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How to Respond? An Introduction to Current Bay–Delta Natural Resources Management Options

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INTRODUCTION

As one of the best-studied estuaries on the planet, San Francisco Bay and its upstream brackish and freshwater tidal regions (“Bay–Delta”; [Figure 1](#)) has an impressive history of research and scientific progress. The past 2 decades have been especially eventful, with significant advances in experimentation, development of new research tools, an increasing move toward open science, reliance on conceptual and simulation models to guide research, and an expansion to relatively unstudied elements of the ecosystem. The breadth of the current science enterprise is highlighted in some excellent articles and white papers (e.g., [Brown et al. 2016a](#); [MacWilliams et al. 2016](#); [Moyle et al. 2016](#); [Johnson et al. 2017](#); [Sherman et al. 2017](#); [Connon et al. 2019](#)).

Much of the scientific research forms the foundation of our understanding of recent and long-term changes in the Bay–Delta and its watershed, and continues to guide resource management ([Sommer et al. 2019](#)). While the heavy reliance on science for natural resources management is highly desirable, my experience is that many scientists and policy-makers have only a hazy idea about what tools are available to address different resource management issues. This communications gap is not surprising given the system’s complex geography and ecology. There also aren’t any comprehensive reference documents that catalogue our regional “toolbox.” Environmental regulatory documents such Biological Opinions can be helpful, but examples for the Bay–Delta are typically long, overly technical, and emphasize relatively few facets of the toolbox, e.g., water operations and habitat restoration.

The main issue is that a lack of an understanding of practical management approaches makes it less likely that research will be designed to generate actionable

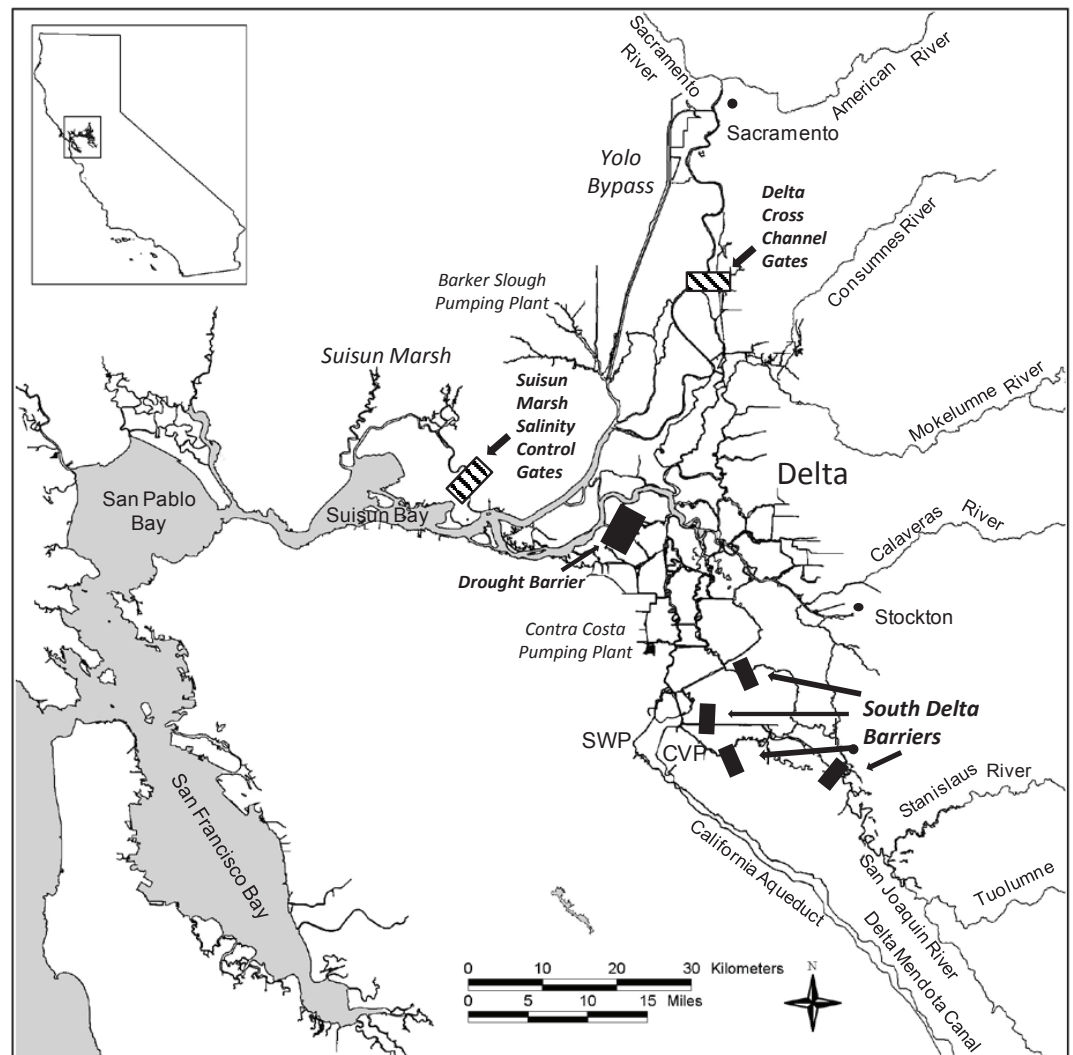


Figure 1 Map of the Bay–Delta including some of the major water management features. Clifton Court Forebay is located at the same location as the SWP. Knights Landing Outfall Gates and Wallace Weir are located just upstream of the Bay–Delta region shown in this figure. Head of Old River Barrier is the southernmost barrier among the set of four South Delta barriers.

