Southwest Climate Adaptation Science Center Final Report

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Informing policy response to declining water supply in the Colorado River Basin: linking water supply management with outcomes for fish communities

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PUBLIC SUMMARY

Water-supply managers in the Colorado River Basin are tasked with balancing consumptive water use with natural water supply. Decisions associated with water-supply policy can include where and how much water consumption occurs, where water could be stored, and how to operate reservoirs. Water-supply decisions often affect other resources including energy production, recreation and aquatic ecosystems.

The goal of this project was to model how different water supply management scenarios might affect riverine ecosystems with a specific focus on potential impacts on federally listed fish populations, including threatened humpback chub (*Gila cypha*) and endangered Colorado pikeminnow (*Ptychocheilus lucius*) and razorback sucker (*Xyrauchen texanus*). Threats to these endemic species include introduced non-native fish species that often become invasive, like smallmouth bass (*Micropterus dolomieu*), and altered physical conditions that may favor these non-native fish species over the endemic fish species. Changes in how water supply may be managed in the Colorado River Basin can affect physical conditions in rivers by altering how much water flows through a particular river segment at a given time, by changing the extent of riverine ecosystems between reservoirs, and by determining the quality of water released from storage reservoirs with fixed release elevation (*e.g.*, full reservoirs generally release colder water). To address our goal, we developed tools that coupled water storage models, river temperature models and fish population models to examine how different scenarios to operate Lake Mead, Lake Powell, and Flaming Gorge Reservoir, the three largest reservoirs in the watershed, may affect fish populations.

We developed our work plan when available water supply was diminished. At the end of our project period (May 2022), Lake Powell and Lake Mead contained historically low water levels, and our models were being used in evaluating different options for operating Lake Powell by the Bureau of Reclamation and other stakeholders.

PROJECT SUMMARY

Purpose and Objectives

During the period of our study (April 2020 – May 2022), Colorado River Basin (hereafter, "Basin") managers and stakeholders were negotiating water-supply agreements to determine water supply and storage in the Basin after current agreements expire in 2026. These Basin-wide decisions can have significant impacts on various resources in the river segments between the reservoirs (Bair et al., 2019). The primary objective of this project was to combine existing data and models with new analytical approaches to forecast potential ecological responses to a wide range of future management and climate scenarios. Ecological responses were focused on threatened or endangered fishes because of stakeholder interest and federal mandate under the Endangered Species Act. The original goals of this project were to help forecast various fish responses to reservoir storage, consumptive use, watershed runoff, and reservoir operations across the Basin over timescales of decades, and initial products focused on these goals. However, low runoff in 2020, 2021, and 2022 accelerated the rate of decline in storage in the Basin, leading our team to shift focus towards development of near-term forecasting tools to help meet information needs of stakeholders working in the Basin.

Organization and Approach

As part of our project, we consulted with resource managers and researchers throughout the Basin to synthesize understanding and focus analyses on specific species, geography, and potential management scenarios. Initial analyses focused on coupling existing hydrology, water temperature, and fish response models to provide general forecasts for a broad set of fish species at decadal timescales under different water supply and storage scenarios. At the same time, based on stakeholder input, we began to build more accurate models of smallmouth bass population dynamics in the Green River and Yampa River to address specific questions regarding water storage and management of Flaming Gorge Reservoir. As the water elevation of Lake Powell declined in 2021 and 2022, we continued development of these models, while also adapting the water storage, water temperature, and smallmouth bass models to aid in near-term forecasting of potential smallmouth bass invasion of the Colorado River in Grand Canyon. This study developed tools to help quantify the risk of smallmouth bass entrainment and population expansion at different elevations of Lake Powell, which in turn can support managers as they evaluate formal NEPA (National Environmental Policy Act) analysis of changes to the operation of Glen Canyon Dam in 2023 to potentially prevent establishment of smallmouth bass.

Project Results, Analysis, and Findings

Results from our project occurred in five categories:

- Results from our evaluation of possible fish responses to future management and runoff scenarios illustrated the potential for large changes in the coming decades if drought continues and consumptive uses are not reduced.

  Among our findings, we demonstrated that many fish response metrics were less affected by changes in where water was stored (i.e., Lake Mead or Lake Powell) than they were by the overall balance between water supply and use. We also showed that the ability to use designer flows to reach environmental goals is likely to decline over time.

