What is a Fish Out of Water? The Economics Behind the Joint Management of Water Resources and Aquatic Species in the United States

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Abstract

The health of many marine, coastal, freshwater, and other aquatic ecosystems is inextricably linked to water quality and quantity management decisions. In this article, we survey contributions by economists that quantify the impacts of water resource management on aquatic species in the United States, and, in some cases, quantify opportunities for welfare gains from managing water and aquatic species systems jointly. Existing studies address multiple water uses, such as agricultural irrigation and hydropower generation, as well as different societal benefits from aquatic species such as commercial and recreational fishing and endangered species preservation. The studies employ a variety of methodologies including stated and revealed preference, bioeconomic modeling, and reduced-form econometrics. We conclude with a discussion of future research directions that could enhance understanding of tradeoffs between water and aquatic species management outcomes and identification of opportunities for gains from joint management in the United States.

Contents

1. Introduction

There has been increasing recognition that the health of many marine, coastal, freshwater, and other aquatic ecosystems is inextricably linked to water quality and quantity management decisions. This recognition has led to a growing interest amongst researchers and policymakers in environmental management approaches that can account for these interactions (e.g., Barbier et al. 2011; Keeler et al. 2012; Levin and Lubchenco 2008). One framework increasingly discussed in these contexts is ecosystem-based management (EBM), which recognizes the full array of interactions within ecosystems, including biophysical linkages between the aquatic species and the water resources they depend on, as well as the users and regulators associated with the resources.

One benefit of operationalizing joint management of water resources and aquatic species under an environmental management approach such as EBM is the potential to resolve conflicts between aquatic ecosystem stakeholders. Widely publicized examples of such conflicts include historical droughts in the western United States forcing regional agencies to make painful choices between providing water to homes, farms, businesses, or preserving streamflow for vulnerable fish stocks. Other agencies around the United States are being sued under the Endangered Species Act (ESA) for failing to provide adequate water supply to protect habitats for endangered aquatic species (e.g., Brown 2015). Improved understanding of the socioeconomic tradeoffs associated with the management of linked hydrologic and ecological systems is especially important as expected impacts of climate change include degraded water quality via changes in storm frequency and intensity, snowmelt, and drought (e.g. Bosch et al. 2014; Murdoch et al. 2000) and changing flows and variability of freshwater resources (Milly et al. 2005; Milly et al. 2008). Studies predict these quality and quantity changes will lead to reductions in aquatic species habitat (e.g., Wenger et al. 2011) and survival (e.g., Jonsson and Jonsson 2010).

Economic frameworks and tools are well suited to quantify ecosystem services and the potential benefits of jointly managing water resources and aquatic species relative to current and alternative policies and provide insight into system characteristics associated with gains from joint management (e.g., Holland et al. 2012). Specifically, frameworks such as cost benefit analysis can provide a means of organizing system components, costs, and benefits of various policy designs (e.g., De Young et al. 2008). Despite the advantages of using economic analysis to understand the benefits of joint management across ecosystem components, its use is relatively limited and further development is needed to improve our ability to quantify outcomes from various management strategies and understand tradeoffs effectively (e.g., Leslie and McLeod 2007).

Improving our understanding of opportunities for gains from joint management of multiple ecosystem components (e.g., water resources and aquatic species) is particularly important because implementing joint management is challenging and costly. Often, a large number of policies and institutions have purview over at least one component within an ecosystem and therefore coordination or even major regulatory changes may be required for joint management to be operationalized.

Most research by economists examining gains from joint management across aquatic ecosystem components is relatively recent but builds off bodies of work on water resources and aquatic species as independent management problems and work outside of economics exploring ecosystem linkages. Water and aquatic species system components have been studied by natural and physical scientists and economists independently for decades. Additionally, there has been significant work examining biophysical relationships between water resources and aquatic species, often building on sub-disciplines known as “ecohydrology” or “hydroecology” that are dedicated to studying the processes underlying these connected systems (e.g., Hannah et al. 2004). Other work by economists leverages these work strands to examine the impacts of water resource management and outcomes on aquatic species; although falling short of examining joint management questions, data and methods could be used in extensions that address joint management, and therefore this work represents a substantive portion of our review. More recently, ecologists have recognized the important linkages between in-land resource management decisions and marine outcomes and there are calls for improving understanding of how to design policies that acknowledge the land-sea connection (e.g. Halpern et al. 2009).

