LCR. Mark-recapture studies of humpback chub in western Grand Canyon at a fixed site would give us the best chance of addressing these needs. If estimates of capture probabilities in this western JCM are comparable to estimates for the LCR-JCM study, or if differences can be explained statistically by including environmental covariates in the analysis, we may be able to develop statistical models to provide rigorous estimates of abundances at other aggregations. Importantly, the NSE and JCM experience has shown us that at least six days of sampling at a location are required to accurately estimate capture probabilities (and resulting abundances) so it is not surprising that two-day sampling events have not yet led to usable abundance estimates.

***Translocated humpback chub***

Translocations are an important management tool recognized by the LTEMP and BiOp as a key component of humpback chub management and a potential means to avoid mechanical removal of trout in the mainstem Colorado River near its confluence with the LCR. At the same, the 2016 PEP panel on fisheries indicated there was a need to make the translocation program more rigorous quantitatively, to identify goals, and to design translocations to address key uncertainties about the effectiveness of this management action. There is clear evidence that humpback chub translocated upstream of Chute Falls grow much more quickly and likely survive at higher rates, suggesting a benefit to humpback chub. At the same time, however, the Chute Falls translocation effort does not provide much additional redundancy to the humpback chub population: If something catastrophic happens to the LCR population downstream of Chute Falls, it will also likely negative effect the population upstream of Chute Falls. Further, the translocation process involves costs (e.g., potential handling mortality). These downsides to the Chute Falls translocation effort suggest a need to not just show that growth and survival rates are greater upstream of Chute Falls, but to make a counter-factual comparison to test the hypothesis (**H9**) that the Chute Falls translocation is adding a sufficient number of adults to the population to justify the costs. We plan to test **H9** through a joint analysis by U.S. Geological Survey Grand Canyon Monitoring and Research Center (GCMRC) and U.S. Fish and Wildlife Service (USFWS) scientists. Dependent on the results of this analysis, USFWS will reconsider the need for continuation of Chute Falls translocation, including the conditions (e.g., overall adult chub abundances) under which this management action is most useful.

Mainstem translocations are identified as a management tool in the LTEMP EIS and BiOp, with the goal of establishing and/or augmenting reproducing populations in the mainstem CRe. Establishment of new reproducing populations within the mainstem CRe may also enable the CRe population of the humpback chub to meet downlisting or delisting criteria (2002 Humpback Chub Recovery Goals). Resolution of hypotheses **H5-H8** regarding whether there is sufficient food for more humpback chub (is it merely temperature that limits mainstem populations in the lower half of the CRe) clearly will inform the use of this tool. However, there are additional, untested hypotheses underlying application of mainstem translocation. For example, the hypothesis (**H10**) that humpback chub imprint on a spawning area when they are a few days old would suggest that fish artificially translocated to the mainstem CRe may still travel back to the LCR for spawning purposes, even if they otherwise remain far downriver at other times. Translocated individuals that return to spawn in the LCR but do not otherwise remain there could potentially add some demographic redundancy to the CRe humpback chub population overall, in the sense that individuals would experience different conditions and different drivers if they mainly live downriver. However, it would clearly be preferable to have reproduction occurring in places other than the LCR from a recovery perspective. Translocating ripe adults and having them spawn (as opposed to translocating juveniles) might be a reasonable alternative approach if **H10** is supported. Importantly, if olfactory cues are important in guiding humpback chub to spawning sites, humpback chub translocated to the mainstem downstream of the LCR would be more likely to return to the LCR than would humpback chub translocated to tributaries: Compared to humpback chub adults in tributaries downstream from the LCR, humpback chub in the mainstem would be more likely to encounter olfactory cues that might trigger them to move upstream into the LCR when they reached reproductive maturity.

Translocations into Havasu Creek are intended to establish a secondary reproducing subpopulation, adding demographic redundancy for humpback chub and meeting downlisting or delisting criteria specified in Recovery Goals. While there is compelling evidence that this effort is succeeding there is also concern that the amount of habitat currently available for humpback chub in Havasu Creek is insufficient to maintain a large enough subpopulation, and the BiOp identifies the need to consider translocation further upriver in Havasu Creek. During this workplan, we plan a feasibility study to be led by USFWS, however, in the future, this effort could be used to test various hypotheses about the most effective approaches to translocation (juveniles vs. ripe adults, hard vs. soft releases, timing, etc.).

1. **Proposed Work**

### 4.1. Project Elements

#### Project Element G.1. Humpback chub population modelling

Charles B. Yackulic, Research Statistician, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

Maria Dzul, Fish Biologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

The objectives of this project are to provide better tools to understand the current state of the humpback chub resource (e.g., adult population size) and to predict its future state in response to management decisions. During the FY2015-17 workplan, our work focused on: 1) examining drivers of growth in the Colorado River and LCR (Dzul and others, 2016), 2) development of mark-recapture models to jointly model the dynamics of rainbow trout and humpback chub populations, allowing us to test hypotheses about environmental conditions versus interspecific interactions (Yackulic and others, In Review), 3) using data from the LCR PIT-tag antenna array to quantify the flux of rainbow trout that move into the LCR every winter (Dzul and others, In Review), 4) aiding in analysis of age-0 and age-1 humpback chub abundances in the LCR over the last 15 years (Van Haverbeke and others, in prep.), and 5) collaborating with GCMRC’s economist to develop decision support tools from humpback chub and rainbow trout population models (Project J; Bair et al., in review). In addition, we provide annual estimates of humpback chub abundances for BiOp triggers and helped interpret the recent decline in spring spawner abundance.

In FY2018-20, we plan to: 1) incorporate fish translocated upstream of Chute Falls into population models to assess translocation effectiveness, addressing **H9**; 2) develop new models to understand how food availability, intraspecific densities, and the asynchrony between food availability and temperatures in the CRe interact to affect humpback chub survival, growth and spawning probability, as well as to better understand current trends in adult abundance, addressing **H1 – H4** (this project element may also address **H5-8** using data from the JCM-West project; 3) integrate new forms of portable remote antenna data (including shore-based single antennas in the LCR, and portable remote antennas in the Colorado River) into our population models, helping to address **H3 and H4**; and, 4) analyze drivers of key population processes, especially humpback chub recruitment and outmigration rates to better understand whether trout management is necessary.

#### Project Element G.2, Annual spring/fall humpback chub abundance estimates in the lower 13.6 km of the Little Colorado River

Kirk Young, Fish Biologist, U.S. Fish and Wildlife Service, Arizona Fish and Wildlife Conservation Office

Randy Van Haverbeke, Fish Biologist, U.S. Fish and Wildlife Service, Arizona Fish and Wildlife Conservation Office

Implementation of the BiOp on humpback chub in the CRe requires data on humpback chub adult abundance at the LCR confluence. However, the most efficient way to collect these data is to sample adult humpback chub that spawn during the spring along the lower 13.6 km of the LCR where capture probabilities are much higher than in the mainstem. Fall sampling along the lower 13.6 km of the LCR in turn provides yearly estimates of the abundance of young-of-the-year that have not left the LCR during the monsoon and the best approximation of a long-term dataset of juvenile humpback chub production. Data collected during these trips are all used to estimate spring and fall closed population abundance for various size classes of humpback chub (e.g., 100-149 mm, 150-199 mm, > 150 mm, and > 200 mm total length (TL)), and during some years provides abundance estimates of other native fishes (Van Haverbeke, 2013). The project also marks juvenile humpback chub (< 100 mm TL) with visible implant elastomer (VIE) tags in the fall in conjunction with JCM project (Project Element G.3) to improve our understanding of juvenile humpback chub production and outmigration. Specific objectives for FY 2018-2020 (similar to objectives for previous years) are:

1. Determine length stratified estimates of humpback chub (e.g., >100 mm, ≥150 mm, ≥200 mm) in the lower 13.57 km of the LCR during the spring and fall.
2. Generate a population estimate of age 0 humpback chub (40-99 mm) during fall.
3. Collect data on PIT tagged fish in support of humpback chub population modelling.
4. Collect additional data on fishes in the LCR such as size, species, sexual condition and characteristics, and external parasites (i.e., *Lernaea cyprinacea*).

Modifications to this project element from previous years include continued collaboration with fish biologists from the Navajo Nation, expansion of remote sensing efforts throughout the LCR, and exploration of changes to sampling methods (e.g., extra gear types) that could eventually lead to a single fall trip in future years.

#### Project Element G.3, Juvenile Chub Monitoring near the Little Colorado River Confluence

Mike Yard, Fish Biologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

Charles B. Yackulic, Research Statistician, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

Maria Dzul, Fish Biologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

This project element provides the data to estimate survival, growth and abundance of multiple size classes of humpback chub in the mainstem Colorado River just downstream of the LCR confluence. During FY2018-20, we propose three trips a year (April, June/July and October), down from four trips in prior years. These trip times were chosen based on species life history and to maximize the cost-effectiveness of this project. Trips will use a variety of gear types to sample fish (e.g., hoopnets, portable remote antennae, nighttime electrofishing). The multistate model used to estimate total adult abundances requires data from this project, and total adult abundances are required for triggers associated with the BiOp. This project also allows us to estimate rainbow trout and brown trout (*Salmo trutta*) abundance in this same reach and we plan to use these data, along with data from Lees Ferry, to continue to track the relationship between rainbow trout production in Lees Ferry and rainbow trout abundances near the LCR. Invertebrate drift and fish weights were also collected as part of this project and provided invaluable secondary information for interpreting the decline in spawner abundance in 2015 and 2016 as being caused by declining fish condition due to decreased food availability.

This project element also includes pre-monsoon sampling in the LCR to better understand variation in juvenile production and outmigration – key vital rates that are important for understanding whether pre-emptive rainbow trout management via trout management flows or mechanical removal is needed to meet population targets (Bair and others, In review; Yackulic and others, In Review). Recaptures of VIE-marked humpback chub in the CRe, especially humpback chub marked through the July LCR sampling are crucial to understanding annual survival and movement out of the LCR into the Colorado River. In FY2018-20, we will increase our use of remote antennas (successfully piloted in the Sept. 2016 JCM trip), which can be used to noninvasively sample previously tagged fish, and can be placed in locations where adult fish are more likely to congregate and are difficult to sample through other means.

#### Project Element G.4, Remote PIT tag array monitoring in the Little Colorado River

Maria Dzul, Fish Biologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

Kirk Young, Fish Biologist, U.S. Fish and Wildlife Service, Arizona Fish and Wildlife Conservation Office

Bill Kendall, U.S. Geological Survey, Colorado State University

Dana Winkelman, U.S. Geological Survey, Colorado State University

Charles B. Yackulic, Research Statistician, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

The objectives of this project are to provide data to track the timing of the annual humpback chub spawn, test hypotheses about trap avoidance, and inform our population model. The antennas read and record PIT-tag codes from marked fish along with a date/time for each reading, as tagged fish pass near antennas anchored to the river bottom or river bank. The value of this form of monitoring was clear in 2015, when we were able to rule out the hypothesis that decreased spawning abundance was due to sampling having missed the actual spawn. Starting in spring 2017, we are piloting shore-based antennas placed at natural pinch points in the LCR as an alternative to the current cross channel PIT-tag antenna arrays. The antennas are less expensive and we are optimistic they will provide as good or better data. During the pilot study we have placed six single antennae in the river at strategic locations (as compared to the 12 antennae used in the current arrays), and we are planning power analyses to determine whether we can use fewer antennae (e.g., 3 or 4).These data can be used within population models as well as to provide information on timing of movement and survival of PIT-tagged native fishes and in FY18-20, we will be developing population models that more fully incorporate the data provided by these antennas.

#### Project Element G.5, Monitoring humpback chub aggregation relative abundance and distribution (\*partially funded – fully fund if possible)

Kirk L. Young, Fish Biologist, U.S. Fish and Wildlife Service

Randy Van Haverbeke, Fish Biologist, U.S. Fish and Wildlife Service

Michael Dodrill, Fish Biologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

Brian Healy, Fish Biologist, National Park Service, Grand Canyon National Park

Aggregations of humpback chub in Grand Canyon are biologically important because they potentially provide redundancy and resiliency for the species. Annually monitoring of the status and trends of humpback chub aggregations and conducting periodic surveys in between aggregations to identify additional aggregations and individual humpback chub are Conservation Measures listed in the BiOp. This project will conduct one mainstem sampling trip per year focused on aggregations. The annual aggregations trip will focus on hoop net monitoring the known aggregations (e.g., RM 30-36, LCR, Bright Angel, Shinumo, Stephens Aisle/Middle Granite Gorge, Havasu, Pumpkin Springs). The primary objective of this annual trip will be to continue a long term CPUE index that has been constructed since the early 1990s (Persons and others, 2017). Portable PIT-tag antennas will also be utilized to detect tagged fish, providing additional information on humpback chub, while reducing handling of fish.

If funding is available, it will be a high priority to also have one additional trip every three years to focus on new aggregations (monitoring in between aggregations as specified by the BiOp). The additional trip to monitor areas outside aggregations will be conducted to maintain a CPUE index in between the aggregations, and search for additional aggregations. If funding is available, we also propose to conduct a seining trip each year. This seining trip would provide information on the distribution and relative abundance across a large geographical extent of Grand Canyon, which is becoming much more important given the expansion of humpback chub in western Grand Canyon. The objective of these trips will be to annually sample all backwaters throughout Grand Canyon for relative abundance of juvenile humpback chub and other native species. Besides native fishes, these trips can provide for effective early detection of aquatic invasive species (AIS) since if spawning of rare AIS occurs, it is most likely their juveniles will first be detected in backwaters where detection probabilities are higher (Dodrill and others, 2015).

#### Project Element G.6, Juvenile Chub Monitoring - West

Mike Yard, Fish Biologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

Charles B. Yackulic, Research Statistician, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

In recent years, catch in humpback chub aggregations in the western Grand Canyon have increased dramatically, but current sampling is insufficient to determine drivers. This project is designed to gain a better understanding of drivers of population dynamics, as well as environmental factors that drive variation in capture probabilities. Understanding the drivers of, and developing rigorous population estimates for, aggregations outside the LCR are identified as needs within the BiOp. Furthermore, the 2016 fisheries PEP specifically recommended additional study in the lower part of the CRe. If drivers are significantly different in the lower part of the river, this may provide redundancy as dynamics will be asynchronous. Furthermore, many of our a priori hypotheses (**H5-H8**) about why dynamics could be different in the lower part of the CRe have significant implications for dam management. One lesson from the NSE study (the precursor to the JCM project) is that six or more days of sampling are required to estimate capture probabilities (and abundance) for humpback chub. In 2017, we are planning a pilot study to determine the best location for JCM-West with three potential sites currently being considered (Havasu: RM 158-167, Parashant: RM 198-205, and Pumpkin Spring: RM 210-217). Sampling will occur during the same trips as JCM (April, June/July, and October) and use the same sampling methods (with the addition of seining) as are currently employed as part of the JCM project.

#### Project Element G.7, Infrared radar cameras (\*fund if possible)

David Ward, Fish Biologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

Handheld forward looking infrared radar (FLIR) cameras will be used to thermally image the Colorado River and identify warm springs within the mainstem that may be correlated with increased humpback chub catch rates. Thermal imaging cameras have been used to map groundwater inputs and temperature distributions in other Arizona streams and have been shown to be effective at identifying and mapping the extent of warm-water springs at RM 30 within Marble Canyon. This relatively low-cost tool will allow identification currently unknown warm water inputs within the Colorado River that may provide important thermal refuges for humpback chub.

#### Project Element G.8, Spatial analysis of ripe fish

David Ward, Fish Biologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

To better understand spawning of humpback chub, we will collect from 2000 through the present along with existing high resolution habitat data from the LCR. Our work will also establish a methodology for linking habitat data to existing long-term fish data, which are already maintained by the GCMRC and may be directly applied to other fish species. Understanding the habitat conditions in which ripe humpback chub are typically caught may help us understand why juvenile production varies so much between years (e.g., if pools that are frequently used are filled in with sediment during years of poor production).

