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Incorporating social-ecological considerations into basin-wide responses to climate change in the Colorado River Basin

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During the last 50 years, construction of dams in the western United States declined. This is partly because of increasing recognition of diverse and unintended social-ecological consequences of dams. Today, resource managers are recognizing the wide array of tradeoffs and are including a more diverse group of stakeholders in decision making for individual dams. Yet decisions at the regional scale maintain a focus on a limited number of resources and objectives, leading to inefficient and inequitable outcomes. Social-ecological changes compounded by climate change challenge this management paradigm. Increasing water demands for humans and the environment and renewed interest in hydropower present opportunities for operations that include climate change mitigation and adaptation strategies while considering tradeoffs and equitable responses at the regional scale.

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Introduction

Historians typically summarize the evolution of water resource development as beginning with individual, single purpose projects. With time, authorizing legislation and project planning have become more complex and wide ranging, such that individual projects typically have multiple purposes, and, in many cases, multiple projects with multiple purposes have been funded by the same authorizing legislation and are operated as a unified system. This sequence of development schemes necessarily has broadened the assessment of the benefits and costs of river regulation and inevitably introduced both regional[7] and segment-specific[8] considerations into the decision framework for operating dams and diversions.

In the case of the Colorado River basin (CRB), regional considerations include the allocation and distribution of water that is diverted for consumptive uses, the production and allocation of hydroelectricity generated by powerplants at dams, and the recovery of wide-ranging fish species that have threatened or endangered status under the Endangered Species Act. Segment-scale considerations are numerous and differ depending on location within the CRB and include recreational, ecosystem, and tribal concerns. Today, there are many segment-scale multi-stakeholder programs in the CRB, including the Upper Colorado River Basin Endangered Fish Recovery Program and the Glen Canyon Dam Adaptive Management Program. While these segment-specific programs frequently consider a broad range of resource priorities, regional considerations often constrain segment-specific management. However, the regional considerations typically only include a narrow range of resource priorities.

[7] Regional scale river management is defined as the coordinated management of basin scale resources and water and energy infrastructure that allow for widespread allocation of these resources.

[8] Segment scale river management is defined as the operation of reservoirs or other water and energy infrastructure where decisions are independent of other parts of the watershed and are independent from regional scale considerations. We define a river segment as a long section of river that is strongly affected by one, or a few, specific dams and/or diversions. For example, we define the Grand Canyon segment of the Colorado River as extending from Glen Canyon Dam to the head of Lake Mead reservoir.

In most of the CRB, decisions about the daily pattern of reservoir release are made based on trade-off analysis among a suite of river resources unique to each segment. However, larger-scale decisions about water storage and allocation, such as the division of water supply between the Upper Basin states and the Lower Basin states, are determined primarily by national and regional considerations that consider local social and/or ecological benefits and costs to a limited extent. During the past 15 years, watershed runoff has been declining and reservoir storage, especially in Lakes Powell and Mead, has declined significantly [1••]. Regional decisions and new negotiations concerning water supply allocation during times of protracted drought have the potential to have profound impacts on river resources at the segment scale, because the quantity of water transferred from upstream to downstream reservoirs has a strong effect on river ecosystems and societal values. We argue that a broader set of benefits and costs could be considered in the decision process to integrate segment-specific and regional environmental and social concerns into large-scale water supply management decisions.

More specifically, regional decisions in reservoir operations throughout the CRB in response to climate change and structural change in the energy sector could include impacts on resources at segment and at regional scales. As dam operations are reconfigured to incorporate climate related objectives, thoughtful analysis of water supply management and energy generation and its impacts on the regional scale is vital [2–4]. Resource management strategies that could incorporate both regional and segment-specific approaches to management of reservoirs to address resource challenges such as warming river temperatures, mitigation of electricity sector emissions, and the inclusion of diverse cultural preferences in decision making.

