Introduction

Water resources and aquatic species have been studied by natural and physical scientists and economists, working independently, for decades. However, it has become increasingly clear that the health of many marine, coastal, freshwater, and other aquatic ecosystems is inextricably linked to decisions about the management of water quality and quantity. This has led to a growing interest among researchers and policymakers in environmental management approaches that consider these linkages and jointly manage aquatic species and water resources (e.g., Levin and Lubchenco 2008; Halpern et al. 2009; Barbier et al. 2011; Keeler et al. 2012). One widely discussed approach is ecosystem-based management (EBM), which considers the full array of interactions within ecosystems, including biophysical linkages between aquatic species and the water resources they depend on, as well as socioeconomic linkages between the users and regulators of these resources, and feedbacks between the natural and social systems. Joint management approaches can incorporate these complexities into the regulation design and evaluation of system outcomes.

A key benefit of the joint management of water resources and aquatic species under an environmental management approach such as EBM is the potential to incorporate information on the trade-offs of allocating water among aquatic ecosystem stakeholders (e.g., farmers
economic frameworks and tools are well suited to quantifying ecosystem services and the potential benefits of jointly managing water resources and aquatic species (e.g., Holland et al. 2012). However, further conceptual and methodological development is needed to improve our ability to quantify outcomes of various ecosystem management strategies and understand the trade-offs between the costs and potential aggregate benefits of such approaches as well as the distribution of benefits across different users and user groups (e.g., Leslie and McLeod 2007). More specifically, frameworks such as benefit–cost analysis can be used to (a) organize ecosystem components (e.g., fisheries, hydrologic resources); (b) compare the costs and benefits of various policy designs relative to the status quo (e.g., De Young, Charles, and Hjort 2008); and (c) provide insights into characteristics of systems that are associated with higher gains from joint management. Despite the advantages of economic tools, their use has been relatively limited and recent; indeed, most work by economists has instead considered water resources and aquatic species as independent management problems.

This article reviews economic research that quantifies the impacts of water resource management on aquatic species in the United States and, in some cases, the potential welfare gains of managing water and aquatic species systems jointly. We find that most studies fall into the former category and do not jointly optimize societal outcomes across both water management and aquatic species management. Although studies in this category fall short of examining joint management questions, data and methods could be used to extend such studies to address joint management.

Our review of the literature discusses the types of water resources and aquatic species studied, policy alternatives explored, the types of methodologies used, and estimates of the benefits of managing water resources, the aquatic species that depend on them, or both.\(^2\) We

\(^2\)Although our review considers all aquatic species, most studies focus on fish and shellfish.
organize this discussion into four sections: water quality and fisheries; water quantity and fisheries; water quality/quantity and aquatic species; and water quality/quantity and endangered aquatic species. In the penultimate section, we discuss implications of current U.S. policies. We conclude with a summary of our findings and suggestions for future research.

**Water Quality and Fisheries**

Of the many studies that estimate the economic benefits of water quality improvements in the United States, only a subset jointly examines water quality and aquatic species outcomes. In this section, we discuss those studies in the literature that quantify outcomes for aquatic species, most of which focus on the linkages between water quality and recreational and commercial fisheries, generally in terms of current or future use values (in contrast to values that arise from the continued existence of the resource—i.e., nonuse values).

Although most studies focus on either recreational or commercial fisheries, some aggregate the estimated benefits of water quality improvements for aquatic species. For example, Carson and Mitchell (1993) estimate the national benefits of achieving the goals of the Clean Water Act, including benefits to both commercial and recreational fisheries. Similarly, several studies estimate the cost of achieving water quality improvements that affect a combination of aquatic species uses (e.g., recreational and commercial harvest) rather than specific uses. Examples of such studies include those that identify cost-effective land use practices to reduce nutrient pollution (i.e., high concentrations of nitrogen and phosphorus) in the Gulf of Mexico and other major U.S. waterbodies (Ribaudo et al. 2001; Wu and Tanaka 2005; Rabotyagov et al. 2014; Whittaker et al. 2015; Xu et al. 2018).