In this article, we focus on contributions by economists that quantify the impacts of water resource management on aquatic species in the United States, and in some cases, quantify opportunities for welfare gains from managing water and aquatic species systems jointly. Although the review includes all aquatic species, most studies relate to fish and shellfish. We review the literature and summarize the types of water resources and aquatic species studied, policy alternatives explored, the range of methodologies used such as stated preference approaches to bioeconomic modeling to reduced-form econometrics, and estimates of the benefits of managing water resources, the aquatic species that depend on them, or both.

We group the studies we review into four categories based on the components and linkages examined. The structure of the paper follows these categories, which are: water quality and recreational/commercial fisheries; water quantity and recreational/commercial fisheries; water quality/quantity and aquatic species; and water quality/quantity and endangered aquatic species.

2. Water Quality and Fisheries

Only a subset of the many studies that estimate the economic benefits of water quality improvements in the United States jointly examine water quality and aquatic species outcomes, and of those that do most focus on recreational and commercial fisheries. Some studies focus on the preservation of endangered species as benefits to aquatic species of water quality improvements, which we summarize in Section 5. In this section, we focus on studies that quantify aquatic species outcomes, most often in terms of use value, although estimates of nonuse values including existence, bequest, and option value of water quality improvements exist (e.g., Greenley et al. 1981). Furthermore, although water quality can influence human health through consumption of contaminated fish, few peer-reviewed studies focus on fish consumption advisories and quantification of human health impacts (see Griffiths et al. 2012 for further discussion).

Although most studies focus on recreational or commercial fishery contexts, some studies estimate aggregate benefits of water quality improvements across several types of benefits tied to aquatic species. For example, Carson and Mitchell (1993) use a contingent valuation survey to estimate the national benefits of meeting the goals of the Clean Water Act, including benefits to both commercial and recreational fisheries. Likewise, several studies estimate the cost of attaining water quality improvements that influence a combination of aquatic species uses as opposed to specific uses such as recreational or commercial harvest. This is the case for a number of studies that identify cost effective land use practices to reduce hypoxia and eutrophication in the Gulf of Mexico and other major United States waterbodies (Rabotyagov et al. 2014; Ribaudo et al. 2001; Whittaker et al. 2015; Wu and Tanaka 2005; Xu et al. 2018).

There are also several studies that use proxies for benefits to fisheries, such as maintenance of streamflow regimes and kilometers of habitat, and therefore do not separate recreational and commercial benefits. For example, Cardwell et al. (1996) develop a model that captures the size and frequency of water supply shortages and habitat available for fish species at various life stages, while Null et al. (2014) use CALVIN, an economic-engineering optimization model, to evaluate dam removal in California's Central Valley, analyzing tradeoffs between hydropower generation and agricultural and urban water supply and additional kilometers of river habitat accessible to anadromous fish species.

2.1. Water Quality and Recreational Fisheries

A number of studies quantify the benefits that accrue to recreational anglers as a result of improved water quality, but generally do not quantify the costs of bringing about that water quality improvement. In this literature, researchers often use non-market valuation methods, including revealed and stated preference methods, to quantify the benefits to recreational anglers of water quality improvements.

Most early studies employ the travel cost method using data from angler surveys to estimate these benefits. For example, Russell and Vaughan (1982) combine survey data with a water quality model to suggest there are nationwide benefits to recreational fishing of several water quality improvement scenarios, including compliance of point source discharges with permit guidelines, cropland sediment loss control, acid mine drainage control, and attainment of the "fishable-swimmable" goal for ambient water quality. Mullen and Menz (1985) estimate the effects of acid deposition, which can lead to the acidification of surface waters and the loss of aquatic life, for recreational fisheries in New York's Adirondacks region.

Several studies employ a contingent valuation survey approach to elicit recreational anglers' willingness to pay for water quality improvements. These studies find positive willingness to pay in contexts as diverse as the Platte River Basin of Colorado (Greenley et al. 1981), Chesapeake Bay (Bockstael et al. 1989; Morgan and Owens 2001; Van Houtven et al. 2014), the Flathead River drainage system in Montana (Sutherland and Walsh 1985), the Monongahela River basin in Pennsylvania (Desvousges et al. 1987), the Tar-Pamlico River in North Carolina (Whitehead and Groothuis 1992), and Lake Erie (Zhang and Sohngen 2018). The measures to improve water quality that are addressed in these studies include reductions in agricultural nonpoint source pollution, protection of streams from nearby mineral and energy development, and optimized construction and operation of wastewater treatment facilities. The authors of these survey-based studies use a variety of approaches to communicate the link between water quality and the status of aquatic species to survey respondents including derivations of the "water quality ladder" (Mitchell and Carson 1981) and photographs of waterbodies to provide visual depictions of the range of variability in water quality parameters along with expert elicitation for translating biochemical measures of water quality into terms that would be meaningful for survey respondents.

