

Grand Canyon Monitoring and Research Center Water-Quality Program Review

September 2017

The U.S. Secretary of the Interior established the Glen Canyon Dam Adaptive Management Program (GCDAMP) in early 1997 to implement the Grand Canyon Protection Act of 1992 (US Department of the Interior, 1992). The GCDAMP advises the Secretary on the effects of Glen Canyon Dam operations and management actions on the values for which Grand Canyon National Park and Glen Canyon National Recreation Area were established. Programs focus on key resources in and alongside the Colorado River and its tributaries in Glen, Marble, and Grand Canyons, Arizona, between the Glen Canyon Dam (GCD) forebay and Lake Mead. The Glen Canyon Dam Long-Term Experimental and Management Plan (LTEMP) is the most recent adaptive management plan for the Colorado River ecosystem (U.S. Department of Interior, 2016a). The selected alternative identified in the LTEMP Record of Decision (ROD) (U.S. Department of Interior, 2016b) describes various data collection, analysis, modeling, and interpretation efforts to be conducted by the U.S. Geological Survey's (USGS) Grand Canyon Monitoring and Research Center (GCMRC).

The GCMRC is the primary science support agency for the GCDAMP. As the lead science provider, the USGS was required to develop a science plan for implementation of the LTEMP (Vanderkooi and others, 2017). In accordance with the science plan, the GCMRC periodically convenes independent review panels to assess the quality, comprehensiveness, and need for various research and monitoring programs. Periodic reviews of various areas of GCMRC's work, including the water-quality program, have been conducted in the past. The last water-quality review was completed in 2001. A review of the water-quality program was recommended as a work element in the FY 2015-2017 triennial work plan of the GCMRC and funding for it was provided under the GCDAMP. The work proposed herein satisfies this recommended work element.

Ongoing Water-Quality Monitoring Program

Water-quality data have been collected in various areas of Lake Powell and the Colorado River by the USGS and the U.S. Bureau of Reclamation (BOR), with assistance from the National Park Service (NPS), since 1964. Early analyses of water quality data emphasized the role of advective mixing in determining the distribution of solutes within the reservoir (Gloss and others, 1980) and the development of oxygen minima in the reservoir metalimnion (Johnson and Page, 1981). Since the mid-1990s, the GCMRC and the BOR have continued water quality monitoring under a cooperative agreement funded via the Water Quality group in the Upper Colorado Regional Office of the BOR. The water-quality

monitoring program is currently designed to address the status and trends in the quality of water in Lake Powell and of water released from the GCD.

The ongoing Lake Powell water-quality monitoring program consists of monthly surveys of the forebay and tailwater (conducted by GCMRC and NPS) and quarterly surveys of the entire reservoir, including the Colorado, San Juan, and Escalante arms of the reservoir to the inflow areas (conducted by BOR, GCMRC, and NPS). The GCD forebay station is located approximately 2.4 km upstream from the dam. Two tailwater sites are located downstream from the dam, one immediately downstream and one at Lees Ferry, approximately 25 km downstream. Depending on reservoir elevation, 21-37 established sites, including the forebay and tailwater stations, are sampled during the quarterly surveys. At each site, initial surface observations (for example, bottom depth, Secchi depth, weather observations) are recorded, after which a depth profile of temperature, specific conductance, dissolved oxygen, pH, redox potential, turbidity, and chlorophyll fluorescence is collected using a Seabird SBE19plusV2. The data are downloaded immediately after collection and viewed in the field to determine stratification patterns. At each site, chemical samples for major ionic constituents and nutrient concentrations are collected one meter below the surface and one meter above the lake bed. Under stratified conditions, samples are also collected from above and below the thermocline and additional depths are sometimes sampled if other chemically distinct layers are observed. Dissolved organic carbon samples are collected at the forebay, tailwater, and tributary inflow sites. Biological samples for chlorophyll concentration as well as samples for phytoplankton and zooplankton species identification are also collected at selected sites. Samples are filtered and preserved in the field for subsequent laboratory analysis.

Analyses for major ion, nutrient, and chlorophyll concentrations are performed by BOR's Lower Colorado Regional Laboratory in Boulder City, NV. Phytoplankton and zooplankton samples are analyzed under contract by BSA Environmental, Inc. Processing of the Seabird profile data is performed in the office after the field survey. All field and analytical data have historically been entered into a database (referred to as WQDB) for analysis and long-term storage. Details of the monitoring program, a description of the WQDB database, and physicochemical data from 1965-2013 are available in a USGS Data Series report (Vernieu, 2015).