#### Project Element G.9, Chute Falls translocations

Kirk Young, Fish Biologist, U.S Fish and Wildlife Service, Arizona Fish and Wildlife Conservation Office

Translocation and monitoring of humpback chub upstream of Chute Falls has been in place as a conservation action in BiOps since 2002 (USFWS 2002, 2011, 2016). We propose to continue translocating juvenile humpback chub to upstream of Chute Falls on an annual basis and to continue annually monitoring them. To date, approximately 3,106 juvenile humpback chub have been translocated upstream of Chute Falls. In conjunction with translocation activities of humpback chub upstream of Chute Falls, we work collaboratively with Southwest Native Aquatic Resources and Recovery Center at Dexter, NM to maintain a long term genetic refuge of humpback chub, and work collaboratively with NPS to provide juvenile humpback chub for translocation activities into Shinumo and Havasu Creeks.

#### Project Element G.10, Havasupai translocation feasibility

Kirk Young, Fish Biologist, U.S Fish and Wildlife Service, Arizona Fish and Wildlife Conservation Office

We propose to first coordinate with the Havasupai Nation about the concept of translocating humpback chub to upstream of Beaver Falls in Havasu Creek. If the Havasupai Nation is supportive, we will work with the tribe to implement surveys and develop feasibility and objective-driven action plans. This project is listed as a conservation action in the LTEMP BiOp (U.S. Fish and Wildlife Service, 2016).

***Project Element G.11, Imprinting study***

David Ward, Fish Biologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

The objective of this project element is to assess whether thyroid induced olfactory imprinting occurs in humpback chub and if it does occur, determine the timing of imprinting. This information can then be utilized to make existing translocation efforts more effective. If humpback chub imprint on chemical cues of their natal stream as larvae then translocated fish may not remain where they are placed once they reach reproductive maturity. Many of these fish may instead attempt to return to the LCR to spawn, thereby reducing the likelihood of establishing additional spawning populations and meeting downlisting or delisting criteria. It is therefore critical to understand if humpback chub imprint on their natal stream of origin as larval fish. Other native fishes of the Colorado River such as the Colorado pikeminnow (*Ptychocheilus lucius*) and Razorback sucker (*Xyrauchen texanus*) imprint on chemical cues at natal spawning areas and return to those areas as adults to spawn ((Irving and Modde, 2000; Scholz and others, 1991). Surges in thyroid hormones have been shown to be good indicators of imprinting in a variety of fish species (Hasler and Scholz, 1983; Morin and others, 1989). We propose to determine if humpback chub experience thyroid-induced olfactory imprinting by measuring levels of the hormone thyroxine (T4) in developing humpback chub eggs and larvae obtained from captive reared hatchery specimens. Understanding imprinting in humpback chub will help managers to determine the metapopulation dynamics of humpback chub in Grand Canyon and may help to explain why the LCR is the only place in Grand Canyon where larval and juvenile humpback chub are consistently found. Eggs and larvae will be collected at daily intervals from the date of fertilization until 20 days post-fertilization and then at 7-day intervals until 70 days post fertilization. Three samples containing 10 eggs or larvae will be collected at each interval. Mean T4 concentration of each sample of eggs or larvae will be assayed to determine when T4 levels peak as an indicator of time of imprinting. Thyroxine will be extracted from eggs using methods described in (Scholz et al.Thyroxine will be extracted from eggs using methods described in (Scholz and others, 1991) where eggs or larvae are minced, mixed with ice-cold ethanol, homogenized, centrifuged and frozen at -80 °C until T4 can be extracted and concentrated using radioimmunoassay. Samples will be assayed for T4 content using a Coat-a-Count T4 Radioimunoassay kit (Diagnostic Products Inc.) which utilizes a procedure based on competitive binding. Concentrations of unknown samples will be determined using a gamma counter to compare bound fractions of T4 to a standard curve with known concentrations of T4 subjected to the same assay procedures. These methods will allow researchers to assess whether or not thyroid induced olfactory imprinting is occurring in humpback chub and the timing of imprinting if it does occur.

***Project Element G.12, Genetics study (\*fund if possible)***

Wade Wilson, U.S. Fish and Wildlife Service, Southwestern Native Aquatic Resources & Recovery Center (SNARRC), Dexter, New Mexico

Kirk Young, Fish Biologist, U.S. Fish and Wildlife Service, Arizona Fish and Wildlife Conservation Office

Randy Van Haverbeke, Fish Biologist, U.S. Fish and Wildlife Service, Arizona Fish and Wildlife Conservation Office

Previous genetic work has suggested that humpback chub downstream from the LCR were clearly connected with the LCR population by gene flow. However, contribution from occasional local reproduction by mainstem aggregations could not be excluded, because sample sizes from each of the aggregations were small. To date, this is the only baseline genetics data that researchers have concerning mainstem aggregations of humpback chub in Grand Canyon. Since this study, annual population has shown that the number of individuals within each aggregation has increased substantially allowing for an opportunity to re-examine population genetics (diversity, population structure, effective size, etc.) among aggregations. An analysis of genetics is currently occurring and if this analysis suggest a need for more work, and if funding is available, we propose additional genetic analysis in FY2018-20.

### 4.2. Deliverables

The work described here will lead to multiple peer-reviewed publications (e.g., research from similar projects in the last triennial workplan led to eight manuscripts that have been published or are in review), as well as annual reports and presentations to the GCDAMP. This project will also provide estimates of quantities relevant to the BiOp at regular intervals.

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1. **Budget**
2. 
3. 
4. 

Project H. Salmonid Research and Monitoring

1. **Investigators**

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1. **Project Summary**

Protection of the endangered humpback chub (*Gila cypha*) near the Little Colorado River is one of the highest priorities of the Glen Canyon Dam Adaptive Management Program (GCDAMP), but a concurrent priority of the GCDAMP is to maintain a high quality rainbow trout *(Oncorhynchus mykiss)* sport fishery upstream of Lees Ferry in Glen Canyon. As such, rainbow trout were an important component in the development of the Long Term Experimental and Management Plan Environmental Impact Statement (LTEMP; U.S. Department of the Interior, 2016b) on Glen Canyon Dam operations, and thus were a major consideration in the flow decisions in the selected alternative in the Record of Decision (ROD; U.S. Department of the Interior, 2016c). 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 humpback chub population downstream. However, ecosystems are dynamic and there has been a large increase in brown trout (*Salmo trutta*) recruitment upstream of Lees Ferry over the past few years (Yard, *unpublished data*). 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.

A major component of the proposed study elements herein focus on how experimental flows will influence recruitment, growth, survival, and dispersal of rainbow trout in Glen and Marble Canyons. However, management of the rainbow trout fishery cannot occur in a vacuum given the recent increase in brown trout in Glen Canyon. Small numbers of brown trout have been present in the canyon since the dam was built but have increased following a time period associated with frequent fall-timed high flow experiments (HFEs). It is currently unclear whether this relationship is causal or coincidental, but research is needed to examine if the proposed flow manipulations help or hinder the expansion of brown trout. Brown trout are superior competitors in other tailwater systems, are typically not stocked past their initial introduction (Dibble, *unpublished data*), and are known to be voracious predators of small-bodied native fishes (Yard and others, 2011). It is therefore prudent and necessary to not only evaluate the effect of experimental flows on rainbow trout, but also to examine how brown trout populations may respond to such flow manipulations.

This proposal utilizes a combination of field, modeling, and laboratory techniques to evaluate the response of trout to experimental flows including Trout Management Flows (TMFs), HFEs, equalization flows, and Macroinvertebrate Production Flows (MPFs). Project Element H.1 capitalizes on knowledge gained from the Natal Origins of Rainbow Trout (NO) and Rainbow Trout Early Life Stage Studies (RTELSS) projects funded in GCDAMP’s FY2013-14 and FY2015-17 work plans. This project proposes a consolidated study design focused on juvenile and adult trout captured during quarterly mark-recapture trips combined with monthly spring-summer trips to evaluate early life-history stages. This project aims to gain a better understanding of the effects of experimental flows on rainbow trout and brown trout recruitment, growth, survival, dispersal, and movement from Glen Canyon Dam to the Little Colorado River confluence. Project Element H.2 develops a rainbow trout recruitment and outmigration model that predicts the response of rainbow trout to alternative flows and physical conditions in the Colorado River Ecosystem (CRe). This model can be used to evaluate the ability of alternative monitoring designs to detect rainbow trout responses to LTEMP flow alternatives. Project Element H.3 uses information on vital rates contained within young-of-year (YOY) rainbow trout and brown trout otoliths to improve recruitment models, identify when brown trout are most vulnerable to flow manipulation, and assess the physiological response of brown trout to different types, durations, and timing of experimental flows, which is data that can be used to manage this nonnative species. Finally, Project Element H.4 extends the Arizona Game and Fish Department (AGFD) long-term monitoring of rainbow trout in Lees Ferry and launches a new citizen science program to gather data on angler catch quality in combination with ongoing creel surveys in a cost-effective way. Collectively, these four projects aim to resolve critical uncertainties about the response of rainbow trout and brown trout to experimental flows proposed in the LTEMP that are now the basis for its associated ROD (U.S. Department of Interior, 2016c).

1. **Background**

The LTEMP and ROD identified flow manipulations including TMFs, spring and fall-timed HFEs, MPFs, and equalization flows as potential policy levers to decrease rainbow trout recruitment (and thereby dispersal) while increasing humpback chub abundance near the Little Colorado River (U.S. Department of the Interior, 2016b). TMFs were designed to limit rainbow trout recruitment in Glen Canyon with the intent of reducing boom-and-bust cycles in the Lees Ferry fishery and limiting dispersal of rainbow trout from Glen Canyon to the Little Colorado River. The ROD also imposed a two-year moratorium on spring-timed HFEs because the 2008 spring HFE appeared to produce a large number of rainbow trout recruits in Glen Canyon (Korman and others, 2011), some of which may have dispersed downstream following this event (Korman and others, 2012). Fall HFEs will likely be the most common experimental flow under the new ROD, but there are concerns from the angling community that these types of experimental floods reduce the aquatic food base during the fall season, a period when trout growth is already low, having negative effects on the population and fishery. Additionally, MPFs were identified as an alternate flow regime in the ROD that could be used to enhance the aquatic food base and increase growth rates of rainbow trout in Glen Canyon as well as native species downstream.

While the above flows have influenced, or have the potential to influence, rainbow trout recruitment, it is unclear how such flows will influence brown trout populations. Brown trout are associated with a high incidence of piscivory (Yard and others, 2011) and also compete with nonnative and native fish species (Hearn, 1987; Kaspersson and others, 2013), so their recent expansion poses a significant threat to the rainbow trout fishery and likely to endangered humpback chub populations that reside in and near the Little Colorado River. In the past, management actions have included labor-intensive mechanical removal of brown trout at the Little Colorado River confluence (Mueller, 2005; Yard and others, 2011) and in Bright Angel Creek (Makinster and others, 2010). However, the high abundance of YOY brown trout in Glen Canyon may require management actions to reduce recruitment before the recruits become reproductively mature adults.

Changes in flow velocity, magnitude, duration, and timing of Glen Canyon Dam operations designed in the LTEMP to manage rainbow trout populations may also be used as tools to manage brown trout recruitment and survival since flows can be scheduled to occur when the species is in their most vulnerable life history stage. A recent synthesis of brown trout data from regulated rivers across the western US found that brown trout recruitment is inversely related to flow velocity (Dibble and others, 2015), which may be due to energetic constraints imposed by high flows. Data from other tailwaters indicate that natural flooding events, similar to HFEs released from Glen Canyon Dam, can have a significant negative effect on brown trout populations. Winter-timed floods can decrease recruitment by scouring eggs and alevins from gravel redds (Strange and Foin, 1999; Wenger and others, 2011), while spring-timed floods can decrease survival following emergence via energetic constraints (Cattanéo and others, 2002; Budy and others, 2008; Jonsson and Jonsson, 2009). While fall-timed HFEs have occurred concurrently with the increase in brown trout recruitment, there is no causal link between the two phenomena. Therefore it is essential that the influence of different types of flows in the selected alternative be evaluated on behalf of both rainbow trout and brown trout in the FY2018-20 work plan. The project elements proposed herein are driven by five overarching research questions that stem from previous research funded in the FY2013-14 and FY2015-17 GCDAMP work plans. Although the majority of the supporting research for these questions stems from investigations of rainbow trout, the questions apply equally to brown trout.

1. **What are the effects of TMFs on trout survival, recruitment, growth, and dispersal?**

TMFs are designed to flood and strand YOY trout in low angle shorelines and induce mortality by rapidly dropping water levels. Since it is unclear the extent to which TMFs will reduce recruitment, this project broadly focuses on the following questions: 1) what proportion of total recruits are vulnerable to stranding and mortality in low angle shorelines; 2) what is the relationship between aerial coverage of low angle shoreline and discharge levels; 3) will survival rates of YOY trout increase following a TMF, thereby partially or fully compensating for direct losses of trout during the TMF; and 4) will TMFs unexpectedly trigger a downstream dispersal event? Therefore, we propose to monitor YOY trout survival (Project Element H.1), recruitment (H.1, H.2), growth (H.3), and downstream dispersal (H.1, Project G) in years with and without TMFs to address these critical uncertainties.

1. **What are effects of spring and fall HFEs on trout recruitment, dispersal, and growth?**

An increase in the growth rate and recruitment of YOY trout in Glen Canyon was observed following the 2008 spring HFE and was attributed to an increase in food availability (Korman and others, 2011). However, it is uncertain whether future spring HFEs will produce a similar response because the 2008 observation was a single, unreplicated event and antecedent conditions at the time of the spring HFE may have been unique (e.g., low trout abundance, higher nutrient availability due to equalization flows). Therefore, if spring HFEs are implemented, we propose to include higher resolution monitoring to detect change in trout populations (Project Element H.1).

The effects of fall HFEs on rainbow trout in Glen Canyon are uncertain even though there have been five fall HFEs conducted to date (2004, 2012–2014, 2016). Mark-recapture data from the NO project clearly shows that fall HFEs do not lead to increased downstream movement (Korman and others, 2015). Additionally, there is some indication that fall HFEs can reduce growth rates of adult trout during late fall and winter in some years (e.g. 2014) but not in others (2016), but results are confounded by strong inter-annual and seasonal variation in growth. Therefore, additional monitoring of trout growth before and after fall HFEs may resolve uncertainties about their effects on trout growth. Further, evidence indicates fall HFEs reduce adult fish growth during fall and winter, which in turn reduces their rate of sexual maturation and fecundity (Korman and Yard, 2017). Therefore, additional monitoring is proposed to examine how adult growth following a fall HFE influences sexual maturation, fecundity, and, by extension, recruitment the following year (Project Element H.1).

1. **What controls the number of trout that disperse from Glen Canyon into Marble Canyon, and the quantity reaching the Little Colorado River?**

The LTEMP model used to simulate rainbow trout movement from Glen Canyon Dam to the Little Colorado River assumed that trout dispersal was a constant proportion of recruitment, and that trout residency in Marble Canyon was constant through time (U.S. Department of the Interior, 2016b). However, NO project data collected from 2011-2016 (which were not available for LTEMP modelling) suggest otherwise. These data indicate that: 1) large numbers of YOY trout disperse from Glen Canyon to the upper and middle portions of Marble Canyon in the summer and fall; 2) trout in Marble Canyon then become the source of trout at the Little Colorado River over the next 1-5 years (Yard and others, 2015; Korman and Yard, unpublished data); and 3) prolonged conditions with clear water and high nutrients will maintain large populations of trout in Marble Canyon which in turn will lead to longer periods of high trout abundance at the Little Colorado River (Yackulic and others, in review). Therefore, we propose to continue evaluating trout dispersal out of Glen Canyon and monitoring trout population dynamics in Marble Canyon and near the Little Colorado River confluence in conjunction with humpback chub monitoring (Project Element H.1, Project G).