Several studies use proxies for fisheries benefits, such as maintenance of streamflow patterns and kilometers of habitat, and thus do not distinguish between recreational and commercial benefits that might be tied to those proxies. For example, Cardwell, Jager, and Sale (1996) develop a model that captures the size and frequency of water supply shortages and habitat available for fish species at various life stages. Null et al. (2014) use an economic-engineering optimization model to evaluate dam removal in California’s Central Valley, analyzing trade-offs between hydropower generation and agricultural and urban water supply and additional kilometers of river habitat for migratory fish species such as salmon and trout.

The remainder of the discussion in this section separates the literature that quantifies the benefits of water quality improvements into two categories, recreational fisheries and commercial fisheries.

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3 Some studies analyze the preservation of endangered species as a benefit of water quality improvements for aquatic species. We discuss these studies in the penultimate section.

4 It is important to note that there are some estimates of nonuse values of water quality improvements (e.g., Greenley, Walsh, and Young 1981). In addition, although water quality can affect human health through the consumption of contaminated fish, a few peer-reviewed studies consider fish consumption advisories or quantify human health impacts (see Griffiths et al. 2012 for further discussion).
Water Quality and Recreational Fisheries

A number of studies quantify the benefits of improved water quality specifically for recreational fishers (often called anglers). In this literature, researchers often use nonmarket valuation methods, including revealed and stated preference methods\(^5\) such as travel cost models, contingent valuation, and random utility models to estimate the benefits of improved water quality. However, these studies generally do not quantify the costs of achieving that water quality improvement.

Travel cost models

Most early studies rely on the travel cost method, using data from angler surveys to estimate the benefits of water quality improvements to recreational anglers.\(^6\) For example, Russell and Vaughan (1982) find nationwide benefits to recreational fishing from several water quality improvement policy scenarios, including compliance of pollutant discharges with permit guidelines, control of cropland sediment loss, control of acid mine drainage, and attainment of established water quality thresholds for human uses such as the “fishable-swimmable” goal.\(^7\) Mullen and Menz (1985) estimate the effects of acid deposition on recreational fisheries in New York’s Adirondacks region and estimate annual losses to New York resident anglers of approximately $1 million (in 1976 dollars).

Contingent valuation

Many studies have used a contingent valuation approach to estimate recreational anglers’ willingness to pay for water quality improvements.\(^8\) These studies find positive willingness to pay in locations as diverse as the Platte River Basin of Colorado (Greenley, Walsh, and Young 1981), the Chesapeake Bay in Maryland and Virginia (Bockstael, McConnell, and Strand 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, Smith, and Fisher 1987), the Tar-Pamlico River in North Carolina (Whitehead and Groothuis 1992), and Lake Erie (Zhang and Sohngen 2018). The policy options for improving water quality that were examined in these studies include reductions in agricultural pollution, protection of streams from nearby mineral and energy development, and optimized construction and operation of wastewater treatment facilities. These studies use a variety of approaches to inform respondents about the link between water quality and the status of aquatic species, including the “water quality ladder,” a commonly used scale for determining whether waterbodies meet established thresholds for human uses (Mitchell and Sohngen 2018).

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\(^5\) Revealed preference methods are based on observed economic behavior, from which individual preferences can be inferred, while stated preference methods are based on responses to survey questions that reveal individuals’ preferences.

\(^6\) The travel cost method is a revealed preference approach that assumes that travel costs represent the price of access to a recreational site. An individual’s willingness-to-pay for visiting a site is thus estimated based on the number of trips that they make at different travel costs.

\(^7\) This goal is aimed at the protection and propagation of aquatic species as well as providing for recreation in and on the water.

\(^8\) Contingent valuation is a stated preference approach based on surveys in which individuals are typically asked how much money they would be willing to pay to maintain the existence of, or improve, an environmental feature, such as water quality.
Carson 1981); photographs showing the variability in water quality of waterbodies; and nontechnical descriptions of measures of water quality.

Random utility models

More recent studies use random utility models\(^9\) to quantify recreational users’ willingness to pay for water quality improvements by estimating the relationship between water quality and water recreation choices. Some of these studies estimate the value of water quality improvements specifically for recreational fishing (Kaoru 1995; Herriges and Kling 1999), while others model the benefits to recreational fishing as one of several components of recreational water use (Phaneuf 2002) or examine recreational fishing in the context of land use and property values (Phaneuf et al. 2008). One study of 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). In one of the few studies in the literature that addresses potential impacts to human health, Montgomery and Needelman (1997) show that pollution from toxics, which can be harmful to anglers who consume the fish they catch, can be more consequential than pollutants that merely reduce the number of fish.