science, and that policy will be comprehensive. This communications gap is of particular concern given the rapid changes occurring in the estuary (e.g., invasive species, climate), as well as some of the extreme ecological and economic effects.

To help address this communication gap, I have summarized our current toolbox for Bay–Delta natural resources management. The management options are relatively diverse, so my treatment of each is relatively brief and does not include any analysis of their efficacy. The goal of this basic summary is to help provide guidance for researchers wishing to conduct “actionable science,” and to better inform resource managers about the range of tools that are used in the Bay–Delta.

I also hope that the review will be of interest to scientists and managers in other parts of the world, since resource management in the Bay–Delta is uniquely diverse and intensive.

For the purposes of this review, I have chosen to catalogue the management approaches into four general types of tools: (1) regulatory; (2) water infrastructure; (3) habitat; and (4) other biological measures (Figure 2). My emphasis for the current article is ecosystem management, not other resource issues such as water supply and other infrastructure. While there are multiple potential definitions of ecosystem management, in the current context I consider ecosystem management as efforts to improve habitat quality and quantity on a regional basis, and tools used to help support target species (e.g., special-status, sport, and commercial).

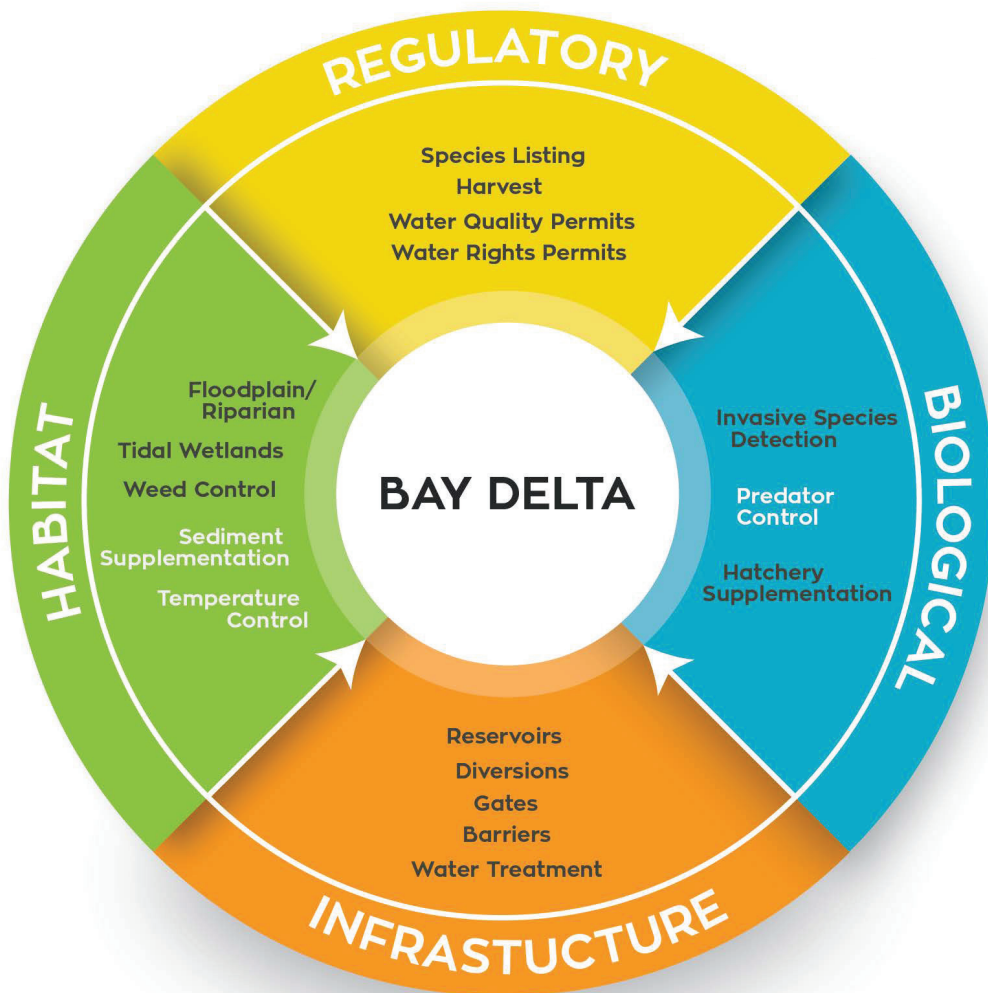


Figure 2 Management options in the Bay–Delta. The text color for suite of actions within each of the four management categories indicates the current level of use in the estuary: 1. *white text*—conceptual or test scale; and 2) *black text*—large-scale. See the text and Table 1 for details.