Water quality monitoring data from Lake Powell have been used to develop a CE-QUAL-W2 model of water column temperature, conductivity, total dissolved solids (TDS), and dissolved oxygen (Williams, 2007). This model is run in forecasting mode monthly by the BOR and results are reported to the BOR Upper Colorado Region Water Resources group. Model results are also shared with the GCDAMP and can be used to inform management decisions. The water-quality monitoring program has also supported, to varying degrees, a host of work by both GCMRC researchers and independent scientists. Topic areas include, but are not limited to; the role of HFES in altering downstream water quality (Hueftle and Stevens, 2001; Vernieu, 2010), the role of storms in changing the clarity of Lake Powell outflows (Wildman and Vernieu, 2017), and the potential role of deltaic sediments as a source of phosphorus loading to Lake Powell (Wildman and Hering, 2011).

Current work being conducted by GCMRC on Lake Powell water quality focuses on analysis of historic data with the eventual goal of constructing a model of outflow soluble reactive phosphorus concentrations from the dam. Historical data analysis will ideally inform new work to identify factors that control phosphorus cycling in Lake Powell such as the role of deltaic sediments, inflows, water level, wind regime, and quagga mussel establishment. The current interest in Lake Powell phosphorus dynamics is driven largely by evidence that soluble reactive phosphorus availability at the GCD outflow controls rates of primary production, aquatic insect availability, and native fish condition in the Colorado River downstream of the dam (Yackulic, 2017). There is also a growing appreciation for the important of interactions between temperature and food availability in ultimately determining fish responses (Dodrill and others, 2016). This makes temperature predictions from the Lake Powell outflow also relevant to downstream work on fish ecology conducted by GCMRC.

Finally, there has been some effort to characterize contaminants in Lake Powell. This work has focused on hydrocarbons, mercury, and selenium. A survey of polycyclic aromatic hydrocarbons in Lake Powell from 2010-2011 revealed dissolved concentrations of phenol >5 µg/L (Schnonauer and others, 2014). Phenol is an EPA primary pollutant but the concentrations documented in Lake Powell are still well below aquatic life criteria (600 µg/L as a 24 hour average) and human health criteria (3.4 mg/L, (U.S. Environmental Protection Agency, 1978). Mercury and selenium were also sampled in organic matter, invertebrates, and fish in the Colorado River and concentrations of these contaminants were found to be relatively high compared to other large rivers (Eagles-Smith and others, 2014; Walters and others, 2015). These contaminants can be toxic to fish and wildlife, appear to biomagnify through the food web, and likely have sources far removed from the observed sinks. Utah and Arizona have issued a mercury consumption advisory for Striped Bass (*Morone saxatilis*) in Lake Powell downstream of Dangling Rope Marina.

Purpose of Water-Quality Program Review

The purpose of this water-quality review is to satisfy requirements under the GCDAMP that the science work of the GCMRC receive periodic independent review. Some important questions that should be addressed by this water-quality review include: 1) what is the status of water quality in Lake Powell and the Colorado River downstream of the GCD and how does it vary over time, 2) how might water quality in Lake Powell and the Colorado River downstream of the GCD change in the future, and 3) how might management of the GCD affect water quality in Lake Powell and the Colorado River downstream of the GCD both now and in the future. The GCDAMP has historically been focused on these questions as they pertain to water in the GCD forebay and outflow from the reservoir. This focus is due to the obvious effects that the dam has on tailwater resources. However, the GCDAMP is also interested in understanding how management decisions regarding GCD impact water quality downstream of the dam. Some management actions that might water quality include: seasonal timing of discharge, variation in reservoir storage, and height of water withdrawal. These research questions must be balanced by the broader water-quality goals of the BOR which include: a mandated biennial progress report on the water quality of the

Colorado River Basin (via the Colorado River Storage Project Act) and an understanding of salinity dynamics in Lake Powell as they relate to the Salinity Control Act.

In order to satisfy GCDAMP requirements, the panel selected as part of this water-quality review is asked to address the 5 questions posed by the GCMRC below. These questions address various characteristics of the program including: the spatio-temporal resolution of monitoring activities, modeling capabilities, data analysis and experimental research priorities, and field sampling methodology. The aim of this review is to provide the GCMRC with the guidance they need to ensure that the science information produced is of the highest quality. The results of the panel and its recommendations will help to inform future water-quality work of the GCMRC as it implements the next Triennial Work Plan for fiscal years 2018-2020 (US Bureau of Reclamation, 2017).

