

Glen Canyon Dam Adaptive Management Program
Science Advisors-Executive Coordinator Program
Review of the GCMRC FY2018 Annual Report

David P. Braun, Ph.D., and Robert S. Unnasch, Ph.D.
Sound Science LLC, March 27, 2019

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I. Introduction

This document presents a review of the report, “U.S. Geological Survey, Grand Canyon Monitoring and Research Center, Fiscal Year 2018 Annual Project Report to the Glen Canyon Dam Adaptive Management Program,” and related presentations by Grand Canyon Monitoring and Research Center (GCMRC) investigators at its Annual Reporting Meeting, March 12-13, 2019. The Bureau of Reclamation (Reclamation) requested that the Executive Coordinator for the Glen Canyon Dam Adaptive Management Program (GCDAMP) Science Advisors Program — Sound Science LLC — prepare this review, focusing on the following four topics:

- The protocols used by the GCMRC in its scientific activities for the GCDAMP
- The GCMRC’s long term monitoring plan
- The GCMRC’s annual monitoring and research plans
- Recommended next steps based on an adaptive management approach.

The last three of these four focal topics — especially the fourth topic — concern matters decided partially to largely at the level of the GCDAMP itself rather than at the level of the GCMRC and its investigative partners. In particular, long-term monitoring plans and the overall structure of adaptive management follow the needs and requirements of the 20-year (FY2018-2037) GCDAMP Long-Term Experimental and Management Plan (LTEMP) and the December 2016 “U.S. Department of the Interior Record of Decision for the Glen Canyon Dam Long-Term Experimental and Management Plan Final Environmental Impact Statement” (*aka* the LTEMP ROD; U.S. Department of the Interior 2016). Comments in the present review concerning the last three focal topics, and especially concerning the last topic, therefore necessarily consider this larger context within which the GCMRC and its investigative partners make decisions concerning protocols, annual monitoring and research, annual reporting, long-term monitoring, and long-term reporting.

The review has four sections. Section II describes the methods applied to address the four focal topics. Section III presents general comments across fourteen projects addressed by the GCMRC FY2018 Annual Project Report (hereafter simply the “GCMRC annual report”) for which Reclamation requested comments (see below). Section IV addresses the first three review topics individually for each of the fourteen reviewed projects. Section V summarizes the key findings across all projects and offers recommendations concerning next steps for adaptive management. The fourteen projects reviewed are as follows:

- Project A: Streamflow, Water Quality, and Sediment Transport and Budgeting

- Project B: Sandbar and Sediment Storage Monitoring and Research
- Project C: Riparian Vegetation Monitoring and Research
- Project D: Geomorphic Effects of Dam Operations and Vegetation Management for Archaeological Sites
- Project E: Nutrients and Temperature as Ecosystem Drivers
- Project F: Aquatic Invertebrate Ecology
- Project G: Humpback Chub Population Dynamics
- Project H: Salmonid Research and Monitoring
- Project I: Warm-Water Native and Non-Native Fish Research and Monitoring
- Project J: Socioeconomic Research
- Project K: Geospatial Science and Technology
- Project L: Remote Sensing Overflight
- Project N: Hydropower Monitoring and Research
- Appendix 1: Lake Powell Water Quality Monitoring

II. Methods

The Science Advisors Program provides recommendations to Reclamation, the GCDAMP Adaptive Management Work Group (AMWG), and the GCMRC regarding research and monitoring priorities, knowledge integration, and the adaptive management of natural, cultural, and recreational resources affected by Glen Canyon Dam operations and associated adaptive management actions. As part of this effort, the Science Advisors Program conducts independent, external reviews of GCDAMP resource-specific monitoring and research programs, and carries out other advisory tasks as requested by Reclamation or the AMWG. The Executive Coordinator manages the Science Advisor Program and also provides advice as requested by Reclamation.

General Review Approach

The overall approach of the present review follows the guidelines of the U.S. Department of the Interior, Adaptive Management Working Group (Williams et al. 2009; Williams and Brown 2012). The present review applies these guidelines to consider the contributions of the GCMRC annual report to effective adaptive management under the 20-year (FY2018-2037) LTEMP. In particular, the present review looks at three crucial ingredients in effective adaptive management: (1) the production of “smart” information (see below) on which all resource managers and other stakeholders can rely; (2) a relentless focus on reducing uncertainties that affect learning and management; and (3) effective feedback between cycles of learning and also between learning and management action.

To borrow a perhaps overused acronym, adaptive management requires “SMART” information (Williams et al. 2009; Williams and Brown 2012). That is, the information produced to support adaptive management of a project’s focal resources should be:

- **S**pecific: The information provides sufficient specificity (detail) to support thoughtful decision making concerning the resources, investigations, and management actions at stake.

- **M**easurement-Based: The information comes from controlled measurement and tabulation with appropriate accuracy, precision, and repeatability, not from anecdotes.
- **A**ligned: The information is fully aligned with the priorities (resources and management actions) and topics (conditions, processes, cause-effect relationships, and trends) of concern to the adaptive management program.
- **R**ealistic: The information realistically can be produced and analyzed with available methods and resources.
- **T**ime-Bound: The information provides feedback to the investigators, resource managers, and other stakeholders on an appropriate schedule to guide timely decision making.

As noted above, one key purpose of adaptive management is to reduce critical uncertainties that affect resource management. Some uncertainties in adaptive management may result from variability in the ecosystem itself, especially variability that resource managers cannot control. Other uncertainties may result from gaps and weaknesses in knowledge about the ecosystem or the ways that management actions affect (or could affect) the ecosystem. And yet other uncertainties may result from inherent difficulties in observing or tracking the conditions, processes, cause-effect relationships, or trends of concern. These three sources of uncertainty are not mutually exclusive. Effective adaptive management requires that the investigative efforts of the program explicitly recognize and relentlessly seek to identify all sources of uncertainty, reduce those that are within reach, and explicitly identify those that are not.

Finally, responsibility for the feedback process, both between cycles of learning and between learning and management action, lies both with the investigative efforts of each adaptive management program and with the managers and stakeholders of the program overall. We address this review topic in Section V.

GCMRC Project Protocols

The present review of the protocols used by the GCMRC in its scientific activities for the GCDAMP focuses on the extent to which the GCMRC follows the best practicable protocols for each of its projects. Research disciplines rarely offer only one “absolute best” way to investigate a particular problem. Field investigators in particular must select their methods based on knowledge of what options are available to produce the needed data with the needed accuracy and precision, existing investments in methods and the continuities of comparable data they provide, the physical constraints of the environment of the project, and the financial, logistical, and other necessary resources available.

GCMRC investigators collaborate with and/or contract portions of the investigations for the GCDAMP with professional colleagues at other institutions. These investigative “cooperators” include governmental agencies that are also GCDAMP stakeholders, including Reclamation, the National Park Service, U.S. Fish and Wildlife Service, and Arizona Game and Fish Department; and also include colleagues at other research institutions. The AMWG and its Technical Work Group (TWG) oversee the investigations for the GCDAMP.

The GCMRC investigators and cooperators rely on four major, external checks to ensure that each project follows the best practicable protocols:

- (1) The GCMRC periodically organizes “Protocol Evaluation Panels” to review the protocols used in its various projects and presents the results to the GCDAMP stakeholders, as stipulated in the original design of the GCDAMP. The most recent Protocol Evaluation Panels took place in FY 2012, FY2016, and FY2018 and covered investigations of the aquatic food base, native and non-native fishes, and Lake Powell water quality, respectively.
- (2) Cooperating investigators from other institutions bring crucial additional knowledge and external perspectives to their collaborations with the GCMRC.
- (3) GCMRC investigators and formal partners must follow U.S. Geological Survey (USGS) Fundamental Science Practices (FSP), “a set of consistent practices, philosophical premises, and operational principles to serve as the foundation for research and monitoring activities related to USGS science” (<https://www2.usgs.gov/fsp/default.asp>). The FSP ensure that the USGS “provides unbiased, objective, and impartial scientific information upon which our audiences, including resource managers, planners, and other entities, rely... The FSP clarifies how USGS science is carried out and how the resulting information products (including maps, imagery, and publications) are developed, reviewed, approved, and released.” The FSP includes explicit rules for the review of all information products emerging from the work of USGS investigators and their partners (https://www2.usgs.gov/fsp/levels_ba.asp), including several levels of peer and supervisory review within the USGS even before an information product can be submitted for external peer review (see below).
- (4) GCMRC investigators and cooperators submit reports on their work for presentation at external professional conferences and publication in professional books and journals, resulting in external, independent expert review of their investigative methods and reasoning. The USGS FSP governs how GCMRC investigators and cooperators engage with all such external review processes.

The present review examines the extent to which each individual project in the GCMRC annual report has submitted reports on its work for presentation at professional conferences and publication in professional books and journals, resulting in the external, independent expert review of investigative methods and reasoning. The data for this tabulation come from the “Products/Reports” table that appears at the end of each project section in the GCMRC annual report. Meredith Hartwell, GCMRC Technical Information Specialist, and Dr. Barbara Ralston, USGS Office of Science Quality and Integrity, then reviewed these data for the Executive Coordinator and identified the levels of peer review that each information product received, per USGS FSP policies.¹ (All information products listed in the project “Products/Reports” tables in the GCMRC annual report, other than products listed as in preparation, necessarily have received all required levels of internal USGS peer review under FSP guidelines.) The present review also provides comments on the protocols used in the individual projects where appropriate, and indicates where these protocols have been subject to a recent Protocol Evaluation Panel review.

¹ The authors of the present review gratefully thank Ms. Hartwell and Dr. Ralston for their assistance; Scott VanderKooi, GCMRC Chief, for making this assistance available; and Scott and Dr. Charles Yackulic, GCMRC Research Statistician, for clarifying the review history of the predictive models used in the fish investigations.