More recent studies implement random utility models (RUMs) that characterize recreational users' willingness to pay for water quality improvements by estimating links between ambient water quality and water recreation choice among a discrete set of alternatives. Some of these studies estimate the value of water quality improvements specifically for recreational fishing (Herriges and Kling 1999; Kaoru 1995).Others model the benefits to recreational fishing as one of several components o recreational water use (Phaneuf 2002) or examine recreational fishing in the context of land use and property values (Phaneuf et al. 2008). One study in the Patuxent River in Maryland finds that water quality improvements have a small effect on recreational angler welfare due to the existence of a large number of substitute fishing sites (Lipton and Hicks 2003).

The relationship between recreational fishing benefits and water quality can depend on the specific nature of the water quality problem. For example, pollution from toxics, which can be harmful to the health of recreational anglers who consume the fish they catch, can be more consequential than pollutants that merely reduce the number of fish caught (Montgomery and Needelman 1997).

2.2. Water Quality and Commercial Fisheries

Studies that examine linkages between water quality and commercial fishery outcomes tend to use different methodological approaches from those that address recreational fishing. Non-market valuation is less common, potentially because researchers often have access to market prices for outputs (i.e., fish) and inputs (e.g., fishing vessels, gear, and fuel) as well as data on fishing activity, which can be used to calculate the impact of changes in species abundance or distribution on fishery profits.

Many studies exploit bioeconomic models, which incorporate information on the relationships between water quality and linked fish populations and fishing behavior. Advantages include the ability to simulate scenarios outside the temporal scales and policy contexts that were used in any parameter estimation. For example, Massey et al. (2006) use a bioeconomic model to estimate the value of water quality changes for the Atlantic Coast summer flounder recreational fishery. Their model incorporates functional relationships between water quality conditions, summer flounder survival and abundance, and recreational and commercial harvest levels. The model predicts gains from water quality improvements that depend on the spatial scale over which water quality changes occur. Ranjan and Shortle (2017) use a stylized bioeconomic model to demonstrate that optimal management of an aquatic system facing two sources of uncertainty—water quality through pollution and the potential for an invasion impacting the harvested species—may involve unintuitive management approaches due to the system complexities. The paper highlights the need for, but also the challenge of, more integrated aquatic system modeling with multiple components and stressors such as water quality changes and species interactions.

Several studies, using a variety of approaches, seek to model the potentially complex behavior of producers and consumers tied to the commercial fishing industry. For example, McConnell and Strand (1989) find that changes in water quality not only affect supply of commercial fish products but also demand as water quality can influence consumers' perception of the quality of the fish. The authors conclude that in an unregulated fishery, improved water quality may reduce social benefits from fish products because as consumers value the fish more because of better quality, prices rise and producers seeking additional profit may deplete the stock. Huang et al. (2012) explore the influence of consumer demand and output prices on the economic consequences of hypoxia on supply and demand for brown shrimp in North Carolina. The authors find that the state's shrimp industry is too small to influence prices, and as a result, the demand curve is flat and there are no measurable benefits to shrimp consumers from reduced hypoxia. Studies that focus on Gulf of Mexico brown shrimp find that the presence of hypoxia alters fisher behavior and economic outcomes with Purcell et al. (2017) identifying changes in spatial patterns in shrimping effort and Smith et al. (2017) finding increases in the relative price of large shrimp compared to small shrimp.

Management regime is an important factor in understanding the link between water quality and commercial fisheries outcomes. Early studies describe theoretical frameworks in which pollution affects equilibrium growth functions and generates an upward shift in the supply function but assume an open access fishery (Kahn and Kemp 1985; Kahn 1987; Swallow 1994). Other studies explicitly address the role of fishery management in determining the benefits of water quality improvements and have identified situations in which improved water quality may yield limited benefits to commercial fisheries. One reason is that the fishery may be managed inefficiently in the status quo, and therefore rationalizing the fishery–that is, moving away from open access or no management of the common pool resource – would outweigh the gains from improved water quality. For example, Smith (2007) and Smith and Crowder (2011) find that the benefits to North Carolina blue crab consumers and producers from reducing nutrient pollution are small compared to the benefits of reforming the fishery's management program design. Likewise, Huang and Smith (2011) argue that the gains from some form of rationalization of the brown shrimp fishery in the Gulf of Mexico will likely outweigh the gains from reduced hypoxia. Gains that depend on management institutions may also vary over time: Baggio (2016) finds that positive rents can be extracted in the short run from the Long Island Sound lobster fishery in improved water quality scenarios even if the fishery is inefficiently managed, but that in the long run equilibrium positive rents will be dissipated.

