Hydroclimatic change and connections to aquatic ecosystem management in the Grand Canyon

ABSTRACT

The Colorado River below Glen Canyon Dam is a highly modified and managed system, hydrologically and ecologically. Competing demands for water and conflicting management goals have made it difficult to define and implement ecologically beneficial management practices. Projected warmer temperatures and declining runoff of approximately 10% by mid-century will make the already imbalanced supply and demand for water more severe. This will generally translate to less water available to address ecosystem concerns. Furthermore, hydroclimatic change adds complications for scientifically understanding ecosystem processes in this highly altered system and subsequently managing for ecosystem integrity. While direct impacts to aquatic ecosystems are an important part of assessing and planning for the future, the highly managed nature of the system means that human impacts will continue to dominate ecosystem process and function. Management actions have the capacity to build or erode ecosystem resilience to future perturbations. Thus, how water supply and hydropower needs are met within a changing climate has serious implications for ecosystem management opportunities. Continuing to study ecosystem responses to management actions, refine ecosystem goals, place ecosystem objectives in context of larger basin-wide objectives, and build the institutional flexibility to take different management actions will become even more important in the future.

INTRODUCTION

The Colorado River is treasured for its intense natural beauty as well as its service to meet the growing water and electricity needs of nearly 40 million people and irrigation needs for nearly 5.5 million acres of agriculture across seven states (USBR 2012). These two values are often at odds with one another. The management involved to meet human needs, most notably the 40 dams within the Colorado Basin, has altered the physical processes that drive ecosystem function, causing fundamental changes to ecosystem dynamics and native species communities. Current management is governed by the Law of the River, a well-established assembly of statutes and legislation that orchestrate this complex system, and the Glen Canyon Dam Adaptive Management Program (GCDAMP) directs activities below Glen Canyon Dam (Adler 2007). It has become increasingly clear that changes to or within this management framework are needed to address overallocation of water supply, respond to the current drought, and meet future water demands (USBR 2012). It is also clear that management strategies have thus far been unable to address ecosystem concerns. Climate change exacerbates and complicates these issues.

Particularly given the intense human impact on the Colorado River below Glen Canyon Dam, it is difficult to put potential changes to ecosystem management in response to hydroclimatic change into context. In an effort to bring the climate change and ecosystem management discussions closer together, goals for this paper center on identifying ways in which hydroclimatic change may pose additional challenges for aquatic ecosystem management. The following sections synthesize current climate change literature as it relates to potential impacts on Colorado River hydrology and then connects this to aquatic ecosystem management below Glen Canyon Dam. Management of the riparian corridor is also important and interacts with the aquatic ecosystem, but will not be considered in detail. Overall, this paper is intended to further thinking on prioritizing research and management objectives and managing with flexibility under future change.

LITERATURE SYNTHESIS

A changing but uncertain flow regime

Past flows

Prior to the construction of dams along the Colorado River, the river's natural flow regime, characterized by flow magnitude, duration, frequency, timing, and rate of change (Poff et al. 1997), involved sustained flow increases during the winter months associated with the onset of the wet season, large increases in the late spring due to snowmelt runoff, and substantial reductions by the late summer period. Colorado River flows were highly variable, famously marked by large floods that would scour banks, cause debris flows, and transport sediment. Though the historical long term average flow is approximately 16.4 million acre-feet (MAF), annual flow volumes reflect high natural interannual variability, including periods of drought. Within the paleoclimatic 1,200-year tree-ring reconstruction of Colorado River flow, variability is greater than it has been in the past 100 years, with both lower and longer low flow periods as well as higher high flow periods (Meko et al. 2007, USBR 2012). This is the regime to which native species are adapted, and understanding how these physical processes relate to ecosystem functions is critical to improving management for these species into the future.