Key Questions

- 1. How does our ability to model dissolved oxygen, temperature, nutrients, and conductivity in both Lake Powell and in its outflow compare to predictive capability in other systems using the same or different modeling approaches? What, if any, improvements can we make on our current modeling techniques?**

In the past, the Bureau of Reclamation has employed several models to predict water-quality conditions in the Colorado River system including RiverWare™ for modeling salinity and CE-QUAL-W2 for modeling water surface elevations, velocities, temperatures, and water quality constituents (US Bureau of Reclamation, 2006; Williams, 2007). These models have been very helpful to managers and scientists as they provide water quality projections and also support visualizations of water quality from the inlet to the outlet of the reservoir. For future work, there is general interest in developing a model that can predict phosphorus export at the Glen Canyon Dam outlet. A recent water quality knowledge assessment for Lake Powell and the Colorado River downstream of the GCD highlighted some uncertainty associated with our ability to predict temperature and dissolved oxygen at the Lake Powell outflow (Braun, 2017). The CE-QUAL-W2 model predicts temperature and dissolved oxygen with a mean accuracy of 0.5°C and 1.15 mg/L dissolved oxygen (Williams, 2007), but there is often more error at the height of the penstock given that it is frequently located within the reservoir metalimnion. For example, we sometimes observe differences between predicted and observed values that exceed 3 mg/L dissolved oxygen and 2 °C. We are interested in obtaining guidance concerning the best modeling approaches moving forward. Specifically, this over-arching question includes the following additional questions:

- a. Should phosphorus dynamics be modeled via CE-QUAL-W2, or some other modeling platform? The open source General Lake Model (<http://aed.see.uwa.edu.au/research/models/GLM/>), for example, could be coupled with the Framework for Aquatic Biogeochemical Models (Bruggeman and Bolding, 2014) to simulate P dynamics, but such a model would require more vertically resolved data. We would like guidance

regarding the most appropriate modeling platforms to: 1) predict phosphorus concentrations at the Lake Powell outflow, and 2) better identify the mechanisms that control or influence phosphorus concentrations.

- b. Do we have sufficient data to create mechanistic models for water quality parameters in Lake Powell? If not, what additional data should be collected?
- c. Should a model be developed that would link temperature between the lake and the river? This type of predictive capability would be especially important if temperature control methods are employed in the dam intakes as is recommended under the LTEMP ROD.
- d. CE-QUAL-W2 provides an excellent modeling platform for predicting whole-lake temperature and dissolved oxygen profiles, especially given the advection-based hydrodynamics in Lake Powell. However, is this model the best choice for estimating temperature and dissolved oxygen at a single point such as the dam outflow? More specifically, is the degree of accuracy of CE-QUAL-W2 in predicting outflow temperature and dissolved oxygen comparable to that attainable via other modeling approaches?

2. How should analysis of the historical dataset be prioritized to improve our understanding of how management actions and natural mechanisms affect phosphorus dynamics in Lake Powell?

While both nitrogen (N) and phosphorus (P) are known to be important limiting nutrients in freshwater ecosystems, exceptionally high N:P ratios in the Colorado River ecosystem suggest that P is the most limiting in this system. Soluble reactive phosphorus (SRP), the most bioavailable phosphorus, is an important driver of whole-ecosystem dynamics. Preliminary data suggest that declines in SRP availability at the outflow from Glen Canyon Dam over the last five years have propagated through the entire aquatic food web. This decline in SRP has 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 SRP concentration than by models that include flow variables alone. An improved understanding of phosphorus dynamics in Lake Powell could inform conditions under which higher concentrations of SRP are exported from the reservoir.

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 and others, 2015). Available evidence suggests Lake Powell is functioning as a net phosphorous sink given higher concentrations of phosphorous in the reservoir inflows than in the outflow. In particular, Lake Powell outflows often have very low concentrations of SRP that also vary substantially through time. The recent water-quality knowledge assessment highlighted the importance of an enhanced understanding of the mechanisms that control or influence nutrient concentrations in Lake Powell.

Given the large volume of historical nutrient data available for Lake Powell, the river outlet works, and Lees Ferry, and given that there has been relatively little analysis of that data, GCMRC plans to spend time assessing spatial and temporal trends in nutrient concentrations and potential environmental drivers of nutrient availability. We then plan to follow up with targeted experimental work as informed by this historical data analysis. Below we have summarized some ideas pertaining to analysis and experimental work.