Another approach that builds on the complexity of human systems is that of Finnoff and Tschirhart (2011), who develop general equilibrium economic and ecological models of a North Carolina estuary to address the issue of agricultural runoff causing hypoxia that affects fisheries. The authors estimate general equilibrium effects such as the reemployment in the agricultural sector of labor that is released from the blue crab fishery due to increased crab populations that allow for shorter harvest seasons and substitution of household consumption between agricultural goods and blue crab. This study is part of a broader literature that examines the general equilibrium effects of policies to regulate open access resources (e.g., Manning et al. 2016) and points to the need for further research to better understand such potential effects in the joint management of water resources and aquatic species.

There are also several studies that estimate the impacts of specific water pollution events. For example, Jin et al.(2008) track changes in domestic shellfish prices and shellfish imports that resulted from a 2005 red tide event in New England, while Hoagland et al. (2002) estimate the effects of harmful algal blooms across the United States between 1987 and 1992 on commercial fisheries as well as on public health, recreation, and tourism. Similarly, McCrea-Strub et al. (2011) and Sumaila et al. (2012) estimate the impact of the Deepwater Horizon oil spill on Gulf of Mexico commercial fisheries and find that revenue losses range in the hundreds of millions to billions of dollars, depending on the timeframe covered by the analysis. Evans et al. (2016) identify significant economic impacts from temporary closures of polluted coastal waters to shellfish harvesting in Machias Bay, Maine, the majority of which are caused by combined sewer overflows.

In the studies discussed so far, water management outcomes affect aquatic species outcomes; however, the reverse can also occur, with aquatic species influencing water outcomes. One such example is oysters and their ability remove nutrients from the water. Mykoniatis and Ready (2016) develop a bioeconomic model to simulate the societal benefits arising from different harvest regimes of oysters and Blue crabs in Chesapeake Bay, accounting for two positive externalities generated by oysters: nutrient removal and improvements in Blue crab habitat. A study by DePiper et al. (2016) finds that if nutrient credits can be obtained for ecosystem services provided by restored oyster reefs, then optimizing over both nutrient credit and oyster harvest value is superior to optimizing for either harvest value or credit value only. Although shellfish offer an interesting example where an aquatic species provide water quality *and* commercial fishery benefits, work by Kecinski et al. (2018) using field experiments suggests that there may be a tension between consumer willingness to pay for nutrient removal provided by oysters they consume and concerns over the quality of water that the oysters were raised in.

3. Water Quantity and Fisheries

Most studies focusing on aquatic species and water quantity relate to recreational or commercial fish species. As is the case with economic studies that examine links between aquatic species and water quality, several studies that quantify the benefits of maintaining sufficient water supply for aquatic species do not isolate recreational and commercial benefits and often include other non-fisheries outcomes as well. This is common when examining reservoir releases and dam removal as hydropower facilities can provide services including electricity generation and flood protection, but also affect the allocation of water to other uses including agricultural and urban water supply, which can compete with the provision of instream flow to maintain aquatic species habitats (Cardwell et al. 1996; Null et al. 2014; Roy et al. 2018).

3.1. Water Quantity and Recreational Fisheries

Several studies, particularly early ones, opt for contingent valuation or travel cost approaches to estimate the recreational demand for maintaining instream flows. Although most are focused solely on recreational outcomes, some combine benefits to other recreational activities such as rafting and boating. Findings from early contingent valuation studies are mixed, with some studies finding that the value of additional water to recreational fishing does not justify reallocation of water from other uses (Harpman et al. 1993; Johnson and Adams 1988), while other studies find that during periods of relatively low flows, the marginal value of instream flow exceeds the marginal value of water in consumptive uses (Daubert and Young 1981; Douglas and Taylor 1999; Duffield et al. 1992). One study conducted prior to dam removal finds that the benefits to Washington State of removing dams on the Elwha River to restore salmon and steelhead runs in the Pacific Northwest is $138 million annually but does not provide the societal cost of removing the dams as a means of comparison (Loomis 1996). Results from studies that implement travel cost models generally find positive benefits to maintaining instream flows (Loomis and Cooper 1990), with two studies concluding that value of additional instream water for recreational fishing equals or exceeds the value of the water in alternative uses (Loomis and Creel 1992; Ward 1987).