By changing the flow regime, dams and diversions over the past century have fundamentally altered ecosystem dynamics through reduced flood peaks and durations, lower spring flows, and higher average annual flows due to higher summer releases. Dams have also altered the river's thermal regime by releasing cold water from the hypolimnion of Lake Powell and prevented sediment movement downstream (see Siegfried, this volume), with an estimated 94% reduction in historical sand supply (Melis et al. 2012).

Hydroclimatic change

Climate change has already affected the hydrology of the western U.S., revealed in part warmer temperatures by 1-2^{o}C since the 1970s. This has contributed to a declining snowpack and shift toward earlier snowmelt, which decreases late dry season baseflows (Stewart et al. 2005, Hidalgo et al. 2009, Clow 2010, Ficklin et al. 2013). Currently, the Colorado Basin is experiencing one of the most severe droughts on record, with a deficit of 28 MAF and above-average flows in only 3 of the last 14 years (USBR 2012). Though reservoirs within the basin can store over four times the average annual flow, longer droughts such as this pose severe threats to water supply (Nowak et al. 2012).

Projections based on General Circulation Models (GCMs) show warming continuing (see Rhoades, this volume), with increases from 2-6^{o}C by the end of the century and the most severe increases in the Upper Colorado River Basin (USBR 2012, Ficklin et al. 2013). Though there is a general lack of consensus with regard to precipitation, seasonal and spatial distribution is likely to change (figure 1, from Seager et al. 2012), disrupting runoff and vegetation patterns (Christensen & Lettenmaier 2007, Seager et al. 2012). Evaporation, soil moisture, groundwater, vegetation response, as well as precipitation, are important factors affecting climate feedbacks and runoff. Importantly, temperature and precipitation are not independent factors (Nowak et al. 2012). For example, increased evaporative losses and low soil moisture in 2005 produced flows only 75% of average in a year when precipitation was normal (USGS 2010). In assessing this issue, Seager et al. (2012) found declines in precipitation minus evaporation by mid-century based on an ensemble mean of 16 GCMs from the Coupled Model Intercomparison Project 5 (CMIP5) of the Intergovernmental Panel on Climate Change Assessment Report Five (IPCC AR5). Focusing on temperature effects, Nowak et al. (2012) determined that one degree of