Addressing change for wildlife, energy, and culture with existing water storage and hydropower facilities

Large dams are a locus of coupled social-ecological systems, offering opportunities to restructure tradeoffs and possibly provide co-benefits when attempting to manage for climate change at the regional and segment scale. Moreover, as drought and hydrological variability increase, the operational flexibility of dams may provide opportunities to respond to, and mitigate for, rapid changes that may be otherwise impossible, excessively costly, or untimely with other structurally based management alternatives. Informed climate adaptation and mitigation will require society to identify river resources, societal objectives, and management scales at which decisions are made to adequately address multiple objectives (Table 1). This is necessary to identify opportunities that incorporate regional or segment-specific approaches to management of regulated rivers that attempt to maintain or enhance all resource outcomes. Examples from the CRB illustrate opportunities in climate adaptation and mitigation that consider management at regional and segment scales, including native fish management, mitigation of electricity sector emissions, and consideration of indigenous heritage (Table 1).

Native fish management

Recent advances in ecological science identify opportunities to manipulate river ecosystem function and services using environmental flows, and in some cases with limited costs to water delivery or hydropower generation [5,6,7•,8]. Development of effective strategies for implementing environmental flows necessitates defining not only benefits and costs at the river segment scale [2,9] but also the downstream river resource objectives. Defining these objectives is complicated because most regulated rivers, especially in the CRB, have novel assemblages of species, both native and invasive that ultimately lead to novel ecosystems [10–12]. In the western rivers of the U.S, these novel ecosystems abound due to flow regulation, sediment trapping, thermal change, and introduction of non-native species [13,14].

Regional decisions about where and how much water to store in reservoirs in the CRB will have profound influences on water temperature and aquatic ecosystems. Large, full dams typically thermally stratify, and fixed penstocks are typically located at depth, such that releases are drawn from the hypolimnion. As a result, reservoir release water temperatures during the summer are typically much cooler than would occur naturally, winter water temperatures are warmer, and seasonal peak water temperatures are shifted later in the year and determined by reservoir mixing as opposed to solar insolation or air temperatures [15,16]. If regional decisions are made to store less water in some large reservoirs, and water continues to be released from fixed-elevation penstocks, the water temperature of summer and fall reservoir releases will warm considerably. In some river segments of the CRB, this warming will be much greater than the direct effects of warming air temperatures (KL Dibble, unpublished). While the thermal regimes that would result from warmer summer reservoir releases more closely resemble natural thermal regimes, endemic and federally listed fish populations are currently declining in many parts of the CRB because of the proliferation of introduced non-native fish species. In contrast, native fish populations are thriving in the Grand Canyon segment of the CRB whose thermal regime has been modified by cool summer reservoir releases, and some scientists speculate that warmer reservoir releases might threaten those native fish populations [17–19]. Thus, until management options are developed for sustaining native fish populations under warmer thermal regimes, it may be beneficial to maintain the Grand Canyon segment of the CRB under the existing modified thermal regime. To achieve such a goal, it

Table 1

Resources, objectives, and management scales in the Colorado River Basin. A green border is where a resource objective is given consideration at the indicated scale; blue border, a resource objective is given limited consideration at the indicated scale; red border, a resource objective is given no consideration at the indicated scale

Resource[a]	Objective	Decision scale: Segment	Decision scale: Regional
Water supply	Allocate water supply consistent with the Law of the River[b]	Monthly reservoir releases and stream flow in segments of the CRB are consistent with regional scale agreements. Annual attributes of stream flow are constrained by federal, state and other requirements for endangered species act compliance and to meet other riverine resource objectives.	Depletions from the natural flow regime are consistent with the Law of the River. These depletions reduce stream flow. Regional patterns of depletions are based on international treaty, interstate compacts, federal and state law, and administrative agreements. Annual reservoir releases and stream flow in segments of the Colorado River are made consistent with regional scale agreements.
Energy generation	Increase availability and reduce costs of energy generation	Hydropower generation is optimized, constrained by federal, state and other requirements for water supply allocation, endangered species, and other resources. Monthly and daily patterns of reservoir releases are scheduled to meet the stated goal, but are constrained by federal, state and other requirements for endangered species act compliance and to meet other riverine resource objectives.	Hydropower generation is optimized based on demand within the Western Interconnection but is constrained by regional water-supply and water-supply allocation agreements.
Native fish management	Downlist or recover endangered native fish	Endangered native fish recovery is given consideration and influences monthly reservoir operational decisions and invasive species and other riverine resource management.	No consideration given to how reservoir storage and operational decisions impact endangered native fish recovery. The magnitude of diversions that are consistent with the Law of the River is given a minor consideration.
Mitigation of electricity sector emissions	Reduce costs of electricity sector emissions	No consideration given to hydropower generation and its impact on the mitigation of electricity sector emissions.	No consideration given to how reservoir storage and operation may increase or decrease the opportunity to mitigate electricity sector emissions.
Indigenous heritage[c]	Consider indigenous preferences	Consideration is given to indigenous prefrences for resource management, constrained by federal, state and other requirements for endangered species management and water allocation.	No consideration given to how reservoir storage and operational decisions may impact the status of resources and resulting management actions for which indigenous communities have preferences.
River recreation	Consider recreational preferences	Consideration is given to recreational prefrences for resource management, constrained by federal, state and other requirements for endangered species management and water allocation. Efforts are made to consider optimizing objectives where different recreational activities have different stream flow requirements that are controlled by reservoir releases.	No consideration given to how storage and operational decisions may improve or diminish recreational management objectives of either reservoirs or river segments.