Long-Term Monitoring Plan

The present review of the relationship of the reported projects to the GCMRC long-term monitoring plan examines the extent to which each project focuses on a stable set of indicators for the eleven priority resources addressed under the LTEMP, and the twelve types of experimental dam operations and non-flow management actions specified in the LTEMP. The eleven LTEMP priority resources and their objectives are as follows (U.S. Department of the Interior 2016):

1. *Archaeological and Cultural Resources.* Maintain the integrity of potentially affected National Register of Historic Places (NRHP)-eligible or listed historic properties in place, where possible, with preservation methods employed on a site-specific basis.
2. *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.
3. *Humpback Chub.* Meet humpback chub recovery goals, including maintaining a self-sustaining population, spawning habitat, and aggregations in the Colorado River and its tributaries below the Glen Canyon Dam.
4. *Hydropower and Energy.* Maintain or increase Glen Canyon Dam electric energy generation, load following capability, and ramp rate capability, and minimize emissions and costs to the greatest extent practicable, consistent with improvement and long-term sustainability of downstream resources.
5. *Other Native Fish.* Maintain self-sustaining native fish species populations and their habitats in their natural ranges on the Colorado River and its tributaries.
6. *Recreational Experience.* Maintain and improve the quality of recreational experiences for the users of the Colorado River Ecosystem. Recreation includes, but is not limited to, flatwater and whitewater boating, river corridor camping, and angling in Glen Canyon.
7. *Sediment.* Increase and retain fine sediment volume, area, and distribution in the Glen, Marble, and Grand Canyon reaches above the elevation of the average base flow for ecological, cultural, and recreational purposes.
8. *Tribal Resources.* Maintain the diverse values and resources of traditionally associated Tribes along the Colorado River corridor through Glen, Marble, and Grand Canyons.
9. *Rainbow Trout Fishery.* Achieve a healthy high-quality recreational rainbow trout fishery in Glen Canyon National Recreation Area (GCNRA) and reduce or eliminate downstream trout migration consistent with National Park Service (NPS) fish management and Endangered Species Act (ESA) compliance.
10. *Nonnative Invasive Species.* Minimize or reduce the presence and expansion of aquatic nonnative invasive species.
11. *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.

The twelve types of experimental dam operations and non-flow management actions specified in the LTEMP are as follows (U.S. Department of the Interior 2016):

1. Fall High Flow Experiments (HFEs) > 96-hr duration (\leq 45k cfs, in October or November)
2. Fall HFEs \leq 96-hr duration (\leq 45k cfs, in October or November)
3. Humpback chub translocation
4. Larval humpback chub head-start program
5. Macroinvertebrate production flows
6. Mechanical removal of invasive fish species
7. Mechanical removal of rainbow trout from LCR reach
8. Proactive Spring HFEs \leq 45k cfs in April, May, or June
9. Riparian vegetation restoration
10. Spring HFEs \leq 45k cfs in March or April
11. Trout management flows
12. Summer Low Flow Experiments (LFEs) (*second decade only*).

The LTEMP also recognizes a thirteenth, implicit set of management actions that may affect priority resources: Routine dam operations, particularly for hydroelectric power generation and operation of the Colorado River water storage and delivery system (U.S. Department of the Interior 2016).

Annual Monitoring and Research Plans

The present review of the relationship of the reported projects to their annual monitoring and research plans considers two questions:

1. Did the work accomplished by each project in FY2018 match the monitoring and research plans under which the work was carried out?
2. Does the work proposed for each project for FY2019 for monitoring and research match the needs identified in the LTEMP and GCDAMP Triennial Work Plan for FY2018-2020?

Next Steps for Adaptive Management

The recommendations in the present review concerning next steps for adaptive management consider the GCMRC FY2018 Annual Project Report as a whole rather than at each project separately. None of the projects presented in the GCDAMP Triennial Work Plan for FY2018-2020 and discussed in the GCMRC annual report addresses only a single LTEMP priority resource or single LTEMP experimental or management action. Adaptive management — learning by doing — in the GCDAMP under LTEMP instead must look at multiple streams of information concerning LTEMP experimental or management actions and their effects across the priority resources, and concerning other factors that may confound or compound these effects. The recommendations in the present review concerning next steps for adaptive management therefore focus on identifying information streams that the GCDAMP might consider, for refining or expanding adaptive management of dam operations and non-flow management actions.

III. General Comments

The general comments below address five topics that cross-cut all projects discussed in the GCMRC annual report:

- (1) The extent of external peer review of the methods and reasoning for each project, as a crucial check on these methods and reasoning.
- (2) The extent of external peer review of the predictive, quantitative models of fish ecology that the GCMRC and GCDAMP increasingly use to evaluate assumptions and predict the consequences of LTEMP experiments and management actions.
- (3) The extent of use and presentation of summary indicators of resource condition.
- (4) The extent of use of alternative, competing hypotheses to identify the data requirements for each project.
- (5) The discrimination and quantification of system inputs and their variability.

External Peer Review of Methods and Reasoning

External peer review provides a crucial check to ensure that each project follows the best practicable protocols and produces “SMART” information in support of adaptive management. Table 1 tabulates the extent to which the products and reports listed for each project for FY2018 in the GCMRC annual report have received such external peer review, in addition to multiple levels of internal USGS peer review per FSP guidelines. Table 1 includes presentations at professional conferences, both because the USGS FSP guidelines cover such presentations and because authors must submit abstracts of their proposed presentations for peer review for acceptance by conference organizers.

Table 1. External peer review status of project products and reports listed in the GCMRC annual report

Project	Authors = GCMRC & Cooperators			Authors = GCMRC Only			Authors = Cooperators Only			Totals, All Authors			
	Professional Publication	Professional Presentation	Data Release	Professional Publication	Professional Presentation	Data Release	Professional Publication	Professional Presentation	Data Release	Professional Publication	Professional Presentation	Data Release	Grand Total
A	2	2			1					2	3		5
B	8		4				2			10		4	14
C	4	1	1			3				4	1	4	9
D	3					1				3		1	4
E													
F	1	2		1	1					2	3		5
G	5	1			2		1	2		6	5		11
H	1		1		1					1	1	1	3
I	4						1			5			5
J	4	4			1					4	5		9
K													
L													
N		2									2		2
Appendix 1		1									1		1
Total	32	13	6	1	6	4	4	2		37	21	10	68

Table 1 shows that the GCMRC project teams, in aggregate, successfully submitted 37 reports to professional publications, had 21 papers accepted for presentation at professional conferences, and successfully submitted 10 data products for publication. Most of these products were produced jointly with cooperators, and some were produced exclusively by cooperators. The methods and reasoning of nearly every project thus were subjected to external peer review and benefited from the perspectives of external partners. It also should be noted that the USGS FSP guidelines result in a minimum of five independent expert reviews for each externally published or presented work. The 37 reports that appeared in or were accepted by professional publication series in FY2018 thus potentially received a collective minimum of 185 expert reviews. The GCDAMP benefits greatly from such extensive expert review, in two ways: First, this level of review helps ensure that the GCMRC and its cooperators follow methods consistent with current best practices in every discipline and follow lines of reasoning consistent with current state of knowledge in every discipline. Second, such review typically provides crucial suggestions for alternative methods and arguments.

Table 1 also shows that some of the GCMRC projects with the longest histories, such as the two focused on sediment dynamics (Projects A and B), continue to submit works for external review, reflecting their continuing efforts to ensure that their methods and reasoning are up to date. At the same time, some of the newer projects, such as those focused on riparian vegetation and socioeconomic studies (Projects C and J), sought extensive external review as well. Five projects received relatively little or no external peer review, but is not necessarily a shortcoming: Project E (nutrients), in its first year, only involved pilot studies to help determine the best methods and investigative paths to pursue, for which external review is not yet appropriate. Project K involves only the deployment of existing methods and technologies, for which external review is not needed. Project L was not funded. Project N, “monitoring and research associated with operational experiments at [Glen Canyon Dam] to meet hydropower and energy resource objectives,” uses methods previously externally peer reviewed and had relatively modest funding for FY2018. Appendix 1, similar to Project E, involved only pilot studies in FY2018.

External Peer Review of Predictive Models

A noteworthy feature of the GCDAMP over the past few years is its increasing use of predictive, quantitative ecological models. Such models were developed for and used extensively in the development of the LTEMP, to predict the likely effects of proposed experiments and management actions particularly on humpback chub and rainbow trout abundances and vital rates (growth and recruitment). These models were updated in 2017-2018 to examine the possible interactions of brown trout with rainbow trout and to predict the likely effects of proposed management actions on brown trout abundances and vital rates in the Colorado River ecosystem. Projects G, H, and I continue to refine and improve these models and are increasingly supported by Project J, resulting in the application of socioeconomic modeling methods to predict the cost effectiveness of alternative management actions to control trout numbers.

Both conceptual and predictive, quantitative ecological models are crucial decision support tools in many programs of adaptive management. They integrate multiple types of information and represent multiple causal relationships to predict the consequences of changes in individual inputs or constraints on system outputs, such as humpback chub and rainbow trout abundances

and vital rates. However, such models typically are mathematically complex; incorporate numerous assumptions about how the represented system works; and use complex computational methods. For these reasons, it is crucial that these decision support tools receive stringent external peer review, to assure the resource managers and other stakeholders in an adaptive management program of the reliability of the model outputs.

The GCMRC annual report tables of products and reports for Projects G-J list several publications, professional presentations, and data releases that necessarily would have subjected the humpback chub, rainbow trout, and other predictive models for fishes to external peer review. However, these external reviews mostly address recent updates to these models rather than their origins and may not address fundamental methods and assumptions. Further, the 2018 report on the 2017 brown trout workshop and analyses (Runge et al. 2018) does not document the details of the models, although the associated data release (Yackulic et al. 2018) does. For these reasons, the present reviewers consulted with Scott VanderKooi, GCMRC Chief, and Dr. Charles Yackulic, GCMRC Research Statistician, to clarify the review histories of the predictive models used in the fish investigations, beginning with development of the draft LTEMP Environmental Impact Statement. These individuals clarified that the LTEMP models were all externally peer reviewed: The lead agencies for development of the LTEMP — Reclamation and the National Park Service — asked the GCMRC Chief to conduct and oversee an external peer review process that essentially followed USGS FSP guidelines. A minimum of two external experts reviewed each model and its associated drafts of text sections. The GCMRC Chief “ensured that the authors responded to and addressed these reviews ... and served as editor/approving official for the final drafts returned to the LTEMP writing team” (Scott VanderKooi, personal communication, February 19, 2019). Two other external experts deeply familiar with the modeling methods also informally reviewed the models before they were formally reviewed (Charles Yackulic, personal communication, February 19, 2019).

Indicators of Resource Condition

As noted above, the SMART information for an adaptive management program should include information that is fully aligned with the priorities (resources and management actions) and topics (conditions, processes, cause-effect relationships, and trends) of concern to the adaptive management program. The LTEMP identifies, and the LTEMP ROD confirms, eleven priority resources and objectives for these resources. In turn, the GCMRC annual report begins with a very useful table, listing the LTEMP priority resources along with a narrative statement identifying which GCMRC projects are providing information relevant to (aligned with) each priority resource. (We recommend that future annual reports retain this table, but change its design to a cross-tabulation of resources versus projects, to make it easier to identify which projects pertain to which resources, and *vice versa*.)