Water Quality and Commercial Fisheries

The methodological approaches used in studies that examine linkages between water quality and commercial fishery outcomes tend to be different from those used to examine recreational fishing. Nonmarket valuation is less common for commercial fisheries, most likely because in this case, researchers often have access to market prices for both 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. We divide our discussion of the literature on water quality and commercial fisheries into the following categories: bioeconomic models, the role of management, general equilibrium models, water pollution events, and the impacts of aquatic species on water quality.

Bioeconomic models

Many studies use bioeconomic models, which model the linkages between water quality, fish populations, and fishing behavior and can be used to predict impacts of policy changes. Advantages of this approach include the ability to consider scenarios and outcomes that are outside the temporal scales and policy contexts that were used to develop model parameters. For example, Massey, Newbold, and Gentner (2006) estimate the impact of water quality changes on the Atlantic Coast summer flounder recreational fishery. Their bioeconomic model predicts gains from water quality improvements; these gains depend on the spatial scale over which water quality changes occur. Ranjan and Shortle (2017) show that optimal management of an aquatic system that faces two sources of uncertainty—water

\(^9\)Random utility models present individuals with a discrete set of alternatives to choose among.
quality due to pollution and the potential for invasive species to affect the harvested species—
may require joint modeling as it may not be possible to predict outcomes from single-stressor
models because the combined impact of dual stressors can result in behavior that is complex,
nonlinear, and characterized by thresholds. The authors highlight the need for—and the
challenge of—more integrated aquatic system modeling that includes multiple ecosystem
components and stressors such as water quality changes and species interactions.

Several studies combine bioeconomic models, or theory from these models, with informa-
tion or models related to fish product markets to characterize the potentially complex
behavior of producers and consumers that comprise the commercial fishing industry. For
example, McConnell and Strand (1989) show that changes in water quality affect not only the
supply of commercial fish products but also the demand for them because water quality can
affect consumers’ perception of fish quality. More specifically, the authors find that in an
unregulated fishery, improved water quality may actually reduce the social benefits of fish
products because as consumers value the fish more due to its higher quality, prices rise and
producers seeking additional profit may deplete the stock. Huang et al. (2012) explore how
consumer demand and output prices affect the economic implications of nutrient pollution
for the North Carolina brown shrimp fishery. The authors find that the state’s shrimp in-
dustry is too small to influence prices, which means that the demand curve is flat and thus
there are no measurable benefits to shrimp consumers from reduced nutrient pollution.
Studies that focus on Gulf of Mexico brown shrimp find that nutrient pollution alters com-
mercial fishing behavior and economic outcomes, with Purcell et al. (2017) finding changes
in spatial patterns in shrimping effort and Smith et al. (2017) finding increases in the price of
large shrimp relative to small shrimp.

Role of management

The type of fisheries management is an important factor for understanding the relationship
between water quality and commercial fisheries outcomes. Early studies of this issue exam-
ined theoretical frameworks in which pollution affects the growth of fish populations and
thus decreases the quantity of fish supplied at any given price, but they assume an open access
fishery—that is, a fishery in which access and harvest are unrestricted (Kahn and Kemp 1985;
Kahn 1987; Swallow 1994). Other studies explicitly address the role of fishery management
and have identified contexts in which water quality improvements may yield limited benefits
to commercial fisheries. One explanation for this result is that the fishery may be managed
inefficiently under the status quo. For example, Smith (2007) and Smith and Crowder (2011)
find that the benefits of reducing nutrient pollution for North Carolina blue crab consumers
and producers are small compared to the benefits of reforming the fishery’s management
program. Similarly, Huang and Smith (2011) argue that the gains from improving the man-
agement of the brown shrimp fishery in the Gulf of Mexico would likely outweigh the gains
from reduced nutrient pollution. Gains that depend on management institutions may also
vary over time. For example, Baggio (2016) finds that positive rents can be extracted in the
short run from the Long Island Sound lobster fishery under improved water quality scenarios
even if the fishery is inefficiently managed, but that in the long run, equilibrium positive rents
will decline. Together, these studies suggest that analyses of policies that may influence water
quality and commercial fisheries should also consider the fishery management regime in place.