- Our synthesis of existing models and literature as well as development of relationships with various fish experts and stakeholders allowed us to focus our modeling efforts on river segments that were most affected by water management scenarios, on management decisions being considered by water managers in the system, and species with the highest likelihood of a response to management decisions.

- Near term forecasts of the risk of smallmouth bass establishment in the Grand Canyon under different inflow and water management scenarios can assist managers in formal analysis of operational alternatives to help prevent smallmouth bass establishment.

- Predictive tools developed as part of this project will continue to be developed and made available to inform future water management decisions.

Conclusions

Native fish population status and trends throughout the Basin are linked to water management decisions. Our project developed models that can provide managers, policy makers, and stakeholders with short-range scenario outcomes to help support management decisions and assist policy makers and stakeholders in understanding the trade-offs associated with alternative long-term water-supply scenarios. Our project developed quantitative forecasting tools that can be used in current management and long-term policy development to include consideration of native fish communities in the management of the Colorado River.

FULL REPORT

1.0 Purpose and Objectives

Background

If the low natural water supply experienced within the Colorado River Basin since 2000 (Fig. 1) continues, then current consumptive water may exacerbate the issue (Wheeler et al., 2022). The project described here built off, and was closely linked with, the Future of the Colorado River project (hereafter, "Futures Project") within the Center for Colorado River Studies at Utah

State University. The Futures Project was focused on how changes to water policy, including consumptive water use, might affect reservoir storage and, by extension, flow regimes and water temperatures within the rivers of the Colorado River Basin. The purpose of the project described here was to develop fish population models, and link them to the models developed by the Futures Project to help answer the question, “What are the potential outcomes for fish communities based on different policies regarding management of the water supply provided by the Colorado River?”

The Futures Project was conducted between 2018 and 2021 (Fig. 2), and there was an overlap of approximately nine months in the work of the Futures Project and of the project described here. The work of the Futures Project was summarized in multiple white papers and a 2022 *Science* article (Wheeler *et al.*, 2022). Wheeler *et al.* (2022) forecasted future total reservoir storage in Lake Mead and Lake Powell under different policy combinations of reduction in consumptive use in the Upper and Lower Basin (Fig. 3). The focus of this paper was