1. **What controls the quality of the trout fishery?**

There is consensus that the quality of the Lees Ferry fishery depends on growth rates of rainbow trout and the number of juvenile trout that recruit into the adult population, which are then targeted by anglers. The LTEMP trout model assumed that fish growth was inversely related to density, and that flow was the only factor that influenced recruitment (U.S. Department of the Interior, 2016b). More recent findings indicate that greater food availability during the spring and summer leads to better growth of juvenile rainbow trout and higher recruitment (Korman and others, 2011; Korman and others, 2015; Yackulic, unpublished data). There is also increasing evidence that nutrient availability (specifically soluble reactive phosphorus, SRP) plays an important role in recruitment and adult trout growth. These findings identify deficiencies in the LTEMP trout model because they indicate that: 1) factors other than flow can have important effects on recruitment; and 2) interannual and seasonal variation in nutrients may be a more important determinant on growth than density as assumed in the LTEMP model. Resolving this uncertainty about growth is critical with respect to managing the Lees Ferry fishery. Therefore, we propose to continue studying trout growth and recruitment in relation to both top-down and bottom-up factors such as fish density, nutrient availability (SRP), and the prey base to identify key factors that promote a high quality trout fishery in Lees Ferry (Project Elements H.1, H.2, H.3, H.4, Projects F, E).

1. **What factors regulate brown trout population dynamics in Glen Canyon, and if control measures are implemented, what is the efficacy of those management actions?**

As mentioned above, it is unclear what factors led to the recent increase of brown trout abundance in Lees Ferry, and another unknown is the efficacy of various flow and non-flow control options. Should tagging and release of brown trout be permitted by the National Park Service (NPS), we will estimate state variables and vital rates of this aquatic invader to inform future management actions, whether they be flow or non-flow related (Project Element H.1). If managers decide to proceed with a mechanical removal effort, all brown captured from the proposed effort could be removed, which could remove ~18% of the brown trout population each year (Project Element H.1). Removal efforts, if approved, would be coordinated with otolith microstructural analysis to examine hatch and emergence dates to improve experimental flow timing in the future (Project Element H.3). Further, physiological data can be used to gauge the effectiveness of experimental flows on brown trout growth and condition which may, in turn, influence survival and cohort strength the following year (Project Element H.3). Additionally, routine monthly monitoring of nonnative fish by AGFD during the summer and fall (Project Elements I.2 and H.4) will provide a general estimate of population trends using catch-per-unit-effort (CPUE) data. Collectively, the sampling effort proposed herein will improve our understanding of the population dynamics and efficacy of control options for brown trout in Glen Canyon.

1. **Proposed Work**

### 4.1. Project Elements

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

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The overarching goal of this study element is to determine the effects of LTEMP ROD flows on the recruitment of YOY rainbow trout in Glen Canyon, the growth rate of juveniles and adults, and dispersal of YOY trout from Glen Canyon. Another central objective of this study is to increase our understanding of the key factors that control the abundance and growth of the Glen Canyon trout population. This improved understanding could lead to the identification of other policies that could benefit the Lees Ferry fishery and limit the downstream dispersal of rainbow trout to the Little Colorado River, as well as controlling brown trout should this species become more established in Glen Canyon. Although monitoring programs are important for documenting population characteristics (e.g., abundance, size distribution, and occurrence) and trends, monitoring as a sole method of data collection is not a very effective approach in time or cost for determining causation, particularly when quantifying and separating out effects from complex interactions that occur among multiple factors. In order to study multiple flow treatments and avoid potential confounding effects, we propose to use a seasonal sampling design with spatial replication to determine trout responses to experimental flows within and across years.

Specifically, the proposed project will evaluate:

1. The effect of TMFs on recruitment and dispersal.
2. The effects of higher and potentially more stable flows in spring and summer during equalization events on recruitment, growth, and dispersal.
3. The effect of fall HFEs on recruitment of trout in Glen Canyon, 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).
4. The effect of spring HFEs on recruitment, growth, and dispersal.

The proposed study design combines two main study elements into a single overall project that evaluates all stages of the trout life cycle, these project elements are: 1) Trout Reproductive and Growth Demographics (TRGD); and 2) Trout Early Life Stage (TELS). Both of these elements are entwined, thus for maintaining context we describe the sampling and analytical methods used together. The first element, TRGD, would be similar to the NO effort in Glen Canyon, but is restricted to quarterly sampling periods where juvenile and adult trout are sampled in two reaches to reduce trip length and cost (i.e., selected reaches consist of both low-angle and high-angle shoreline). The modelling and other analytical approaches for this element have already been developed which helps avoid costs associated with model development (Korman and Yard, 2017). The second element, TELS, focuses on sampling early life stages of trout on a monthly basis during the spring-summer period in these same reaches to understand how flow regimes, and in particular TMFs, influence recruitment. This element will use existing methods established for the RTELSS project (Korman and others, 2011; Avery and others, 2015) as well other enhanced methods (Korman and others, 2009).

For the TRGD study element, fish sampling will be conducted in two 3-km reaches representing rainbow trout populations in the upper, middle, and lower portions of Glen Canyon by using boat-mounted electro-shockers (200–250 V, 20–25 A, pulsed DC). As previously mentioned, brown trout will also be sampled; however, estimates of state variables and vital rates will only occur if the tagging and release of brown trout is allowed by NPS. Each of these reaches will be sampled four times per year in October, January, April, and July. Over the next three years of the FY18–20 work plan, a total of twelve five-day trips will be conducted. The scheduling of these trips is organized around the timing of anticipated LTEMP flow experiments and in particular fall HFEs, which will be the most common experimental flow. Growth between October-January and January-April trips will represent post-HFE conditions in years when HFEs are conducted. Growth over those periods when HFEs are not conducted will form the experimental controls to compare growth rates in years when HFEs are conducted. We will conduct mark-recapture by tagging rainbow trout ≥ 75 mm (fork length) with passive integrated transponder (PIT) tags in each of the two reaches on the four main trips (October, January, April, and July). These data will be integrated into an open population model to estimate abundance, recruitment, and growth in each reach for trout ≥ 75 mm. The TRGD PIT-tag effort provides an annual estimate of recruitment based largely on catches during July, October, and January trips, but provides no details on whether that recruitment was influenced by a TMF. For example, a low estimate of recruitment in fall in a year when a TMF was conducted could have occurred because: 1) recruitment was poor in that year, and the TMF had no effect; or 2) recruitment was high in that year, but the TMF was effective at reducing it. Measuring recruitment as an end point in the fall via the TRGD PIT-tagging effort (or by sampling with catch-per-unit effort methods) cannot separate these alternatives without the TELS study element.

The TELS study element of this proposal has led to significant changes being made to the sampling structure of the past RTELSS program (Korman and others, 2011; Avery and others, 2015). We propose to continue with redd surveys. They provide a measure of spawning activity that can be related to estimates of trout abundance, fecundity, and rates of sexual maturation as determined by the TRGD study element of this project. If reduced growth leads to reduced spawning activity, this should be evident in the count of all detectable redds. Bi-monthly redd surveys will be made from December through May. This provides a means to test our hypothesis that reduced adult growth can ultimately lead to reduced recruitment as we think occurred in 2015 (Korman and Yard, 2017).

We also propose to move all of the TELS sampling sites into the same two study reaches (the past RTELSS sites were small in size [30–50 m lengths] and broadly distributed throughout Glen Canyon). Both backpack and boat-mounted electro-shockers are to be used in sampling both YOY of rainbow trout and brown trout. A total of five TELS trips will be conducted annually between May and September, focused on early life stages, which are required for a detailed assessment of TMFs (i.e., the TRGDs quarterly sampling trip will also collect data on YOY in July for purposes of integrating independent estimates). For TELS mark-recapture, visual implant elastomer (VIE) tags will be used for marking small fish (40-74 mm). These trips would also be five days in length but would be cheaper owing to much reduced crew and logistic requirements. In each of the two reaches, spatially referenced sites will be continuously distributed on the left and right bank and cover a total of 1 km of shoreline on each side. These 1-km sections will be selected so that a low-angle shoreline is present on one side and a high-angle shoreline on the other. The TELS monthly sampling effort provides before- and after-TMF estimates of YOY abundance and can therefore directly measure the mortality caused by the TMF. Even if TMFs cause significant mortality, potential compensatory survival responses following the TMF could lead to little change in the final recruitment for that year as measured in the fall. Thus the TRGD PIT-tagging based estimate of recruitment is also needed to determine if higher mortality from the TMFs as measured by the TELS component of the study ultimately translates into lower recruitment (as determined by the TRGD study element). For the small trout < 75 mm, these data will also be integrated into an open population model to estimate abundance, recruitment, growth, and survival in each reach.

This design also offers a number of advantages: 1) the continuous sites allow us to conduct more effective mark-recapture of all stages of the trout life cycle. The RTELSS study assumed that capture probabilities are constant across all trips (Avery and others, 2015), and this has led to some problems in the past that the newer TELS approach will avoid; 2) we expect TMFs to be more effective in low-angle shorelines than steep ones because small fish are hypothesized to more likely be stranded in the former shoreline type. Comparing the trends in populations between May and September in years when TMFs are conducted provides a rigorous evaluation of TMF effects (which will be replicated in two reaches); and 3) by having TRGD PIT-tag estimates of recruitment in the same location where TELS estimates of abundance are obtained, we will be able to integrate both independent sets of results into the same open population model. That is, data from both efforts will be used to provide more robust and consistent estimates of how flow is effecting survival and recruitment of YOY trout.

Lastly, one of the key objectives of TMFs is to reduce dispersal of YOY trout from Glen Canyon into Marble Canyon. It is likely that small trout move downstream and repopulate Marble Canyon during years when the Lees Ferry fishery has large recruitment events. The downstream movement of small trout appears to be governed by high densities and growth conditions in Glen Canyon (Yard and others, 2015). It is therefore critical to quantify dispersal in both TMF and non-TMF years to determine if this objective is being met. The House Rock reach (17.3-19.5 river miles downstream from Lees Ferry) rarely detects YOY trout in the electrofishing catch because channel morphology and hydrology are not considered suitable for trout reproduction. Similar data from 2016 from the NO effort showed no YOY in upper and middle Marble Canyon in July but significant numbers in September. In contrast, YOY were abundant in Glen Canyon on both July and September trips. This pattern shows that movement of YOY from Glen Canyon occurred in 2016 sometime between July and September. This reach is therefore ideal for monitoring the influx of recruits migrating to and repopulating Marble Canyon. This provides a means to test the assumption underlying the LTEMP model for trout recruitment. This can be accomplished relatively easily based on a comparison of length frequencies in Glen Canyon and Marble Canyon on July and October trips conducted on the JCM mainstem trips (Project G). This design is very similar to what was done under the NO project. Growth between April-July trips and July-October trips will be used to quantify conditions during the high growth period which are potentially affected by spring HFEs, TMFs, and inter-annual trends in nutrient concentrations in flow from Glen Canyon Dam. Growth over these periods in years when such flows are conducted can be compared to those when they are not. The logistical cost is not included in this proposal but is identified here due to the linkage between this project and the JCM project.

This study will contribute to a better understanding of other factors affecting trout dynamics in Glen Canyon which in turn may be controlled by flow and ROD experiments. This study will measure seasonal variation in the growth of trout in Glen Canyon. Drift rate measurements taken on each trip will be used to better define the relationship between trout growth and drift rates (Project F). We will also relate estimates of trout growth to gross primary production and nutrient levels (Project E). These integrated efforts will provide insights on the mechanism by which flow and non-flow factors (e.g. nutrients, primary production) control the trout population.

***Project Element H.2, Rainbow Trout Recruitment and Outmigration Model***

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Michael Dodrill, Fish Biologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

The objectives of this project element are to: 1) develop a rainbow trout recruitment/outmigration model which can be updated annually based on ongoing monitoring and research under various hypotheses of drivers (e.g., flow, nutrients, rainbow trout densities, etc.) and used to predict the response of rainbow trout to alternative flows and physical conditions; and 2) use this model to evaluate the ability of alternative monitoring designs to detect rainbow trout responses to LTEMP ROD flow alternatives.

The ability to predict the strength of rainbow trout recruitment and outmigration relative to management alternatives outlined in the LTEMP Biological Opinion (U.S. Department of Interior, 2016a) is of central importance to effective management of multiple resources in the CRe. Flow alternatives outlined in LTEMP include TMFs, HFEs and MPFs, which may directly or indirectly effect the rainbow trout population in Lees Ferry. TMFs are designed to increase mortality of YOY rainbow trout, by stranding a portion of the population in low-angle shorelines with the aim of decreasing recruitment and ultimately outmigration. Outmigration of rainbow trout from Lees Ferry to downstream areas, particularly near the Little Colorado River confluence, is seen as detrimental to native fish conservation goals. Although the overall emigration rate is small, large recruitment events can lead to increased outmigration (Korman and others, 2015). HFEs and other flows, such as equalization flows, may indirectly effect the rainbow trout population, via increased YOY habitat or increased food availability. For example, large numbers of recruits were observed following years with spring-timed HFEs or higher than average equalization flows, likely driven by increased juvenile survival and growth, resulting from increased food availability or habitat (Cross and others, 2013; Kennedy and others, 2014; Avery and others, 2015). MPFs are designed to improve insect production, which will likely benefit rainbow trout, but may also benefit humpback chub downstream. Assessing the potential tradeoffs associated with MPFs requires an understanding of effects on both rainbow trout outmigration and humpback chub dynamics downriver. Releases from Glen Canyon Dam under the LTEMP flow alternative may influence rainbow trout recruitment and outmigration and monitoring these responses has a large bearing on the effective management of resources in the CRe.

Other non-flow factors, including nutrients and trout density likely also play an important role in determining recruitment and outmigration, but have been subject to much less investigation (but see Project E). Variation in the concentration of nutrients (especially phosphorous) correlates to variation in invertebrate drift and initial analysis of recruitment over the last fifteen years suggests that concentrations of soluble reactive phosphorous (SRP) is the single best predictor or rainbow trout recruitment (Yackulic, *unpublished data*). Across many western tailwater fisheries, the density of conspecifics can influence growth and other aspects of population dynamics (Dibble and others, 2015). For instance, intraspecific competition for invertebrate drift may increase under higher trout densities, decreasing growth rates and playing a role in both recruitment and outmigration dynamics.

The annually updatable recruitment and outmigration model will be used to test hypotheses related to different factors including both flow and non-flow factors. The model is designed to integrate data from different research and monitoring schemes including long-term catch per effort, RTELSS, NO, and the proposed monitoring scheme (Project Elements H.1, H.4). The model can also be used to determine the statistical power of different monitoring schemes to detect effects of different flow experiments. For example, under one monitoring scheme it may be necessary to repeat a particular flow experiment three times to detect a 50% increase in recruitment 90% of the time, whereas another monitoring scheme may require repetition of a flow experiment six times to have the same statistical power of detecting a 50% increase in recruitment. Quantifying statistical power in this management relevant fashion should aid in illustrating the strengths and weaknesses of alternative monitoring strategies to detect changes in rainbow trout recruitment. This effort can be used to guide future sampling designs, ensuring that sampling methodology is adequate to measure rainbow trout recruitment responses to LTEMP flow alternatives.

***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***

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Mike Yard, Fish Biologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

Josh Korman, Fish Biologist, Ecometric Research, Inc.

Charles Yackulic, Research Statistician, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

The objective of this research is to fill critical information needs pertaining to trout early life-history strategies and growth and condition responses to experimental flow manipulation to inform management of brown trout and rainbow trout in Glen Canyon. In this project YOY otoliths will be used to examine: 1) rainbow trout early life history vital rates to inform recruitment models; 2) brown trout hatch and emergence dates to inform the timing of experimental flows; and 3) the immediate physiological response of brown trout to HFEs and TMFs, including variations in responses due to flow timing and duration. Results will identify when brown trout are most vulnerable to flow manipulation to develop tools to manage this aquatic invader.

The LTEMP and its associated ROD identified flow manipulation as a potential tool to regulate rainbow trout recruitment and enhance endangered humpback chub populations in Grand Canyon. In the past, the RTELSS project collected data on vital rates and monitored the response of rainbow trout to nonnative fish suppression flows (2003–2005), equalization flows (2011), and spring and multiple fall-timed HFEs (2008, 2011-2014, 2016; Korman and others, 2011; Avery and others, 2015). Vital rate data has provided a more mechanistic understanding of downstream emigration events and population-level changes in adult rainbow trout in Grand Canyon (Korman and others, 2011; Korman and others, 2012; Melis and others, 2012), so we propose to continue collecting monthly rainbow trout early life history information from May to September in FY2018-20 in conjunction with the TELS project (Project Element H.1).