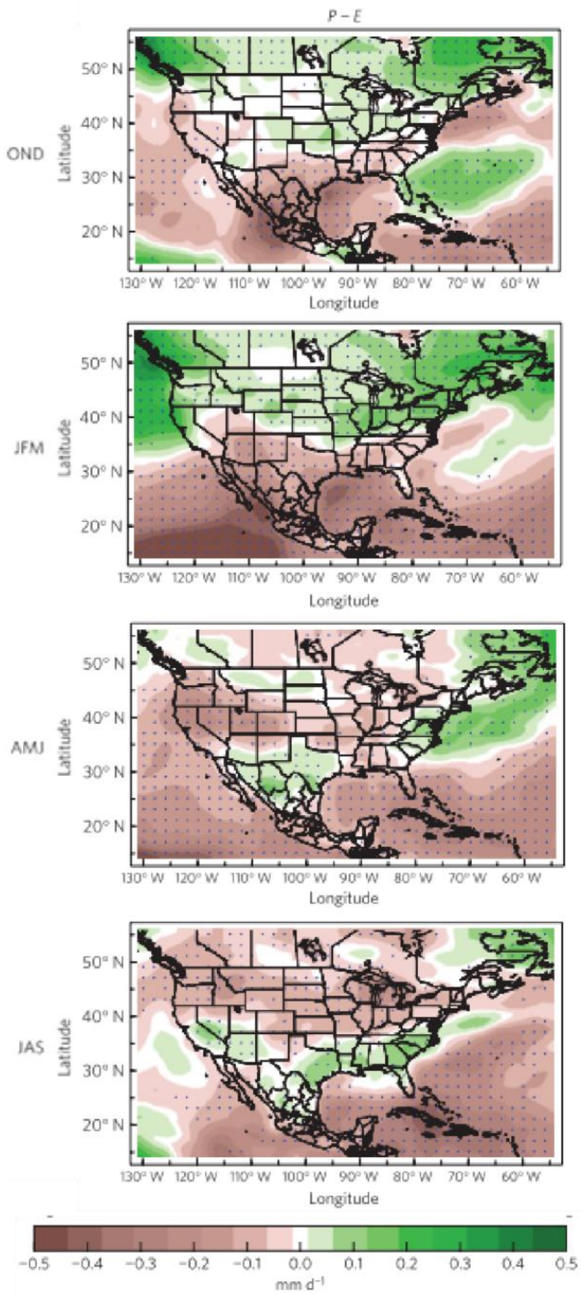

Figure 1 (from Seager et al. 2012). Change in P−E by season for 2021–2040 minus 1951–2000 from the average of 16 CMIP5 models using the RCP85 emissions scenario. Dots indicate that three-quarters of the models and the all-model mean agree on the sign of the projected change.

warming is associated with an annual streamflow decline of 13.8%. Others have found this to range from 2-9% per degree of warming (Vano et al. 2012). Though considerable uncertainty remains, modeling results and other analyses suggest climate change may cause an overall 10% reduction (5-30%) in Colorado River flow by mid-century (Christensen & Lettenmaier 2007, Barnett & Pierce 2009, USGS 2010, Seager et al. 2012, Ficklin et al. 2013). Such reductions are similar to some of the lowest flow periods identified in the 1,200-year tree-ring record (Meko et al. 2007, Seager et al. 2012). Also, due to amplification of the hydrologic cycle, research suggests that extremes in precipitation and drought are likely to increase in the future.

Key scientific uncertainties regarding these future projections in flow include future global greenhouse gas emissions, how GCMs respond to changing greenhouse gas concentrations, the method used to downscale climate data to spatial scales necessary for hydrologic modeling, and the hydrologic model used to determine flows (Maurer 2007). How ecosystems and humans respond to change is another important realm of uncertainty (see Levy, this volume). Vegetation change also affects important land-atmosphere feedbacks and could substantially alter runoff patterns. Particularly important for aquatic ecosystems where hydrology is a central driver, climate change research targeting hydrologic uncertainty is needed to better understand potential future trajectories and uncertainty concerning specific species or ecosystem functions. Unfortunately, climate change projections at a spatial and temporal resolution necessary for effective hydrologic modeling and management decision-making remains elusive (Jiang et al. 2013), causing scientists to resort to other methods such as hydrologic sensitivity analysis (Vano & Lettenmaier 2013). These uncertainties will play out within the context of continued land use change and population growth, the character and magnitude of which is also uncertain.

Aquatic ecosystem management impacts

Primary impacts of Glen Canyon Dam

For the Colorado River below Glen Canyon Dam, climate change is occurring within the context of already highly altered physical processes that have had profound yet not fully understood effects on the aquatic ecosystem and riparian communities. Primary ecosystem impacts of dams relate to altered habitat and temperature regimes (Poff et al. 2007, Olden & Naiman 2010). By preventing the large floods that once passed through the Grand Canyon, important processes no longer rework sandbars to create backwater habitat for the endangered humpback chub (see Gonzalez, this volume). Additionally, the diurnal fluctuations in flow due to releases for hydropower generation erode these important sandbars. The water released from the dam also keeps temperatures below the dam much colder in the summer than native species such as the humpback chub are adapted to and create ideal conditions for non-native rainbow trout which prey on and compete with native fish (Coggins & Yard 2011). Consequently, many of the proposed management alternatives involve adjusting the magnitude, duration and timing of releases from the dam as well as the depth of water withdrawal from the reservoir (which would affect temperature). Determining what those changes should be within the context of the water supply and hydropower constraints, and now climate change as well, requires rigorous science, clear goals, and adaptive management (Pitzer 2010).