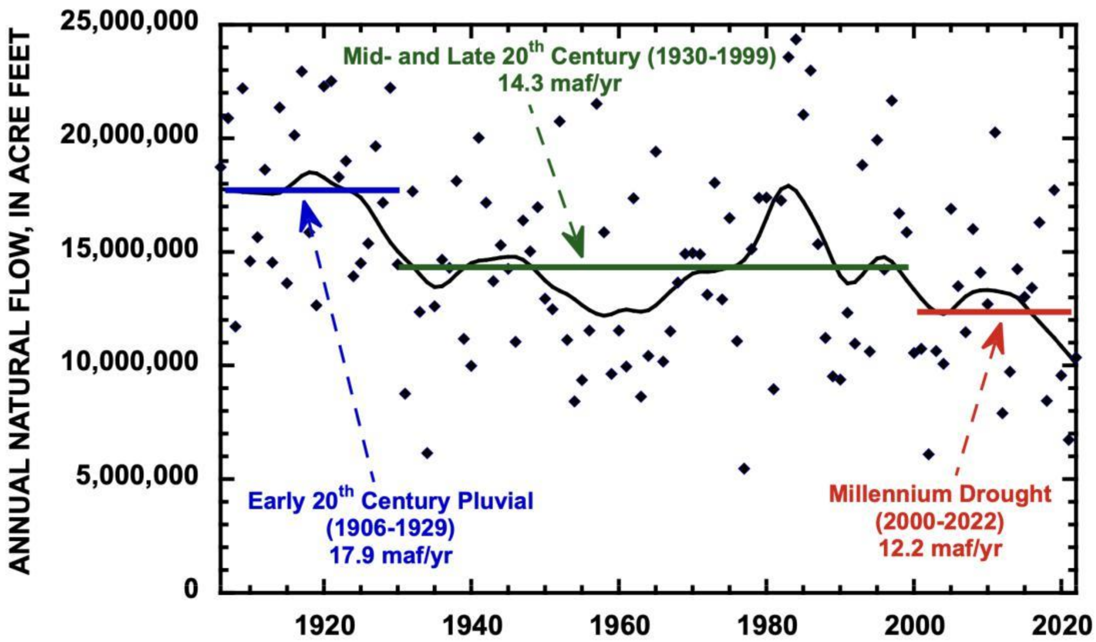

Figure 1. Graph showing estimated natural flow of the Colorado River at Lees Ferry as estimated by the Bureau of Reclamation. Data include provisional estimates for 2022 and mean annual flow for three periods is indicated by horizontal solid lines. Data downloaded from https://www.usbr.gov/lc/region/g4000/NaturalFlow/provisional.html. The abbreviation MAF/yr refers to million acre feet per year.

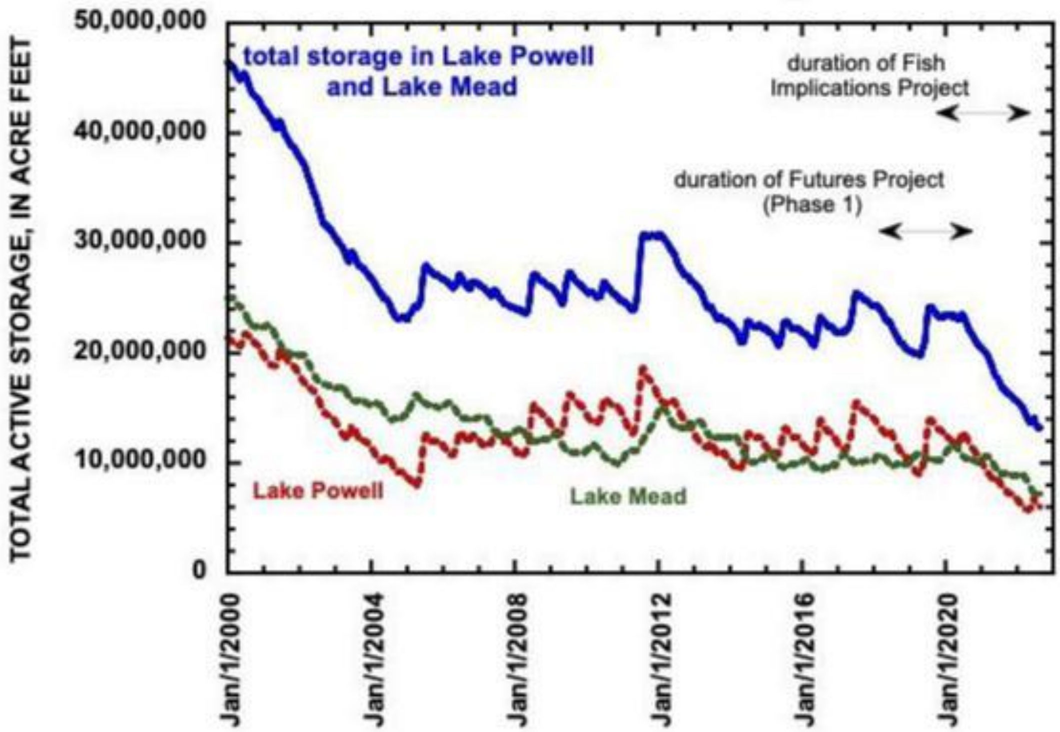

Figure 2. Graph showing water storage in Lake Mead and Lake Powell during the 21st century and the duration of relevant research projects (including the Futures Project and Fish Implications Project). Note the large decrease in reservoir storage between 2000 and 2005 and the large decrease beginning in mid-2000. The recent decrease in storage occurred at the same time that our research project was conducted. Data downloaded from https://www.usbr.gov/uc/water/hydrodata/reservoir_data/site_map.html