Several studies quantify the tradeoffs between water use for hydropower generation and maintaining instream flows for aquatic species tied to recreational fishing. Ward and Lynch (1996) develop an optimal control model for New Mexico's Rio Chama Basin and find that an optimal allocation can increase total system benefits over historical benefits by exploiting complementarities between the hydroelectricity production, instream recreation, and downstream lake recreation. However, the reallocation leads to differential impacts among users with an increase in hydropower benefits and loss in recreational benefits. Kotchen et al. (2006) conduct an ex post analysis of a FERC relicensing agreement for hydroelectric dams on the Manistee River in Michigan which required natural river flows rather than maximizing flow through turbines during periods of peak electricity demand. Returning to natural flows increased the number of Chinook salmon emigrating from the Manistee River to Lake Michigan, and a random-utility travel cost model shows that benefits to recreational fishing exceed the cost to electricity producers.

An important characteristic of these studies is the assumptions made or the approach to characterizing the biophysical link between streamflow and aquatic species status. Some studies involve primary data collection, allowing the researchers to ask about actual fish catch (Loomis and Cooper 1990; Loomis and Creel 1992). Other studies that rely on trip data omit quantifying species and instead directly correlate visitation information with observed streamflow on visitation days (Duffield et al. 1992), or present survey respondents with photographs of the river at different streamflow levels, leaving it up to the respondent to decide how these streamflow levels are linked to the utility they receive through recreational harvest of aquatic species (Ward 1987). Some studies simply posit a relationship between streamflow and the species abundance that is presented in state preference surveys (Douglas and Taylor 1999). Other studies use a regression-based approach that estimates the effect on the number of fish caught per unit of time of stream variables, such as flow measured at stream gages, and other determinants of habitat such as marine productivity as proxied by ocean upwelling (Johnson and Adams 1988). Still other studies use fish habitat or calibrated population models to estimate the relationship between water quantity and aquatic species outcomes (e.g., Daubert and Young 1981; Kotchen et al. 2006; Roy et al. 2018).

3.2. Water Quantity and Commercial Fisheries

The literature on water quantity management and commercial fisheries outcomes is much smaller than the parallel work related to recreational fisheries. To our knowledge, there are only three such studies, though several of the studies we discuss in Section 5 related to endangered species involve species of salmon that are commercially valuable. Fisher et al. (1991) develop a model of the response of the California salmon fishery to changes in water flows in and out of the San Francisco Bay/Delta, which also affect hydropower generation, irrigation, and urban use. The authors show that coordinated controls in which water inflows are increased and exports decreased in dry years has a substantial impact on smolt survival and subsequent harvests, though costs and benefits are not quantified. Garnache (2015) combines a fishery model, salmon population model, and agricultural production model to study potential welfare gains from coordinating institutional management in California's Yolo Bypass floodplain and estimates large total surplus gains to farmers and fishers from coordinating the institutions to jointly manage the freshwater and marine ecosystems. The magnitude of the gains however, depend on the fishery management structure. Kennedy and Barbier (2016) take a bioeconomic modeling approach to evaluate measures to prevent declining freshwater flows in Georgia, which increase estuarine salinity and in turn reduce commercial harvest of blue crab. The authors find measurable benefits to fishery profits from implementing minimum flow standards on regional rivers, although they do not directly quantify the costs of obtaining these minimum flows on the water management side.

4. Impacts on Aquatic Species of Concurrent Management of Water Quality and Quantity

In some cases, water quality and quantity dimensions are examined together in a single economic analysis. One common situation in which this arises is when the water quality parameter of interest is water temperature, which is closely related to the amount of water in a waterbody and is known to have effects on aquatic species (e.g., Marchetti and Moyle 2001). Thus, some water quantity management actions are implemented with the main purpose of influencing stream temperature (e.g., Webb et al. 2008). Several economic studies address the issue of water temperature management directly. Wu et al. (2000) examine the benefits of stream bank vegetation and canopy cover on stream temperature and therefore steelhead trout in the John Day River Basin in Oregon; they find that there is a threshold effect in the relationship between water quality and abundance in the fishery, which has implications for the allocation of management funds. Watanabe et al. (2006) examine the efficient allocation of management activities to meet federally mandated decreases in water temperatures (by EPA's TMDL criteria) and to enhance salmonid populations in the Grande Ronde River Basin in northeastern Oregon, which is an important spawning and rearing habitat for spring/summer chinook salmon and rainbow trout, species that are listed as threatened under the ESA.