Adaptive management programs typically make extensive use of indicators of the status and trends in their priority resources and other summary information on system condition and dynamics. The LTEMP ROD in fact directs the Department of the Interior, in consultation with the AMWG, to develop “monitoring metrics for the goals and objectives using those in Appendix C of the LTEMP Final Environmental Impact Statement (FEIS) as a starting point.” Neither the current triennial work plan nor the GCMRC annual work plan for FY2018 calls for the GCMRC to develop such metrics (indicators). On the other hand, some projects do report

such indicators, specifically for sediment and for humpback chub and rainbow trout population sizes and distributions. We suggest that the development of indicators for all eleven LTEMP priority resources should be accelerated, as it will take time to develop SMART indicators for all of the resources, including time for pilot testing before full implementation, and time for the GCMRC (and other parties as needed) to establish suitable methods for the indicators and subject these methods to external peer review.

Alternative, Competing Hypotheses

Adaptive management programs require more than simply information about the status and trends in their priority resources, i.e., more than information simply to answer questions about *what* conditions occur among these priority resources, *when*, and *where* in the system. Adaptive management programs also require information about *how* management actions and other factors (*aka* drivers, constraints, confounding and compounding factors, etc.) affect these conditions, and *why*. Adaptive management programs require these latter types of information to understand and predict the potentially inter-twined consequences of changes in management practices and changes in other factors affecting resource condition, and make management decisions based on this understanding.

However, ecological systems are highly complex, shaped by multiple (and possibly innumerable) causal relationships at multiple spatial scales. Teasing apart and fully understanding causal relationships is difficult even with simple, mechanical systems, and far more so with complex systems. Further, these causal relationships may play out over timespans of days to years, involve both leading and lagging effects, and involve multiple, intersecting chains and cascades of effects. Additionally, adaptive management programs focused on large and unique systems such as the Colorado River below Glen Canyon Dam face severe constraints on when and therefore how often they can conduct management experiments; and not all drivers may be active at all times. As a result, investigations to understand causal relationships in such systems can take years to play out.

Scientists have long embraced the use of alternative, competing hypotheses to speed up the process of teasing out and understanding causal relationships (Chamberlin 1965). Investigators who pursue only one line of inquiry at a time risk running into dead ends and may ignore alternative explanations. Instead, however, investigators can pose alternative, competing hypotheses and attempt to identify and collect data that can efficiently discriminate among these alternatives. Designing investigations in this way results in a process known as “strong inference” (Platt 1964), that both enriches and accelerates inquiry.

The use of strong inference in adaptive management can have two important benefits. First, it can accelerate the pace of learning. It does this by more quickly separating out stronger from weaker hypotheses about causal relationships and their underlying mechanisms and helping investigators avoid side tracks and dead ends. Charles Yackulic of the GCMRC independently spoke on this point, in his presentation on “Phosphorous, Metabolism and Fish” (Project E) at the GCMRC Annual Reporting Meeting, March 12, 2019. Second, the use of strong inference in adaptive management provides a means for addressing the perspectives of different stakeholders and other experts, who may have different understandings about how the system works. These different understandings can be phrased as alternative hypotheses, which the adaptive management program can then consider side by side.

We suggest that the GCDAMP potentially presents several opportunities for applying the methods of strong inference — as also suggested by Yackulic at the 2019 Annual Reporting Meeting. Projects in the triennial work plan focused primarily on questions of what, when, and where potentially might not benefit from applications of strong inference. However, Projects E, F, and G already benefit from the methods of strong inference, and other projects in the triennial work plan potentially might as well, including the studies of Lake Powell water quality, as discussed below in the comments on individual projects. Predictive models are useful tools for generating alternative hypotheses by running the models under alternative assumptions.

Discriminating and Quantifying System Inputs

The GCDAMP has long recognized that conditions in the Colorado River ecosystem below Glen Canyon Dam — particularly sediment storage and water temperature — and the effects of dam operations on these conditions depend on crucial inputs from the surrounding watersheds and from Lake Powell. Investigations over the past few years, described in the current and previous triennial work plans and GCMRC annual reports, have identified additional crucial inputs. These additional crucial inputs particularly include aquatic nutrients (biologically available phosphorus and nitrogen) and both native and non-native aquatic organisms. Further and equally important, these investigations have produced increasing evidence that these inputs are subject to their own sources of variability. For example, sediment discharges from the Paria and Little Colorado River watersheds vary in response to variation both in precipitation and in watershed surface conditions that affect soil erosion. Further, both of these sources of variation may be subject to long-term effects from changes in land-use, land cover succession, and climate. Similarly, nutrient discharges from Lake Powell appear to vary in response not only to variation in nutrient inputs to the lake but to hydrologic, thermal, and chemical dynamics within the lake and its inflow deltas. These latter dynamics in turn may be affected by lake levels and therefore by the hydrology of the Upper Basin in general, as laid out in Appendix 1 to the GCMRC annual report and in several presentations to the TWG over the past year, including by Bridget Deemer of the GCMRC at the 2019 Annual Reporting Meeting. The triennial work plan for FY2018-2020 also notes that runoff following wildfires in watersheds tributary to the Colorado River below the dam may deliver ecologically significant pulses of phosphorus to the river.

We suggest that it is crucial for the GCDAMP to begin keeping separate, explicit track of variation in all important inputs. Further, we offer two arguments in support of this suggestion:

- (1) Variation in crucial inputs can confound or compound the effects of LTEMP experiments and management actions. Consequently, it is crucial for the GCDAMP to be able to distinguish the effects of LTEMP experiments and management actions on the ecosystem below the dam, from the effects of variation in important inputs. At present, the absence of an ability to systematically distinguish these two types of effects creates significant uncertainty for interpreting the results of LTEMP experiments and management actions.
- (2) It is crucial for the GCDAMP to understand the factors that affect variation in important inputs, especially if those factors could result in long-term, systematic changes in these inputs. The GCDAMP already needs to be aware of the potential for long-term changes in the availability of water to supply Lake Powell, and therefore to generate electricity through the dam and maintain the river below the dam. Similarly, the GCDAMP also needs to be aware of the potential for long-term changes in inputs of sediment, nutrients,

and non-native organisms. For example, the investigative team for Project A already plans to produce reports on the long-term histories and trajectories of sediment discharge from the Paria and Little Colorado River watersheds. The team could be asked whether the data collected to calculate the reach-specific sediment budgets could also be used to produce a time series of estimates of total sediment inflow (load). The team for Project E similarly could be asked about the feasibility of producing a time series of estimates of input nutrients loads. GCMRC and other experts also may identify other system inputs amenable to such tracking.

(3) Comments by Individual Project

Project A: Streamflow, Water Quality, and Sediment Transport and Budgeting

Project A is a keystone monitoring project for the GCDAMP and implementation of the LTEMP. Almost every other project depends on data for one or more of the parameters monitored by Project A. Its suspended sediment flux data and resulting sediment budget estimates are crucial to decision-making for high-flow experiments (HFEs). The GCMRC annual report and the current triennial work plan both indicate close attention to the need for maintaining data quality, comparability, and spatial and temporal resolution. All measurements are made using standard USGS and other peer-reviewed techniques. In fact, investigators note in the triennial work plan that the project has published its results and interpretations in over 80 peer-reviewed journal articles, books, and proceedings articles in the areas of hydrology, water quality, and sediment transport. The GCMRC annual report does not indicate any plans for changing protocols.

We noted above (see General Comments) that Project A potentially could produce a time-series record of sediment inputs to the Colorado River ecosystem and information on factors that shape input dynamics. The project investigators may already be considering this possibility. The project plans include producing three articles on sediment inputs: (1) an analysis of Paria River hydrology, 1920s–present, with implications for long-term sediment management in the Colorado River ecosystem (lead author Topping); (2) a report on geomorphology, hydraulic geometry, and sediment transport in the Paria River (lead author Topping); and (3) a report on sediment transport and geomorphic change in the Little Colorado River (lead author Dean). The GCMRC annual report also indicates that Dean and Topping in FY2018 submitted a paper to the Geological Society of America Bulletin on geomorphic change and biogeomorphic feedbacks along the Little Colorado River. The GCMRC annual report states that this paper has been revised and resubmitted to the journal after an initial round of journal peer review. Separately, Sankey et al. (2017) have published forecasts of watershed erosion under different scenarios of climate change and wildfires across the western U.S., including the catchments tributary to the Colorado River above and below Glen Canyon Dam. The study results predict widespread increases in sediment erosion in runoff. Such forecasts should be of considerable interest to the GCDAMP.

Much of the work of Project A, producing critical data streams for the GCDAMP, is not driven by hypotheses specific to the project. However, the data produced by Project A are crucial for hypothesis testing by other GCMRC projects. At the same time, the work by Project A on understanding sediment dynamics and its drivers in the Paria and Little Colorado River watersheds is likely hypothesis-driven. However, the project descriptions in the current triennial

work plan and GCMRC annual report do not explicitly identify these hypotheses or indicate whether the project is testing or plans to test competing hypotheses through strong inference.

Project B: Sandbar and Sediment Storage Monitoring and Research

Project B has several roles in the adaptive management program. These include: (1) tracking the effects of individual HFEs on sandbars, (2) monitoring the cumulative, multi-year effects of successive HFEs and intervening operations on sandbars and sand conservation, and (3) investigating the interactions between dam operations, sand transport, and eddy sandbar dynamics. In contrast to Project A, Project B focuses on the direct measurement of sand storage. The design of Project B, as set out in the current triennial work plan, includes multiple explicit hypotheses. However, these are not alternative, competing hypotheses based on different assumptions about how the system works, the testing of which will help distinguish viable from questionable assumptions. Rather, the Project B hypotheses all aim to refine the emerging descriptive picture of how HFEs affect sandbar and sediment storage responses to HFEs of varying types and magnitudes, depending on location in the system and other constraints.

The GCMRC annual report notes that no HFEs required monitoring under Project B in FY2018. The protocols used in Project B are evolving. The GCMRC annual report states that “Because about 90% of the sand that is available for redistribution by dam operations is submerged ... the monitoring method must include measurements of sediment on the bed of the river in eddies and pools. Bed sediment data collection combines multibeam and single-beam sonars, coupled with conventional topographic surveys for areas above the water surface.” The annual report identifies multiple publications through which these methods and analyses of their resulting data have been peer reviewed. However, the GCMRC annual report also states that the investigators are modifying the data-processing system for Element B.1, Sandbar Monitoring Using Topographic Surveys and Remote Cameras, to increase throughput and reduce manual steps; and are adapting “machine learning” software for digital image processing. This latter work has been peer-reviewed in one journal so far, according to the GCMRC annual report. The report also states that, under Element B.1, the investigators are conducting previously unplanned work on “an empirical model that predicts sandbar volume based on streamflow and sediment supply, calibrated to the long-term sandbar monitoring data. Because this model predicts sandbar volume at a daily time-step, it can be used as an intelligent interpolation of sandbar size for the periods between the annual sandbar surveys.” The digital image processing methods and the empirical model should both be subjected to external peer review or additional such review, given their potential importance and the extent of innovations involved. The GCMRC annual report states that automation of data processing, and automation of image analysis, will speed up the feedback turnaround rate for Element B.1. These are important contributions to the feedback process for adaptive management.