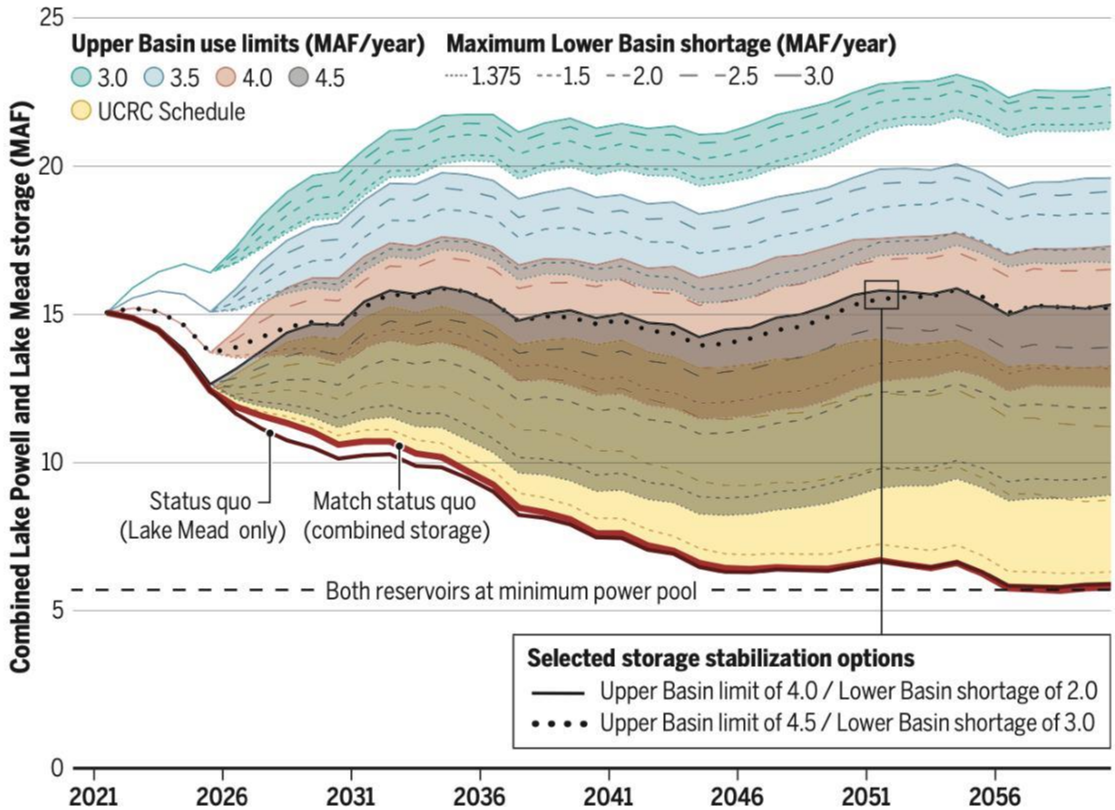

Figure 3. Graph showing average combined reservoir storage in Lake Mead and Lake Powell under different combinations of reduced consumptive water use in the Upper and Lower Colorado River Basin (or "Basin"), assuming hydrologic conditions since 2000 continue. Results show combined reservoir contents using a range of Upper Basin consumptive use limits (colored ribbons) along with a range of Lower Basin maximum consumptive use reductions (line styles) triggered when the combined storage falls below 15 million acre feet (maf). The status quo lines use the projected Upper Basin consumption predicted by the Upper Colorado River Commission in 2016. Figure from Wheeler *et al.*, (2022). The abbreviation MAF/yr refers to million acre feet per year.

on the potential outcomes to total reservoir storage and discussion of the implications of a declining water supply on the reliability of water supplies. The Fish Implications Project built on this work and initial results were presented in Bruckerhoff et al. (2022) along with findings from the Futures Project reflecting this transition.

Although the condition of riverine ecosystems is of international, national, regional, and local interest, large scale water-supply decisions in the Colorado River Basin have rarely considered potential impacts on river ecosystems (Bair et al., 2019). To help decision makers understand impacts on river ecosystem, river scientists can synthesize their assessments of the implications of significant changes in flow regime and river temperature on riverine ecosystems downstream from large reservoirs. In the absence of such synthesis, the scientific community sometimes offers conflicting advice or recommendations, or no advice, on major impending water-supply decisions. Nonetheless, there is increasing recognition that large-scale water policy decisions can affect ecosystem conditions. Dibble *et al.* (2021) demonstrated that the amount of water stored in reservoirs affects the drivers of ecosystem processes and characteristics in the river into which the reservoir releases its water. The primary ecosystem drivers determined by reservoir releases are the flow regime and the water temperature. Reservoir release temperatures are much warmer from relatively empty reservoirs. Dibble *et al.* (2021) indicates that future fish communities throughout the Colorado River system may be shaped by future patterns of declining runoff caused by the policy changes in response to a declining water supply.