**General equilibrium models**

In another approach that builds on the complexity of human systems, Finnoff and Tschirhart (2011) develop general equilibrium economic and ecological models of a North Carolina estuary to examine how nutrient pollution from agriculture affects fisheries. The authors find general equilibrium effects such as the reemployment in the agricultural sector of labor that is released from the blue crab fishery and substitution between the consumption of agricultural goods and blue crab by households. This study, which is part of a broader literature that examines the general equilibrium effects of policies to regulate open access resources (e.g., Manning et al. 2018), highlights the need for further research to increase our understanding of such potential effects of the joint management of water resources and aquatic species.

**Water pollution events**

Several studies estimate the impacts of isolated water pollution events beyond broader water quality trends. For example, Jin, Thunberg, and Hoagland (2008) identify significant changes in domestic shellfish prices and shellfish imports that resulted from a 2005 red tide event in New England, while Hoagland et al. (2002) find disparate estimates in the literature of the effects of harmful algal blooms (in 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 from the hundreds of millions to billions of dollars, depending on the timeframe covered by the analysis. Finally, Evans et al. (2016) find that temporary closures of polluted coastal waters due to sewer overflows have significant economic impacts on shellfish harvesting in Machias Bay, Maine.

**Impacts of aquatic species on water quality**

The studies discussed thus far have examined how water management outcomes affect aquatic species outcomes. However, aquatic species can also affect water outcomes. For example, oysters have the ability to remove nutrients from the water, which can improve water quality. With this in mind, Mykoniatis and Ready (2016) develop a bioeconomic model to simulate the societal benefits of different harvest regimes for oysters and blue crabs in Chesapeake Bay. More specifically, they consider two positive externalities generated by oysters—nutrient removal and improvements in Blue crab habitat—and find that controlling oyster harvest on public grounds is superior to implementing aquaculture on leased grounds, sanctuaries that are never harvested, or reserves that are periodically harvested. DePiper, Lipton, and Lipcius (2017) examine cases in which managers can receive credits through water quality trading programs by restoring oyster reefs. The authors find that jointly optimizing the value of the credits and the value of oyster harvest is superior to optimizing either harvest value or credit value alone. Although shellfish are a useful example of how an aquatic species can provide both water quality and commercial fishery benefits, based on field experiments, Kecinski, Messer, and Peo (2018) find that there may be a conflict between
consumer willingness to pay for the nutrient removal provided by the oysters they consume and concerns about the quality of water that the oysters were raised in.

**Water Quantity and Fisheries**

Most economic studies of the linkages between aquatic species and water quantity also examine either recreational or commercial fish species. However, as with studies of aquatic species and water quality, a number of studies that quantify the benefits of maintaining sufficient water supply for aquatic species do not consider recreational and commercial benefits separately and often include non-fisheries outcomes as well (e.g., electricity generation). This is particularly common when examining reservoir releases and dam removal, because although hydropower facilities provide services such as electricity generation and flood protection, they 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, Jager, and Sale 1996; Null et al. 2014; Roy et al. 2018). In the remainder of the section, we review studies that examine water quantity and recreational and commercial fisheries outcomes separately.

**Water Quantity and Recreational Fisheries**

Studies that link water quantity and recreational fishing have used different approaches to characterize the biophysical link between streamflow and aquatic species abundance. Some studies rely on primary data collection (i.e., surveys), allowing researchers to ask about actual fish catch (Loomis and Cooper 1990; Loomis and Creel 1992). In contrast, studies that rely on trip data do not quantify species; rather they either directly correlate visitation information with observed streamflow on visitation days (Duffield, Neher, and Brown 1992) or present survey respondents with photographs of the river at different streamflow levels, leaving it 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 assume a relationship between streamflow and species abundance, which is presented in stated preference surveys (Douglas and Taylor 1999). Other studies use a regression-based approach that estimates the effect of stream variables (e.g., flow measured at stream gages) and other determinants of habitat (e.g., marine productivity) on the number of fish caught per unit of time (Johnson and Adams 1988). Finally, some studies use fish habitat or 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).