Current management

The concept of balancing ecosystem objectives to mitigate for altered habitats and physical processes is still relatively new and certainly very much in flux. Not until the creation of the Glen Canyon Dam Adaptive Management Program (GCDAMP) in 1996 was there a serious mechanism for managing ecosystems within the context of water and power supply (Adler 2007, National Research Council 2007). This program has twelve articulated goals (see Table 1), eight of which pertain to ecosystems (GCDAMP 2001). Though the conservation of native fish, including the

Table 1. Glen Canyon Dam Adaptive Management Program Goals (GCDAMP 2001)
1. Protect or improve the aquatic foodbase so that it will support viable populations of desired species at higher trophic levels.
2. Maintain or attain viable populations of existing native fish, remove jeopardy from humpback chub and razorback sucker, and prevent adverse modification to their critical habitat.
3. Restore populations of extirpated species, as feasible and advisable.
4. Maintain a naturally reproducing population of rainbow trout above the Paria River, to the extent practicable and consistent with the maintenance of viable populations of native fish.
5. Maintain or attain viable populations of Kanab ambersnail.
6. Protect or improve the biotic riparian and spring communities, including threatened and endangered species and their critical habitat.
7. Establish water temperature, quality, and flow dynamics to achieve the Adaptive Management Program ecosystem goals.
8. Maintain or attain levels of sediment storage within the main channel and along shorelines to achieve the Adaptive Management Program ecosystem goals.
9. Maintain or improve the quality of recreational experiences for users of the Colorado River ecosystem, within the framework of the Adaptive Management Program ecosystem goals.
10. Maintain power production capacity and energy generation, and increase where feasible and advisable, within the framework of the Adaptive Management ecosystem goals.
11. Preserve, protect, manage, and treat cultural resources for the inspiration and benefit of past, present, and future generations.
12. Maintain a high quality monitoring, research, and adaptive management program.

endangered humpback chub as well as the flannelmouth sucker, bluehead sucker, and speckled dace, is the central management goal, others relate to supporting the food base, water quality, the riparian community, and sediment processes, all of which help maintain fish populations (Hamill & Melis 2012). Actions to meet other stated goals, including maintaining a viable non-native trout fishery in the cold-water reach below the dam and maximizing hydropower generation, largely conflict with actions to support native species. Successfully reconciling these various goals necessitates detailed scientific understanding of the system, one of the reasons successful management within this reach has remained elusive.

To improve understanding and adaptively manage the system, scientists are conducting experiments and monitoring the ecosystems below the dam. A series of three high flow experiments (HFEs) has been the primary method for exploring benefits from altering dam operations (see Lane, this volume). Although insights into maintaining and building sandbars have been made, unintentional increases in trout abundance have raised concerns over risks to humpback chub (Melis et al. 2012). Important to understanding underlying mechanisms of ecosystem change, subsequent research revealed trout population increases were responding in part to an increase in the midge and blackfly abundance, the primary food supply for fish, after the 2008 HFE (Kennedy et al. 2013). Given the key finding that aquatic ecosystems were food-limited, Kennedy et al. (2013) suggested that reintroducing seasonal temperature variability that the dam prevents could encourage production of aquatic insects whose life histories are trigged by temperature extremes. Scientists are also trying to explain a notable 50% increase in humpback chub populations between 2001 and 2008, perhaps due to warmer waters caused by drought (Hamill & Melis 2012).

Management under climate change

The potential impacts of regional hydroclimatic change on aquatic ecosystems below Glen Canyon Dam are not well understood. This is explained in part by the fact that understanding of current dam impacts is limited and that the system is still responding to previous changes. However, the general consensus is that increasing temperatures, overall declining flows and increases in variability will in effect increase the number of bad years that ecosystems experience. This is expressed in the recent USBR supply and demand study, which found that the percent of vulnerable years for ecosystems increased to around 30% by mid-century (from 9% in the current decade), where vulnerable years were determined solely using metrics of water availability for target environmental flows (USBR 2012). It is also generally understood that ecosystem components will respond differently to changing temperature regimes. Warmer summer temperatures may increase water temperatures downstream of the dam, which could encourage some non-native fish species present in the system (Kennedy et al. 2013). A more dramatic scenario would occur if lowering reservoir levels forced the release of warm water from the epilimnion, which could result in water temperatures downstream approaching 30^{o}C (USGS 2008). However, native species are also adapted to warmer temperatures than are currently present in the river and higher temperatures could encourage productivity (including algae) at the base of the food web (Kennedy et al. 2013).