Audience

The primary audience of this project was the community of stakeholders who participate in the development and implementation of policy that guides water-supply management. This community includes the governments and agencies of federal and state government, including the United States and Mexican national governments and those of the seven states in the United States and two states in Mexico. Relevant United States (U.S.) departments are the Department of the Interior and the Department of Energy. Relevant bureaus within the Interior include the National Park Service (NPS), Bureau of Reclamation (BOR), and U.S. Fish and Wildlife Service (USFWS). Other traditional stakeholders include those who represent the interests of agricultural, municipal, and industrial users of Colorado River water, including irrigation and water conservation districts and regional municipal water user districts, as well as consumers of federally subsidized hydroelectricity. Stakeholders also include the sovereign Native American Tribes that hold adjudicated rights to the Colorado River, are in the process of adjudicating those rights, or provide advice and guidance due to their membership on various adaptive management programs. Non-traditional stakeholders include nongovernmental organizations (NGOs) who represent river and reservoir recreation and environmental concerns.

Goals

The original goals of this project were to 1) develop tools useful in considering the outcomes for a suite of non-native and native fish species to new water-supply policy and 2) use those tools to illustrate how different water-supply policies may cause very different riverine ecosystem outcomes. When this project was conceived in 2018, storage in Colorado River Basin reservoirs was just beginning to decline after a few years of stability (Fig. 2), and critical storage levels were thought to be in the distant future. At that time, our focus was informing renegotiation of the Interim Shortage Guidelines that had been adopted in 2007, which primarily concern operations of Lake Powell and Lake Mead, include policy concerning reducing consumptive use when reservoir storage is low, and have a 2026 deadline for renegotiation. Work early during the project reflected these broad goals (*e.g*., Bruckerhoff *et al*., 2022; Schmidt *et al.*, 2022a,b). During the project period (2020-2022), storage levels in Colorado River reservoirs declined substantially (Fig. 2), and stakeholder concerns expanded from planning for policy beyond 2026 to also managing near term responses to declining reservoir elevations. To help meet stakeholder goals, the scope of our project expanded from modeling potential future scenarios to using modeled outcomes to inform current management scenarios.

Work later in the project focused primarily on how one non-native fish species, the smallmouth bass (*Micropterus dolomieu*), might respond to changing conditions in the Green River and Yampa River segments and the Grand Canyon segment of the Colorado River Basin. While there are numerous invasive, non-native species found in the Colorado River Basin, smallmouth bass are considered the greatest threat to native fish (Johnson et al., 2008). In the Green and Yampa rivers, we developed a smallmouth bass model by modifying and updating a previously developed population model for smallmouth bass (Breton *et al*., 2015).

Starting in fall 2021, we transferred the smallmouth bass model developed for the Green and Yampa rivers to the Grand Canyon segment to help respond to stakeholder concerns regarding the imminent invasion of smallmouth bass into the Grand Canyon. Our models regarding entrainment and establishment risk of smallmouth bass have provided a scientific grounding regarding potential risks of different Lake Powell reservoir elevations, different seasonal release patterns from Glen Canyon Dam, and have assisted the Interior Secretary's Designee in developing operational alternatives for Glen Canyon Dam to potentially prevent the establishment of smallmouth bass in the Grand Canyon.

2.0 Organization and Approach

Our general approach included: 1) meeting with resource managers and researchers across the Basin to determine the status of different species, including existing models, 2) modifying and updating existing models with newer data when possible, transferring models from one river segment to another when possible, and developing and fitting new models when necessary, and 3) coupling fish models with water storage and ecosystem driver models developed as part of the Futures Project. We focused on the downstream effects of operations at Lake Powell and Flaming Gorge Reservoir (Fig. 4). We did not consider the downstream effects of operations of Lake Mead, because the tailwater is very short and leads directly into Lake Mohave. Our approach was similar to the phases we proposed at the beginning of the project. We had originally proposed to work in five phases:

- Phase 1: Knowledge Synthesis

Figure 4. Map showing the Colorado River Basin and areas served by Colorado River water. Also shown are Flaming Gorge Dam and Glen Canyon Dam, the primary areas of study. Image adapted from https://www.usbr.gov/lc/images/maps/CRBSmap.jpg.

- Phase 2: Evaluation of different water management scenarios concerning consumptive uses and losses and different management rules at Lake Mead and Lake Powell.