Several studies, particularly early ones, use contingent valuation or travel cost approaches to estimate the recreational fishing demand for maintaining instream flows. The findings from early contingent valuation studies are mixed, with some finding that the value of additional water for recreational fishing does not justify the reallocation of water from other uses (Johnson and Adams 1988; Harpman, Sparling, and Waddle 1993), while others find that during periods of relatively low flows, the marginal value of instream flow for recreational fishing exceeds the marginal value of water in consumptive uses such as agriculture (Daubert and Young 1981; Duffield, Neher, and Brown 1992; Douglas and Taylor 1999).
Results from studies that use travel cost models generally find that maintaining instream flows has positive benefits (Loomis and Cooper 1990), with two studies concluding that the value of additional instream water for recreational fishing equals or exceeds the value of the water in alternative uses (Ward 1987; Loomis and Creel 1992).

Several studies estimate the trade-offs between water use for hydropower generation and maintaining instream flows for aquatic species that are targeted by recreational fishing. For example, a study on dam removal estimates the benefits to Washington State of removing dams on the Elwha River to restore salmon and steelhead runs in the Pacific Northwest at $138 million annually, but the study does not indicate the societal cost of removing the dams (Loomis 1996). Ward and Lynch (1996) model New Mexico’s Rio Chama Basin and find that total system benefits can be increased (relative to historical benefits) by exploiting water allocation strategies that simultaneously enhance hydroelectricity production, instream recreation, and downstream lake recreation. However, this reallocation of water affects users differently, with hydropower benefits increasing and recreational benefits decreasing. Kotchen et al. (2006) conduct an ex post analysis of a relicensing agreement for hydroelectric dams on the Manistee River in Michigan, which required natural river flows rather than the maximization of flow through turbines during periods of peak electricity demand. The authors find that reverting to natural flows increased the number of Chinook salmon migrating from the Manistee River to Lake Michigan; moreover, using a travel cost model, they find that the benefits to recreational fishing exceed the cost to electricity producers.

Water Quantity and Commercial Fisheries

The literature on water quantity management and commercial fisheries outcomes is much smaller than the water quantity management literature related to recreational fisheries. To our knowledge, there are only three such studies, although several of the studies in our later discussion of endangered species concern salmon species that are commercially valuable. First, Fisher, Hanemann, and Keeler (1991) model 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 find that coordinated controls in which water inflows are increased and water exports are decreased in dry years have a substantial impact on smolt survival and subsequent harvests, although they do not quantify costs and benefits. Second, Garnache (2015) combines a fishery model, a salmon population model, and an agricultural production model to examine the potential welfare gains from coordinating institutional management of water in California’s Yolo Bypass floodplain and finds that coordinating institutions to jointly manage the freshwater and marine ecosystems results in large gains to both farmers and fishers. In the third study, Kennedy and Barbier (2016) use a bioeconomic model to evaluate measures to slow the decline in freshwater flows in Georgia; such declines in water flows increase estuarine salinity, which reduces commercial harvest of blue crab. The authors find measurable increases in fishery profits from implementing minimum flow standards on regional rivers, although they do not directly quantify the water management costs of achieving these minimum flows.
Impacts of Joint Management of Water Quality and Quantity on Aquatic Species

In some cases, the impacts of water quality and quantity on aquatic species are examined together, in a single economic analysis. In this section, we discuss the findings of four types of studies, those that focus on: water temperature; wetland and marsh restoration; reservoir releases; and non-fish species.

Water Temperature

One case in which water quality and quantity and aquatic species are often managed jointly is when the water quality variable of interest is water temperature. Water temperature is closely related to the amount of water in a waterbody and known to affect aquatic species (e.g., Marchetti and Moyle 2001), thus resulting in some water quantity management actions being implemented with the main purpose of influencing stream temperature (e.g., Webb et al. 2008). Several other economic studies address the issue of water temperature management directly. For example, Wu, Adams, and Boggess (2000) examine the benefits of stream bank vegetation and canopy cover on stream temperature and thus steelhead trout in the John Day River Basin in Oregon; they find a threshold effect whereby reductions in stream temperature above 20\(^{\circ}\)C have little effect on steelhead abundance, but for temperature reductions below 20\(^{\circ}\)C, further reductions have significant effects on abundance. This threshold effect suggests that the allocation of management funds according to typical allocation rules or guidelines will not be efficient. Watanabe, Adams, and Wu (2006) examine the efficient allocation of management activities to meet federally mandated decreases in water temperatures and to protect salmon populations in the Grande Ronde River Basin in northeastern Oregon. They find that the efficient choice of management activities is heavily driven by the size, shape, and condition of streams and their immediate surroundings.