Although the RTELSS program has provided useful information pertaining to the response of YOY rainbow trout to flow manipulation, this information is not necessarily analogous to brown trout since the two species have different life history strategies (fall spawning brown trout, spring spawning rainbow trout). Since we lack basic life history data for YOY brown trout in Glen Canyon, we propose to determine brown trout hatch and emergence dates via back-calculation using brown trout otoliths (Korman and others, 2011). YOY brown trout will be collected monthly from May through September in collaboration with the TELS project, with additional specimens collected during TRGD sampling in October, January, and April or during AGFD trout monitoring trips (Project Elements H.1, H.4), as needed. Results will inform the timing of TMFs and HFEs to target periods when brown trout are emerging from gravel redds and may be vulnerable to stranding on low-angle shorelines.

In addition to the timing of experimental flows, the magnitude and duration of TMFs and HFEs are likely to elicit an immediate growth and physiological response that may influence the species’ survival, and by extension, cohort strength the following year. Otoliths record a daily history of growth between each otolith increment, so we will extract and prepare otoliths for microstructural analysis and calculate recent daily growth rate using the width of daily otolith increments in the week leading up to, during, and after each flood (Secor and others, 1991; Gilliers and others, 2004; Amara and others, 2009). In addition, otoliths will be checked for a “check” (a dark line indicating daily growth rings are placed very close together) to determine whether growth is interrupted in response to environmental conditions. Pre-flow sampling will occur within one week prior to each experimental flood and be paired with two trips scheduled within six weeks after each flood.

Growth rate data will be paired with a pre- and post-flood quantification of triglycerides, a main storage fat that is a sensitive biochemical indicator of fish health (Parrish, 1999; Cleary and others, 2012). Briefly, lipids will be extracted gravimetrically using a modification of the Bligh and Dyer (1959) method and separated into lipid classes via enzymatic assay. Growth rate and physiological condition measurements will be compared to those from fish captured during non-TMF and non-HFE years to account for normal seasonal fluctuations in growth that occur regardless of the occurrence of experimental flows. Biological variables such as fish density will be incorporated into models to account for density-dependence effects on growth and condition. Collectively, this data can be used to assess the effectiveness of experimental flows as a tool to manage brown trout populations.

All rainbow trout and brown trout otolith work proposed in this project element will minimize loss of life to the extent practicable by utilizing incidental mortalities and fish collected and euthanized per NPS conditions on permits for GCMRC and its cooperators. In addition, we will coordinate sampling efforts with research and monitoring activities proposed in Project Elements H.1 and H.4 to take advantage of incidental mortalities thereby reducing loss of life per Tribal concerns.

***Project Element H.4, Rainbow Trout Monitoring in Glen Canyon***

David Rogowski, Fish Biologist, Arizona Game and Fish Department

The objective of this project is track the status and trends of rainbow trout in the Lees Ferry section of Glen Canyon National Recreation Area and continue to gather long-term trend data on relative abundance, size composition, distribution, recruitment, and angler satisfaction and catch quality.

The fish community downriver of Glen Canyon Dam has been sampled by AGFD using electrofishing methods since the early 1980s (Maddux and others, 1987), which were standardized in 1991. This program can detect population level changes in the rainbow trout fishery over a five-year time scale and has provided long-term trend data used to manage the rainbow trout fishery (McKinney and others, 2001; Makinster and others, 2011). This program underwent refinements following protocol evaluation panels (PEPs) in 2000, 2009, and 2016 (Anders and others, 2001; Bradford and others, 2009). The 2016 PEP recommended continuing to collect long-term trend data in Lees Ferry (this project) while also incorporating mark-recapture methods into the sampling design to estimate vital rates (Project Element H.1). We propose to conduct two sampling trips per year (summer and fall) to assess the status and trends of the fish population using CPUE metrics. During these trips 36 sites will be sampled using a random stratified design based on mile and shoreline type. In lieu of a spring trip (as has been done in the past), we will conduct four monthly sampling trips from June-September that are focused on the detection, status, and population trends of nonnative species including brown trout in Glen Canyon (Project Element I.2). The July trip will include both rainbow trout and nonnative monitoring components. This effort will begin to build similar long-term trend datasets for other species and provide the opportunity to rapidly respond to new aquatic invaders (e.g., green sunfish; *Lepomis cyanellus*).

In addition to the proposed monitoring using standardized electrofishing methods, we will conduct angler creel surveys to estimate angler effort, catch, and harvest on an annual basis. As was done in the FY2015-17 work plan, we propose that creel surveys be funded by the GCDAMP in FY2018-19 and by AGFD in FY2020. Creel surveys will be scheduled on a monthly and weekend/weekday basis to allocate survey effort relative to angling effort during the year. These interviews will be conducted near the boat ramp for anglers fishing in the upriver section (between Glen Canyon Dam and the Lees Ferry boat ramp) and in the walk-in section (from the Lees Ferry boat ramp downstream to the Paria River). The angler surveys provide data on angler catch rate, including angler estimates of fish ≥ 14” and fish ≥ 20” in length; however, angler estimates do not provide accurate length information associated with the catch, thus AGFD cannot accurately assess whether goals related to angler catch quality are being met. Therefore, we propose a new citizen science project to assess whether goals related to angler catch quality are being met by utilizing fishing guides to collect length data on fish caught by clients. Participating guides will measure fish caught by clients on randomly selected (to the extent practicable due to guiding schedules) weekend days and weekdays, and will be paid ~$10/day for participating. Guides will measure all fish caught in a day to ensure a representative sample. AGFD is conducting a small pilot project this year (2017), with 2–3 guides collecting length information on a total of 20–30 days. The pilot study will allow us to refine our methods and data collection as needed to obtain accurate length information and minimize guide time commitment. For FY2018–20 AGFD plans to expand the citizen science project to more guides and more sample days. Exact numbers of guides and days will depend on guide interest and desired sample size (informed by 2017 data).

**4.2. Personnel and Collaborations**

The overall project lead for Project H is Dr. Michael Yard, a Fish Biologist at GCMRC who specializes in rainbow trout population dynamics and statistical modeling. Dr. Charles Yackulic is a Research Statistician specializing in population dynamics with an emphasis in modeling linkages and vital rates between trout populations. Dr. Josh Korman is a Fish Biologist with Ecometric Research Inc. specializing in analytical models and database development, population dynamics, and modelling capabilities. Dr. Kimberly Dibble is Fish Biologist at GCMRC with expertise in fish physiology, otolith microstructural analysis, and metadata analysis. Dr. David Rogowski is a Fish Biologist with the Arizona Game and Fish Department and is responsible for some of the long-term fish monitoring programs in Glen and Grand Canyons and is experienced in statistical models and database management. Clay Nelson is a Fish Biologist at GCMRC who has extensive field experience working with native and introduced fishes in Glen and Grand Canyons. Dr. Ken Sheehan is a Fish Biologist at GCMRC who specializes in habitat modeling and linkages to aquatic organisms and environmental spatial analysis. Michael Dodrill is a Fish Biologist with expertise in fish habitat and trout bioenergetics modeling.

**4.3. Deliverables**

Journal articles and state monitoring reports will be prepared in FY2018–20 covering several of the following components of this project:

* Direct and indirect effects of HFEs on the rainbow trout fishery
* Factors driving spatial patterns in abundance, growth, and condition of trout in Lees Ferry
* Trout management flows as a mechanism to control RBT recruitment dynamics in Glen Canyon
* Modeling of rainbow trout recruitment and outmigration into Marble Canyon
* Brown trout growth and condition responses to HFEs and TMFs using otolith microstructural and lipid class analysis
* Early life history studies of brown trout in the Colorado River
* Long term trends in fish community structure using CPUE indices

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1. **Budget**







Project I. Warm-water Native and Non-native fish Research and Monitoring

1. **Investigators**

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1. **Project Summary**

Maintenance of self-sustaining native fish populations within the Colorado River and its tributaries and minimizing or reducing the presence and expansion of aquatic invasive species are specific resource goals outlined in the Long-Term Experimental and Management Plan (LTEMP) and its associated Record of Decision (ROD) and Biological Opinion for operation of Glen Canyon Dam (U.S. Department of Interior, 2016). Declines in native fish populations throughout the southwest are commonly linked to adverse interactions with invasive warm-water fishes (Marsh and Pacey, 2005, Clarkson and others 2005). In the Colorado River, and especially the upper Colorado River, warm-water predatory fishes are implicated in lack of recruitment and population declines in native fish (Martinez and others 2014). For this reason, regulation and control of invasive fish is an important management action identified in all recovery plans for Colorado River endangered fishes including humpback chub (*Gila cypha*) recovery goals (USFWS 2002) (under revision). For these reasons, knowledge about the status and trends (e.g. distribution and relative abundance) of native and invasive fishes within the Colorado River ecosystem (CRe) and the relative risks that invasive fish pose to native species are necessary in this work plan for effective management of warm-water fishes, both native and non-native. This project has two primary goals: One goal is to monitor native fish species of the CRe to provide information on their status and trends, and the other goal is to monitor invasive warm-water fish species. This project aims to provide scientific information that facilitates effective warm-water fish management in the following ways.

By conducting system-wide fish monitoring to track trends in native fishes and by refining existing monitoring efforts and employing new monitoring tools to improve early detection capability of invasive warm-water fishes.

By assessing and quantifyingthe relative risks posed by warm-water non-native fish to humpback chub and other native fishes utilizing a combination of field and laboratory research.

Maintaining a natural native fish assemblage is an important resource goal outlined in the LTEMP and long-term monitoring is the tool we use to determine the status of these fish populations. Long-term monitoring allows the ability to detect trends and test hypotheses in regard to temporal variation in fish populations, but its strength also lies in the ability to interpret and detect unexpected trends or surprises (Lindenmayer et al. 2010, Dodds et al. 2012, Melis et al. 2015). When designed properly, a long-term monitoring program is a powerful tool for quantifying the status and trends of key resources, understanding system dynamics in response to stressors, and investigating the efficacy of alternative management actions. Without long-term monitoring, science-based decisions for fisheries management are often not possible (Walters 2001).

Preventing new invasions is the least expensive and most effective way to control invasive species when compared to the cost of control projects after invasions occur (Leung and others, 2002). Therefore, we seek to improve detection of potentially problematic warm-water invasive fishes within the CRe in Grand Canyon by expanding monitoring efforts and testing new environmental DNA (eDNA) detection tools. Long-term, monitoring is used to both to evaluate trends in native and non-native fishes and to detect non-native fish invasions when they occur. This monitoring is currently conducted by the Arizona Game and Fish Department (AGFD) at Lees Ferry and throughout the CRe. We propose to increase monitoring efforts at Lees Ferry by adding three additional two-night sampling trips to include 12 sites where warm-water species are likely to aggregate and spawn. This will maximize our ability to detect range expansions of existing warm-water invasive species and detect invasive fishes that may pass through the dam. Monthly monitoring during the summer months between the dam and Lees Ferry will focus on locations with warmer water where non-native fishes are most likely to occur. Currently, AGFD conducts system-wide fish monitoring using electrofishing, angling and and hoop netting from Lees Ferry (river mile (RM) 0) to Pearce Ferry (RM 281). Other fish monitoring efforts focused on humpback chub (project G) and the small-bodied fish monitoring conducted by the National Park Service downstream of Bright Angel Creek (Funded outside this work plan by the Bureau of Reclamation) also provide important detection data related to invasive warm-water fishes. As the elevation of Lake Mead has decreased due to drought, the western segment of the river has reemerged, creating the need to extend sampling efforts for native fishes as well as invasive species detection for an additional 15 miles to the Lake Mead interface.

Additional surveillance is also warranted upstream of Blue Springs in the Little Colorado River drainage to identify sources of non-native and potentially invasive fish that are likely to move into the CRe during high flows. Invasive warm-water species such as green sunfish (*Lepomis cyanellus*), channel catfish (*Ictalurus punctatus*) and bullhead catfish (*Ameiurus spp.*) typically move downstream with spring flooding and inhabit isolated pools between Grand Falls and Blue Springs. If new invasive warm-water species like smallmouth bass (*Micropterus dolomieu*) begin to follow this same dispersal pattern, this may represent a significant risk to downstream resources. Reproduction by smallmouth bass in these warm isolated pools could produce extremely high numbers of smallmouth bass which would then be transported downstream into the Colorado River during monsoon flood events. Because this area is geographically considered outside of the scope of the GCDAMP, we will work with the Navajo Nation and AGFD to gather information on what fish species are present or likely to be present and then use that information to assess the potential risks to native fish downstream.

New tools such as eDNA will be tested to validate the presence or absence of key invasive species, determine the spatial extent of invasions within the mainstem Colorado River and estimate the relative biomass of aquatic invaders. Environmental DNA that is collected from the environment in which an organism lives, rather than directly from animals themselves. In aquatic environments, animals including fish, shed cellular material into the water via reproduction, saliva, urine, feces, etc. This DNA may persist in the environment for several weeks, and can be collected in a water sample which can then be analyzed to determine if the target species of interest are present (Carim et al. 2016). Ficetola and others 2008 first demonstrated that detection of vertebrates using eDNA in water samples was possible and interest in using this tool to improve detection sensitivity and cost efficiency over aquatic field surveys has grown rapidly and been shown to be effective in many aquatic systems (Goldberg and others 2011). Environmental DNA can have higher sensitivity and lower cost than traditional sampling methods especially when attempting to detect very rare organisms. Water samples for eDNA analysis are relatively easy to collect in conjunction with exiting monitoring trips and data can be paired with standard electrofishing and hoop netting data to compare the sensitivity of each approach. Collectively, the expansion of existing monitoring efforts combined with new eDNA detection tools are critical first steps for preventing the establishment and spread of warm-water invasive fishes in CRe.

Management and removal of invasive aquatic species can be difficult once a species become established because of the large scale of the problem and the few effective tools that are available (Dawson and Kolar 2013). This creates the need to understand which species pose the greatest threats. Assessing the risks posed by existing or new warm-water invasive fish provides managers with the scientific information needed to make decisions about what management activities are warranted. Hilwig and Andersen (2011), compiled a literature review of the potential risks posed by individual species, but those risks need to be validated and quantified based on existing environmental conditions, species abundances, and expected future conditions in the Little Colorado River and CRe. Although extensive research to evaluate rainbow trout (*Oncorhynchus mykiss*) and brown trout (*Salmo trutta*) predation on juvenile humpback chub under various environmental conditions was conducted in the previous work plan, other warm water invasive species in the Little Colorado River may also be detrimental to humpback chub and other native fish. To that end, risks posed by other warm-water invasive fishes such as channel catfish and bullhead catfish will be quantified using diet analysis and bioenergetics modeling. Laboratory studies will be conducted to quantify predation risk from common carp (*Cyprinus carpio*) and small bodied fishes such as fathead minnow (*Pimephales promelas*) and plains killifish (*Fundulus zebrinus*) on humpback chub eggs and larvae. These studies will determine if warm-water invasive fishes present more or less of a predation threat to juvenile humpback chub than predation by trout. This information gives context from which to evaluate potential management actions such as trout removal and will ensure that any future aquatic invasive species removal efforts are focused only on species that pose the highest threat to humpback chub populations.

In addition to evaluating the risks posed by invasive fish species we will also evaluate the risks posed by infestation of Asian fish tapeworm (*Bothriocephalus acheilognathi*) in humpback chub. Asian fish tapeworm is an invasive species that infests warm-water cyprinid fishes. Asian fish tapeworm monitoring has occurred annually within the Little Colorado River and additional monitoring will be conducted in this work plan on Asian fish tapeworm in humpback chub inhabiting the mainstem Colorado River as identified in the 2016 Biological Opinion. Asian fish tapeworm is an invasive aquatic species that is potentially fatal to host species (Hoffman and Schubert 1984) and has been identified as one of six potential threats to the continued existence of endangered humpback chub (USFWS 2002). Asian fish tapeworm was first documented in the Little Colorado River in Grand Canyon in 1990 (Minckley 1996) and was hypothesized to be a cause of long-term declines in condition of adult humpback chub from the Little Colorado River (Meretsky and others 2000). Monitoring Asian fish tapeworm infestation in humpback chub in the mainstem Colorado River will provide a baseline context and relative risk assessemtn with which to evaluate the potential impacts of this invasive parasite on humpback chub populations.