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 re-inundated. It has been hypothesized that inundation of these sediments may lead to surges of SRP flowing out of the deltas into Lake Powell (Wildman and Hering, 2011). In many systems, P release during re-inundation is driven by shifting redox conditions, wherein iron-bound P is released as water becomes anoxic (Boström and others, 1988; Kinsman-Costello and others, 2014). In Lake Powell, this mechanism is not likely to be very important since iron-bound P makes up only a very small fraction of the total P in deltaic sediments (Wildman and Hering, 2011). Instead, the mineralization of organic P under dry conditions (when sediments are more aerobic) may produce a sizeable, loosely bound, and easily exchangeable SRP pool that can be mobilized into the water column upon re-inundation. In fact, previous characterization of sediment P fractions in Lake Powell's sediment delta show that a sizeable fraction of P is bound to organic material (Wildman and Hering, 2011). P mobilized from deltaic sediments is most likely to be transported towards the dam in spring when there is less biological uptake of SRP within the reservoir 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 metalimnion and hypolimnion waters, leading to increased SRP discharge at Glen Canyon Dam. However, an alternative hypothesis is that high inflow nutrient loading itself may bring high concentrations of SRP into Lake Powell. Distinguishing between the potential sources of SRP is important for predicting how climate, water policy, or both may affect overall phosphorous cycles in Lake Powell.

To understand the fate of nutrient loading to Lake Powell's inlets, GCMRC is currently using the USGS program LOADEST in combination with historic discharge and nutrient concentrations (records generally exist from 1990-2000) from the NWIS stations: Green River at Green River, Colorado River near Cisco Utah, and San Juan River at Bluff. Modeled riverine nutrient loading for this decade will be compared to nutrient measurements in the Lake Powell dataset to look for an advective signal of riverine nutrient loading and to create a reservoir-wide phosphorus budget. Given the capacity for co-precipitation of phosphorus with calcite in other lake ecosystems (Hamilton and others, 2009) and given that the geochemistry of Lake Powell appears to favor calcite formation (Reynolds and Johnson, 1974), GCMRC plans to use the long term dataset to look for relationships between phosphorus concentrations and factors that control, or are influenced by, calcite deposition including: chlorophyll *a*, pH, bicarbonate [HCO_3^-], conductivity, alkalinity, turbidity, and secchi depth. Finally, we will look for spikes in Lake Powell phosphorus concentrations during years where a high inflow event follows particularly low water level conditions. After mining the historical database, targeted field incubations could be conducted to better understand within-lake phosphorus cycling.

In addition to exploring in-reservoir drivers of phosphorus cycling, the potential for experimental flows, as recommended by the GCDAMP, to modify downstream nutrient regimes will further be examined by conducting targeted nutrient sampling before, during, and after experimental flows. Previous sampling efforts have documented the capacity for changes in flow at GCD outlets to affect the chemistry of water below the dam. For example, work by Hueftle and Stevens showed that the 1996 spring high flow event diminished bottom water hypoxia in Lake Powell as far as 100 km uplake while also resulting in high salinity, high oxygen concentrations, and damped dissolved oxygen (DO) and pH fluctuations in the dam tailwater (Hueftle and Stevens, 2001). Nutrient data collected 4 days before and 2 days after the high flow event showed drops in phosphorus concentration at both the penstock and river outlet works, 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 high flow experiment also showed elevated DO concentrations downstream of the dam (at maximum 120% of saturation), but relatively minimal effects on the structure of the water column upstream of the dam (Vernieu, 2010).

3. Is current monitoring being conducted at an appropriate number of depths and/or sites and at an appropriate temporal frequency to give accurate information on the current status and trends of water-quality conditions and to inform predictions using either the current modeling approach or a potentially improved model?

With respect to nutrients, the current monitoring program places more emphasis on horizontal spatial resolution (e.g. >10 sites sampled for nutrients and ions) than on vertical

resolution. For example, nutrients are collected only from the surface and bottom DEPTHS with an additional sample or two collected mid-water column during stratified conditions. Will the current vertical data resolution allow us to effectively model SRP concentrations at the Lake Powell outflow? In addition, is the current laboratory reporting level of SRP sufficiently low to detect changes associated with changes in the management of GCD?

4. Are there additional types of measurements or newer methodologies that should be incorporated into the routine monitoring program?