Hence, in each case I provide examples of the types of organisms or habitats for which the tools have been used. Also, my focus is on the upper estuary (Delta and Suisun regions) so the review does not address actions in the tributaries of San Francisco Bay, and Delta tributary issues are covered only briefly (Figure 1).

The summary of natural resources management options was based on a combination of existing literature, and personal experience with some of the tools. In addition to a narrative summary for each, I include information about the level to which each tool is currently being used: (1) conceptual (not field-tested); (2) test-scale (small-scale and feasibility studies); and (3) large-scale (one or more of the following: multiple examples; physically large; periodically used for management). In summarizing each component, in the text and Table 1, I provide examples of challenges relative to technical feasibility based on my own professional judgement and input from agency colleagues. These summaries were not intended as comprehensive assessments of the strengths and weaknesses of each approach; rather, my goal was to provide readers with qualitative insights. More rigorous approaches such as structured decision-making (Gregory et al. 2013) and companion engineering studies could yield much more insight into quantitative differences between the tools, and help readers to understand many potential trade-offs, including social and cultural factors, economics, legal constraints, and environmental effects.

My coverage of the different management tools is educational rather than an endorsement of one approach versus another. Although each tool is described individually, resource-management problems in the Bay-Delta typically require a multi-faceted approach. For example, a regulation may help to identify a need for a change in water-quality criteria, but infrastructure or land-use changes may be required to meet the new standard. Readers should therefore assume that no one action is sufficient to address most resource needs.

REGULATORY

A regulatory approach is often the first step in implementing major changes in water or ecosystem management. Passing new laws and regulations is therefore a key tool that mandates agencies and private parties to implement actions to protect or improve management of different resources. The tools below represent the primary “top-down” regulatory approaches to initiate such changes (Table 1; Figure 2). However, there are many other types of state (e.g., California Environmental Quality Act; Section 1602 Streambed Alteration Agreement) and federal (National Environmental Policy Act; Rivers and Harbors Act) regulations that need to be considered, depending on the specific issue. A complex array of state and local approvals also is needed to implement virtually all of the management actions described in the “Water Infrastructure,” “Habitat,” and “Other Biological Measures” sections.

Table 1 Summary of major tools used for ecosystem management in the Bay–Delta. The basis for the “Current level of use” was the following: (1) conceptual (*not field-tested*); (2) test-scale (*small-scale and feasibility studies*); and (3) large-scale (*one or more of the following: multiple examples; physically large; periodically used for management*). For the “Example technical constraints” column, all tools may have substantial economic, social, cultural, and legal issues (*not shown*). More unique constraints are shown in the “Example technical constraints” column.

Management category	Management tool	Example species or habitats	Current level of use	Example technical constraints
Regulatory	Species listings (habitat, take)	- Salmonids - Delta Smelt - Green Sturgeon - Longfin Smelt	Large-scale	- Substantial administrative steps required.
	Harvest	- Salmonids - Sturgeon	Large-scale	- Substantial administrative steps required. - Effects on specific commercial, recreational, and cultural groups can be large.
	Water quality permits	- Open water - Inshore	Large-scale	- Substantial legal and administrative steps required.
	Water rights permits	- Multiple fishes and habitats	Large-scale	- Substantial legal and administrative steps required.
Water Infrastructure	Reservoir releases	- Multiple fishes and habitats	Large-scale	- Water availability can be limiting. - Operational constraints may limit some options.
	Operable gates	- Multiple fishes and habitats.	Large-scale	- Operational constraints may limit some options. - May interfere with migratory movements of some fishes.
	Diversions	- Salmonids - Delta Smelt - Longfin Smelt	Large-scale	- Operational constraints may limit some options.
	Barriers	- Salmonids	Large-scale	- Infrastructure available for only some locations. - Operational constraints may limit some options. - Potential adverse effects on hydrodynamics, fish movements.
	Water treatment	- Open water	Large-scale	- Not all contaminants treated by conventional technologies. - Operational constraints may limit some options.
Habitat	Floodplain and riparian restoration	- Salmonids - Wildlife	Large-scale	- Suitable properties are not always available.
	Tidal wetland restoration	- Delta Smelt - Waterfowl	Large-scale	- Suitable properties are not always available.
	Aquatic weed removal	- Shallow water habitat	Large-scale	- Recent major weed removal activities have been successful locally for floating varieties, but weeds continue to cover large areas of the Delta. - Multiple weed types complicate removal process. - Current regulatory permits limit some treatment options.
	Sediment supplementation	- Delta Smelt - Tidal wetlands	Test-scale (one project)	- Major environmental concerns about effects of sediment introduction on water quality. - Logistic challenges for sediment transport and supplementation.
	Temperature management	- Delta Smelt - Salmonids	Conceptual	- Air temperatures are major driver of water temperature, and are not feasible to control. - No proven management actions yet in the Delta.
Additional biological measures	Predator control	- Salmonids - Delta Smelt	Test-scale	- High density and mobility of predators throughout the Delta. - Possible compensatory effects if one predator type or size class is removed.
	Hatchery supplementation	- Salmonids - Delta Smelt	Large-scale (Salmonids)	- Substantial legal and administrative steps required. - Culture and supplementation techniques may be challenging to develop. - Concerns about effects of hatchery fish on wild populations.
	Invasive species detection	- Multiple habitats	Large-scale	- Detection at low abundance can limit effectiveness.