1. **Background**

Prior to construction of Glen Canyon Dam water temperature in the Colorado River in Grand Canyon historically fluctuated from near freezing in the winter to almost 30 °C in the summer (Vernieu and others 2005). At this time the Colorado River was dominated by native fishes and introduced warm-water fish such as channel catfish (Hayden 1992, Minckley and Marsh 2009). With the completion of Glen Canyon Dam in 1963 and subsequent filling of Lake Powell, river temperatures dropped to 7-10 °C by 1973 with little annual variation. This shift in the thermal regime dramatically altered the fish assemblage of the Colorado River in Grand Canyon, changing it from an assemblage dominated by warm-water species to one dominated by cold-adapted rainbow trout for many years. Constant cold water has kept warm-water introduced fishes from becoming established throughout Glen, Marble and most of Grand Canyon. Cold water releases from Lake Powell persisted (from 1983, when the reservoir filled completely until 2005 when drought conditions caused water elevations in Lake Powell to drop and warmer surface waters to become entrained in the penstocks and released downstream (8 – 16 °C), once again creating a varied thermal regime in the Colorado River in Glen, Marble and Grand Canyons for a few years. This short period of warmer water within a system dominated by cold water may be one reason for the unique pattern of native fish increases in recent years in the CRe, compared to dramatic declines that have occurred in most other portions of the Colorado River basin and most other streams throughout the desert southwest during the same time period.

In cooperation with AGFD, fish community monitoring occurs annually in the spring from Glen Canyon Dam to the Lake Mead inflow (482 km) using a variety of methods: boat-mounted, DC electrofishing conducted at night, angling downstream of the Little Colorado River, and hoop nets. Methods were standardized in 2000 and employ a stratified random sampling design to provide a catch-per-unit-effort index of abundance for the fish species that are present (Speas and others 2003). This long-term system wide monitoring program provides the baseline context under which population changes can be compared and assessed. We propose to continue this long-term system-wide monitoring as it provides trend information on multiple species of native and non-native fish throughout the CRe. This monitoring program also provides detection capability for new warm-water invasive fishes which may be entering the CRe from Lake Powell, by passing through Glen Canyon Dam, by descending tributaries such as the Little Colorado River, or swimming upstream from Lake Mead.

Identifying sources of warm-water invasive fishes in the CRe early improves the likelihood that a successful rapid containment/eradication response can be accomplished before negative impacts on endangered populations occur (Martinez and others 2014). Preventing the introduction and spread of warm-water invasive fishes is far more environmentally and fiscally desirable than undertaking control or eradication efforts after they become established (Martinez and others 2014, Cucherousset and Olden 2011). Invasive fish have high proliferative potential, and once established, eradication is often essentially impossible and control typically requires long-term and expensive efforts where successful outcomes are uncertain (Martinez and others 2014, Pimentel and others 2000; Simberloff 2003; Mueller 2005; Johnson and others 2009; McIntosh and others 2010). As indicated in the 2016 Biological Opinion for the LTEMP, the Bureau of Reclamation will conduct planning and compliance for implementation of rapid response control efforts for newly establishing or existing deleterious invasive species within and contiguous to the action area (USDI 2016). Before any management actions can occur monitoring must first detect those invasions and research must be conducted to evaluate risks and inform managers whether or not control efforts are actually warranted. This project provides for the integration of science and invasive species management.

1. **Proposed Work**

### Project Elements

***Project Element I.1, System-Wide Native fish and Invasive Aquatic Species Monitoring***

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Charles Yackulic, Research Statistician, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

David Ward, Fish Biologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

The primary objective of this project element is to provide long-term data collection on the longitudinal distribution and status of the fish community in the mainstem Colorado River from Lees Ferry (RM 0) to Lake Mead (RM 281). System-wide monitoring throughout this section of the Colorado River is a necessary monitoring component to assess populations of native fish in the Colorado River, and to ensure that LTEMP goals are being met. This project provides information on three important goals identified in the LTEMP ROD, (U.S. Department of Interior, 2016): 1) Meeting humpback chub recovery goals, including maintaining a self-sustaining population, spawning habitat, and aggregations in the Colorado River and its tributaries downstream of Glen Canyon Dam, 2) Maintain self-sustaining native fish species populations and their habitats in their natural ranges on the Colorado River and its tributaries, and 3) Minimize or reduce the presence and expansion of aquatic invasive species. Annually, AGFD conducts two spring river trips from Lees Ferry to Diamond Creek, and one fall river trip from Diamond Creek to Pearce Ferry and uses standardized electrofishing, hoop netting catch, and angling catch per unit effort (CPUE) indices to track the relative status and trends of most common native and non-native fish species in the CRe. The current monitoring project is designed to detect population level changes in target fish species over a five-year time scale, although yearly changes in CPUE for some species such as rainbow trout and flannelmouth sucker (*Catostomus latipinnis*) are evident. In addition yearly changes in species distribution for both native and non-native fishes are often discernable. Annual monitoring of native and non-native fish in the CRe has been ongoing since 2000 (Makinster and others, 2010).

The fall trip mentioned previously concentrates on sampling non-native and potentially invasive species from downstream of Diamond Creek (RM 225) to Pearce Ferry Rapid (RM 281.4) when water temperatures are warmest and when sampling is most likely to detect non-natives moving upstream from Lake Mead. The elevation of Lake Mead has decreased due to drought and the Colorado River has reemerged. Sampling downstream of RM 225 began in 2007, and downstream of RM 270 in 2015. This section of river is of particular interest because western Grand Canyon holds large numbers of native fish, relative to upstream segments. For this reason, AGFD has increased the spatial extent of its downstream monitoring effort in the reach immediately upstream of Pearce Ferry. Catches of humpback chub and other native species from 2016 hoop netting were highest in the reach from just upstream of Diamond Creek to Pearce Ferry (RM 220 – 281). These results suggest a possible range expansion of humpback chub in Western Grand Canyon. Additionally, in 2012 AGFD detected the first razorback sucker (*Xyrauchen texanus*) in over 20 years in this system, and subsequently in 2013 and 2014. The reach downstream from Pearce Ferry to Lake Mead (RM 281 – 296) may also be important habitat for native fish, including the endangered humpback chub and razorback sucker; however, are not being monitored during current trip because of a navigation hazard (Pearce Ferry Rapid at RM 281.4). A preliminary monitoring effort by AGFD in February 2017 accessed the lower 15 miles downstream of Pearce Ferry rapid via the South Cove boat ramp of Lake Mead. AGFD was able to sample RM 287-296 with 20 hoop-net sets. While only one humpback chub (and one gizzard shad (*Dorosoma cepedianum*), and one speckled dace (*Rhinichthys osculus*)) was captured it does suggest that humpback chub are utilizing this stretch of the river. We propose to continue monitoring the segment of the Colorado River downstream of Pearce Ferry rapid. The timing of monitoring has yet to be determined, however February may not be the best time as water temperatures are too cold. The objective for this project is to spatially extend the standardized fisheries monitoring to Lake Mead, and provide data which can be used to assess progress towards meeting LTEMP goals related to native as well as non-native fish. Preliminary sampling of this reach, as well as sampling upstream of Pearce Ferry in 2016, demonstrated that the western Grand Canyon may be essential for meeting the humpback chub recovery goals as specified by the LTEMP.

Annual Asian fish tapeworm monitoring will also be conducted in conjunction with fall fish monitoring efforts. Monitoring of fish parasites such as Asian fish tapeworm is identified as a requirement of the 2016 Biological Opinion for operation of Glen Canyon Dam. Thirty to 60 humpback chub of various sizes will be held on the river bank in a 1893-liter collapsible tank and will be treated according to methods described in Ward 2007, where individual fish are held in perforated buckets inside a larger holding tank treated with Praziquantel at 6 mg/l. Each fish will receive two Praziquantel treatments 48 hours apart with the number of tapeworms quantified from each individual fish. Praziquantel has been used since 1985 to remove parasites in many different fish species in hatcheries. Following treatment all fish will be released alive back into the river. These methods are identical to those that have been used ongoing Asian fish tapeworm monitoring in the Little Colorado River. This monitoring effort will be used to establish an annual baseline infection level by fish size and to evaluate the potential impacts of Asian Tapeworm on humpback chub populations inhabiting the mainstem Colorado River. This information will be used to determine whether year-to-year variation in the prevalence of tapeworm infestation is linked to annual variation in growth, survival or abundance of juvenile humpback chub in the mainstem Colorado River.

As part of this work element we also propose to summarize and report on the number of native and non-native fish that were caught as well as euthanized throughout the CRe annually from all fish monitoring projects. This summary information will require researchers to be accountable for all taking of life that occurs within the canyon in response to tribal concerns and will also facilitate identification of range expansions or new aquatic invasive species detections that might not be apparent without evaluations across projects conducted by various cooperating agencies.

#### Project Element I.2, Improve early detection of warm-water Invasive fishes

Dave Rogowski, Fish Biologist, Arizona Game and Fish Department

Kim Dibble, Fish Biologist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

Kirk Young, Fish Biologist, U.S. Fish and Wildlife Service

The non-native species currently present within Grand Canyon are only a fraction of the potential non-native fish species that could establish themselves in the Colorado River. Many invasive fishes that are not yet established in the CRe have caused population declines and even extinctions in the upper Colorado River Basin and in other southwestern river systems (Minckley and Deacon, 1991). For these reasons methods to improve early detection of warm-water invasive fish species are warranted. This project element proposes to improve detection efficiency by increasing sampling effort at Lees Ferry to detect invasive fish species that are coming downstream through the dam from Lake Powell as well as an evaluation of new eDNA tools to increase detection efficiency in western Grand Canyon for fish moving upstream out of Lake Mead and in from tributaries such as the LCR.

AGFD currently conducts a single targeted non-native monitoring trip at Lees Ferry during July at 12 locations within the Lees Ferry area. We propose to increase this monitoring effort to include monthly sampling (June – Sept) (a single night in duration) during the summer at locations in the river where water temperatures are seasonally higher than in the thalweg or areas known to have had non-native fish species in the past (e.g. springs, backwaters, and areas just below the dam). This monitoring effort will include electrofishing and minnow trapping conducted at a total of 12 sites.

Traditional field methods including hoop netting and standard electrofishing may not detect rare species at the early stages of invasion, species that may not be susceptible to capture, or species residing in deeper areas outside of the range of standard sampling methods. Therefore, we propose 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 and into the mainstem CRe from tributary inputs (Carim et al. 2016; Goldberg et al. 2011; Klymus et al. 2015). Since mitochondrial DNA from a range of aquatic organisms can persist for up to several weeks in a water body at very low concentrations, we propose to collect this DNA by filtering water samples at sites near tributary junctions and in the western Grand Canyon (Carim et al. 2016). Filtered samples will be preserved in the field and sent to a genome sequencing laboratory to determine if the target species of interest have been present in the CRe. Since the concentration of eDNA in a water body is proportional to the biomass of the aquatic invader, relative abundance can also be estimated (Klymus et al. 2015). In the past, water samples were traditionally tested for a single species of interest (e.g., smallmouth bass) using conventional, isothermal, or quantitative polymerase chain reaction (PCR) methods; however, recent advancements in eDNA technology now allow for the comparison of eDNA sequences in a sample to an online database using a metagenomics approach, which provides data on all of the species in a water sample. Collection of water samples will take place on AGFD system wide fish monitoring trips in conjunction with fish sampling to evaluate the sensitivity of eDNA technology to detecting aquatic invaders. Occupancy models will be developed using direct capture and eDNA data to examine detection probability and the relative sensitivity of each type of technology. The goal of these monitoring efforts is to improve detection ability and efficiency so that management agencies can deploy resources to rapidly contain or eradicate aquatic invaders before they spread in Grand Canyon, thereby reducing potential negative impacts to native species.

#### Project Element I.3, Assess the risks warm-water non-native fish pose to native fishes

David Ward, Fish Biologist, USGS

The objective of this project element is to evaluate impacts of warm-water invasive fishes on humpback chub in both laboratory and field settings and to determine if these species represent more or less of a predation threat to juvenile chub than predation by trout. Work conducted in the previous work plan focused on the potential negative impacts that rainbow trout and brown trout may have on humpback chub populations through predation and competition (Ward and others 2015, Ward and others 2016) but other warm-water invasive fishes are also likely to negatively affect humpback chub populations within the Little Colorado River. The potential magnitude of those interactions relative to impacts of trout remains uncertain. Predation on humpback chub by channel catfish and black bullhead catfish (*Amerius melas*) has the potential to be high but impacts have not been quantified. Other invasive warmwater species like common carp and fathead minnow may also have detrimental impacts on eggs and early larval stages of humpback chub negatively impacting recruitment. Management actions to control these species may be warranted depending on the magnitude of these interactions. Control of these warm-water invasive fishes within the Little Colorado River may be more cost effective than trout removal in the mainstem Colorado River if they are having population-level impacts on humpback chub, but these questions have not been evaluated. Relative predation vulnerability of humpback chub to predatory warm-water fishes will be assessed in the laboratory in overnight trials using methods similar to those employed for rainbow and brown trout in the last work plan (Ward and others 2015). Twelve replicate artificial streams at 20 °C will be used to evaluate relative predation vulnerability of multiple size classes of juvenile humpback chub to channel catfish, black bullhead catfish, and smallmouth bass during overnight trials using four predators and 12 prey fish per tank. Humpback chub eggs and larvae will also be exposed to predation by common carp, fathead minnow, and plains killifish in replicated overnight laboratory trials to compare the relative predation risk these predators pose for humpback chub at early life stages.

Information collected from this project element gives context within which to evaluate the potential management actions such as trout removal. Hilwig and Andersen (2011) provided a comprehensive literature review of potential risks posed by individual species but these risks also need to be quantified relative to existing abundance and environmental conditions. Laboratory studies will be used to isolate confounding variables such as effects of temperature and turbidity on predation vulnerability and to quantify relative predation impacts of channel catfish, common carp, fathead minnow, and plains killifish on humpback chub eggs, larvae, and juveniles under conditions present in the Little Colorado River. Field evaluations of catfish diets will be used in conjunction with relative abundance data to model population level impacts of these warm-water invasive fishes on humpback chub within the Little Colorado River. Combining laboratory studies, field studies, monitoring efforts, and modeling will allow researchers to understand how predation by existing invasive warm-water fishes and predation by new invasive species may impact humpback chub at various life stages and at a population level. This integration of science and management will allow managers to improve decisions about management actions designed to conserve Colorado River native fishes and ensure that any future management actions that are undertaken are focused only on only those fishes that are actually having the most detrimental impacts on native fish populations.

* 1. **Deliverables**

This work will result in multiple peer-reviewed publications as well as data to support potential management actions by the resource management agencies. Information will be provided in the form of oral and written presentations to the GCDAMP at annual reporting meetings.

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1. **Budget**







Project J. Socioeconomic Monitoring and Research in the Colorado River Ecosystem

1. **Investigators**

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1. **Project Summary**

Project J is designed to identify preferences for and economic values of downstream resources and evaluate how these metrics are influenced by Glen Canyon Dam (GCD) operations, including proposed experiments in the Glen Canyon Dam Long-Term Experimental and Management Plan Environmental Impact Statement (LTEMP EIS) (U.S. Department of Interior, 2016). The research will also integrate economic information from the project with data and predictive models from long-term and ongoing physical and biological monitoring and research studies led by the Grand Canyon Monitoring and Research Center (GCMRC) to develop integrated assessment models (multidisciplinary models [e.g., biology and hydropower] that incorporate social and economic considerations), improving the ability of the Glen Canyon Dam Adaptive Management Program (GCDAMP) resource managers and stakeholders to evaluate and prioritize management actions, monitoring and research.