Wetland and march restoration can result in improvements along both quality and quantity dimensions. In a meta-analysis of studies that quantify the value of wetlands, Woodward and Wui (2001) find that commercial fishing services are among the highest valued services from wetlands. Batie and Wilson (1978) estimate a production function in which oyster habitat attributes are characterized by the acres of wetlands of various levels of biological quality and salinity conditions and find that the marginal value of wetland acres for oyster production is significantly lower than the marginal value associated with residential development. Lynne et al. (1981) establish a relationship between marsh acreage and annual catch of blue crabs in the Gulf Coast of Florida and show the marginal value of marsh varies based on marsh extent and fishery effort. Bell (1997) estimates state-level production functions for recreational estuarine fisheries in the southeastern United States in which recreational catch is a function of acres of salt marsh and the number of fishing trips. He concludes that if commercial fisheries and other economically useful functions are added to the recreational fisheries, it may be more efficient for the State of Florida to acquire more coastal land for preservation from development. Johnston et al. (2002) highlight the potential need for a larger scope of evaluation, showing that multiple types of economic values are derived from the Peconic Estuary System, but urge caution when attempting to aggregate economic values. Finally, some contingent valuation studies elicit willingness to pay from survey respondents for aquatic habitat improvements that include both water quality and quantity dimensions (e.g., Loomis et al. 2000).

Reservoir releases can impact both water quality and quantity, species populations, and commercial and recreational users. Jager and Smith (2008) provide a review of optimization studies of reservoirs that generate hydropower and can influence flow regimes that affect aquatic ecosystem health. The authors identify three classes of optimization problems: (a) maintaining streamflow regimes that maximize hydropower generation while satisfying legal requirements, including environmental flows, (b) timing releases from dams to meet water quality constraints on dissolved oxygen, temperature, and nutrients, and (c) timing releases to improve the health of fish populations. The authors find that maintaining instream flows typically decreases hydropower revenue but may increase aggregate benefits to society.

Finally, a limited set of studies examine benefits to non-fish and shellfish aquatic species. For example, Brown and Hammack (1973) and Van Kooten et al. (2011) study the impacts of wetland management on waterfowl abundance, which in turn has important implications for recreational hunting benefits. In another example, Pongkijvorasin et al. (2010) examine coastal groundwater management and its effects on nearshore marine water quality and the abundance of a form of marine algae that has market value.

5. Water Quality, Water Quantity, and Endangered Aquatic Species

Almost all existing economic studies on the links between water management and endangered species relate to the case of water quantity and stream habitats for migratory salmon in the western United States. Several subspecies of salmon are considered endangered, and some of these subspecies also have societal value in consumptive use, such as for recreational fishing and Native American harvests. A variety of water management actions, including reservoir operations, flow augmentations, and diversions to alternative uses such as irrigation, can influence the status of salmon populations. Populations can also be managed directly through harvest regulations for open ocean salmon fisheries as well as hatchery operations, transportation of smolts in barges or trucks, and control of other species that prey on salmon throughout their life cycle.

Several studies examine the tradeoffs between managing water to protect endangered salmon habitats and providing water for irrigation in agriculture. Adams and Cho (1998) examine the tradeoff between maintaining minimum water levels in the Upper Klamath Lake of Oregon to protect endangered fish, where maintaining lake levels reduces irrigation water supplies and the capacity of the lake to stabilize water supplies during drought. The analysis shows that the cost of maintaining lake levels can be substantial in severe drought years, during which costs can exceed 60 percent of farm profits. Aillery et al. (1999) analyze changes in agricultural profit in the Columbia-Snake system under alternative salmon recovery measures and find significant heterogeneity in the impacts on the agricultural sector across the scenarios.

Economists have also studied tradeoffs between optimizing water allocations for salmon habitat versus hydropower generation. Paulsen and Wernstedt (1995) use a linear programming approach to identify cost minimizing management strategies for a given level of harvest in the Columbia River Basin and find that actions that mitigate the degradation of habitat or enhance reproduction in tributary streams, such as removal of barriers to migration in streams and hatchery operations, are likely more cost effective than actions that attempt to facilitate migration of the species through the main stem. Kuby et al. (2005) develop a multi-objective optimization model for the Willamette River watershed of Oregon that enhances salmonid migration and spawning by maximizing draining area reconnected to the sea and minimizes loss of hydropower and storage capacity. They find that removing 12 dams reconnects 52% of the basin while sacrificing only 1.6% of hydropower and water-storage capacity, but that additional ecological gains come with increasing per-unit economic costs.