Element B.2, Bathymetric and Topographic Mapping for Monitoring Long-term Trends in Sediment Storage, operates on a two-year cycle of data collection and analysis. The GCMRC annual report states that FY2018 was an “analysis” year focused on the data collected in FY2017. The GCMRC annual report also states that the analyses carried out in FY2018 incorporate a method developed previously and published (and peer reviewed) in 2018 “for evaluating the degree of indeterminacy in mass-balance sediment budgets using a signal-to-noise ratio (SNR) analysis.” The method will improve the ability of the project team to quantify the

uncertainty in its estimates of sediment storage. Element B.3, Control Network and Survey Support, involves upgrades to georeferencing capabilities, particularly in the Grand Canyon.

The GCMRC annual report indicates that the team is making strong progress on improving turnaround time for making sediment storage and sandbar data available, for assessing the impacts of individual HFEs and other high-flow releases; and on publishing reports on the long-term patterns of effects of past HFEs and other high-flow releases. Improved turnaround is crucial for adaptive management of the HFEs under the LTEMP, and for assessing the effects of HFEs and other high-flow releases on campsites.

We also note that the data produced by Project B may have crucial bearing on ecological questions not presently on the list of priorities for the GCDAMP but directly related to the management of humpback chub, other native fishes, and non-native fishes. Specifically, the data produced by Project B may be suitable for assessing the distribution of *aquatic habitat types* and the impacts of HFEs and other high-flow releases on the condition and distribution of these types. As discussed among GCMRC and stakeholder attendees at the 2019 Annual Reporting Meeting following a question from one of us (Braun), investigations of the abundances and distributions of aquatic habitat types along Glen, Marble, and Grand Canyons have not received much attention in recent years, for reasons that may due for some reconsideration. From the standpoint of the aquatic environment in these main-stem canyons, sandbars and other exposed deposits are the above-water manifestations of a potentially wide array of low-velocity, channel-margin aquatic habitat types.

The increasing presence of native fishes in and upstream from the Colorado River Inflow arm of Lake Mead has triggered a number of investigations, including intensive larval/small-bodied fish surveys in the Grand Canyon, 2014-2016 (e.g., Kegerries et al. 2016). These larval/small-bodied fish surveys have now sampled low-velocity aquatic habitat types in every segment from Pearce Ferry (RM 280) up to Phantom Ranch at the Bright Angel Creek confluence (RM 89). The survey methodology recognizes and focuses sampling on numerous low-velocity aquatic types, including backwaters, eddies, embayments, isolated pools, pocket waters, pools, shoals, and slackwaters (Kegerries et al. 2016). The resulting survey data indicate that native fish — including razorback sucker and flannelmouth sucker — use such habitats as larvae as nursery habitat or as resting/hiding habitat during larval drift to nursery habitat, and may use some of these habitats as adults as spawning sites. As discussed below for Project G, humpback chub similarly may use such low-velocity habitat settings in various ways. Further, fish biologists working in other large rivers have found that channel sections along which lateral and reverse currents draw drifting fish larvae out of the main line of downstream flow into low-velocity settings (termed “interception habitat” by Jacobson et al. 2016) constitute another type of aquatic habitat crucial to the survival of the larvae and their movement into low-velocity nursery habitat (Kinzli and Myrick 2010; Worthington et al. 2014; Jacobson et al. 2016).

We suggest that data previously produced by Project B potentially could be used, both retrospectively and going forward, to map low-velocity, channel-margin habitat *and* potential interception habitat. The results could then be used to explore questions concerning, for example, whether the abundances and distributions of different aquatic habitat types and conditions along the main-stem have varied over time, including in response to specific dam operations, and whether the abundances and distributions of different fish species and life stages have varied meaningfully in relation to variation in habitat conditions.

Finally, Project B already tracks a small number of core indicators of year-to-year pre/post-HFE change in sandbars and sediment storage. Are there other indicators that could be reported by Project B, such as overall sand storage by reach?

Project C: Riparian Vegetation Monitoring and Research

Much of the ongoing work of the vegetation monitoring and research is focused on two LTEMP vegetation resource goals:

- Maintain native vegetation and wildlife habitat, in various stages of maturity, such that they are diverse, healthy, productive, self-sustaining, and ecologically appropriate.
- 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.

The GCMRC annual report identifies three project elements being actively pursued: vegetation monitoring at small- (C.1) and landscape-scales (C.2), and modeling vegetation responses to flow regimes (C.3). A nascent fourth project element focuses on providing decision support for a variety of vegetation management activities. Together, these four project elements address the key scientific questions identified in the triennial work plan concerning riparian vegetation, indicating good progress in completing that work.

The current vegetation research largely focuses on documenting vegetation extent, structure and composition at multiple spatial scales and trying to understand vegetation changes relative to dam operations. However, as noted in the LTEMP, the historic flood plain vegetation communities have become isolated well above the current river level. As a result, the Colorado River vegetation communities below the dam are, in effect, undergoing primary ecological succession. As a further result, there are few if any reference sites to help to answer the question, “What should these communities look like?” Thus, it is difficult to assign adaptive management goals for the vegetation to inform flow management decisions. The vegetation management work to date has produced a number of interesting and informative publications and reports which together could be integrated to begin creating a valuable conceptual ecological model for the riparian vegetation. Creating such a conceptual ecological model would help frame the development of a suite of management goals for the riparian vegetation and better identify future monitoring variables and the required statistical power needed to inform those goals.

We also note that the landscape-scale monitoring element (C.2) is planned to undertake a 5-year change assessment. However, our reading of the project description suggests that this assessment depends on data from the now-postponed (2018) overflights listed in Project L. Therefore, it is not clear how, or whether, this 5-year assessment can be accomplished.

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

Project D has two elements in the triennial work plan. Element D.1 focuses on assessing the geomorphic effects of dam operations and site-scale vegetation management on the condition of

archaeological sites and the surrounding lands. This is necessarily a long-term effort, and the GCMRC annual report indicates that the project team is making progress on a number of fronts. However, in cross-walking the annual report with the triennial work plan, we noticed two missing pieces. First, the triennial work plan identifies planned meetings with the Tribes during 2018 to discuss pilot vegetation removal sites. The annual report does not indicate if these meetings occurred, although the presentation on riparian vegetation monitoring at the Annual Reporting Meeting mention tribal consultations and coordination. Second, a deliverable for Element D.1 identified in the triennial work plan is an annual report on vegetation removal and site monitoring provided to all stakeholders. We did not find reference to such a report in the GCMRC annual report.

Element D.2 is a retrospective report that compiles and synthesizes all existing reports and data on the impacts of dam management and vegetation on cultural resources. A draft of this report is currently in review and is expected to be published in 2019 as anticipated in the triennial work plan.

Project E: Nutrients and Temperature as Ecosystem Drivers

As summarized in the GCMRC annual report, “The primary goals of this project are to: 1) identify processes that drive spatial and temporal variation in nutrients and temperature within the [Colorado River ecosystem], and 2) establish quantitative and mechanistic links among these ecosystem drivers, primary production, and higher trophic levels. Parallel work in Lake Powell that aims to identify the controls on nutrient concentrations in the Glen Canyon Dam outflow is ongoing with external funding from Reclamation (see Appendix 1).”

The temperature data used in Project E are collected by Project A. Water temperature affects the Colorado River ecosystem through effects on fish bioenergetics, condition and population dynamics; primary and secondary productivity; and aquatic chemical reaction rates. Nutrients, particularly biologically available nitrogen and phosphorus (N, P) affect the ecosystem through effects on gross primary productivity (GPP), with the biological availability of P potentially particularly severely limiting. However, in addition to temperature and nutrients, other factors such as turbidity and time of day (the natural daily light cycle) also affect GPP. Turbidity in turn is affected by suspended sediment. Project E seeks to disentangle this complicated set of interactions.

Project E is a major new direction of investigations for the GCDAMP, following exploratory work under the previous triennial work plan, and in many ways is still in an exploratory stage. It has strong bearing on the Natural Processes resource and on all aquatic biological resources. The table at start of the GCMRC annual report does not note, but we also suggest, that Project E has close links to two other LTEMP priority resources: Tribal Resources and Non-Native Invasive Species.

As noted in the triennial work plan, the majority of the work proposed for the present three-year cycle for Project E focuses on better characterizing the biological availability and cycling of P in the river, including conducting trials of monitoring methods. As a result, its annual and long-term monitoring plans — and its ideas for mesocosm experimentation — are all evolving and have not stabilized enough to be submitted for external peer review. However, methods for monitoring N, P, dissolved oxygen (DO), and primary production are extremely well established

in the larger disciplines of freshwater ecology and water quality studies. The main challenge for Project E is that many of these methods have not previously been used (or used very little) in the Colorado River ecosystem and require some trial and error to work out logistical and other details and optimal temporal and spatial (horizontal and vertical) sampling designs. It is crucial that the team document the peer-reviewed foundations for the protocols they use and promptly submit any modifications for peer review.

The Project E team reports “...substantial progress in developing and applying models of gross primary production (GPP) to understand river-wide patterns in GPP and link the base of the food web to drivers including light and nutrients ... [and in] development of semi-automated techniques for classifying submersed aquatic vegetation in the Glen Canyon reach from imagery, providing a means for future monitoring of change in vegetation.” The modeling and image classification methods presumably will be subjected to external peer review once they stabilize.

We also recommend that the team explicitly assess the compatibility of its measurements of P below the dam with the measurements of P from Lake Powell, given the problems that have turned up with the latter datasets (see comments on Appendix 1, below). Reported data on both soluble reactive P (SRP) and total P concentrations in the lake — and therefore presumably potentially also in the river below the dam — may be affected by differences in measurement protocols, which could include protocols for the preparation of sampling equipment, sample collection, sample preservation and transport, laboratory handling of samples, laboratory equipment maintenance and calibration, laboratory measurement procedures, quality assurance and quality control (QA/QC) procedures, and so forth. Given the potential ecological importance of P in the Colorado River ecosystem, all measurements of P from the lake and the river need to be fully comparable with each other, with respect to accuracy, precision, detection limits, and data on covariates (water temperature, pH, DO, salinity, and so forth).