Wetland and Marsh Restoration

Wetland and marsh restoration has been found to improve both water quality and quantity and the associated societal benefits from aquatic species. In a meta-analysis of studies that quantify the value of wetlands, Woodward and Wui (2001) identify multiple functions and ecosystem services that wetlands provide. Johnston et al. (2002) highlight the need to evaluate a large range of economic values provided by wetlands, as they do for the Peconic Estuary System near Long Island, New York. However, they urge caution when attempting to aggregate economic values. In addition, some contingent valuation studies elicit willingness to pay for aquatic habitat improvements that include both water quality and quantity dimensions (e.g., Loomis et al. 2000) and find benefit estimates that exceed the costs of the habitat improvements.

The literature has also identified a trade-off between maintaining or expanding wetlands to support fisheries and allowing residential development. Early work by Lynne, Conroy, and Prochaska (1981) that examines the relationship between marsh acreage and annual catch of blue crabs in the Gulf Coast of Florida finds that the marginal value of marsh varies based on the size of the marsh and amount of fishing effort. Such place-based studies have produced
conflicting results concerning the value of fisheries versus development. For example, Batie and Wilson (1978) find that the marginal value of wetland acres for oyster production is significantly lower than the marginal value associated with residential development, while Bell (1997) finds that if the value of commercial fisheries and other economically useful functions (e.g., flood control, water purification) are added to the value from recreational saltwater marsh fisheries, it may be more efficient for the State of Florida to acquire more coastal land for protection than to allow it to be developed.

Reservoir Releases

Another strand of the literature examines the impacts of reservoir releases on the benefits from aquatic species. This research finds that reservoir releases can affect water quality and quantity, species populations, and commercial and recreational users. For example, Jager and Smith (2008) review optimization studies of reservoirs that generate hydropower, which 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. Hydropower facilities can also offer flood protection and determine 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, Jager, and Sale 1996; Null et al. 2014).

Non-Fish Species

Finally, a small set of studies examine benefits to non-fish and shellfish aquatic species. For example, Brown and Hammack (1973) and Van Kooten, Withey, and Wong (2011) study the impacts of wetland management on waterfowl abundance, which in turn has important implications for recreational hunting benefits. Both studies find that hunting benefits justify higher levels of wetland creation. In another example, Pongkijvorasin et al. (2010) examine coastal groundwater management and its effects on nearshore marine water quality and the abundance of a type of marine algae that has market value. They find that including the algae’s market value in the regulator’s objective results in only slightly lower rates of groundwater extraction.

Water Quality, Water Quantity, and Endangered Aquatic Species

Almost all existing economic studies on the links between water management and endangered species have focused on 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 range of water management actions, including reservoir operations, flow augmentations, and diversions to alternative uses such as irrigation, can affect salmon populations. These 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. In the discussion that follows, we examine trade-offs between protecting salmon and providing irrigation water and hydropower generation.

**Trade-offs between Protecting Salmon and Providing Irrigation Water**

Several studies examine the trade-offs between managing water to protect endangered salmon habitats and providing water for irrigation in agriculture. For example, Adams and Cho (1998) examine the trade-off between maintaining minimum water levels in the Upper Klamath Lake of Oregon to protect endangered fish and maintaining water supplies for irrigation and the capacity of the lake to stabilize water supplies during drought. They find that the cost of maintaining lake levels to protect fish can be substantial in severe drought years, with costs potentially exceeding 60 percent of farm profits. Aillery et al. (1999) analyze changes in agricultural profit in the Columbia-Snake river system under alternative salmon recovery measures and find significant heterogeneity in the impacts on the agricultural sector depending on the type of measure.