The above studies quantify the costs of achieving improvements in salmon habitat but they do not compare these costs to the benefits of protecting the habitat and we are unaware of other studies estimating benefits for the same systems. Studies of other systems use contingent valuation approaches to estimate the economic benefits of salmon recovery (e.g., Bell et al. 2003; Loomis 1996; Olsen et al. 1991).

In contrast to most studies that focus on instream flow on relatively large rivers where water stored in major dams provides the primary source of both agricultural water security and augmented instream flows, Newburn et al. (2011) examine the role of stored groundwater or small privately owned on-site reservoirs. The study analyzes the potential effects of ESA listing on the agricultural producer's water management and land use decisions. Their results suggest that agricultural producers have shifted away from on-site surface water storage toward unregulated resource inputs (i.e., groundwater). Hence, a policy intended to protect instream flows in one season may do so at the expense of flows in other seasons.

While most of these studies focus on salmon as the aquatic species of concern for management, other endangered aquatic species have also been studied by economists. Several studies examine the benefits and costs of increasing instream flows to protect critical habitat requirements of the endangered Rio Grande silvery minnow. One study uses a contingent valuation survey to find that New Mexico households have a positive willingness to pay to restore instream flows for the silvery minnow (Berrens et al. 1996), and another study finds that augmenting Rio Grande instream flows to protect the silvery minnow would actually increase overall net benefits by moving water from lower to higher-valued users (Ward and Booker 2006). Woodward and Shaw (2008) use the minnow as motivation to develop an economic model of the optimal allocation of water under pure uncertainty when there is a lack of knowledge about the true dynamics of the relationship between the species' growth and instream flows. McCarl et al. (1999) show that the economic impacts to the agricultural sector of pumping limits for the Edwards Aquifer to provide habitat for the endangered fountain darter are low for relatively small changes, but rise quickly for larger pumping reductions.

6. Conclusions and Future Directions for Research

This article has reviewed the economics literature on management problems that involve linked water resources and aquatic species. Several conclusions can be drawn from this review, but further work is needed to illuminate critical questions from the perspective of research or policy.

With few exceptions (e.g., Garnache 2015; Huang and Smith 2011; Smith 2007), most studies do not actually jointly optimize societal outcomes across both water management and aquatic species management such that policy instruments in both systems are simultaneously available to the policymaker. Instead, most studies focus on estimating the marginal effects of improvements in water quality and quantity on the welfare of anglers, assuming a static system in which species population dynamics are not subject to exogenous forcing from the hydrologic system. A number of other studies focus on the costs associated with water management actions to improve aquatic species outcomes, including several studies that seek to identify cost effective water management approaches for achieving a certain improvement in a habitat indicator. As policymakers seek opportunities to improve societal outcomes associated with linked water resources and aquatic species, more comprehensive studies focused on joint optimization of water and species outcomes are needed.

Among studies accounting for links between water resources and aquatic species and examining the potential for welfare gains from joint optimization of outcomes across water and aquatic species, we find that the results are mixed. Some studies find only minor benefits to improving water quality or availability for influencing aquatic species outcomes, while other studies find that water management that accounts for benefits to aquatic species uses can be significantly more cost effective than measures that ignore this linkage. Drivers of cost effectiveness include the baseline level of biophysical conditions in each resource type and the degree to which the water resource or aquatic species is already efficiently managed.

We identify variation in the extent to which relevant human and natural system components have been studied. The types of relevant water management strategies are extensive and can be both direct (e.g., reservoir and dam operation) and indirect (e.g., land use change). We find that water use within the electricity sector for hydropower generation and agricultural sector for irrigation are relatively well-studied uses of water that compete with water availability for aquatic species. However, little is known about the tradeoffs between water availability for aquatic species and withdrawals for thermoelectric cooling in the power generation sector, an important component of water withdrawals in the United States, as well as the role of municipal and industrial water uses.

Key conclusions can also be drawn about the status in the literature of identification of the benefit to aquatic species of improved water management. Existing studies identify the benefits of making water available for aquatic species in the form of recreational angler willingness to pay for water quality improvements and profits from harvest in the commercial fishery sector, generally taking the recreational or commercial fisheries management approach as given. However, there is the potential for benefits to depend on the commercial fishery management strategy (e.g., Smith and Huang 2011), a finding likely applicable in the recreational context as well (see e.g., Arlinghaus et al. 2019) and meriting further work. For endangered aquatic species, the societal value of the species is generally represented as the need for a policymaker to meet a certain regulatory threshold for water quantity or quality for the species' habitat. Additionally, despite the potential for these values to be large, there are few studies (e.g., Greenley et al. 1981) that isolate potential existence or bequest values associated with aquatic species that might be influenced by water management decisions.