Project E proposes 11 hypotheses concerning N and P dynamics below the dam. As the GCMRC annual report acknowledges, most of these hypotheses are not alternatives based on alternative assumptions for which data are sought for strong inference. However, the GCMRC annual report indicates that the project team is aware of potential alternative hypotheses and is working toward articulating these for testing once project methods stabilize for data collection and laboratory analysis. These potential alternative hypotheses concern: (a) the processes by which P may be mobilized (or immobilized) in the lake, the river below the dam, and in tributary inflows below the dam; (b) differences in the contributions of different tributaries to SRP and total P; and (c) the biological uptake of P in the river and its effects on GPP. The GPP modeling will provide a potentially powerful tool for exploring the implications of different assumptions on these topics.

As noted above (see General Comments), Project E may present another instance where it would be possible and meaningful to develop one or more measures of inputs to the Colorado River ecosystem. Both P loads and mass balances might be amenable to such tracking. As with the other projects, Project E also might benefit from identifying a few core indicators of resource condition — in this case, indicators of key “Natural Processes”. Finally, the focus of Project E on nutrients raises a related question: Might inputs of dissolved and particulate organic matter from Lake Powell and the tributaries below the dam also contribute to biomass production in the river below the dam?

Project F: Aquatic Invertebrate Ecology

Also known as the Food Base project, Project F tracks spatial and temporal variation in the species mix and abundance of aquatic macro-invertebrates, particularly the aquatic larvae of several families of flying insects. Its monitoring of macroinvertebrate conditions before versus after “bug flows” is crucial to evaluating the effects of these experimental releases from Glen Canyon Dam. Humpback chub, rainbow trout, brown trout, and other native and non-native fishes depend particularly heavily on aquatic macroinvertebrates as prey/food items. Monitoring of macroinvertebrates is a long-established means for studying the integrity of freshwater ecosystems and their ability to support complex food webs, particularly healthy fish populations. The GCMRC has pioneered methods for intensively monitoring the composition and abundance of the emergent (flying) forms of these same species, both as additional indicators of what is going on in the water and as indicators of what is available to species in the larger (non-aquatic) ecosystem that may feed on these flying forms. Aquatic insect abundance and emergence are fundamental natural processes in rivers. Project F thus directly informs progress towards the LTEMP goal for Natural Processes and provides information essential to attaining other LTEMP goals including for Humpback Chub, the Rainbow Trout Fishery, Other Native Fish, Nonnative Invasive Species, and Recreational Experience. Project F, including its experimental investigations of insectivory among riparian fauna (bats, etc.) in collaboration with an Arizona State University PhD candidate, also informs progress toward LTEMP goals for Tribal Resources.

Project F has subjected its concepts and methods to regular external peer review. Its work presently involves further innovations in field methods — including citizen-science monitoring of bat vocalizations — that the project team undoubtedly will submit for external review as well. Further, the project is investing in new modeling approaches: The GCMRC annual report states that the project team has built a model to predict the response of the aquatic food base to Bug Flows and compared its predictions to the results of Bug Flows to test model assumptions. The GCMRC annual report describes this as “a Bayesian discrete choice model that integrates invertebrate drift monitoring and rainbow trout diet data” to improve understanding of rainbow trout foraging dynamics. Reports on the innovations in field methods and the new modeling presumably will go out for review as well. The team also proposes to convene a Protocol Evaluation Panel in FY2019 to help it further tune up the project: “The last food base PEP was carried out in 2012 and resulted in fundamental changes to the aquatic ecology program.” This PEP was not anticipated in the triennial work plan. However, the proposed PEP would be timely given the rapid emergence of Project F as a pivotal set of investigations of ecosystem dynamics potentially affected by dam operations and other factors. The studies of aquatic-riparian food web interactions will necessarily be reviewed through Arizona State University’s PhD academic procedures.

Project F explicitly seeks to address several hypotheses, some of which are merely descriptive (addressing questions of what, when, and where). However, a few are alternative, competing hypotheses potentially suitable for evaluation through strong inference that address questions of how and why. The modeling work in the project could be particularly helpful for examining potential implications of alternative assumptions that could be subjected to testing against data for strong inference. Testing of multiple competing hypotheses will help the project evolve to

catch up to the extent of knowledge that exists in the older projects on sediment, hydrology, temperature, and fishes; and help Project E evolve as well.

The triennial work plan for Project F notes that the avian community along the Colorado River below the dam may be affected by aquatic insect production, just as may the bat community. However, the GCMRC annual report does not mention any monitoring of insectivorous bird species numbers or analyses of non-lethal tissue samples to assess aquatic versus riparian food ratios. It would be helpful to know whether bird monitoring poses particular challenges that impede its inclusion, compared to the inclusion of bats.

As with the other projects, Project F might benefit from identifying a few core indicators of resource condition. It is true that “food base” is not itself an LTEMP priority resource. However, food-base dynamics clearly are a crucial aspect of “Natural Processes” and clearly shape several other resources.

Project G: Humpback Chub Population Dynamics

The hypothesized drivers of humpback chub vital rates and abundance include depressed turbidity, depressed temperatures, negative interspecific interactions, and a depressed aquatic food base. The triennial work plan states, “Monitoring and research activities associated with humpback chub are mostly mandated by Biological Opinion (BiOp) associated with the LTEMP EIS, which provides limited flexibility for additional work. Within these constraints, proposed activities also seek to respond to recommendations made by the August 2016 Fisheries PEP including: 1) focusing inferences on open models and vital rates (movement, growth, and survival), rather than solely 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], and 4) critically examining the effectiveness of translocation programs.”

The mandates of the BiOp, together with the resulting need for strict comparability among humpback chub monitoring data and estimates of vital rates over time and space, limit the flexibility of Project G to pursue innovations in methods. However, within these limits, Project G is exploring ways to increase the efficiency with which it expends resources to obtain its data. These explorations include decreasing the effort associated with the existing juvenile chub monitoring (JCM) project and improving the efficiency of humpback chub monitoring while “... maintaining acceptable precision on vital rates and adult humpback abundances that are derived from open multistate models that integrate data from the LCR [Little Colorado River] and JCM monitoring.” The project is also “...testing less expensive technology to track humpback chub movement into the LCR” and exploring the feasibility of hypothesis-driven monitoring downriver of the LCR to determine whether the JCM sampling protocols “... can lead to estimates of capture probability, abundance and vital rates (and ultimately strong inferences on drivers) at sites that likely have lower densities, but higher capture probabilities.”

Project G field protocols are mostly well-tested over multiple seasons, and based on standard protocols within the discipline in many respects. The empirical models used to estimate vital rates and abundance from mark-recapture surveys apparently are very sensitive to changes in survey protocols. As a result, the Project G team is very cautious about any possible changes in field protocols. On the other hand, the empirical models — which are also used to assess how

population metrics may vary in response to possible drivers — have evolved significantly. The modeling work under Project G has been subjected to external peer-review. Further innovations also should be submitted for such review. Further, the project was a major focus of the 2016 Fisheries PEP, the findings of which included recommendations for improving monitoring and modeling. The FY2018-2020 triennial work plan is the first plan to fully address these latter recommendations, and also the first to address the measures mandated by the BiOp for the LTEMP, included in the LTEMP ROD. Modeling innovations in FY2017-2018 include development of “... a new version of the multi-state model to estimate adult humpback chub parameters. The new model is a Bayesian model that includes random effects.”

Project G includes one other potentially significant innovation: Element G.9, Backwater Seining. The GCMRC annual report states,

“Seining represents a useful monitoring tool for assessment of both juvenile native (particularly age-0) and nonnative fish due to the high capture probability of the sampling gear and ability to easily sample across large spatial extents. Understanding the relationship between backwater catch rates and local population size in collaboration with Project Element G.6 could be particularly insightful ... Additionally, we began developing a hierarchical Bayesian model to relate removal sampling used to estimate capture probability with single pass seining (the majority of sampling) across broad riverscape scales. Continued development of novel modelling approaches will aid this project in developing robust long-term assessments of juvenile and nonnative fishes in the Colorado River.”

While these innovations in field methods and modeling will necessarily be thoroughly peer-reviewed, we also note that the descriptions of Element G.9 in the triennial work plan and GCMRC annual report do not indicate if the team has a taxonomy or geospatial database of “backwaters” around which to build a spatial sampling design. As noted for Project B, above, the mapping of channel, shoreline, and sandbar morphology has the potential to identify and characterize not only sandbars (the present emphasis of Project B) but also low-velocity aquatic habitats, including along the western Grand Canyon where humpback chub numbers are increasing. As noted above (see Project B), “backwaters” are a sub-type of low velocity, channel-margin habitat. Humpback chub may use several such sub-types for a variety of critical activities, as may other native fishes. For example, larval fish surveys along the Lower Grand Canyon recognize and sample several low-velocity habitat types in every segment of the canyon, including backwaters, eddies, embayments, isolated pools, pocket waters, pools, shoals, and slackwaters (Kegerries et al. 2016). The resulting survey data indicate that native fish larvae use such habitats as nursery habitat or as resting/hiding habitat during larval drift to nursery habitat.

We recommend that the Project G team consider whether seining of backwaters *and other low-velocity channel-margin habitat types, if systematically defined, mapped, and sampled*, could contribute to understanding of humpback chub and other species’ use of low-velocity channel-margin habitats as aspects of their ecology and population dynamics. The distributions and abundances of low-velocity, channel-margin habitats presumably vary by reach in response to dam operations (which affect sediment supply and hydrology) and local channel (macrohabitat) morphology. In addition, we suggest that the Project G team might evaluate the likely comparability of their surveys in backwaters (and other low-velocity, channel-margin habitat types) to the larval fish surveys along the Lower Grand Canyon (e.g., Kegerries et al. 2016).

Project G explicitly recognizes multiple, alternative hypotheses amenable to testing through strong inference. These hypotheses concern the factors that shape humpback chub condition, vital rates, and abundances in different parts of the ecosystem, including downstream from the LCR confluence. Project G depends on output from many other projects (especially A, B, E, F, H, and I) for information on factors that may impinge on humpback chub condition, vital rates, and abundances in different parts of the ecosystem. Consequently, Project G cannot “test” hypotheses concerning causal relationships in isolation, e.g., by using its quantitative models alone. However, the models (both for estimation and for prediction) provide effective tools for examining potential implications of alternative assumptions that could be subjected to testing against data for strong inference.

Project G generates estimates of humpback chub abundances by location, as mandated under the BiOp, and also estimates of condition and vital rates — all with measures of the possible ranges of error in these estimates. These are crucial indicators for adaptive management under the LTEMP, including serving as triggers for management actions to reduce RBT numbers in the LCR confluence area.