Species Listings

Many types of native species in the Bay–Delta have experienced long-term declines in abundance and distribution, coincident with habitat loss and multiple other stressors. Fish and wildlife agencies can increase protections for sensitive species through listings under the Federal Endangered Species Act (FESA) and California Endangered Species Act (CESA). The listing process is fairly arduous, requiring lengthy reviews of species status, drivers of abundance, and an assessment of extinction risk (e.g., <https://www.fws.gov/endangered/esa-library/pdf/listing.pdf>). A related legal process is that the protections for these species can change if their populations decline or improve substantially. Examples of some of the highest Bay–Delta profile species listed under FESA or CESA include winter-run Chinook Salmon *Oncorhynchus tshawytscha*, spring-run Chinook Salmon, Delta Smelt *Hypomesus transpacificus*, Longfin Smelt *Spirinchus thaleichthys*, Steelhead Trout *Oncorhynchus mykiss*, Green Sturgeon *Acipenser medirostris*, Giant Garter Snake *Thamnophis gigas*, and California Black Rail *Laterallus jamaicensis coturniculus*. Such protections are relatively strong and require permits for activities that have the potential to harm species or their habitat such as water diversions, water discharge, construction, and operations and maintenance. For example, permitted activities set maximum levels of take: the number of individuals that can be killed or disturbed by the applicant. The intended result of these protections is that activities by agencies, industries, or other groups reduce their overall effects on listed species and habitats.

Harvest

Related to the previous regulatory tool, fish and wildlife agencies also set harvest limits for species for which there is recreational or commercial harvest. The legal authority for these types of regulations is different from FESA or CESA, which focus on endangered species rather than less-sensitive species that support recreational or commercial harvest. Examples of these types of regulations are fishery limits for salmon set by the Pacific States Marine Fisheries Commission, and the sport totals for White Sturgeon *Acipenser transmontanus*, Striped Bass *Morone saxatilis*, and Largemouth Bass *Micropterus salmoides* set by the California Fish and Game Commission. The decisions about how to set specific target limits are complicated, relying on data about harvest effort, population size, and modeled projections (e.g., Klimley et al. 2015).

Water Quality

There are numerous water quality issues in the Bay–Delta, so there is a focus on industrial, agricultural, and municipal dischargers that release contaminants into the region's waterways and watershed. The primary regulatory groups that deal with these water-quality constituents are the United States Environmental Protection Agency (US EPA), and several entities in the California Environmental Protection Agency (CAL–EPA). Under the state's Porter–Cologne Water Quality Control Act (SWRCB 2018) and the federal Clean Water Act (<https://www.epa.gov/cwa-404/clean-water-laws-regulations-and-executive-orders-related-section-404>; National Pollutant Discharge Elimination System–NPDES), the state and regional

water boards have the primary regulatory responsibility for protecting the water quality for the Bay-Delta.

In recent years, there has been a major regulatory emphasis on setting limits for Total Maximum Daily Load for multiple constituents, including heavy metals (mercury, copper, selenium) pathogens, sediments, PCBs, nutrients (nitrogen), and pesticides (e.g., orthophosphate, diazinon, and chlorpyrifos). In one of the highest-profile actions, the Central Valley Regional Water Board in 2010 required the Sacramento Regional Wastewater Treatment Plant to implement a major upgrade (EchoWater, <https://www.regionalsan.com/echowater-project>) to their wastewater treatment plan to reduce nitrogen inputs into the Delta. This upgrade represents one of the major public works projects in Sacramento's history.

Salinity is also a primary focus of Bay-Delta water management, primarily as a result of State Water Resources Control Board Decision 1641 (SWRCB; herein "D-1641"), which sets salinity targets at compliance points along the axis of the estuary to support drinking water quality and ecosystem management (SWRCB 1995). A unique compliance criteria is the management of the location of the salt field based on a metric called "X2," the distance of the 2ppt isohaline from the Golden Gate Bridge (Jassby et al. 1995). This metric reflects seawater intrusion into the upper estuary, and is strongly influenced by Delta inflow and tides. D-1641 includes seasonal targets for location of X2 based on the historical pattern of this variable, and by water year type during winter and spring (SWRCB 1995).