[a] There are other downstream resources (vegetation, historic and cultural sites) that are not discussed in detail here. Reservoir storage and daily operations are not the primary driver of all resource states under the management alternatives discussed.
[b] The allocation of water in the Colorado River Basin is governed by a series of compacts, federal laws, and decrees, contracts, and regulatory guidelines collectively known as 'The Law of the River' [24].
[c] Access to water and energy resources are an important issue in indigenous communities. However, for the most part, these challenges are considered at segment and regional scales when decisions are made in the resource categories of water supply and energy generation [28].

would be necessary to maintain a relatively large water storage volume in Lake Powell, but to do so would involve tradeoffs with other resources (Table 1). Managers could include the reservoir release water temperature in future decisions about water storage, invest in infrastructure to mitigate lowered storage, release water through alternative withdrawal structures at the cost of foregone hydropower, or modify seasonal allocations of discharge to minimize rates of downriver warming.

Mitigation of electricity sector emissions

Decisions regarding water storage are also complicated by the electricity sector's evolving supply of and demand for energy. Large dams in the western U.S., and the CRB in particular, supply hydropower to the Western Interconnection, an integrated electricity grid powered by an ever-changing combination of thermal and renewable energy sources [20]. Existing hydropower-producing dams are capable of producing renewable energy that offsets carbon dioxide emissions produced by thermal electricity generation [21].[9] However, hydropower generation commonly tracks demand for energy throughout the day by matching generation with energy prices. Given the relatively lower operating costs of hydropower compared to thermal energy, system generation costs are minimized if hydropower replaces the most expensive generation when demand is highest.

An electricity sector emissions mitigation alternative is to consider the electricity sector costs of emissions along with generation in the dispatch of hydropower. The documented social cost of carbon [23] coupled with structural changes (renewable integration, low natural gas prices) reducing the margins between on and off-peak pricing encourage the use of existing hydropower facilitates to offset emissions and decrease the combined costs of energy generation and emissions [24]. Yet, the non-market benefits of renewable energy are complex. Minimizing social costs from energy production is dependent on transmission constraints as well as the combination and location of generation [25•,26]. Therefore, detailed modeling of the electricity sector is required to identify where and when it is cost-effective to alter load-following hydropower to offset emissions. Taking into consideration the extent and dynamics of these coupled social-ecological systems, considering tradeoffs at the regional scale in an iterative, systematic analysis may prove beneficial by providing co-benefits in multiple resource categories [27]. In addition, minimizing social costs in the electricity sector requires flow alteration, similar to that for managing the thermal regime, and consideration of tradeoffs of impacts to other resources such as recreation, native species, and indigenous heritage are necessary (Table 1).

Indigenous heritage

Indigenous population's access to water and energy resources is important and often considered in segment and regional scale resource management decisions [24,28]. However, indigenous communities support for resource development may diminish if it occurs in conflict with indigenous heritage [29••]. To avoid this risk, operating existing dam infrastructure to adapt to and mitigate for climate change across multiple jurisdictional boundaries that include regional and segment-scale considerations might be better pursued by implementing collaborative environmental governance.[10] This governance would require collective action of private and public stakeholders [31,32] within an institutional framework that would engage and sustain collaboration from indigenous stakeholders [33]. Regional scale decisions that broaden the assessment of tradeoffs, and alteration of water and energy management to address this, may constrain or alter segment-specific management and these changes in management may conflict with indigenous heritage.