Project H: Salmonid Research and Monitoring

Project H combines field, modeling, and laboratory techniques to evaluate the response of rainbow and brown trout to experimental flows. It has four elements: Element H.1, Experimental flow assessment of trout recruitment (*aka* the Trout Recruitment and Growth Dynamics or “TRGD” project); Element H.2, Rainbow and Brown Trout Recruitment and Outmigration Model; 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; and Element H.4, Rainbow Trout Monitoring in Glen Canyon. Together, these four elements will help resolve critical uncertainties about (a) the effects of LTEMP experimental flows (trout management flows, *aka* TMFs, and HFEs) on trout survival, recruitment, growth, and dispersal; and (b) the effects of actions taken to directly manage trout numbers and distributions. Project H also provides crucial data — together with Projects A, B, E, F, and G — to help improve understanding of the factors that shape trout numbers, distributions, and interactions with humpback chub.

The Project H team in FY2018 implemented “... a new sampling scheme ... in Glen Canyon where juvenile and adult trout (rainbow trout and brown trout) are sampled in two sub-reaches four times a year, and in a single sub-reach (-4 mile sub-reach) five times a year.” This sampling design also supports work under Project I: “Per National Park Service (NPS) guidance, brown trout are removed from the lowest sub-reach (-4 mile sub-reach) and monitored in the upper two less populous sub-reaches. In these two non-removal sub-reaches, brown trout are PIT tagged and released unharmed to monitor movement, growth, determine the variation in capture probabilities, and improve understanding of other controlling factors (flows, nutrients temperature, trout density, and size structure) for this species in Glen Canyon. All brown trout removed in other areas are euthanized and put to beneficial use. Lastly, the removal efforts in the -4 mile sub-reach will be used as a secondary measure of removal efficacy.”

We observe that, elsewhere in the presentation of Project H in the GCMRC annual report, the investigators note that differences between 2018 and earlier trout catch rates “... *show a seasonal increase ... that is likely due to changes in capture probability* [emphasis added] and catchability

of small fish captured by electrofishing.” The investigators further note that “Many factors like fish density, size, and temperature ... will influence capture probability; yet, the critical assumption of constant capture probability is not often asked or tested, and when assessed has been shown to be false, particularly for boat electrofishing in Glen and Grand Canyons... Considerable modifications are needed to update the existing Glen Canyon trout population model.” Along these same lines, the investigators for Element H.1 note, “The analytical design we intend on using to determine how trout (rainbow trout and brown trout) dynamics in Lees Ferry respond to weekend stable flows designed to improve aquatic insect egg survival (Bug Flows) during spring and summer of 2018 will require some additional years with and without flow treatments ... Until we modify and update the population TRGD model we will be unable to assess the effect of both the 2017 non-HFE and 2018 HFE on rainbow trout growth.” The previous sampling designs and models used in the study of trout species in the river were heavily peer-reviewed, including via the 2016 Fisheries PEP. The models (both for estimation and for prediction) in use (and undergoing improvements) in Project H again provide an effective tool for examining potential implications of alternative assumptions that could be subjected to testing against data for strong inference. Consequently, all changes and advancements in monitoring protocols, capture probabilities, and modeling should be subject to intense scrutiny, as soon as possible, to minimize the time needed to stabilize them.

Overall, we note that Project H stands on a foundation of many years of high-quality, fine-grained data and decades of larger-scale surveys of fish abundances both system-wide and in the Lees Ferry reach. Changes to monitoring protocols that might interfere with the ability of the GCDAMP to look at trends over time, due to changes in data comparability (e.g., due to changes in capture probabilities), therefore need to be examined carefully and fully reported. Only in this way can any effects of such changes be taken into account fully in data analysis and interpretation. The GCMRC annual report indicates that the teams working on Elements H.1 and H.4 are aware of this need. The GCMRC annual report also indicates that the H.4 team has taken steps to test for data comparability; the H.1 team may need to do something similar.

Project H is on track and producing several metrics (indicators) of rainbow and brown trout abundances, condition, vital rates, and distributions. These are crucial indicators of resource condition for adaptive management under the LTEMP, including serving as triggers for management actions to protect humpback chub numbers in the LCR confluence area and as keys to understanding how dam operations and other factors shape the riverine ecosystem. One possible area for expansion might be to develop measures of rainbow trout and brown trout use of different aquatic habitat types relative to the availability of these habitat types (defined via analysis of the findings of Project B), as discussed above for Projects B and G.

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

Project I continues and improves monitoring to detect and map the distributions of potentially problematic non-native warm-water fish. Much of the conventional monitoring that supports Project I is carried out by the Arizona Game and Fish Department (AGFD) through its long-term, system-wide monitoring program. As noted above for Project H, the AGFD takes precautions to maintain data comparability over time in this larger program, even as it has evolved. The improvements in monitoring under Project I include the addition of a night of GCMRC sampling during the summer in the Lees Ferry reach, in habitat settings where rare non-native fishes have

been caught before and in warmer settings, such as spring inflows, and sloughs/backwaters, to improve early detection of rare nonnative species in Glen Canyon (Element I.2). The improvements in monitoring also include tests of environmental DNA (eDNA) detection tools.

Project I also is investigating the potential risks posed to humpback chub by large-bodied warm-water invasive fish such as the channel catfish, bullhead catfish; small-bodied invaders such as fathead minnow and plains killifish, the latter of which could prey on humpback chub eggs and larvae; and the parasitic Asian fish tapeworm. The assessment of tapeworm incidence uses humpback chub caught in the AGFD effort, which the GCMRC tests for tapeworms using standard, non-lethal protocols that have been used at hatcheries since 1985, with the tested individuals subsequently released back to the river.

The descriptions of Project I in the triennial work plan and GCMRC annual report pose numerous science questions but no formal hypotheses. However, its work under Element I.3, which assesses the risks warm-water nonnative fish pose to native fish, does address cause-effect relationships that might be suitable for the application of strong inference. Element I.3 uses laboratory similar to those employed in previous studies of predation by rainbow and brown trout to assess the effects of confounding variables such as temperature and turbidity on predator behaviors and humpback chub predatory avoidance behaviors.

The GCMRC annual report states that “Laboratory evaluations of predation risk focused on assessing the potential impacts of smallmouth bass on juvenile humpback chub, bonytail chub and roundtail chub ... In general, smallmouth bass are at least four times as predacious as a rainbow trout under similar laboratory conditions but are approximately equivalent to brown trout in terms of predation risk for equivalent sized fish.” This statement is supported by a graph showing regression lines and error bars, captioned “Percent probability that a juvenile chub 60 mm, 110 mm and 215 mm total length (TL) will survive predation by smallmouth bass in 24-hour laboratory predation trials conducted at 20 °C as bass size increases from 140 to 280 mm TL” (Figure 2). We suggest that future versions of this graph show the data points as well as the regression lines and error bars, and be accompanied by information on sample sizes and the statistical methods applied.

Element I.1 did not collect any eDNA pilot samples in FY2018. The delay in testing this method compresses this part of the project into FY2019-2020. Early detection is crucial for managing the impacts of non-native species, and eDNA has been proposed precisely as a tool for early detection. Its application involves complex procedures and logistical considerations for sample collection and preservation, laboratory sample extraction and DNA analysis, and statistical comparisons against databases of DNA profiles of numerous species. Given these complexities, the project team should pursue testing of this method as soon as possible, to begin working out the best protocols for its application along the river below the dam.

The estimation of risk — in this case, the risks posed by potentially problematic warm-water invasive fish — involves multiple assumptions. Element I.3 notes several factors that could shape the risks posed by individual non-native fishes for humpback chub. A more explicit statement of criteria that can be used to assess these kinds of risks would help stakeholders evaluate the work under I.3 and possibly help the investigators articulate additional hypotheses for testing. For example, the risks posed by introduced species may include not only predation but also competition for food or habitat, habitat alteration (one of the possible effects of common

carp, for example), or acting as carriers (vectors) for the transmission of pathogens. Further, interactions between native and non-native species may be habitat-specific. For example, as the GCMRC data indicate, channel catfish prefer relatively deeper habitat, which could affect the likelihood of encounters between this species and humpback chub.

We also have a more speculative suggestion: A more explicit statement of criteria for assessing risk might make it possible to establish an indicator of overall risk for an individual introduced species (or a suite of such indicators, by invader life stage versus native species life stage), and perhaps a cumulative indicator of overall risk across all invaders. Such an indicator or suite of indicators could provide a ready index to track system condition, to accompany the narrative discussions of the presence, abundance, and potential impacts of invasive species already produced.

Project J: Socioeconomic Research

Project J has two priorities in the current triennial work plan. Element J.1 focuses on updating an earlier assessment and implementing a survey of tribal members to determine their preferences and priorities in resource management and protection. The investigative team for this element crucially includes individuals with experience surveying members of Native American communities. This Element was to be implemented in 2018 according to the triennial work plan, and in fact is a continuation of work begun under the immediate preceding triennial work plan (FY2015-2017). However, the survey instrument remains under development and the researchers continue pursuing approval from tribal leadership to survey their members. From all indications, there is a high probability that the actual survey will not be initiated before the end of this triennial work plan. The description of Project J in the triennial work plan references work carried out under the FY2015-2017 triennial work plan, but we could not identify any publications or reports about this work, leaving it difficult to understand the foundations of the program of work, or its prior progress. Given the hurdles this Element has faced — and continues to face — it may be reasonable to ask if there are “low-hanging fruit” in indicators that reflect tribal preferences that could be currently assessed to allow for some preliminary analyses. As documented in the 2017 Knowledge Assessment, the National Park Service collects data on the condition and evidence of vandalism at archaeological and cultural sites. These data could be used to produce an annual indicator of resource condition for Archaeological and Cultural Resources. Further, tribal representatives on the AMWG and TWG, and guest speakers at TWG and other meetings, have also spoken of other possible indicators, such as the frequency and magnitude of interference that tribal members experience when conducting traditional activities along the river; the extent of alterations to culturally significant vistas; the availability of minerals, plants, or animals needed for particular cultural practices; and harm particularly to animal life forms.

The second Element (J.2) focuses on further development and integration of decision-support models for the management of rainbow trout. This work is based on work published by Bair and others (2018). The revised models appear to be significant improvements over the previous models and may be ready for publication soon, fulfilling one of the promised products in the current triennial work plan.

Project K: Geospatial Science and Technology

The triennial work plan identified four Geospatial Project Elements that together provide support to a diversity of GCMRC researchers, manage the existing geospatial data, develop tools for data access and sharing, and to help improve the quality of geospatial information collected. The work reported in the current GCMRC annual report touches on all aspects of this proposed work. The map and data portals referenced in the report all seem to be well in development and promise to be powerful tools for sharing the Center's information.