For the Grand Canyon aquatic ecosystems, how management responds to climate change may have more important implications than direct climate change impacts. Glen Canyon Dam is and will continue to be the overriding influence on the flow regime and consequently ecosystems. Though temperature increases and changes to tributary inflows will impact Grand Canyon aquatic ecosystems, dam operations and adjustments made in response to climate change will be an overriding driver of aquatic ecosystems. With management already unable to balance often conflicting goals, climate change adds additional complications. Challenges will arise simply from attempts to meet the ever-growing water demand whether or not this is exacerbated by climate change, an objective that will remain a top priority. The USBR (2012) study concludes that a combination of measures will be required in the future, including conservation and reuse, groundwater storage, desalination, supply augmentation, and agriculture to urban water transfers. Even with these measures in place, however, scenario analysis revealed that vulnerabilities will likely persist. Such declines in overall water availability will decrease the water available for ecosystem management (such as high flow experiments), particularly if it remains unclear how best to use that water for ecosystem support. This makes studying ecosystem responses to management actions but also understanding likely management responses to water shortages even more important,.

The fact that the system is already highly managed could provide opportunities to buffer against certain ecosystem impacts. In general, with the dam in place, changes in the seasonal timing of flows have relatively little downstream impact (aside from changes in unregulated tributaries) whereas long term changes to annual flow volumes and temperature have greater potential to jeopardize certain ecosystem objectives. Aside from water availability and sediment supply, dam operations can control most aspects of the river's hydrologic regime. Future management can thus be viewed as a more complicated and extreme case of understanding ecosystem response and reconciling objectives than what is currently found on the river today. Like today, successful management in the future is conditional upon flexibility in management, available water, as well as beneficial actions being understood well enough to implement.

Climate change is likely to make shortcomings of current management objectives more apparent. That is, vague goals lacking an articulated framing vision and absence of established baselines or future targets with which to measure success could allow ecosystem concerns to be pushed aside as water supply and demand management becomes tighter (USGS 2008). On the other hand, climate change may serve to stretch competing objectives to a point that forces more clear reconciliation of competing objectives.

Furthermore, climate change may help instigate larger scale changes to management of the basin in the future, which may present opportunities to revisit goals and limitations that current management must take as given. Some have suggested improving planning at the basin scale, where certain watersheds and reaches would be managed for particular objectives that would be coordinated to meet overarching basin objectives (USGS 2008). This might entail choosing to spend more money and effort on parts of the basin deemed to have greater potential for maintaining sustainable ecosystems dominated by native species than does, for example, the reach below Glen Canyon Dam. Though rarely discussed given feasibility challenges and general lack of political will, some have suggested revisiting aspects of the Law of the River, pointing out that it may not be possible to reconcile various objectives and maintain the flexibility needed as conditions change (Adler 2007).

CONCLUSIONS

The Colorado River and aquatic ecosystems within Grand Canyon have experienced rapid environmental change due to human land and water use over the last century and such pressures will continue into the future. Hydroclimatic change will have direct ecosystem impacts but also profoundly affect human response. There is a recognized need to adjust management practices to better support ecosystems into the future and doing so requires greater scientific understanding of the impacts certain actions may have, particularly within the context of climate change. Such knowledge will also inform how conflicting management goals are reconciled in the future. Direct human impacts on the Colorado River will continue to be a dominating force for ecosystems, so how we choose to manage the system in the future with the added complication of climate change will be a primary ecosystem driver. Whether this is seen as discouraging or inspiring, perhaps climate change can catalyze action and bring issues into focus that must to be resolved to better manage ecosystems in a changing future.

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