This review focuses on water management and aquatic species outcomes, but there is potential value to future work by economists taking a broader scope of analysis. Roy et al. (2018) highlight advantages of increasing the scale of decision-making and considering multiple decisions (e.g., dam removals) in a region jointly and considering social objectives in addition to economic and biological. There is also room to expand the scope of aquatic resources considered. We are aware of only a handful of existing economic studies that track the abundance of species other than fish, shellfish, or invasive species as the relevant outcome of water management. To the extent that these other species such as amphibians, mammals, and riparian vegetation are valued by society, greater attention should be paid by economists to understand tradeoffs and complementarities with water management. Furthermore, the calls for integrating socioeconomic considerations into EBM of fisheries (e.g., Marshall et al. 2019)—which generally focuses on marine food webs and impacts of fishing—could be leveraged and potentially broadened to also consider linkages between terrestrial land use and water policy and marine species outcomes (e.g., water quantity impacts on salmon populations, which in turn can affect orca populations).

We find that a variety of methodological approaches are used in the literature. Contingent valuation and travel cost models are especially common for estimating the benefits of water quality for recreational fishing. Recent studies use explicit bioeconomic and hydroeconomic modeling which concurrently model the underlying biophysical systems and the economic systems tied to them. However, many of these approaches cannot easily accommodate uncertainty and thresholds, identified as a key area of future research in nature resource and environmental economics generally (e.g., LaRiviere et al. 2018). One potential method that can incorporate uncertainty is Management Strategy Evaluation (MSE), although more work is needed to include broader social and economic objectives (Bunnefeld et al. 2011).

Future research on the value of improved water management on aquatic species could also adopt approaches from natural capital valuation. Existing studies such as those that estimate accounting prices for water resources (e.g., Fenichel et al. 2016) and fish stocks (e.g., Fenichel and Abbott 2014) as capital assets under real-world management could be extended to encompass both water and species management problems and the linkages between them. For example, Bond (2017) estimates the intermediate service values of wetlands for supporting fishery stocks separately from their final demand value in protecting coastal infrastructure from storm events.

Currently, in the United States as well as most parts of the world, policies to allocate water treat ecosystems as residual claimants. Under this structure, water available for ecosystems is what remains after agricultural, residential, and industrial needs are met, and the quality of the remaining water is often unregulated and thus polluted. As a result, decisions are not accounting for the full benefits of water management actions. However, several existing policies can motivate additional economic research that can help clarify the marginal benefits of improved water quality and supply for ecosystem uses in relation to alternative uses. For example, the Sustainable Fisheries Act of 1996 and the Magnuson-Stevens Fishery Conservation and Management Reauthorization Act of 2006 define the optimal exploitation of United States coastal fisheries to account for ecosystem concerns, including the establishment of advisory panels to apply ecosystem principles in fisheries management plans. These policies led to revisions of water quality standards in aquatic ecosystems in Alaska to protect salmon eggs and prevented the extension of a sewage pipeline in Hawaii that threatened fishery habitat (Hogarth 2003). Another relevant policy is the National Estuary Program (NEP), which is a non-regulatory policy that allows state governors to nominate an estuary of national significance and request a management conference that is charged in part to develop a comprehensive conservation and management plan to maintain stable shellfish, fish, and wildlife populations. NEP plans have been implemented in estuaries including the Peconic Estuary (Stephenson and Grothe 2009) and the lower Columbia River and Estuary (Thom et al. 2011).

In addition to policies that directly mandate or encourage institutions to consider ecosystem externalities when designing policies under their purview, other relevant policies focus on facilitating coordination between institutions. For example, the 1995 Recreational Fisheries Executive Order is intended to improve and increase recreational fishing opportunities by encouraging partnerships among federal agencies. This includes evaluating the impacts of federally funded actions on aquatic ecosystems and identifying recreational fishing opportunities that are limited by water quality and habitat degradation. This led to decisions such as establishing stream rehabilitation projects during commercial forest thinning projects (USDA 2007) and enforcing best management practices for erosion and sediment control along Oregon rivers (USDA 2005). Furthermore, recent policy changes have encouraged the use of EBM, such as the 2015 Executive Memo signed by the directors of the Office of Management and Budget, the Council of Economic Advisors, and the Office of Science and Technology Policy directing federal agencies to account for ecosystem services in planning within existing agency frameworks and facilitating coordination among agencies. Given the existence of policy mechanisms to effect meaningful change in management problems in which water resources and aquatic species are linked, economic research can continue to play an important role in identifying and quantifying tradeoffs and resolving conflicts.

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