Project L: Remote Sensing Overflight

This Project has been tabled pending resolution of how it can be funded, with the intention to repeat the 2013 overflights sometime after 2021. This delay will likely significantly impact other GCMRC Projects and it would be valuable for the GCMRC annual report to identify those linkages. For example, the vegetation maps developed as part of the landscape-scale vegetation monitoring (Project C.2) were produced using the 2013 overflight data. The plan to assess 5-year changes in the vegetation seems to have depended on the now-postponed 2018 overflights. It would be of value for this Project report to list those other projects impacted by this delay. It would also be useful for the GCMRC annual report to describe how each project affected by the delay in Project L has adjusted its work to accommodate the changes in Project L.

Project N: Hydropower Monitoring and Research

Project N is intended "... to identify, coordinate, and collaborate on monitoring and research opportunities associated with operational experiments at GCD to meet hydropower and energy resource objectives, as stated in the LTEMP ROD. Operational experiments include experiments proposed in the LTEMP EIS (e.g., HFEs, macroinvertebrate production flows, trout management flows) or experiments that improve hydropower and energy resources (e.g., change in ramp rates, change in daily flow range, fluctuating flow factors, monthly volume patterns), while remaining consistent with long-term sustainability of other downstream resources."

Neither the triennial work plan nor the GCMRC annual report identifies specific methods or either short-term or long-term investigative plans that the present review can address. The annual report also does not indicate whether Project N has analyzed the effects of the FY2018 macroinvertebrate production flow ('bug flow') experiment. The goals of Project N overlap with those of Project J.

Appendix 1: Lake Powell Water Quality Monitoring

The Lake Powell Water Quality Monitoring (LPWQM) program is not funded by the GCDAMP. However, its data are crucial for understanding how dynamics in the lake shape several pivotal downstream inputs to the river through the dam, including water temperature, chemical constituents including nutrients, microorganisms, and particulate organic matter. Consequently, the LPWQM data must meet GCMRC needs for accuracy, precision, detection limits. LPWQM methods therefore must be evaluated and, where necessary, modified to meet GCMRC requirements. In FY2018 the GCMRC signed a five-year agreement with Reclamation for continued support of the LPWQM Lake Powell water-quality monitoring program. The

agreement provides funding for GCMRC involvement in the program over the next year with the potential for funding for up to five years.

The triennial work plan for the LPWQM notes,

*“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 [2017] knowledge assessment ... in which this category consistently had the highest uncertainty... This lack of understanding impedes our ability to predict how various actions discussed in the LTEMP BiOp (e.g., retrofitting the dam to draw waters from different reservoir depths) will affect the [Colorado River ecosystem], 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 nutrient and temperature conditions.”*

Further, the GCMRC annual report states, “In early FY 2018, GCMRC convened a Protocol Evaluation Panel comprised of scientists with relevant expertise to conduct an independent review of the Lake Powell Water Quality Monitoring Program and evaluate the water-quality work of the GCMRC in Lake Powell.” This review was funded under the previous (FY2015-2017) triennial work plan. Recommendations from this review strongly shape GCMRC plans for the LPWQM.

The substantial history of water quality monitoring in Lake Powell and its inflows creates a need for maintaining backward data comparability as the program moves forward. The existing monitoring program will be continued under the new agreement: The GCMRC annual report states that “The ongoing Lake Powell water-quality monitoring program [will continue to consist] of monthly surveys of the reservoir forebay and tailwater (conducted by GCMRC) and quarterly surveys of the entire reservoir, including the Colorado, San Juan, and Escalante arms of the reservoir to the inflow areas (conducted by Reclamation).” The GCMRC will then use the historic data and established lake modeling tools to explore the historic interplay of inflows, inundation and exposure of deltaic deposits at the major inflows, and the establishment of quagga mussel in the lake on P concentrations in the lake and its discharge. The current triennial work plan states that these analyses will inform the development of future sampling and experimental plans, and, over the longer term, support development of a predictive model for SRP concentrations in the dam outflow.

In addition to this continuation of the existing monitoring program and mining of its data, the LPWQM program is expanding. This expansion focuses on upgrades to monitoring at the existing Wahweap station to provide more information on variation in water quality parameters with depth, thermal stratification, and the effects of penstock operations on these conditions.

The LPWQM program will also collect water samples to measure nutrient concentrations at crucial depths at each inlet site (Escalante, San Juan, and Colorado) during the regular quarterly sampling, to help "... determine to what extent excess P may be getting mobilized off of sediment deltas during higher inflow events. Depending on the results of this sampling and the historical data analysis, additional targeted sampling may be conducted in the reservoir inlets to better ascertain the controls on nutrient transformation and transport." The LPWQM program also is implementing other recommendations of the FY2018 Protocol Evaluation Panel, to "improve data management including metadata" and "implement more detailed and formalized sensor calibration and QA/QC of field and lab procedures."

The GCMRC annual report states that existing components of the LPWQM program continued in FY2018 as planned, and the GCMRC put substantial effort into integrating and running QA/QC on the historic database and making sure that new data are the best possible. In addition, GCMRC conducted six complete forebay surveys and four partial surveys of the Glen Canyon Dam draft tubes and Lees Ferry to supplement the quarterly surveys. Of particular note, the GCMRC compared P concentrations (total and SRP) in lake survey samples, measured at the Reclamation water quality laboratory at Boulder City, Nevada, to concentrations measured on duplicate samples at a laboratory that specializes in P readings, especially at low concentrations. These comparisons identified large, systematic differences in the measurement results on duplicate samples between the two laboratories. The annual report states that Reclamation and the GCMRC are working to determine why these systematic discrepancies exist, but does not indicate what solutions may be available, either for addressing backwater compatibility among data streams or for ensuring future compatibility.

The GCMRC annual report also does not indicate, either for Project E or in Appendix 1, whether these discrepancies exist in or affect existing and new GCMRC data on P concentrations in the river *below* the dam. As we noted above, in our comments on Project E, the potential ecological importance of P in the Colorado River ecosystem dictates that all measurements of P from the lake, the river, and its tributaries below the dam be fully comparable with each other, with respect to accuracy, precision, detection limits, and data on covariates (water temperature, pH, DO, salinity, and so forth).

The GCMRC annual report indicates that there is still work to be done in the updated LPWQM program before the GCMRC and Reclamation will be able to draft a new long-term monitoring plan for review, to meet Reclamation, NPS, and GCDAMP needs. This includes work on: (a) instrument calibration, (b) field spatial (location and depth-based) sampling designs, (c) QA/QC for field sample handling and subsequent lab analyses, and (d) data integration and access. The LPWQM program work under the current triennial work plan is, in many ways, exploratory, collecting data and trying out procedures to help the program leadership develop the next generation of the program, including data collection, data management and access, and analysis and modeling. The GCMRC also is exploring the possibility of predictive modeling of total and dissolved P discharge (loads) from the dam based on antecedent conditions in the lake and upstream (inflows) and dam releases. As with Project E, this work is urgent, so that work can proceed on understanding nutrient inputs to the river below Glen Canyon Dam, and the effects of these inputs on the ecosystem. As also with Project E, the results will likely significantly affect F, G, H, and I, as well.

(4) Summary and Possible Next Steps for Adaptive Management

This final section summarizes the key review findings across all projects and offers recommendations concerning next steps for adaptive management. Some of the following comments and recommendations apply to the GCDAMP overall rather than specifically to the work of the GCMRC. The GCMRC is a crucial component of the GCDAMP. Its triennial and annual work plans are products of intense discussions and decisions among the GCMRC and its investigative partners, Reclamation, and the AMWG and its TWG, members of which include the agencies responsible for implementing the LTEMP. Some of the recommendations here pertain to these larger decisions, as they affect GCMRC monitoring, research, and planning.

Documenting Changes in Protocols

The opportunities for specific experimental releases and other management actions under the LTEMP may only occur once every few years. Further, while the conditions of the LTEMP priority resources along the Colorado River below Glen Canyon Dam may change in response to experimental releases, other management actions, and changes in other factors (drivers), may unfold over many years or even decades. As a result, adaptive management in the GCDAMP and implementation of the LTEMP require very high levels of long-term data integrity and comparability.

However, the GCMRC and other institutions involved in monitoring the Colorado River, its tributaries below the dam, and Lake Powell necessarily may need to modify their monitoring protocols over time. These needs emerge as improvements become possible, through new technologies and improved knowledge in various fields of investigation at large; and as funds need to be stretched further, resulting in searches for ways to sustain or improve monitoring at lower costs. The GCMRC annual report for FY2018 identifies several changes that have occurred or are taking place in the monitoring protocols of several projects.

The GCMRC and the other institutions involved in monitoring in support of the GCDAMP should always prepare documentation on all changes in protocols for mission-critical data streams. This documentation should include an assessment of whether and how these changes may affect backward data comparability. Changes in protocols could include changes in detection limits, spatial sampling design, methods used to measure or collect samples, etc. Such changes in protocols may simply increase data accuracy or precision, or sustain existing levels of accuracy and precision at lower costs, but even so should be documented. The GCMRC and its cooperators may want to consider producing two types of documentation on changes to monitoring or research protocols for mission-critical data streams. One type might be technical documentation for the project files, so that each project maintains a complete record of all decisions that have affected data continuity. The other type might be aimed at a less technical audience, to inform the GCDAMP as a whole.

The GCMRC annual report identifies several instances where changes in project methods could affect backward data compatibility, such as changes in fish survey methods and the detection of electronically tagged fishes that could affect “capture” probabilities. The annual report indicates that associated project teams have assessed or are assessing the possible magnitudes and implications of such effects. The GCMRC annual report also identifies possible problems with

data compatibility in the monitoring of phosphorus in Lake Powell and possibly downstream. The GCDAMP should look forward to a report on these problems and their resolution.

External Peer Review of Methods and Reasoning

As stated in the General Comments section, external peer review of the methods and reasoning applied in each project provides the investigators with crucial feedback on these methods and reasoning. Further, these external reviews provide the entire GCDAMP community with crucial information on the strengths of the foundations on which these projects rest.

Conceivably, a long-standing project may not innovate once it settles into a set of stable methods, and therefore may not need such ongoing peer review by external experts. However, the investigative disciplines serving the GCDAMP necessarily have evolved since the GCDAMP began and will continue to do so. As a result, the best methods available have also evolved, and currently they may provide greater accuracy, greater precision, or more data at lower costs; or may allow investigators to collect new kinds of data that are strongly relevant to the objectives of the program. The GCMRC and its partners in fact may originate some of these innovations themselves. Further, the objectives of the GCDAMP itself have evolved, as has its understanding — and thinking — about how the Colorado River ecosystem ‘works’ and responds to dam operations, other management actions, and other system drivers. As a result, innovation in methods and reasoning is the norm rather than the exception for all the monitoring and research projects included in the current triennial work plan and addressed in the GCMRC annual report.