Salinity also has been a focus of recent Biological Opinions under FESA and Incidental Take Permits under CESA. For example, the 2008 Delta Smelt Biological Opinion issued to the State Water Project (SWP) and federal Central Valley water project included X2 requirements in fall (USFWS 2008). This represented a time-period outside of that required by D-1641, and required X2 to be located more downstream during the fall of above-normal and wet water years.

Water Rights

In addition to the quality of water, there is a regulatory emphasis on water rights, which control water diversions from the Bay-Delta, as well as inflow and outflow. The SWRCB has the primary responsibility for regulating water rights in the Bay-Delta and has a long history of making decisions that fundamentally affect water management in the system. Along with the Federal Energy Regulatory Commission, decisions by the SWRCB affect streamflow in the tributaries to the Bay-Delta. Moreover, a primary driver of Bay-Delta management is SWRCB D-1641, which sets seasonal targets for the percentage of inflow that can be diverted by the previously mentioned state and federal water export facilities (the SWP and the CVP), which are the two major water diverters from the southern portion of the Delta. D-1641 also includes specific minimum inflows for the San Joaquin River for February through June, depending on water year type.

Water Infrastructure

California has one of the most heavily engineered water distribution systems on the planet. Water infrastructure encompasses the various engineering components that are used to adjust Delta flow inputs, outputs, distribution, and quality. These facilities represent major investments in public infrastructure, providing the primary means to supply high-quality water to support California's economy. At the same time, they are also some of the most frequently used tools to manage aquatic resources in the Bay-Delta and its watershed. The tools can be categorized into five major groups: (1) reservoirs; (2) water diversion; (3) gates; (4) barriers; and (5) water treatment (Table 1, Figure 2).

Reservoirs

Reservoirs are the primary tool by which inflow to the Bay-Delta is managed. Most inflow to the system depends on the operation of a network of large reservoirs throughout the Sacramento and Central Valley (Mount 1995). In addition to flood management and hydropower production, these reservoirs allow water to be stored during high-flow periods, particularly winter and spring. Release of stored water allows project operators to meet mandated criteria for flow, water quality, and habitat, and provides a key tool to maintain suitable conditions during drier and warmer seasons. At the same time, it is well understood that reservoir development has substantially changed the hydrograph in the Bay-Delta and watershed as compared to historical conditions (Brown and Bauer 2010). Altered hydrology may compound the effects of downstream habitat changes, including channelization and the loss of much of the historical riparian, floodplain, and tidal wetland habitat (Whipple et al. 2012).

Water Diversions

The Bay-Delta provides the hub of the water distribution system for California, relying on both large and small diversions to support economic uses of water. The two largest water diversions are the SWP and CVP, located in the South Delta (Figure 1). In addition to the two large water projects in the South Delta, there are substantial pumping plants in Barker Slough and Contra Costa County, as well as over 2,000 smaller agricultural water diversions in the Delta, most of which are unscreened (Herren and Kawasaki 2001).

The South Delta export facilities are complex, including a forebay (SWP only), multi-stage fish facilities, and pumping plants that distribute water southward. In general, these export facilities are operated to maximize the amount of water delivered (when there is demand from customers), while meeting regulatory criteria for water quality and species protection. The effects of South Delta exports on the ecosystem continue to be one of the major topics of research and management in the Bay-Delta (Grimaldo et al. 2009; Sommer et al. 2019). The primary environmental issues include entrainment of many types of fishes, effects on Delta outflow, and local influences on hydrodynamics.

As noted above, D-1641 places limits on the percentage of Delta inflow (I) that can be exported (E): "E/I Ratio" of up to 35% of in winter-spring; up to 65% during

summer-fall. In winter and spring, there are also Old and Middle River flow criteria that must be met under the USFWS (2008; 2019) and NMFS (2009; 2019) Biological Opinions, so exports must be moderated depending on risks to species. In addition, the 2009 NMFS Biological Opinion (NMFS 2009) included a limit on the percentage of San Joaquin River inflow that could be diverted (i.e., “I/E Ratio”). The bottom line is that the actual amount of exports varies substantially each month, based on water demand, endangered species management, water quality criteria, and tidal cycles.

During drought periods, all types of water diversions must be reduced dramatically to avoid seawater intrusion into the Delta, which would make these sources unsuitable for use by local water users or exporters. When available, reservoir releases can also be used in tandem with export reductions to help reduce the degree of seawater intrusion. The most recent example of this was a historical drought during 2012–2015, when the SWP had to decrease their diversions to health and safety levels to prevent seawater intrusion into the central Delta.

Gates

A unique feature of the Bay–Delta is that gates have been installed in two strategic locations to enhance or decrease flows into target regions; Delta Cross Channel (DCC) and Suisun Marsh Salinity Control Gates (SMSCG; [Figure 1](#)). These facilities are in addition to Knights Landing Outfall Gates and Wallace Weir, located upstream of the Delta.