Most studies examine instream flow in relatively large rivers, where water stored in major dams provides the primary source of both agricultural water security and augmented instream flows. However, Newburn, Brozovic, and Mezzatesta (2011) examine the role of stored groundwater or small privately owned on-site reservoirs. The study analyzes the potential effects of ESA listing of salmon on the water management and land use decisions of agricultural producers in Sonoma County, California. They find that agricultural producers have shifted from on-site surface water storage to unregulated water sources such as groundwater aquifers. This suggests that a policy intended to protect instream flows in one season may do so at the expense of flows in other seasons as producers shift across water sources, thus leading to unintended negative consequences for fish survival.

**Trade-offs between Salmon Protection and Hydropower Generation**

Economists have also examined trade-offs between optimizing water allocations for salmon habitat and using water for hydropower generation. For example, Paulsen and Wernstedt (1995) find that management actions that mitigate the degradation of habitat or enhance reproduction in the Columbia River Basin’s 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. Using an optimization model for the Willamette River watershed of Oregon, Kuby et al. (2005) find that removing twelve dams reconnects 52 percent of the basin to the sea, thus enhancing salmon migration and spawning, while sacrificing only 1.6 percent of hydropower and water-storage capacity, but that additional benefits to salmon would incur increasing per-unit economic costs.

Although these studies quantify the costs of improving salmon habitat, they do not compare these costs to the benefits of protecting the habitat. There are some studies that use
continent valuation approaches to estimate the economic benefits of salmon recovery in the same regions, although they are not tied to the same water management strategies and as a result the benefits are not directly comparable to the costs (Olsen, Richards, and Scott 1991; Loomis 1996; Bell, Huppert, and Johnson 2003).

Other Endangered Species

Although most studies focus on salmon, economists have studied the management of other endangered aquatic species. Several studies examine the benefits and costs of increasing instream flows to protect critical habitat of the endangered Rio Grande silvery minnow. For example, using a contingent valuation survey, Berrens, Ganderton, and Silva (1996) find that New Mexico households have a positive willingness to pay to restore instream flows for the silvery minnow. Ward and Booker (2006) find that augmenting Rio Grande instream flows to protect the silvery minnow would increase overall net benefits by moving water from lower to higher-valued uses while Woodward and Shaw (2008) use the minnow to illustrate the importance of accounting for uncertainty in management program design. Finally, McCarl et al. (1999) find that the economic impacts on the agricultural sector of limiting pumping from the Edwards Aquifer in Texas to provide habitat for the endangered fountain darter are low for relatively small reductions in pumping but rise sharply for larger pumping reductions, suggesting that there is potential for an active water market to emerge.

Policy Implications

In the United States, as well as in most parts of the world, water allocation policies often treat ecosystems as residual claimants. That is, 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. This means that policy decisions do not account for the full benefits and costs of water management actions. However, several existing policies can provide the basis for new economic research that can help improve our understanding of the marginal benefits of improved water quality and quantity for ecosystem uses relative 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 U.S. coastal fisheries in a way that accounts 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 for 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 nonregulatory policy that allows state governors to nominate an estuary of national significance and request a management conference that is charged (in part) with developing a comprehensive conservation and management plan to maintain stable shellfish, fish, and wildlife populations. NEP plans have been implemented in several estuaries, including the Peconic Estuary (Stephenson and Grothe 2009) and the lower Columbia River and Estuary (Thom et al. 2011).
Finally, several existing 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. It requires evaluation of the impacts of federally funded actions on aquatic ecosystems and identification of recreational fishing opportunities that are limited by water quality and habitat degradation. The Executive Order’s requirements led to actions 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, the use of EBM has been encouraged by recent policy changes, such as a 2015 Executive Memo, which directs federal agencies to account for ecosystem services in planning within existing agency frameworks and facilitates coordination among agencies.10

Given the existence of these policy mechanisms, which link water resources and aquatic species, and their potential to effect meaningful change, economic research will continue to have an important role to play in identifying and quantifying trade-offs and resolving conflicts among stakeholders.

**Conclusions and Future Directions for Research**

This article has reviewed the economics literature on the joint management of water resources and aquatic species. Existing studies consider 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. These studies use a variety of methodologies. Contingent valuation and travel cost models are especially common for estimating the benefits of water quality for recreational fishing, while researchers have used bioeconomic and hydroeconomic modeling more in commercial fisheries contexts.