- Phase 3: Identification of the thresholds at which “no analogue” conditions would exist, which could complicate scenarios of future fish communities.
- Phase 4: Creation of simple models that can be linked to the water resource models used by the Futures Project.
- Phase 5: Outreach with fish scientists and water managers.

We completed significant work in all phases of the project, but the order of our work and the nature of our outreach changed as management agencies requested real time forecasts based on management scenarios as Lake Powell’s water storage continued to decline between 2020 and 2022. Our project began with multiple virtual meetings with managers and research scientists working in the Upper Colorado River Endangered Fish Recovery Program and San Juan River Basin Recovery Implementation Program, which helped us to identify existing models, key publications, and sources of data to update existing models and fit new models. Our initial analyses then focused on relatively simple metrics of temperature suitability, thermal tolerances, ability to implement designer flows, and river connectivity, applied to a broad suite of species and explored their response under a wide range of conditions over decadal time scales (Bruckerhoff *et al.*, 2022). As drought in the Basin increased, we continued dialogue with stakeholders to understand the decision context, and fish experts working in these systems to identify the key species of interest. These conversations allowed us to focus our scope in terms of species, geography, and viable management options. Work in the latter half of the project became focused on making forecasts over more immediate time scales (e.g., what were the potential impacts of different monthly water release scenarios under the Drought Response Operations Agreement (DROA) on the probability of smallmouth bass establishment in the Grand Canyon segment?)

All model forecasts concerning the fate of fish communities included consideration of the management context of the future Colorado River: how much and where water is consumed, how much and where water is lost to reservoir evaporation, the rules that concern diversion of stream flow, and the operation of reservoirs.

Future Hydrology

No one can predict with precision the future hydrology of the Colorado River (Seager et al., 2013). Therefore, we identified different scenarios where the drought conditions experienced since 2000 may continue or the process of aridification intensifies and mean annual runoff may continue to decrease. Salehabadi *et al.* (2022) developed different sequences of wet and dry years that could be run under any specific scenario of a future mean annual flow. For purposes of most of our modeling, we assumed that the hydrologic supply conditions of the 21st century continue, and we used a hydrology scenario developed by Salehabadi *et al.* (2022) that resamples hydrological inputs observed since 2000. This scenario maintains statistical features of the drought since 2000, such as mean and variance.

Reservoir Operations

To help inform future management decisions, we identified a wide range of possible scenarios for reservoir operations and forecasted their impacts using a variety of hydrologic scenarios. Specifically, we evaluated the implications of filling Lake Mead first (hereafter FMF) and the implications of filling Lake Powell first (hereafter FPF) and compared outcomes of these scenarios to outcomes from a continuation of current management rules. The FMF scenario would relegate Lake Powell to a secondary storage facility, filled only after a succession of very wet years. Preferential storage in either Lake Mead or Lake Powell has the potential to reduce evaporative losses. Environmental outcomes of FMF could include 1) re-exposure of rapids in lower Cataract Canyon and side canyons in Glen Canyon, and 2) beginning of the process of re-creating a riverine ecosystem in parts of Glen Canyon. Outcomes of FMF in the Grand Canyon segment below Glen Canyon Dam could be highly dependent on whether Glen Canyon Dam was physically modified. If Glen Canyon Dam was physically modified to allow passage of water and associated constituents (e.g., sediment) FMF could lead to restoration of a more natural streamflow, temperature, and sediment supply regime of the Colorado River in the Grand Canyon. However, if Glen Canyon Dam was not altered sediment supply could remain depleted and temperature and streamflow may be highly variable. The FPF alternative would use Lake Mead only as a secondary facility. Potential outcomes of the FPF scenario could include maintaining: 1) more water above both dams to allow flexible power generation, 2) fragmentation between Lake Mead and the western Grand Canyon, potentially limiting movement of non-native fish species into western Grand Canyon, and 3) higher likelihood of water being available for designer flows.

Near-Term Forecasts of Fish Responses to Lake Powell Operations

Recent work, focused on near-term forecasts of smallmouth bass entrainment and establishment in the Grand Canyon segment, has used 24-month studies from BOR that included forecasts of reservoir elevations, inflows and outflows to forecast water temperatures, smallmouth bass entrainment and population growth. Given the shorter time frame of these forecasts, focus has shifted towards identifying changes to monthly allocations or bypassing of water through the deeper river outlet works (also called jet tubes) to cool the river and help prevent smallmouth bass establishment.