Therefore, a key challenge for collaborative environmental governance is that existing water resource infrastructure may be more adaptable and opportunistic with an ability to quickly address system changes, potentially outpacing institutional change. Establishing institutions (or reshaping existing institutional structures) and long-term financing to support collaborative environmental governance in segment-scale multi-stakeholder programs is thus crucial to the successful implementation of adaptation and mitigation schemes that incorporate management preferences of indigenous populations [34]. Such distributional considerations are important in collaborative environmental governance, with equitable solutions dependent on the inclusion of indigenous peoples and other marginalized populations historically excluded from decision-making for water resource management [35–37]. This is especially true of those whose deep connections to the environment are uniquely affected by resource management on landscapes that encompass regulated rivers [38]. However, collaborative environmental governance at the regional scale exposes the traditional ecological knowledge systems of indigenous peoples and their associated cultural practices to multiple risks, given the act of exchanging certain information may be culturally inappropriate [39]. To address these risks, collaboratively engaging with indigenous peoples through shared governance could emphasize impacts to their livelihoods and cultural practices [35,40]. These strategies need to emphasize culturally important species on landscapes of indigenous importance and take into consideration critical issues with indigenous sovereignty that may limit local adaptation or mitigation options [31,36].

Conclusion

Managing novel ecological and ever-changing human systems is no small task; central to this challenge is managing the existing novel ecosystem functions and services that have been created by the dramatic development of dams and diversions in the CRB while at the same time balancing the values associated with water, energy, and cultural ecosystem services at the segment and regional scales. Here, we describe a holistic approach

[9] Renewable energy potentially offsets other emissions in the electricity sector including thermal generation by-products such as sulfur and nitrous oxides that impact health and visibility [22].

[10] Collaborative environmental governance involves the interaction of a diverse set of public and private stakeholders acting on agreed goals that are only collectively achieved [30].

to planning for reservoir reoperations that might address the societal impacts of declining runoff in the CRB, which includes the requisite comprehensive assessment of benefits and costs of managing existing water storage and hydropower facilities to adapt to and mitigate for climate change across scales. Although difficult because of the codified rules in water allocation, addressing future water supply problems requires a systematic, anticipatory approach, identifying and collaboratively implementing solutions. Our examples for managing climate change utilizing large dams in the CRB are contextual. The prolonged drought in the CRB has resulted in declining reservoir storage and warmer river temperatures and concomitantly increased the threat of expanding the range of invasive nonnative aquatic species. Meanwhile, the integration of renewables, low natural gas prices, and an increasing social cost of carbon position hydropower as a cost-effective option to offset greenhouse gas or other energy sector emissions. These conditions will inevitably change. Opportunities to manage ecosystems through environmental flows or cost effectively mitigate for emissions are dependent on future scenarios, some that are partially dependent on the water resource and energy development and governance choices made today [41]. The future can include development or decommissioning of water and energy infrastructure in parallel with opportunities to take advantage of existing facilities ability to effectively and efficiently contribute to climate change adaptation and mitigation while restoring ecosystem function and services.

On a global scale, North American attempts to operate existing infrastructure to balance biodiversity needs with water storage and hydropower generation, adapting to and mitigating novel ecosystems and electricity sector emissions, provides an opportunity for knowledge exchange from regional scale assessments occurring in the Global South [42,43]. This is especially true if novel social-ecological system comparisons occur across continents and provide insight into adaptation and mitigation strategies that are partially dependent on past choices made in ecosystem management, water resource development, and electricity sector expansion. Taking full advantage of these opportunities and insight requires transdisciplinary research that integrates major components of social-ecological systems, diversity of stakeholder perspectives, and consideration of indigenous and marginalized peoples' livelihoods and cultures. Considering climate change adaptation and mitigation at the regional scale will improve our ability to identify new opportunities for managing existing water storage and hydropower facilities to maximize benefits and minimize social and environmental costs.

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