The current water quality monitoring program conducts a series of 21-37 profiles quarterly using a Seabird Electronics SBE19plus-V2 equipped with sensors for temperature, pressure, conductivity, pH, oxidation reduction potential, DO (SBE 43 membrane-type sensor), chlorophyll *a* (WET Labs Fluorometer ECO-AFL/FL), and turbidity (WET labs ECO-NTU). At a subset of these sites, filtered and unfiltered water samples are collected and preserved for analysis of a suite of nutrients and major ions (TSS, TDS, Ca, Mg, Na, K, CO₃²⁻, HCO₃⁻, Cl⁻, SO₄²⁻, SiO₂, CaCO₃, TP, SRP, NH₃, NO₃⁻+NO₂⁻, and TKN). Dissolved organic carbon samples are collected at the forebay, tailwater, and tributary inflow sites. Samples for analysis of dissolved metals are collected at least once yearly (usually in the summer) from the major inflows, confluences, sites where previous anomalies have been noted, and from near the outflow. With the exception of the inflow sites (which are sampled 1m below the surface) metal samples are collected from one meter off the bottom of the lake bed. Net tows and surface water sampling at these sites support analysis of phytoplankton and zooplankton assemblage and abundance as well as filter-based quantification of surface water chlorophyll *a* concentrations. Currently, the most utilized measurements in this dataset are those that the CE-QUAL-W2 model requires including; temperature, salinity, DO, TDS, and phytoplankton. Dissolved solute data, however, could support hydrodynamic and geochemical models that would likely improve our understanding of nutrient cycling in the system.

The quarterly sampling effort consumes a significant amount of time (5+ days) and resources and thus the relative cost/benefit of additional measurements should be considered. In addition to the whole-reservoir quarterly sampling, more targeted monthly sampling at the dam forebay, penstocks, and below the dam is also conducted. Below, we list some additional methodological questions for the panel to consider:

- a. Should we switch the current membrane-type DO sensor for an optical DO sensor? Currently the SeaBird is only calibrated once a year, so an optical DO sensor may provide for more stable calibration.
- b. With the recent interest in reservoir phosphorus cycling (as well as nutrient availability more broadly), should grab nutrient sampling be supplemented and/or modified in any way? In particular, would the use of a HydroCycle-P04 (<http://wetlabs.com/hydrocycle>) wet chemistry phosphate sensor (2.3 ug P/L detection limit) be feasible and informative towards efforts to model

P availability in reservoir outflows? Also, should we add total dissolved phosphorus to the current suite of analyses conducted?

- c. The BOR installed a thermistor string at the GCD forebay in 2012, but the string was lost in 2016 and has not yet been replaced. Could the installation of thermistor and conductivity loggers help inform Lake Powell modeling efforts? If so, at how many sites and depths should these be deployed?
- d. Are continued filter-based measurements of chlorophyll *a* concentrations necessary or are they redundant with newer probe-based estimates of chlorophyll *a* concentrations?
- e. Should the program consider periodic collection of data on any additional contaminants in water from sites above and below the Glen Canyon Dam? If so, which contaminants would be most relevant to examine?
- f. The analysis of plankton data has been extremely limited up to this point. The 2001 PEP recommended that plankton sampling be limited to quarterly samples at Wahweap, a mid-lake site, and an up-lake site (Jones and others, 2001), but this sampling reduction was not incorporated. Should the program consider cutting the amount of plankton sampling? Or is the current quagga mussel invasion grounds to continue with the current sampling regime?
- g. Are DOC samples giving us valuable data? Should this sampling be expanded or discontinued? Similarly, should we explore the utility of adding a CDOM (colored dissolved organic matter) sensor to the SeaBird?
- h. Currently there is no detailed protocol for QA/QC. Typically one QA/QC sample is collected for every 20 field samples which includes a duplicate of the field sample and a trip blank, field blank, or equipment blank. Reagent spikes have also been created in the past. Are these current QA/QC practices adequate?
- i. The previous water-quality review panel recommended a weather station be setup from a dock at the Wahweap site and suggested that ancillary wind speed and direction data be collected from the roofs of the floating restrooms spread throughout Lake Powell (Jones et al. 2001). This recommendation was not followed, so we do not have a good understanding of how representative the weather station at the Page airport is for over-lake conditions. Should we consider installing a weather station?
- j. The previous water-quality review panel suggested that nutrient data should be collected at the gaging stations for Lake Powell's primary inflows (on the San Juan, Green, and Colorado Rivers). This would provide a stationary inflow site given that the inflow sites within the reservoir move each trip (as they are dependent on water levels). Should we consider adding this sampling?

Suggested Priority Reading List

- Braun, D.P., 2017, GCDAMP FY 2017 Knowledge Assessment--final report from the executive coordinator for the Science Advisors Program: Glen Canyon Dam Adaptive Management Program (GCDAMP), Science Advisors Program, Technical Work Group (TWG): 36 p., http://gcdamp.com/images_gcdamp_com/2/26/GCDAMP_FY_2017_Knowledge_Assessment-Science_Advisor_Program_Final_Report_2017-04-30.pdf
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Expanded Reading List

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