3.0 Project Results, Analysis, and Findings

Evaluation of impacts associated with future scenarios of runoff and alternative paradigms of management using simple fish response models

One of the first analyses as part of this project involved forecasting the responses of a series of simple fish metrics to a range of future scenarios. We used modeled hydrology and river temperatures to compare the outcome of combinations of water storage scenarios and consumptive use limits on metrics that can inform ecosystem management. This work focused on the Grand Canyon due to the urgent need to consider extreme future scenarios for water storage in Lake Powell. We compared current water management operations to two extreme endpoints: the FMF and the FPF management scenarios. We compared outcomes of these management options in combination with three levels of consumptive use restrictions, all under the assumption that the hydrologic conditions experienced since 2000 persist. Our models indicate projected levels of Lake Mead and Lake Powell could continue to decline regardless of where water is stored if consumptive use was not limited.

Low reservoir levels are expected to limit environmental flow delivery and increase fragmentation regardless of where water is stored if water supply remains depressed, unless consumptive use declines (Bruckerhoff et al., 2022). Our models forecasted the warming of Lake Powell releases that are now occurring and that the temperatures of the Colorado River downstream from Glen Canyon Dam could become suitable for smallmouth bass. Water storage decisions – whether FMF or FPF – can provide management flexibility, but these water storage policies may be less important in determining downstream ecological conditions when consumptive uses remained greater than total water supply. These results indicate that environmental management alternatives tied to reservoir operations can be more adaptive and flexible if there is more water in storage. These results assume continued persistence of Glen Canyon and Hoover Dams, and we made no attempt to compare ecological outcomes in which dams were removed. This work is published in Bruckerhoff *et al.* (2022).

Synthesis of existing models and literature

As we were forecasting conditions in the Grand Canyon using simple fish related metrics, we consulted with Upper Basin fish experts and reviewed literature to help develop fish population models that may provide more accurate forecasts of fish responses. We compiled descriptions of life history attributes and estimates of demographic rates from reports and published papers. For non-native species, we also considered studies beyond the Green River and Grand Canyon that focused on red shiner (*Cyprinella lutrensis)*, smallmouth bass, northern pike (*Esox Lucius*), rainbow trout (*Oncorhynchus mykiss*), and brown trout (*Salmo* *trutta*). For native species, we focused on synthesizing information for humpback chub, razorback sucker, and Colorado pikeminnow. After meeting with researchers studying the Upper Basin and reviewing the literature we decided to focus our initial effort at developing population models in the Upper Basin on the upper Green River because of the availability of data and existing models. We focused on non-native smallmouth bass since this species is considered the greatest threat to native fishes in many parts of the Upper Basin (Johnson et al., 2008).

Forecasting the risk of smallmouth bass entrainment and establishment in the Grand Canyon

As the elevation of Lake Powell dropped in 2021 and 2022 (Fig. 2), fish biologists and decision makers in the Colorado River Basin became increasingly focused on the potential for smallmouth bass invasion of the Grand Canyon segment. Over the last two decades, native fish populations have increased dramatically in the Grand Canyon (Van Haverbeke *et al.*, 2017), and Dibble *et al.* (2021) hypothesized that the lack of established populations of warmwater invasive, non-natives like smallmouth bass was likely a key factor contributing to the positive trends in Grand Canyon. To help inform stakeholders, we used knowledge gained from our Green River modeling to quantify the risk of a smallmouth bass invasion downstream from Glen Canyon Dam (Lake Powell holds large populations of non-native fish including smallmouth bass). Our assessment focused on quantifying both the risk of entrainment (immigration from Lake Powell via dam passage) and establishment (expected rates of population growth resulting from the thermal suitability of daily releases from Lake

Powell). Both entrainment and establishment were known to be linked to Lake Powell surface elevations, however, the lack of a quantitative understanding of thresholds was making it difficult for decision makers to set management targets.