This project involves two related socioeconomic research elements. These elements build on research in the GCDAMP Fiscal Years 2015 – 2017 Triennial Budget and Work Plan (FY15-17 TWP) (U.S. Department of Interior, 2014) and include: a) implementation of a tribal member population survey to assess preference for and value of downstream resources (**Element 1**); and b) development and integration of decision support models, using economic metrics, to evaluate and prioritize monitoring of, and research on, resources downstream of GCD, including proposed experiments in the LTEMP EIS (**Element 2**).

**Element 1:** The proposed quantitative population-level tribal research is designed to provide an efficient and timely approach to assessing tribal values, perspectives and knowledge of Colorado River Ecosystem resources. The tribal member population surveys would apply a set of standard methods extensively used in resource economics studies for valuing ecosystem services. The research would inform on tribal perspectives (e.g., perspectives on management actions) and preferences for trade-offs (e.g., tradeoffs between energy and other downstream resources) related to operation of GCD. This information is critical when developing quantitative adaptive management models that assess the most cost-effective management actions and value of reducing scientific uncertainty (e.g., **Element 2)**. This project element would build on the qualitative research in Project 13.2 in the FY15-17 TWP. The qualitative research in FY17 is being accomplished through workshops with tribes involved in the GCDAMP, coordinated with recent work, including a National Park Service (NPS) nonuse survey focused on national and regional populations (Neher and others, 2016), as well as direct use recreation studies (Bair and others, 2016; Neher and others, in review; Neher and others*, in prep*. This work is scheduled to be completed prior to implementation of **Element 1**.

**Element 2**: This project element would develop a series of integrated assessment models to improve the GCDAMP’s capacity to organize scientific information and evaluate and prioritize, monitoring, research and management alternatives specific to the operation of GCD, including proposed flow experiments in the LTEMP EIS. This project element will build on the framework of a bioeconomic model developed to evaluate rainbow trout (*Oncorhynchus mykiss*) management strategies in relation to humpback chub (*Gila cypha*) population goals (Bair and others, in preparation and current research in Project 13.3 in the FY15-17 TWP). Current research includes the exploration of which uncertainties in humpback chub population parameters have the greatest implications for management decisions (i.e., quantitative adaptive management model) and the explicit trade-offs (efficacy and cost) between trout management flows (TMFs) and rainbow trout removals at the Little Colorado River (LCR). **Element 2** will systematically assess management triggers related to rainbow trout removal (e.g., adult humpback chub abundance, juvenile humpback chub recruitment), explore which uncertainties in experimental flow response (e.g., TMFs) have the greatest implications for management decisions, and address the impacts of long-term trends in recruitment of rainbow trout and humpback chub on monitoring and research priorities.

**Element 1** addresses the LTEMP EIS objective to respect the “interests and perspectives of American Indian Tribes” and **Element 2** addresses the LTEMP EIS objective to “determine the appropriate experimental framework that allows for a range of programs and actions, including ongoing and necessary research, monitoring, studies, and management actions in keeping with the adaptive management process” (U.S Department of Interior, 2016). **Element 2** also considers hydropower and attempts to “minimize emissions and costs to the greatest extent possible, consistent with improvement and long-term stability of downstream resources” (U.S. Department of Interior, 2016). **Element 2**’s focus on adaptive management modeling is consistent with the GCDAMP fisheries review panel’s recommendation that the program, “adopt [a] decision theoretic approach to adaptively manage the rainbow trout fishery and humpback chub population” (Casper and others, 2016). A decision-theoretic approach to adaptive management is when a, “predictive model or set of models are created that represent alternative ideas of how the system works” and those priors are evaluated through predicted or actual future resource states (Casper and others, 2016). This approach, would allow the GCDAMP to “optimize” monitoring and research by identifying the relative efficiency of learning opportunities. The proposed project elements therefore address the LTEMP EIS resource goals related to humpback chub, tribal concerns, hydropower, and rainbow trout.

1. **Background**

Project J would meet critical socioeconomic information needs identified by the GCDAMP (AMWG, 2012a). Furthermore, the implementation of proposed experiments in the LTEMP EIS are, “contingent on the responses of one or more socioeconomic metrics” (VanderKooi and others, 2016). These metrics include the status and trade-offs associated with resources of Tribal importance because operation of GCD also has direct effect on downstream resources of cultural value and traditional use in Glen Canyon National Recreation Area (GCNRA) and Grand Canyon National Park (GCNP). The Grand Canyon Protection Act (GCPA) of 1992 states that, “…monitoring programs and activities conducted under subsection (a) shall be established and implemented in consultation with…tribes…” (GCPA, sec. 1805(c)). Therefore, measures of resource status or health and appropriate management will need to be determined individually by the federal agencies in consultation with the tribes (AMWG, 2012b). **Element 1** addresses this need and, in coordination with the tribes, is critical for furthering the understanding of tribal preferences for, and socioeconomic impacts associated with, resource management decisions, including the proposed and ongoing experiments identified in the LTEMP EIS (U.S. Department of Interior, 2016).

The role of the GCMRC, and cooperators, is to provide information on physical and biological resources while also providing information related to socioeconomic aspects of resources (VanderKooi and others, 2016). **Element 2** will focus on development of a set of integrated assessment models, utilizing research at GCMRC and in the LTEMP EIS, to formally model tradeoffs and prioritize monitoring and research. This is important because, it is the “absence of decision making mechanisms” in adaptive management programs that make systematic prioritization of investment in monitoring, research, and management alternatives difficult (Scarlet, 2013). Including economic assessment of investment in monitoring and research is an important component of such programs (Doremus, 2010). While previous research has developed a decision support system for the Colorado River Ecosystem in GCNRA and GCNP downstream from GCD, modeling of management scenarios of other resources (e.g., sediment storage, native fish) were very uncertain due to limited empirical data (Walters and others, 2000). Utilizing ongoing biological research by GCMRC and cooperators, **Element 2** will continue to improve the GCDAMP’s ability to prioritize research, including evaluating proposed experiments and actions identified in the LTEMP EIS (U.S. Department of Interior, 2016).

1. **Proposed Work**

### 4.1. Project Elements

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

Lucas Bair, Economist, U.S. Geological Survey

John Duffield, Research Professor, University of Montana

The **objective** of **Element 1** is to identify tribal member preferences and values associated with management of resources downstream of GCD, through a tribal member population survey, in order to inform decision making processes in the GCDAMP. Defining individual tribe’s preferred actions and perspectives associated with management of downstream resources is important when evaluating potential actions and developing adaptive management models that prioritize monitoring and research. Emphasis will be placed on resources of tribal significance that are affected by dam operations and flow experiments in the LTEMP EIS. The assessment of tribal preferences and values will be achieved through in-person interviews with tribal members, using choice experiment methods to explicitly evaluate management actions and tradeoffs between resource attributes. The project will be implemented in FY18, conditional on successful completion of Project 13.2 in the FY15-17 TWP, and coordinated with other tribal related studies, including the Bureau of Reclamation’s Tribal Associated Values Studies project (U.S. Bureau of Reclamation, 2017).

**Hypotheses** in **Element 1** include:

* Do tribal member preferences for and values of downstream resources differ among resource attributes?
* Do tribal member preferences for and values of downstream resources differ among tribes and the general population?

To test these **hypotheses**, the tribal preference relationships among resource attributes (e.g., hydropower, native fish) will be generated and assessed. These hypotheses posits that there will be significant variation in each tribes’ preferences for and values of downstream resources by resource attribute and significant differences across tribes and with the general public. This research will enhance understanding of tribal preferences for and values of downstream resources, and is critical in development of formal adaptive management models in **Element 2**, prioritizing monitoring and research decisions within the GCDAMP.

The efficient way to undertake Tribal research will be to build on the comprehensive NPS national and regional non-use survey (Neher and others, 2016). The non-use value survey was completed for purposes of informing NPS planning and management needs. The proposed tribal socioeconomic tasks are to build on (and benefit from) the larger NPS effort. The NPS study sampled Native Americans, but only in proportion to their presence in the national and regional populations, which resulted in too small a sample size (particularly for the subset of just GCDAMP tribes) for interpretation, necessitating the tribal member sample in **Element 1**.

The population surveys would expand on the qualitative effort in Project Element 13.2 in the FY15-17 TWP and use a set of resource valuation tools that are extensively used in resource economics studies used for valuing ecosystem services. The AMWG (2012b) specifically identified both revealed and stated preference methods for use in its socioeconomic program. Similarly, these tools and their applications have been previously reviewed in the context of both direct recreation and non-use values for Colorado River related studies (Welsh and others, 1995; Bair and others, 2016; Neher and others, in review). With respect to nonuse, only stated preference measures are feasible, and for purposes of this tribal socioeconomic study choice experiments would be used. This is a widely utilized approach in resource valuation and is the specific approach utilized in the NPS non-use valuation study (Neher and others, 2016) for purposes of the Final LTEMP EIS (U.S. Department of Interior, 2016).

For the choice experiment **methods**, downstream resource attributes of tribal importance (e.g., hydropower, native fish) and their potential variation with different future management actions will be defined and will shape the experimental design. The experimental design will be based on the number of attributes and future scenarios defined in Project 13.2 in the FY 15-17 TWP. It is important to note that comparisons among resource attributes can contain explicit cost information (e.g., forgone hydropower benefits) when comparing future resource attributes. Statistical models appropriate for the experimental design and elicitation format will be developed to evaluate the relationship between preferences, or values, and resource attributes. The models will provide information on the relative preferences and values for resource attributes and the rates of substitution between resource attribute tradeoffs.

Implementation of the tribal population surveys would include a sample frame of registered tribal members and a total of at least 2,000 potential respondents, across tribes, who would be randomly selected or identified through consultation with tribal councils and government agencies. Surveys would be implemented using an in-person survey format. It will be necessary to undertake a separate survey of non-respondents, those who were asked to take the survey and didn’t, in order to meet the standards for a scientifically valid population survey. The non-response survey will be conducted in-person and will focus on collecting data on demographics and a subset of the survey questions. The target non-response sample is 60 from each participating tribe. Individual participant’s anonymity will be protected, as required by university the Office of Management and Budget, and the scientific integrity of the research is concomitant with the scientific peer review process. The availability and archival of survey data will be determined in consultation with individual tribes.

Project **Element 1** will be implemented in cooperation with the tribes, including tribal staff in research (e.g., survey implementation and scientific presentation and publication) and utilizing tribal survey agents who can overcome language limitations. Funding will be available to tribal staff and survey participants, as appropriate, to achieve successful collaboration and project completion.

**Results** of **Element 1** are critical in informing decisions in the GCDAMP. Specifically, the results of **Element 1** will inform quantitative adaptive management model development and improve the ability of the GCDAMP to prioritize monitoring and research in an effort to meet desired future conditions while considering various perspectives of stakeholders.

#### Project Element J.2, Applied Decision and Scenario Analysis

Lucas Bair, Economist, U.S. Geological Survey

Mathew Reimer, Associate Professor, University of Alaska

Michael Springborn, Assistant Professor, University of California at Davis

Charles Yackulic, Research Statistician, U.S. Geological Survey

The **objective** of this project element is to improve the GCDAMP’s ability to consider, organize and prioritize monitoring, research, and long-term management related to the operation of GCD, including proposed experiments in the LTEMP EIS. To accomplish this, project **Element 2** will build on the framework of a simulation model developed to evaluate cost-effective rainbow trout management strategies in relation to humpback chub population goals (Bair and others, in preparation) and current research addressing critical uncertainties in humpback chub population parameters (Donovan and others, in preparation) as well as trade-offs between trout management flows and rainbow trout removals (Reimer and others, in prep). Specific attention will be paid to methods that improve decision making processes when evaluating resource tradeoffs related to monitoring, research, and management decisions. Evaluation efforts will focus on decision frameworks and analytical tools that best apply to the GCDAMP resources when considering the need for collaboration, complex biophysical/socioeconomic interactions, and stakeholder perspectives (including results of **Element 1**).

The Non-native Fish Control Downstream from Glen Canyon Dam Environmental Assessment (NNFC) (Reclamation, 2011), informally **hypothesizes** that in mitigation of the effects of rainbow trout on humpback chub flow actions may be more cost-effective in the long-run relative to the proposed non-native removal efforts in the Little Colorado River reaches (Reclamation, 2011). This is the type of hypothesis that is addressed in current research (Reimer and others, *in prep*. **Element 2** will further address how LTEMP EIS experiments (e.g., active learning with respect to TMFs) and future trends in rainbow trout and humpback chub recruitment can be used to further refine and test this hypothesis (e.g., passive learning with respect to long-term trends in hydrology).

This project element will develop and implement a series of integrated assessment models to support applied decision and scenario analysis to the GCDAMP. Analytical model development of downstream resources in support of adaptive management has been prioritized in past workplans, based on resources that exhibit significant economic value and/or that garner a significant portion of the GCMRC annual budget; are impacted by operational decisions at GCD; and have sufficient predictive modeling frameworks developed to assess future resource states (U.S. Department of Interior, 2014). The initial focus of **Element 2** will be to develop **methods** to identify the importance of learning with respect to LTEMP EIS experiments (e.g., TMFs). When considering the “optimal” learning path, it is important to consider the short-run costs associated with experimentation relative to long-run benefits of meeting resource goals. In the case of TMFs, evaluation of foregone hydropower and costs associated with emissions will be formally considered when evaluating flow experiments, rainbow trout removal and humpback chub recovery goals. This model development will combine the decision frameworks established to formally assess the cost-effective approach to TMFs and rainbow trout removal (Reimer and others, *in prep*) and formal adaptive management modeling (Donovan and others, in preparation). Additionally, we will explore how management action constraints (e.g. information from project **Element 1**) or variations in humpback chub recovery goals (i.e., quantified desired future conditions) alter the “optimal” learning path.

As with previous modeling efforts (Bair and others, in review) the proposed model development utilizes cost-effectiveness analysis. Like cost-benefit analysis, cost-effectiveness analysis is a standard economic practice. However, cost-effectiveness fundamentally asks a different question than cost-benefit analysis. Cost-benefit analysis assigns an overall net benefit (or net cost) to a future management action. Cost-effectiveness analysis in-turn identifies the least cost alternative, when faced with competing or complimentary management actions, to reach a defined objective. In this case, the objective is humpback cub recovery, as defined by the U.S. Fish and Wildlife Service (U.S. Fish and Wildlife Service, 2002). Implementing cost-effectiveness analysis is consistent with the Record of Decision’s (ROD) goal, not to maximize benefits but to determine an operation at GCD that limits impact to hydropower while meeting recovery and long-term sustainability of downstream resources (Reclamation, 1996). There are several qualities of cost-effectiveness analysis that lends itself to the GCDAMP’s task of evaluating and prioritizing management actions, monitoring and research where incremental decisions must be made, under uncertainty, understanding that many overarching objectives are set through public processes (U.S. Department of Interior, 2014; Bair and others, in review).

While the initial task is focused on research to identify the “optimal’ learning with respect to flow experiments (e.g., TMFs), the modeling effort will include an evaluation of the cost-effectiveness of various combination of rainbow trout management triggers and the importance of variation in rainbow trout and humpback cub recruitment under changing environmental conditions. These additional tasks include:

1. Identify cost-effective combinations of rainbow trout removal triggers. This task will build on the bioeconomic model exploring cost-effective rainbow trout removal at the LCR to achieve adult humpback chub abundance goals (Bair and others, in preparation). Modeling various rainbow trout management triggers (e.g., rainbow trout abundance, sub-adult humpback chub abundance, humpback chub recruitment) in multiple configurations may lead to improved management (i.e., cost-effective outcome through minimizing management actions) (Baxter and others, 2008). This model development will incorporate the proposed management action triggers for humpback chub in the LTEMP EIS and ongoing conservation efforts of the U.S. Fish and Wildlife Service (U.S. Department of Interior, 2016).
2. Incorporate long-run trends in rainbow trout and humpback chub recruitment into models that consider the “optimal” learning that occurs with rainbow trout management experiments (e.g., TMFs). This approach accounts for non-stationary dynamics in natural systems (e.g., hydrology) by incorporating passive learning (Nicol and others, 2015), in parallel with active learning (i.e., LTEMP EIS experiments), to improve the ability to prioritize monitoring and research opportunities.