The DCC provides a pathway for more inflow to reach the central Delta region ([Figure 1](#)). By opening the DCC Gates, Sacramento River flows have a relatively direct path via the Mokelumne River and Georgiana Slough to the export pumps, thereby reducing intrusion of oceanic salinity via the West Delta (Monsen et al. 2007). During high inflow periods (>700 cms), the gates are closed to prevent flooding in the central Delta. Moreover, the DCC gates are often closed for long periods during winter and spring to protect endangered juvenile Chinook Salmon that are migrating down the Sacramento River (NMFS 2009; Plumb et al. 2016). Closing the gates reduces movement of young Chinook Salmon into the central Delta, where survival is low.

Perhaps the most unusual water management tool in the Bay–Delta is the SMSCG ([Figure 1](#)). To my knowledge, there is no facility like it in other estuaries. Suisun Marsh is an especially important region in the Bay–Delta because it is a primary stop for waterfowl on the Pacific Flyway, and because it supports a wide suite of aquatic and terrestrial species (Moyle et al. 2014). However, the region is sensitive to salinity intrusion, which can increase when upstream water diversion levels are high. This is a major concern for wetlands managers, who depend on low-salinity water for managed waterfowl habitat. To help address this issue, the two major water diverters in the region, the SWP and the CVP, took the unique step of constructing operable gates in the 1980s to tidally “pump” freshwater into the marsh during key periods. Three gates were constructed on Montezuma Slough, the primary corridor for tidal flows through Suisun Marsh. The gates are operated

tidally as needed during the fall-spring. Specifically, the gates are opened during ebb tides to allow freshwater from the Delta to enter Montezuma Slough and flush throughout the marsh. During flood tides, the gates are closed, preventing high-salinity water from intruding into the marsh (from the western outlet of Montezuma Slough). The net effect is that the SMSCG tidally pumps low-salinity water into the marsh. Note, however, that these tidal gate operations can have a water cost to project operations. Redirecting low-salinity water into Suisun Marsh causes some eastward salinity intrusion along the main tidal axis of the estuary, so additional flow (via export reductions or reservoir releases) is needed to counteract an upstream shift in the salt field (X2, as previously described).

New state and federal permits for the SWP and CVP allow the SMSCG to be used in a novel way: the gates can be operated to support fish habitat (USFWS 2019; CDFW 2020). Under the new proposal, the gates would be operated during summer or fall of below-normal, above-normal, and some dry years to direct more low-salinity water into Suisun Marsh. This concept was tested in August 2018, a below-normal year when summer salinities would have otherwise been too high for Delta Smelt to occupy the marsh. Initial results of the pilot effort showed that these operations successfully reduced salinities during the rearing period for Delta Smelt, providing access to high-quality marsh habitat.

Barriers

Barriers are essentially non-operable gates that can be installed in channels for specific environmental or economic purposes. The best examples of these are the South Delta Temporary Barriers (Figure 1), a set of rock barriers that are seasonally installed to maintain water levels and circulation in channels near the SWP and CVP export facilities (USFWS 2008; NMFS 2009). These barriers are in place by agreement among the SWP, CVP, and South Delta Water Agency. Three rock barriers (Old River at Tracy; Grantline; and Middle River) are typically installed during low flow periods (e.g., summer-fall) when the export facilities affect agricultural water users in the south Delta most strongly. A related project is the Head of Old River Barrier, which is seasonally installed to help protect migrating salmon. The construction material for each of these four barriers is subsequently removed from the South Delta channels at the end of their operations period.

As previously noted, the historic drought of 2012–2016 resulted in major challenges in preventing salinity intrusion into the Delta (Kimmerer et al. 2019). Extended low flow conditions led to salinity intrusion into the Delta, putting the state's water supply at risk. Water managers took the remarkable step of installing a temporary rock barrier during 2015 in False River, one of the key corridors through which salinity enters the central Delta ("Drought Barrier"; Figure 1). Kimmerer et al. (2019) concluded that the barrier successfully prevented landward intrusion of salt by reducing tidal dispersion in Franks Tract, a flooded island that affect Delta water quality and hydrodynamics.

Water Treatment

California has over 900 wastewater treatment plants that reduce inputs of municipal and industrial contaminants into the state's waterways (WEF 2013). The largest Delta facilities are located in Sacramento and Stockton, but there are also numerous smaller facilities to service other Delta towns. Typical steps include: (1) initial treatment, to remove debris; (2) primary treatment, in which settling or sedimentation is used to remove finer particulates; (3) secondary treatment, in which biological and chemical processes are used; and (4) tertiary treatment, an advanced step that is sometimes used to further clean the discharge (i.e., remove dissolved nitrogen). As noted previously, one of the biggest regional changes in water treatment is the EchoWater project upgrade by Regional San in Sacramento to help reduce nitrogen inputs to the Delta. This project follows a similar engineering upgrade to Stockton Wastewater Treatment Plant, which had substantial benefits to water quality (Beck et al. 2018).