**Key Conclusions and Findings**

We draw four main conclusions from this review. First, we find that, with few exceptions (e.g., Smith 2007; Huang and Smith 2011; Garnache 2015), most studies do not jointly optimize societal outcomes across both water management and aquatic species management. Rather, most studies focus on estimating the marginal effects of improvements in water quality or quantity on the welfare of recreational and commercial fishers.

Second, among studies that do explicitly account for the linkages between water resources and aquatic species and that examine the potential for welfare gains from joint optimization of outcomes across water and aquatic species, we find mixed results. Some studies find only minor benefits to aquatic species of improving water quality or availability, while others find that water management measures that account for benefits to aquatic species uses (e.g., recreational and commercial fishing) can generate substantially greater net benefits than measures that ignore the interconnections between aquatic and ecosystem outcomes.

10The 2015 Executive Memo was signed by the directors of the Office of Management and Budget, the Council of Economic Advisors, and the Office of Science and Technology Policy.
Third, while evidence on the benefits of jointly optimizing societal outcomes across water and aquatic species management is scarce, conclusions can still be drawn about the benefits to aquatic species of improved water management. Existing studies identify many cases in which there are benefits to making water available for aquatic species in terms of recreational angler willingness to pay for water quality improvements and profits from harvest in the commercial fishery sector. However, there is also the potential for benefits to depend on the commercial fishery management strategy (e.g., Huang and Smith 2011), a finding that is likely applicable in the recreational context as well (see, e.g., Arlinghaus et al. 2019) and thus merits further research.

Fourth, we find that there is variation in the extent to which relevant human and natural system components have been studied. In particular, we find that although water use within the electricity sector for hydropower generation and the agricultural sector for irrigation is relatively well-studied uses of water that compete with water availability for aquatic species, little is known about the trade-offs between water availability for aquatic species and withdrawals for thermoelectric cooling in the power generation sector or the role of municipal and industrial water uses.

**Future Directions for Research**

Based on our findings and conclusions, we suggest some future directions for research that would help increase understanding of the trade-offs between water and aquatic species management outcomes, identify gains from the joint management of water resources and aquatic species in the United States, and leverage the existing policy mechanisms described in the previous section.

**Expanding the scope of analysis**

We have focused here on water management and aquatic species outcomes, but there is a need for economists to expand the scope of analysis. As already noted, future studies should go beyond estimating the effects of changes in water quality or quantity on the welfare of recreational and commercial fishers to jointly optimizing societal outcomes across both water management and aquatic species management. Moreover, Roy et al. (2018) highlight the advantages of increasing the scale of decision-making by jointly considering multiple decisions (e.g., dam removals) in a region as well as considering social objectives in addition to economic and biological objectives. It would also be helpful to expand the scope of aquatic resources considered. We are aware of only a handful of economic studies that track the impact of water management on the abundance of species other than fish, shellfish, or invasive species. To the extent that species such as amphibians, mammals, and riparian vegetation are valued by society, it is important for economists to examine the trade-offs and complementarities with water management. Furthermore, the calls for integrating socioeconomic considerations into EBM of fisheries (e.g., Marshall et al. 2018)—which generally focuses on marine food webs (i.e., feeding relationships among marine species within a community) 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).
Several important classes of water management decisions, and their impacts on aquatic species, also merit further research. Such research needs include developing additional evidence on trade-offs 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) and the role of municipal and industrial water uses. In addition, more research is needed on the impact of water management decisions on the existence or bequest values associated with endangered aquatic species.

Need for application of new methodological approaches

Many of the methodological approaches that have been used in the literature cannot easily accommodate uncertainty and thresholds, which have been identified as key areas for future research in resource and environmental economics more generally (e.g., LaRiviere et al. 2018). One method that can potentially incorporate uncertainty is Management Strategy Evaluation, which aims to assess the trade-offs associated with various management strategies while incorporating potential sources of uncertainty (Butterworth 2007; Punt et al. 2014). However, more work is needed to include broader social and economic objectives (Bunnefeld, Hoshino, and Milner-Gulland 2011).

Future research on the value of improved water management on aquatic species could also adopt approaches from natural capital valuation. More specifically, 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 cover both water and species management problems and the linkages between them. For example, Bond (2017) uses the natural capital approach to separately estimate the value of wetlands in supporting fishery stocks and their value in protecting coastal infrastructure from storm events.

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