Smallmouth bass in Lake Powell and in other reservoirs are concentrated in the upper portions of the water column. As lake elevations decline, and water continues to be drawn through the penstocks (centered at a fixed elevation of 3470 ft above sea level) the probability that smallmouth bass pass through Glen Canyon Dam increases. We synthesized information on smallmouth bass demography (including the minimum population size required for establishment), fish survival during passage through hydropower tubes, and densities in Lake Powell to develop Bayesian forecasts of entrainment risk at different elevations that incorporated uncertainty and allowed for forecasts over different time intervals (Eppehimer et al., 2024a,b).

In addition to increasing entrainment risk, lower elevations of Lake Powell may lead to release of warmer water that is more suitable for smallmouth bass reproduction. We developed a model to forecast the expected population growth rate of smallmouth bass under different thermal conditions (Eppehimer et al., 2024a, b). Smallmouth bass are a warmwater non-native species that typically spawn at water temperatures of 16°C (~60°F) or greater, and warm temperatures are also needed for growth and survival of young fish (Shuter et al., 1980). Using projected, daily river temperatures under different hydrologic and management scenarios, we were able to estimate the corresponding population growth rate, known as lambda (lambda > 1 indicates population growth). Illustrating the connection between smallmouth bass population dynamics and water storage decisions, we modeled the likelihood of temperatures suitable for smallmouth bass population growth as a function of Lake Powell elevation at the beginning of a water year.

Our work illustrates the design and use of near-term, biological invasion forecasting models that can be developed rapidly and coupled with hydrologic models to address natural resource management scenarios related to water supply issues. Based on presentation of these models to various decision makers and subsequent findings of evidence of SMB reproduction below Glen Canyon Dam by NPS biologists, we continued this work to develop additional scenarios that could help prevent establishment of smallmouth bass. We presented four scenarios, an analysis of their expected effectiveness, and qualitative expectations of resource tradeoffs at a public meeting in August 2022.

4.0 Conclusions and Next Steps

Impact of ongoing water-supply imbalance on workflow and project direction

Our project was originally focused on informing the upcoming renegotiation of the Interim Shortage Guidelines. Low natural runoff in 2020, 2021, and 2022, matched by continued large Basin-wide consumptive uses and losses, caused reservoir storage to decline dramatically (Fig. 2). Decreasing water storage has resulted in the temperature of reservoir releases to increase greatly, and in 2022 water temperatures in the Colorado River downstream from Glen Canyon Dam at Lees Ferry were the warmest observed in the last fifty years (U.S. Geological Survey stream gage 09380000; U.S. Geological Survey, 2022).

Development of models through this project helped to evaluate scenarios to inform immediate river management decisions in the Grand Canyon segment of the Basin. Although much of our original focus was on development of fish response models in the Green River and synthesis of related data in the Upper Basin, declining reservoir elevations at Lake Powell and predicted warming in the Grand Canyon significantly shifted the geographic and temporal scope of project workflow.

Novel contributions and relevance of project

Although the scope of the project has shifted since the inception of the proposal, we have generated numerous novel contributions at the intersection of Basin-wide fish and water supply management scenarios that may become increasingly relevant due to ongoing drought and declining reservoir elevations. Quantifying the linkage between water supply decisions and ecosystems, particularly fishes, can help inform managers to include impacts to ecosystems in their decisions regarding water supply. We have made significant advances in quantifying these relationships with predictive models and these models have facilitated decision processes by managers. These quantitative linkages inform designing and testing future water management scenarios, and they can help managers and stakeholders examine resource tradeoffs and economic benefit/cost analyses, which are crucial in a complex, heavily managed system such as the Colorado River Basin.

Next steps

As of the end of the project period (2022), the Colorado River total federal reservoir storage was at less than 35% of capacity (Fig. 2). To inform future management under low storages and low flows conditions, our models can be adjusted to further identify quantitative and qualitative relationships between water supply conditions and ecosystem responses. The models could be expanded to simulate complex basin-wide operations from a native fish-centric perspective (all possible actions to maintain and enhance existing native fish communities). Subsequent comparisons to other river management goals such as recovering river 'naturalness', maximizing recreational benefits, and sustaining human-centric water supply can identify overlap and disparity in short- and long-term resource maximization scenarios. Quantifying trade-offs among these different scenarios could help identify management scenarios that are mutually beneficial for various goals across various stakeholder groups. The tools, products, and results of this project are adaptable to continue to inform water management questions across the Colorado River Basin. Models developed in this project may be expanded to other parts of the Basin, especially across the Upper Basin.

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