As a result, the GCMRC and its partners face a constant need for ongoing external review by experts in the relevant investigative disciplines. As noted in the General Comments section of the present review, above, the USGS FSP guidelines mandate multiple levels of review for all information products written by USGS investigators. These guidelines include support for investigators when they submit works for publication in professional journals. The GCDAMP benefits greatly from the intense scrutiny that comes with the external peer review of reports on GCMRC and partner investigations. In fact, we suggest that GCMRC and partner investigators should submit every substantial innovation in methods and reasoning for external, expert review. By substantial, we mean any innovation that: (1) affects data accuracy or precision in ways that could alter interpretations and decision making, or that could alter backward data compatibility; (2) introduces new types of data or new lines of inquiry concerning priority resources or factors that may shape them; or (3) introduces new or improved concepts for understanding how the Colorado River ecosystem ‘works’ and responds to dam operations, other management actions, and other system drivers.

Our review recognizes the great extent to which the GCMRC and its partners maintain an almost steady stream of information products submitted for external, expert peer review leading to publication. These products include presentations at professional meetings, the abstracts for which must be reviewed and approved by the conference organizers and the contents of which are subject to several levels of review within the USGS under its FSP. It is also worth noting that submitting a work for publication does not guarantee its publication. The feedback instead may send the authors “back to the drawing board.” However, such feedback is essential for helping ensure that the methods and reasoning being applied in investigations by the GCMRC and its partners are the right ones for the job. At the same time, our review identifies instances

where projects are in exploratory stages with their methods and/or reasoning, and not yet ready to submit their innovations for external review.

Further, external peer review through professional conferences and publications are not the only mechanisms available to the GCMRC investigators and their partners for obtaining crucial feedback from external experts. As noted in the section on General Comments, the rules of the GCDAMP provide for periodic Protocol Evaluation Panels to review the methods and reasoning used in its various investigations. The most recent Protocol Evaluation Panels took place in FY2016 and FY2018 and covered the investigations of native and non-native fishes, and Lake Powell water quality studies, respectively. The investigations of the food web (Project F) benefited greatly from a Protocol Evaluation Panel in 2012 and its investigators propose conducting a new one in FY2019. This proposed accelerated cycle of review of food-base studies by an expert panel appears to be appropriate, given that this is one of the newest and most rapidly growing projects in the overall program. The GCMRC and the GCDAMP at large may want to consider whether other projects undergoing significant waves of innovation or exploration might also benefit significantly from a Protocol Evaluation Panel.

External Peer Review of Predictive Models

As noted in the General Comments section of the present review, above, the GCMRC, its investigative partners, and the GCDAMP increasingly rely on predictive, quantitative ecological models as decision support tools. Examples discussed in the GCMRC annual report include models to predict the likely effects of proposed experiments and management actions particularly on humpback chub, rainbow trout, and brown trout abundances, condition, and vital rates; the effects of ‘bug flows’ on aquatic insect emergence at different locations along the river; and the effects of SRP on gross primary productivity, in relation to other factors such as river discharge, temperature, and turbidity. These kinds of predictive models serve two important purposes in adaptive management programs: (1) they permit examinations of the possible effects of different management actions (which for the GCDAMP includes different types of dam releases), to support decisions on which actions to prioritize; and (2) they allow the investigators to identify real-world implications of different assumptions that can be represented in runs of the model, so that these implications — predictions — can be compared to reality, thereby testing these assumptions. The latter purpose can provide crucial guidance for designing experiments in support of strong inference, by identifying contrasting implications of different assumptions.

As we stated in the General Comments section of the present review, predictive, quantitative ecological models integrate multiple types of information and represent multiple causal relationships to predict the consequences of changes in individual inputs or constraints on system outputs. Such models typically are mathematically complex; incorporate numerous assumptions about how the represented “system” works; and use complex computational methods. For these reasons, it is crucial that these decision support tools receive stringent external peer review. Such reviews should help assure the resource managers and other stakeholders in an adaptive management program of the reliability of the model outputs.

Our review of the individual projects in turn noted several instances throughout the GCMRC annual report where investigators describe ongoing work to build or improve predictive models in support of adaptive management. All such advancements should be subjected to external, expert review when each model reaches a point of stability in its methods.

Further, some stakeholders may not be familiar with particular types and methods of modeling, even as the GCDAMP relies increasingly on such modeling to support decision making. The GCDAMP might request communications to the AMWG or TWG from the investigators, to help the stakeholders understand better how each model works and its reliability in support of adaptive management.

Indicators of Resource Condition

We state in the section on General Comments that the individual projects, and the GCDAMP overall, might benefit from the development of repeatable, “SMART” indicators of condition for all of the LTEMP priority resources. Projects that produce data needed under the BiOp already do so, as do projects that produce data needed to guide decisions on whether, when, and in what form to conduct HFEs and other flow experiments. Our review identifies other opportunities for articulating such indicators, particularly for resources that do not fall into either of these two categories. For example, the National Park Service collects standardized metrics on the conditions of Archaeological and Cultural Resources, which it summarized for the 2017 TWG Knowledge Assessment. Further, Tribal representatives to the AMWG and its TWG have described several potentially useful types of indicators that also might be tracked on the condition of Archaeological and Cultural Resources and Tribal Resources. These indicators could be put in place even while work continues on Project J, Element 1, Tribal Perspectives for and Values of Resources Downstream of Glen Canyon Dam: Tribal Member Population Survey.

We recognize that some projects are not yet at points of development where it will be easy to develop possible “SMART” indicators. Further, we recognize that the LTEMP ROD assigns the lead agencies for the LTEMP primary responsibility for leading the development of such indicators. Our comments here are intended to encourage both the GCDAMP and the project teams to pursue the development of such indicators. Developing such indicators — even just running pilot tests of possible indicators — will benefit the overall process of adaptive management, as we argue in the section on General Comments, above.

Strong Inference

We argue in our General Comments, above, that all investigations, and especially those crucial to adaptive management, benefit from adopting the methods of strong inference. Voices within the GCMRC are also calling for greater use of these methods. Strong inference involves three core elements: (1) articulating alternative, competing hypotheses to address questions of “how” and “why”; (2) identifying types of evidence that, if collected, would allow the investigators efficiently to discriminate among the alternative hypotheses based on which ones fit or do not fit the evidence; and (3) collecting, analyzing, and weighing the needed evidence. The cycle then repeats as understanding evolves. As we note in our General Comments, harnessing the methods of strong inference can both enrich and accelerate the pace of learning.

Our review of the individual projects identifies several projects, for which the methods of strong inference may not be appropriate. These consist of projects focused only on producing key data streams to support decisions on LTEMP experiments and management actions. However, the methods may be a good fit for the remaining projects and, in fact, several of these latter projects are beginning to explicitly incorporate these methods.

We also note that stakeholders in adaptive management programs almost always bring a diversity of perspectives to the program. These different perspectives include or entail differences in the ways they may interpret the same body of facts — differences in their understandings about the “how” and “why” of the subject system and the way it works. Strong inference provides a mechanism for learning, when investigations must consider alternative perspectives and hypotheses. It should be possible to harness stakeholder input to the process of identifying potential alternative hypotheses for testing. We return to this point, below, at the end of Section V.

Discriminating and Quantifying System Inputs

We recommend in our General Comments that the GCDAMP begin keeping separate, explicit track of variation in all important inputs to the Colorado River ecosystem below the dam, and presented two reasons for this. First, we suggest that the GCDAMP needs to be able to distinguish the effects of LTEMP experiments and management actions on the ecosystem below the dam, from the effects of variation in important inputs. At present, the absence of an ability to systematically distinguish these two types of effects creates significant uncertainty for interpreting the results of LTEMP experiments and management actions. Second, we suggest that the GCDAMP needs to better understand the factors that affect variation in important inputs, especially if those factors could result in long-term, systematic changes in these inputs. Knowledge of these factors and forecasts of their potential variation will provide crucial guidance to the GCDAMP on the management challenges it will face, and on what scales of time.

Our comments on the individual projects identify several projects that we suggest could develop indicators of crucial system inputs for routine tracking. Reclamation already tracks and forecasts the availability of water to supply Lake Powell, and therefore to generate electricity through the dam and maintain the river below the dam. Other candidates for such tracking of inputs, we suggest, include inputs of sediment (Project A), nutrients (Project E), and non-native organisms (Project I). The GCMRC, its cooperators, and other stakeholders will best know which may be worth consideration.

Other Possible Ways to Advance Adaptive Management

Finally, we suggest four other ways in which the GCMRC, its investigative partners, and the GCDAMP overall might further enhance adaptive management along the Colorado River ecosystem below Glen Canyon Dam. We present these in order from the more specific to the more general.

First, the investigative projects presented in the current triennial work plan and the GCMRC annual report include multiple instances, in which one project depends on the output of one or more other projects to meet its investigative goals. We suggest that future triennial work plans include a diagram or table indicating such critical dependencies, to make it easier for the GCDAMP to keep track of these interactions. This could help the program avoid or minimize situations, in which a delay in one project affects the investigative schedules of others — as occurred in FY2018 when the postponement of the overflights (Project L) impaired investigations of riparian vegetation dynamics (Project C).

Second, the interactions among projects — or the potential for such interactions — may present opportunities for additional learning. For example, as we discuss in our comments on the individual projects, the data collected by Project B potentially could be used to map not just sandbars and other depositional forms but aquatic habitat types such as low-velocity, channel-margin habitats. Various native and non-native fish may use or require such habitat types for a range of activities over the course of their life cycles. Consequently, the abundances, spatial distributions, and stability/instability of these habitat types may affect the abundances and vital rates of these species. While we did not explore this idea in our individual project comments, we can also suggest that such interactions might affect aquatic macroinvertebrates and macrophytes as well. Such interactions might also affect the results of surveys of aquatic fauna and flora.

Third, systematic assessments of the state of knowledge, such as the 2017 TWG Knowledge Assessment, provide a useful mechanism for identifying areas of uncertainty in understanding of how the system ‘works,’ including interactions among properties of the system and how the system responds to flow experiments, other management actions, and changes in other drivers. Knowledge assessments also provide an opportunity to identify differences in understanding among the investigators and stakeholders that might be addressed through the application of the methods of strong inference. Several project descriptions in the current triennial work plan note important contributions of past knowledge assessments (2005, 2012, 2017) to current project plans.

Finally, methods exist for enhancing the process of identifying critical uncertainties and differences in understanding that could affect adaptive management. For example, it can be useful to bring investigators and stakeholders together in “what if” exercises, in which the participants are asked to consider the question for some part of the system, “*What if your understanding of this part of the system is wrong?*” A question like this leads the participants to consider the assumptions they bring to their understanding of the subject and how a change in these assumptions might lead them to different expectations. Such exercises increase transparency in adaptive management, and also can serve as engines for generating new hypotheses for testing through strong inference.

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