There are numerous challenges in water treatment in the Bay-Delta and its watershed. These include aging infrastructure, rapid population growth, extreme weather events, climate change, and emerging contaminant issues such as new pesticides, herbicides, and pharmaceuticals (Connon et al. 2019). Non-point sources of nutrients and contaminants are particularly challenging since they do not necessarily pass through treatment plants, and are often mobilized during storm events, when management may not be feasible.

Habitat Management

Habitat management represents a broad category of actions used to improve habitat quality or increase habitat area for target species. The primary tools include: (1) floodplain and riparian restoration; (2) tidal wetland restoration; (3) weed removal; (4) sediment supplementation; and (5) temperature management (Table 1; Figure 2). Note that salt-field management (X2), described in the previous Water Quality section, is also considered an approach to habitat management (USFWS 2008).

Floodplain and Riparian Restoration

Much of the historical riparian and floodplain habitat in the Bay-Delta has been lost as a result of a variety of activities, including levee construction, urban development, and agriculture (Whipple et al. 2012). However, research on some of the remnant habitat in the Yolo Bypass and Cosumnes River has revealed the exceptional value of these regions for fish and wildlife (Sommer et al. 2001; Jeffres et al. 2008). In the 1990s, the Yolo Bypass Wildlife Area was established to provide floodplain habitat for wildlife, particularly waterfowl and shorebirds. This area now occupies approximately 6,500 ha and contains a mosaic of habitat types. In recent years, there has been much more interest in the potential to improve and expand this habitat for fishes, such as the 2009 NMFS Biological Opinion (NMFS 2009), which calls for the creation of 8,300 ha of seasonal floodplain habitat. Riparian habitat research has not been a major focus of Delta research, but likely has many of the same beneficial characteristics for target species.

Tidal Wetland Restoration

Like floodplain and riparian habitat, the vast majority of tidal wetland habitat in the Bay–Delta has been lost as a result of development activities (Whipple et al. 2012). The net effect of these changes is that many functional aspects of Delta processes have been substantially altered (Wiens et al. 2016). For example, Sherman et al. (2017) provide a thorough recent review of the benefits of tidal wetlands to some of the key at-risk fishes. In brief, there are many reasons why wetlands benefit the ecosystem, including increased food supply, refuge from predators, and habitat heterogeneity. Based on this recognition, there has been a major effort to increase the amount of tidal wetland habitat to support Delta Smelt and other species (USFWS 2008). The current target in the most recent federal Biological Opinion is over 3,200 ha of tidal wetland habitat, with much of the effort concentrated in the North Delta and Suisun Marsh.

Aquatic Weed Removal

One of the extreme changes to the Delta over the past decade has been the proliferation of aquatic weeds (Ta et al. 2017). For example, the most recent estimates indicate approximately 1/3 of open-water habitat in the Delta has aquatic weed coverage. High densities of aquatic weeds affect Delta recreation and many types of water-management structures. Invasive aquatic vegetation also can negatively affect habitat for listed fishes by altering water quality, altering food supply, and providing refuge for predators. Reducing the expanse of invasive vegetation has therefore been identified as a high priority to improve fish habitat (CNRA 2016). As described by Ta et al. (2017), the California Department of Parks and Recreation is making a major effort to control aquatic weeds, particularly by chemical means. While the efficacy of these efforts has been mixed, one encouraging result is that some treatment locations show an increase in the occurrence of native aquatic plants (Caudill et al. 2019). Mechanical and biological control are also possible options (USFWS 2018). However, overall effectiveness has been hindered by a complex regulatory structure, the lack of a consistent monitoring program, permitting constraints, and funding cuts (Ta et al. 2017).

Sediment Supplementation

One of the most under-appreciated changes in the Bay–Delta is the long-term decline in sediment inputs to the system. The changes include a substantial decrease in sediments delivered from the tributaries (Wright and Schoellhamer 2004), an apparent step-change around 1999 (Schoellhamer 2011), and a degradation in the elevation of channels and shoals (Barnard and Kvitek 2010). Two prominent ecological effects are that there is less sediment available to sustain shallow-water habitats such as wetlands, and a major increase in water clarity. The latter is a major issue for Delta Smelt, which relies on turbid water as refuge from visual predators (Moyle et al. 2016).

In recognition of these changes, sediment supplementation has been considered as a possible tool to maintain habitat conditions (CNRA 2016). However, a major concern is that many local sources of sediments are tainted with contaminants, so projects must be considered carefully. One approach being tested by the

Montezuma Wetlands Project is the use of dredge material as a deep base for tidal wetlands construction, which will then be capped with “cleaner” sediments that would be exposed to the water column (Montezuma Wetlands LLC: <https://montezumawetlands.com/>).

In the absence of sediment supplementation, other measures may help to maintain high turbidities. Aquatic weeds substantially affect turbidity (Hestir et al. 2015), so previously described weed-removal actions may benefit adjacent open-water habitats. Since shoal habitat is often more turbid as a result of wind-wave re-suspension of sediments (Morgan–King and Schoellhamer 2013), the planned creation of large areas of shallow-water habitat could help to maintain suitable turbid conditions at or near restored areas (USFWS 2008; CNRA 2016).