Integrated assessment models will be developed in cooperation with stakeholders, according to needs in evaluating LTEMP EIS experiments and the advancement of scientific knowledge at GCMRC. This deliberate process of building a decision support system through the development of individual analytical, predictive models will enable analysts to identify monitoring and scientific information needs and screen policy options as the GCDAMP advances its goals. **Results** of Element 2 are essential in enabling the GCDAMP to better organize and evaluate the scientific monitoring and research results provided by GCMRC.

**4.2. Deliverables**

Products from this project, led by Lucas Bair, will include annual reports to the GCDAMP, presentations at TWG and AMWG meetings when appropriate, presentations at scientific meetings, and peer-reviewed scientific journal articles. Reports and presentations specific to the research methods and results of **Element 1** will be provided to individual tribes as requested.

• In FY18–20, two manuscripts will be prepared from the results of Project Element J.1 for submission to peer-reviewed scientific journals.

• In FY18–20, three manuscripts will be prepared from the results of Project Element J.2 for submission to peer-reviewed scientific journals.

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1. **Budget**







Project K. Geospatial Science and Technology

1. **Investigators**

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1. **Project Summary**

The geospatial and information technology industries continue to change and expand at a rapid pace. Much of this growth is driven by advances in technology -- from improved sensors for monitoring the Earth to increased digital data storage capacity to newer computer systems designed for processing large data sets more efficiently to the greater emphasis of the “Internet of Things” where the reliance of web-based technologies have revolutionized our world. The purpose of this project is to continue to advance the Grand Canyon Monitoring and Research Center’s (GCMRC) ability to leverage many of these new technologies for the benefit of the Center, the science projects described within this work plan, and the larger Glen Canyon Dam Adaptive Management Program (GCDAMP) that they serve. Work performed within this project makes it possible to share important information about trends in resources of the Colorado River ecosystem to the GCDAMP through web-based, interactive tools and mapping products, allowing the GCDAMP to make informed, time-sensitive decisions on experimental and management actions under the 2016 Long-Term Experimental and Management Plan (LTEMP) and the associated Record of Decision (U.S. Department of Interior, 2016).

GCMRC continues to collect, store, process, analyze, and serve an ever-growing amount of digital data. Much of the data that now exists in the Center has a geospatial component to it. The importance of being able to effectively manage these data has never been greater as technological advances have increased both the demand and the expectancy of more open data availability. This project will continue to build and maintain systems that will handle these data needs, as well as provide high-level support to other science projects in the form of data processing, data management and documentation, geospatial analysis, and access to the Center’s data holdings. Maintaining and improving upon GCMRC’s capacity for providing this level of access will be crucial to effective decision-making during the implementation of the LTEMP.

1. **Background**

There exists a long legacy of spatial data being collected in support of science focused on studying effects of Glen Canyon Dam operations dating back more than 30 years. These data were often disparate between different science projects and certainly between studies focused on different resource types. Only in recent years, with the adoption of more modern Geographic Information System (GIS) and database software, and advancements in data sharing capabilities, has the scope of our research been able to become more integrated across disciplines and among different research efforts.

Data management has been a part of GCMRC since its inception, and was specifically outlined in the 1995 Environmental Impact Statement that clearly defines the Center’s responsibilities for managing data in support of the GCDAMP (U.S. Department of the Interior, 1995). The concept of data management encompasses many facets including, but not limited to, data preservation, design, development and maintenance of systems and applications designed to store and serve the data, building platforms that provide access to these data, and performing the necessary documentation of data sets. This work was also supported in the 1995 Record of Decision (ROD) – specifically in GCDAMP Goal 12, to maintain a high-quality monitoring, research and adaptive management program – and in subsequent documents including the most recent LTEMP EIS. During development of the LTEMP, GIS staff were very much involved with data dissemination to the EIS team, and this role will continue throughout the LTEMP implementation process. Success of LTEMP will rely heavily on the GCMRC’s ability to continue disseminate data to stakeholders, managers, and, when appropriate, to the public.

While this project is still adhering to its role as the lead in GIS application to science projects, additional roles have also accumulated as natural extensions to the geospatial science work over the past few years. The functions of data management was previously addressed within the Data Acquisition, Storage, and Analysis (DASA) program, however, since the reorganization of GCMRC in 2013 away from resource programs and towards a new, project-oriented focus, data management responsibilities are no longer centralized for the Center. Because of this reorganization, positions that traditionally focused primarily on GIS support have had to expand their roles to include data management oversight, as well as providing computer systems expertise, web server and internet technology leadership, the design, development and deployment of technologically-advanced scientific monitoring equipment and, most recently, the exploration into cloud-based data and application services. Some of this capacity has existed within GCMRC for more than a decade, but has not to date been sufficiently described within the context of a work plan. The project elements presented in Section 4 of this project proposal describe this increased capacity more fully.

In addition to its commitment to the GCDAMP and LTEMP, the GCMRC, as a part of the U.S. Geological Survey, must comply with federal guidelines governing many aspects of how geospatial data are collected and maintained by the Center. These aspects range from how specific data are to be collected, to accuracy standards established through federal policy – Federal Geographic Data Committee (FCDC), National Standard for Spatial Data Accuracy (NSSDA, FGDC, 1998), to how data are to be reviewed and released in conjunction with peer-reviewed scientific publications. This last concept is relatively new and is more fully described by the most recent USGS Fundamental Science Practices in response to an Executive Order that redefined the data release policies of federal agencies (U.S. Geological Survey, 2017). As the Geospatial Science project has increased its role in assisting with proper data management for the Center, work performed in this project will continue to lead efforts for adhering to these requirements.

**3.1. Products from Current Triennial Work Plan (FY2015-17)**

Over the last three years, a concerted effort was made to greatly improve upon GCMRC’s online presence, with special attention given to making peer-reviewed data sets and important mapping products made accessible through web-based tools and applications. Additionally, there has been a renewed effort in improving upon the how data are processed and managed within the Center and in direct support of science projects. Both of these aspects (data management and data accessibility) have been greatly improved during fiscal years 2015-17, despite having the Geographer position vacant for practically all of FY2016. Below is an outline of products developed by GIS staff that relate to advances in data management performance and online accessibility to data resources. Links are provided for viewing some of these items online.

1. Leverage Online Portals to Share Geospatial Data
   1. Hosting GCMRC Data via ESRI’s ArcGIS Online (See Section 6)
      1. GCMRC GIS staff have worked to build, maintain and periodically update web-based mapping services that provide access to many of the Center’s most commonly used GIS data sets.
      2. URL Link: <http://www.arcgis.com/home/search.html?q=GCMRC&t=content&restrict=false>
   2. Development and Deployment of the Grand Canyon GIS Portal
      1. GCMRC GIS staff have developed its own online GIS Portal designed to share and allow for collaboration on a suite of geospatial resources hosted by the Center. The portal now contains both commonly used base data such as aerial imagery collected during canyon-wide overflight missions and digital elevation model (DEM) data sets, as well as project-specific geospatial data including biological information from the citizen science light trap work and the recently published Channel Mapping topography/bathymetry data collected in 2009.
      2. URL Link: <https://grandcanyon.usgs.gov/portal/home/index.html>
2. Examples of Direct GCDAMP Support from GIS Staff
   1. Web Applications Showing Sandbar Response to High-Flow Experiments
      1. Work included the design and implementation of a light-weight, relatively simple process to quickly serve pre- and post-high flow experiment (HFE) photographs of sandbar sites. Responsible for the development and hosting of HFE-related photo viewing applications for the 2012, 2013, 2014 and 2016 HFEs released from Glen Canyon Dam.[[4]](#footnote-5)
      2. Links:
      3. 2016: <https://grandcanyon.usgs.gov/gisapps/sandbartour2016/index.html>
      4. 2014: <https://grandcanyon.usgs.gov/gisapps/sandbartour2014/index.html>
      5. 2013: <https://grandcanyon.usgs.gov/gisapps/sandbartour2013/index.html>
      6. 2012: <https://grandcanyon.usgs.gov/gisapps/sandbartour2012/index.html>
   2. 2016 HFE Web Application Showing Anticipated Inundation Areas
      1. Design and implementation of an interactive web mapping application that illustrated anticipated inundation areas in the context of other geographic features (tributaries, rapids, geomorphic features) and other GIS layers (campsites, river miles, day use areas, etc.).
      2. URL Link: <https://usgs.maps.arcgis.com/apps/webappviewer/index.html?id=721001c63d91458883340f05c68c55f4>
3. Recent Project-Specific Work in GIS / Database Development
   1. Geodetic Control Network Database and Application
      1. Designed to standardize both the storage and processing of Global Navigation Satellite System (GNSS) and total station surveys. The backend of the application is a SQL Server Express database which provides a central location for data to be stored and retrieved. By standardizing the storage and processing of GNSS and total station data and lessening the reliance on third party software more control is given to GCMRC to organize, visualize, analyze, and share our control network data.
   2. Processing of Remote Sensing GIS Derivatives
      1. The physical memory required to process and store GIS derivatives of remote sensing data presents challenges for standard GIS software and disk storage methods. These challenges were overcome by processing and storing the data within a spatially enabled database and building upon the database’s built-in functionality. A major benefit of this work is the processing time and storage footprint of the remote sensing derivatives has been greatly reduced leading to a more manageable workflow, data updating model, and data exporting functions.
   3. Sandbar Database and Web Application
      1. Updated existing web application and backend database to run within the U.S. Geological Survey’s Cloud Hosting Solutions. Through this process the serving of sandbar site photos was corrected and improved upon from the previous application and mapping capabilities were updated to utilize the most recent data. This work has provided a model for us moving forward to leverage the cloud hosting and computing power of cloud-based systems. This added functionality will allow us to deliver content through web applications in a more efficient and cost effective manner.

## 4. Proposed Work

### 4.1. Project Elements

#### Project Element K.1, Geospatial Data Analysis and Project Support

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To measure the amount of GIS support provided to all projects in the FY2018-20 Triennial Work Plan, we estimated the number of pay periods required of GIS professional staff to assist with geospatial related tasks for each project element. The level of involvement will be determined in consultation with principal investigators and other researchers for each project with specific geospatial processing, analytical tasks and associated writing assignments described within the appropriate project element. In some cases, senior GIS staff members are assigned as co-investigators to specific projects or project elements that require high-level geospatial application and analytical support. A tentative list of projects that are anticipated to receive this level of support include Sandbar and Sediment Storage (Project B), Riparian vegetation monitoring (Project C), Humpback chub monitoring (Project G), and Salmonid research (Project H). It is likely that other projects may be added to this list during the on-going planning process.

Outline of High-level Support Planned

1. *Sandbar and Sediment Storage*
   1. Serve as internal lead on sandbar database application that has currently been migrated to the USGS Cloud Hosting Solutions platform,
   2. Assist with high-level geoprocessing tasks including channel mapping processing and analysis,
   3. Application development and deployment for larger sandbar repeat photography collection,
   4. Assist with data collection efforts during channel mapping and other field missions.
2. *Riparian Vegetation Monitoring*
   1. Design and develop a riparian vegetation database from current spreadsheets of field collected data,
   2. Streamline data entry process and build in-field computer data entry program, assist with, and
   3. Improve upon current reporting process for determining data collect during site visits and change detection analysis.
3. *Humpback Chub Monitoring*
   1. Continued support for long-term monitoring of humpback chub in the Little Colorado River (U.S. Fish and Wildlife Service), and increased support for newer research conducted by GCMRC in the Little Colorado River.
   2. Support for passive integrated transponder (PIT) tag antenna array modifications and maintenance in the Little Colorado River
   3. Development of updated fish monitoring system to coincide with the need for more spatial resolute data for hoop net sampling and in previously unsampled reaches of the Colorado River.

Other science projects in the FY2018-20 Triennial Work Plan will likely require some level of support from the Geospatial Information and Technology project, however, this work may not be as intensive -- GIS layer development, brief training sessions for staff and cooperators, troubleshooting GIS and other software, data set queries and exporting, and map output generation for publications, presentations and field data collection efforts.

***A table is provided in Section 7 listing geospatial science and technology support planned for other science projects****.*

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

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Geospatial data management incorporates the organization and documentation of both file-based and server-based geospatial data. This needs to be a collaborative effort with GIS staff providing the lead through consultation on the best practices for organizing, storing, using, processing and documenting geospatial data, and GCMRC science staff adhering to protocols and best practices. Each project is unique, and how the geospatial data are organized is the responsibility of the principal investigator or another member of the project assigned as the data steward. This mostly speaks to file-based data (data stored in directories and folders). Server-based geospatial data are final versions of data sets stored within a relational database. These are enterprise-level data sets that range from canyon-wide data collection missions (overflight imagery, digital surface models) to long-term monitoring efforts (Fish Sampling Units, sandbar site and channel mapping topographic surfaces) to more localized reference layers (humpback chub sampling locations in the Little Colorado River). The GCMRC Oracle Spatial Database now contains over 2.5 terabytes of geospatial data, with more being added every year.

One major effort for this project element will be the continued development and deployment of an enterprise GIS system for GCMRC. This encompasses all the components of a full geospatial data content delivery system, and has several levels that are further described here. As previously mentioned, GCMRC maintains an Oracle Spatial Database for storing and serving its geospatial data. This will continue to be the case, and there are plans to stand up a separate, new Oracle Spatial Database that will serve first as a development server, but then will also provide the necessary failover required for providing the most consistently available data possible. The Oracle Spatial Database is the backbone of our enterprise GIS system.

By the end of FY2017, there will also be an internal ArcGIS Server and Portal server that will provide access to these data through services. Services will exist for much more than just individual data layers. New services will be developed that will allow for better place-name search capabilities, more advanced geospatial analysis tools, and better data downloading and map printing capabilities. This internal, content-serving platform will allow for better collaboration of data between staff in different science projects, and help standardize some data processing and map making workflows for the Center. Additionally, how science staff interact with spatial data will change. Data layers, maps, and geoprocessing functions will be made available through more consistent, web-based workflows, and other desktop applications, such as Microsoft Office, will be able to consume web-based maps directly. This will eliminate the need for basic users of geospatial data to even have GIS software installed on their computers – which in turn reduces costs for equipment and time spent by GIS and information technology staff on installation and troubleshooting tasks. Similarly, custom-designed software and applications may be designed for handling and serving geospatial and other data types that are often unique to the GCMRC, allowing scientists, managers and stakeholders to work with data without requiring specialized software.

Moving beyond just geospatial data, this project is poised to further assist with full database development for individual science projects currently lacking relational database support, and that are in dire need of better data storage, analysis, and access capabilities. Additionally, this project will initiate more advanced data processing and computational power through a newly acquired data processing server that leverages server hosted application technology which deploys applications and software from more powerful computer servers to the end users’ desktops and laptops. This new processing environment will be designed for advanced geospatial analysis and better performance on model processing conducted by GCMRC scientists.

Members of this project also serve as liaisons to the USGS data review process (Section 3), assist and train staff in metadata development, data management plan creation and adherence, and other work related to the data publication process. Additionally, this project will lead an effort for better implementation of source control procedures for project-based data processing, scripting and program development, software design and development, and development of web-based applications.

#### Project Element K.3, Access to Geospatial Data Holdings

Thomas M. Gushue, GIS Coordinator, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

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James Hensleigh, Geographer, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

Over the last three years, the GIS team has greatly increased GCMRC’s online presence through the ESRI cloud environment, ArcGIS Online (<https://www.arcgis.com/>), with maps, data layers and applications providing public access to important project-related work. This effort will continue with published data sets, web maps and applications being made available through this online platform. Similarly, this project will lead the Center’s effort to use other cloud environments for providing better access to its data and applications. The USGS Cloud Hosting Solutions is part of the USGS cloud environment that will allow for advanced cloud computing, application deployment and access to information through some of the most advanced data serving systems available today. The type of work performed by GCMRC GIS staff involves standardized source control of all application components, advance system configuration of both local desktop and server environments, and the proper deployment and management of AWS-based components. There are many benefits to leveraging these cloud environments for science applications. They offer scalable resources, many of which only cost the Center while the components are being accessed. The cost of server maintenance, security, data/application availability, storage, and redundancy are all managed by AWS, thus reducing the amount of time needed internally for GIS or information technology staff to perform these duties.

Expanding GMCRC’s online presence through cloud environments is only one, albeit a very novel, example of work conducted in this element. This project will continue to add online content for stakeholder and public consumption through custom-built web applications that are hosted on in-house servers. This work will include the continued efforts of maintaining the existing ArcGIS Server and Portal applications currently available through GCMRC’s website.

Portal URL: <https://grandcanyon.usgs.gov/portal/home/index.html>

New hardware to be developed will include a second, backup web server to allow for redundancy of web services and failover for potential downtimes of the current server. New services will include a custom geocoding service that will allow any mapping application to utilize a set of locations commonly used for site identification (i.e. names of sandbar sites / camping beaches, river miles, etc.). This will allow the GIS staff to maintain and manage river-based site locations more efficiently, and will improve performance of applications that offer geospatial search capabilities.

This project will also begin expanding its capabilities outside of only creating access to geospatial data sets. The project team will be involved with the development of online databases and software designed to interact with science project data. This work will include the development of relational databases designed specifically for particular science projects, and making some aspects of those databases available online.

***Element K.4, Remote Monitoring Systems and Technological Engineering***

Timothy Andrews, Physical Scientist, U.S. Geological Survey, Grand Canyon Monitoring and Research Center

This project element tracks the technical support and electrical engineering expertise provided to other research projects described in this work plan. The type of work performed in this element is varied and must at times adjust to respond to emerging needs within projects. Listed below are specific tasks with individual projects identified, where possible. Some work performed in this element inherently benefits the Center as a whole by improving upon the design and development of common components used by most remote monitoring systems deployed by GCMRC.

1. Work Benefitting the Center
   1. Design, build, test, deploy, or upgrade field equipment required for field operations; provide capability to implement emerging wireless communications technologies;
   2. Produce software programs to perform machine-to-machine, sensor-to-machine, human-to-machine, and machine-to-cloud communications;
   3. Provide power system design for solar-powered, autonomous field operations; write software programs to maximize automated acquisition and processing of large datasets.
   4. Participate in the design of an electroshocking equipment tester with the logistics department. Draft electrical schematics, recommend part purchases, and assist with equipment wiring and testing. (Logistics Support)
2. Project A. Streamflow, Water Quality, and Sediment Transport
   1. Provide technical expertise for communicating with, and controlling GCMRC sediment and water quality monitoring equipment.
   2. Provide radio frequency Wireless and Mobile-to-Mobile communications, Supervisory Control And Data Acquisition (SCADA) hardware and software, power distribution design and implementation.
3. Project G. Humpback chub population dynamics
   1. Provide hardware and software support for the existing Little Colorado River PIT-tag antenna array until it reaches end-of-life.
   2. Participate in the development, installation, and maintenance of a new “pinch-point” PIT-tag antenna array.
   3. Perform software installation and hardware integration for the new Little Colorado River rim computer.
4. Project H. Aquatic Ecology and Foodbase Monitoring
   1. Design, build, and maintain a cellular-based SCADA system for aquatic life monitoring in Glen Canyon

### *4.2. Deliverables*

1. Geospatial data sets, metadata documents, and map outputs in various forms in support of other projects.
2. Online web services that include data layers, interactive maps and custom web applications
3. Project-specific relational databases, and associated applications and software for interaction with those databases.
4. Documentation of standardized processes, source control workspaces, wikis, and publications related to these work elements.

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1. **Budget**







1. **Project Support**



Project L. Remote Sensing Overflight in support of Long-term Monitoring and LTEMP

1. **Investigators**

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1. **Project Summary**

This project seeks to collect system-wide, high-resolution multispectral imagery and a Digital Surface Model (DSM) of the Colorado River corridor from the forebay of Glen Canyon Dam downstream to Lake Mead, and along the major tributaries to the Colorado River. The proposed schedule for this data collection mission would be in May of 2020, during the third year of this Triennial Work Plan (TWP). The data sets derived from previous remote sensing overflights have proven to be extremely valuable to many of the research projects conducted by the U.S. Geological Survey Grand Canyon Monitoring and Research Center (GCMRC) over the past two decades (Draut and Rubin, 2008; Grams and others, 2010; Ralston and others, 2008; Sankey and others, 2015a; Sankey and others, 2015b). More importantly, scientific research which relied heavily on these data were the basis for the 2016 Long-Term Experimental and Management Plan (LTEMP) planning and will be used in the Record of Decision (ROD) implementation process (U.S. Department of Interior, 2016).

The LTEMP states sediment as a resource of key interest and is a primary driver for many of the proposed flows defined in the LTEMP ROD. Specifically, the document describes the long-term effects of High Flow Experiments (HFEs) and other dam operations on sandbar deposition and rehabilitation, an aspect in which strategically collected aerial photography could enhance by providing greater context and understanding of trends measured through the Sandbar and Sediment Storage Monitoring and Research project (Project B). This includes remote camera photographs, topographic surveys conducted at the long-term monitoring sandbar sites, and extended, reach-based channel mapping surveys. Derived data sets classifying system-wide areas of exposed sand will assist these field-based methods in quantifying sediment storage throughout the Colorado River ecosystem (CRe) on a decadal time scale. Additionally, elevation data from the DSM surface will be utilized in conjunction with the topographic and bathymetric data collected during channel mapping surveys (Project B.2) to develop full channel geometry maps for specific segments of the river, allowing for more complete volumetric calculations and improved hydrologic flow modeling of the system over time.

The importance of cultural resources is described in the LTEMP objective and resources. Similar to the sediment storage project, the overflight imagery and derived data sets will play an important role in measuring and tracking changes in sand for cultural resource preservation as defined in LTEMP (East and others, 2016). An imagery data set collected during this TWP would provide the next necessary time interval for future inventory and monitoring of these sites.

Riparian vegetation has also been identified as a key resource in the LTEMP. The ability for researchers (Riparian Vegetation Monitoring, Project C) to monitor changes in woody riparian vegetation in response to dam operations is dependent upon the acquisition of new imagery data sets that are consistent with those previously collected (Sankey and others, 2015b). Data collection needs to conducted at a time interval that allows researchers to track key vegetation behaviors such as, encroachment onto sandbars, a process known to cause channel narrowing (Dean and Schmidt, 2011) and quantify the reduction in exposed sand area (Kasprak and others, 2017). Lastly, classifications derived from the imagery data will be used to detect vegetation succession at the landscape-scale for woody species and some obligate herbaceous riparian species (Ralston and others, 2008). Strategically planning the appropriate time interval for future missions provides optimization of measurements on the long-term response of riparian vegetation to dam operations under the new LTEMP and the preferred alternative.

Fish monitoring efforts occurring in the Colorado River downstream of Glen Canyon Dam, in the Little Colorado River downstream of Blue Springs, and in other Colorado River tributaries in Grand Canyon now use the current overflight data (Durning and others, 2016) for spatial positioning of sampling data, navigating waterways and side canyons, and recording contextual site information. Colorado River fish sampling since 2012 has been based on a Geographic Information System (GIS) reference system derived from the two most recent remote sensing imagery data sets (Yard and others, 2016). While a new imagery data set collected in 2020 may not warrant updating the existing mainstem fish sampling system, the new imagery will certainly be used as a critical data reference for the next five to seven years of fish monitoring.

Use of the proposed May 2020 imagery data set is a distinct and important tool that assists many of the proposed projects in this TWP. The overflight is a resource that has immediate and a decadal trend payoff. For these reasons, this project is mission critical to successfully inform the Glen Canyon Dam Adaptive Management Program (GCDAMP) on performance of the LTEMP ROD.

1. **Background**

The physical, environment and geographic setting of the Colorado River in Grand Canyon has always provided a constant challenge to monitoring resources of the CRe. Remote sensing provides the means for obtaining valuable information on resources and phenomena that span large geographic areas and found in rugged, often inaccessible environments. There have been numerous remote sensing overflight missions conducted in the CRe in Grand Canyon over many decades (Davis, 2002), with a systematic and concerted effort put forth during GCMRC’s tenure as the science provider of the GCDAMP. As the GCDAMP enters its next phase under the new LTEMP, there remains a need to effectively monitor CRe resources holistically and at a temporal increment that provides meaningful information to the program as it relates to LTEMP implementation over the next 20 years.

GCMRC’s Scientific Monitoring Plan in support of LTEMP, notes that the ROD “calls for a comprehensive, decadal-scale assessment of the impact of dam operations on sandbar resources and on the status of humpback chub” (Vanderkooi and others, 2017). Given the physical, geographic and logistical constraints of the study site, it is evident that a need still exists for remotely-sensed data to complement ground-based data collection and assist with the Center’s efforts to effectively assess these impacts for the entire system over decadal time frames. While this proposed work is discussed within the context of the next TWP, the nature and justifications for conducting the next overflight is directed at the Center’s ability to respond to and deliver information for the LTEMP implementation process that tracks decadal-scale changes to resources system-wide. It is also anticipated that future LTEMP studies will require similar information that can be effectively derived from remotely-sensed data acquired over the next two decades.

GCMRC has historically conducted remote sensing overflight missions to collect high-resolution aerial photography in support of scientific research focused on many of the key resources of concern within the CRe. A remote sensing initiative conducted from 1999 through 2000 determined the most appropriate technologies and methods for acquiring high-resolution imagery to document the status of resources and analyze canyon-wide changes to these resources over time (Davis, 2002; Davis and others, 2002). From this effort is was concluded that acquiring digital imagery every four years for the entire length of the Colorado River between Glen Canyon Dam and Lake Mead would be the most appropriate time frame for mapping and performing change detection analysis on these key resources. This led to a series of remote sensing overflight missions conducted in years 2002, 2005, 2009 and 2013 (Davis, 2012, 2013; Durning and others, 2016). Positional accuracies and data integrity of the imagery certainly improved with each subsequent mission during this era. It also became apparent, however, that a quadrennial overflight time frame was resource intensive; in the last TWP we postponed the overflight mission to evaluate our collection window and discover the LTEMP recommendations. After evaluation of the LTEMP ROD we suggest a five- or six-year mission interval would best serve implementation of the ROD.

Listed here are key image products since 2002 and an example of how they have been used:

* *Cartographic products (i.e. River map books) -* Used by all projects with field-data collection component that require high-resolution, spatially accurate features.
* *Colorado River Centerline and River Mile System -* The river mile system was updated based on 2009 and 2013 imagery to reflect the drop in Lake Mead and subsequent “new’ river channel that emerged between River Mile 260 and Pearce Ferry (now at River Mile 281). Lees Ferry is river mile zero and count increases in a downstream progression.
* *DSM -* Merged with bathymetric and topographic data to generate a full channel geometry data set used for hydrologic flow modeling, and to determining low-angle slope characteristics of near-shore environments in Glen Canyon (Kaplinski and others, 2014). Used to asses gully annealing and the effects on active sand (Sankey and Draut, 2014).
* *Geomorphic Base Map -* Classification of channel eddy and geomorphic deposits relative to bounding channel features.
* *Modeled Flowlines -* The DSM from the 2002 overflight mission was used to delineate estimated elevations of modeled flows for the Colorado River between Lees Ferry and Diamond Creek (Magirl and others, 2008).
* *Shoreline -* Extract water surface from imagery that serves as an important boundary layer that demarks the water edge of the river at 226.5 m3/s (8,000 ft3/s) , this layer was used as the basis for delineating the current fish sampling units used by most monitoring efforts in the mainstem (Durning and others, 2017a, *data release*)
* *Land cover classification -* Map exposed sand and other geologic/geomorphic features from the imagery for an expanded set of regions of interest.
* *Vegetation classification -* Monitor and track changes in total vegetation, vegetation-sand dynamism and vegetation succession (Ralston and others, 2008; Durning and others, 2017b, *data release*).

1. **Proposed Work**

### Project Elements

***Project Element L.1, Remote Sensing Overflight in Support of Long-Term Monitoring and LTEMP***

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It is proposed that GCMRC conducts a system-wide remote sensing overflight to collect digital, multispectral imagery of the CRe between Glen Canyon Dam and Lake Mead in May 2020. To maintain consistency with previously collected digital, orthorectified aerial imagery (2002, 2009, 2013), we recommend that this mission be conducted during the same time of year (Memorial Day weekend) and adheres to much of the same data collection parameters and significant logistical requirements as used in preceding missions. For data collection parameters, we require at least the same 4-band wavelength ranges (red, green, blue, and near infra-red), using the same or similar equipment (Leica ADS-80 camera mounted in fixed-wing aircraft), with the option of two cameras and aircraft being made available to increase the rate of data collection, and reduce the impact on dam operations. Wavelengths and other technical details will be specified with the Scope of Work contract and similar to or improved upon those used in previous data collection efforts. The proposed 2020 overflight would be within the LTEMP flow regime, we would request from and work with the Bureau of Reclamation and Western Area Power Administration to maintain a low steady flow of 226 m3/s (8,000 ft3/s) for the duration of the data collection period. This flow adjustment is required to maintain consistency in imagery data sets collected in previous years. This will allow for highly accurate image matching and change detection analysis. If a spring HFE occurs in 2020, we will work closely with other GCMRC scientists and the Bureau of Reclamation to ensure all needs are met. We would not expect the presence or absence of a fall HFE in 2019 to affect the proposed May mission. As the LTEMP states, ‘triggers for a fall HFE would be met 77% of the years in the LTEMP period’, thus we conclude fall HFEs would be a part of the decadal measurement trend.

**4.2. Deliverables**

As the data collection mission is tentatively scheduled to be conducted in the 3rd Quarter of the third year of this work plan, most deliverables are not to be expected until at least midway through the first fiscal year of the next proposed Triennial Work Plan (FY2021-2023). There can be expected, however, an overflight post-mission report that includes specifics on the success of the mission and possibly a tentative timeline for when products will be made available from 1) the entity contracted with to collect the data, and 2) GCMRC staff performing the post-processing of imagery and development of derived data sets.

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1. **Budget**







Project M. Administration

The Administration budget covers salaries for the administrative assistant, librarian, budget analyst, the three members of the logistics support staff, and leadership personnel for Grand Canyon Monitoring and Research Center (GCMRC). Leadership personnel salaries include those for the GCMRC Chief and Deputy Chief as well as half the salary for one program manager. Travel and training includes most of the travel and training costs for administrative personnel and the cost of GCMRC staff to travel to AMWG and TWG meetings. Operating expenses includes 1) GSA vehicle costs including monthly lease fees, mileage costs, and any costs for accidents and damage; 2) DOI vehicle costs including gas, maintenance, and replacements costs; 3) GCMRC’s Information Technology equipment costs; and 4) a $20,000 annual contribution to the equipment and vehicles working capital fund.

**Budget**







**Appendix 1. Lake Powell Water Quality Monitoring**

A proposed statement of work has been submitted to the Bureau of Reclamation to continue Lake Powell water quality monitoring. The proposal is under review and will be included in the final draft of the workplan pending approval.

**Appendix 2a. Potential Budget Allocation Summary by Project and Year**



**Appendix 2b. Potential Budget Allocation – FY2018**







**Appendix 2c. Potential Budget Allocation – FY2019**







**Appendix 2d. Potential Budget Allocation – FY2020**







1. In this proposal, we use “monitoring site” to refer to monitoring locations that are at the scale of individual sandbars, 100’s of meters in length. We use “short reach” to refer to study reaches that include many sites and are on the order of 2 to 5 km in length. We use “long reach” or “sediment budgeting reach” to refer to segments of the river that encompass the entire channel between fine-sediment monitoring gages; these reaches are 50 to 130 km in length. [↑](#footnote-ref-2)
2. Deemer, B.R, C.B. Yackulic, R.O. Hall, T.A. Kennedy, and J.D. Muehlbauer., 2017, Lake Powell nutrient dynamics are a lever on food webs near the Little Colorado River—Annual reporting meeting presentation for FY16—January 26-27, 2017; Phoenix, Ariz., U.S. Geological Survey, Grand Canyon Monitoring and Research Center, Bureau of Reclamation, Glen Canyon Adaptive Management Program, poster. [↑](#footnote-ref-3)
3. River miles downstream from Lees Ferry (river mile 0). [↑](#footnote-ref-4)
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