Temperature Management

Climate change is a primary driver of long-term increases in temperature in California, negatively affecting many Bay–Delta resources (Cloern et al. 2011). In the tributaries, the primary concern is salmonids, a species that requires relatively cold water for spawning, egg development, and rearing. Several dammed tributaries therefore use releases of cold water from reservoirs to meet temperature criteria for salmonids. The situation is much more challenging in the Delta, where upstream reservoir releases have little or no effect on water temperature. Instead, water temperatures in the Delta are driven by air temperatures (Wagner et al. 2011). Since the Bay region tends to have cooler air temperatures in summer, habitats in downstream regions tend to have lower water temperatures. There are, at present, no focused tools to maintain low temperatures in the Delta. This issue is of particular concern because several of the highest-profile special-status species are very sensitive to high Delta water temperatures, and face high risks from climate change (Brown et al. 2016a; Herbold et al. 2018). A high priority for research is to identify whether there are specific habitats (e.g., tidal wetlands, deep pools) that could provide local refuges. To increase the number and distribution of temperature refuges, such areas would be obvious targets for habitat restoration.

Other Biological Measures

In addition to some of the previous resource-management approaches, targeted approaches have been considered to improve the status of listed fishes. Below, I discuss three potential approaches: (1) predator removal. (2) hatchery supplementation, and (3) invasive species detection (Table 1; Figure 2).

Predator Control

Predation from invasive species represents one of the most serious threats to native species in the Bay–Delta. Here, I focus on the potential use of predator control as a management tool because this option has received widespread consideration. However, many of the same issues are relevant to potential competitor control.

Predation represents the major source of mortality for fishes in the Bay–Delta (Grossman 2016), although this type of predation-induced mortality typically does

not generate serious problems unless populations face simultaneous stress from factors such as new species introductions, food limitation, climate change, habitat loss, or poor water quality. It is therefore not surprising that predator control is often considered as a tool to support imperiled populations. Such programs have been tried with diverse animal taxa, but the effectiveness of such efforts is highly variable (e.g., Mueller 2005; Treves et al. 2016). The decision of whether and how to implement such a program is complex, and needs to take into account regional issues (Beamesderfer 2000). In this context, predator control is being considered in the Bay–Delta and its watershed as a potential tool to reduce mortality rates of target fishes, particularly Chinook Salmon (Grossman 2016). This management approach is motivated by apparent low survival of juvenile salmon through the system, particularly in the San Joaquin River drainage. For example, Buchanan et al. (2018) estimated that survival of juvenile salmon migrating through the San Joaquin River is the lowest of any system along the Pacific Coast. Extreme habitat modifications clearly are a major issue along that migration corridor, contributing to high mortality from introduced predators (Grossman 2016).

An overall approach to predator removal has yet to be developed for the Bay–Delta, although the current focus is on removing predators from “hot spots,” where local habitat conditions enhance prey mortality (Lehman et al. 2019). There are no formal criteria to identify hot spots, but the general assumption is that they are typically heavily modified habitats (Sabal et al. 2016; Lehman et al. 2019), often with prominent anthropogenic features that offer ambush habitat for predators. These may include docks, piers, and diversions, but also aquatic weed beds and areas of illumination. The highest-profile example is Clifton Court Forebay, which is the gateway to the SWP’s water diversion (Figure 1). Large numbers of predators have colonized this reservoir, causing high mortality as fish migrate across the body of water before Skinner Fish Facility. For this reason, a pilot predator removal action in Clifton Court Forebay was included in the 2009 Biological Opinion (NMFS 2009). Similar predator removal efforts are also emphasized at the CVP’s fish facilities (Bridges et al. 2019).

There has been some pilot work to examine the potential effects of predator removal such as Cavallo et al. (2012), who conducted predator-removal experiments on the Mokelumne River and examined the response of tagged migrating juvenile salmon. Although their study suggested some initial improvements in survival after predators were removed, survival benefits appears to be short-term, at best. Predator removal was also tested the National Marine Fisheries Service along experimental reaches of the lower San Joaquin River), but there was no evidence that their manipulations resulted in a change in salmon survival or relative predation rates (Michel et al. 2019). It therefore appears that predator removal may not be effective by itself, but could be a useful complement to other management actions such as habitat restoration, flow manipulation, and weed removal.

Hatchery Supplementation: Supplementation with hatchery fish has been widely used to support salmonids in the Bay–Delta watershed, which lost much of their

historical upstream spawning and rearing habitat as a result of dam construction (Sturrock et al. 2019). Hatchery stocks currently contribute heavily to Central Valley salmon populations, but this management option remains controversial because of potential negative effects. Stocking strategies include supplementation with multiple sizes (fry, smolt), locations (river, bay) and variable timing (Huber and Carlson 2015). Although several Chinook Salmon races are produced in hatcheries, the dominant production is fall-run, to support the large recreational and commercial fisheries. Huber and Carlson (2015) estimate that 2 billion juvenile salmon have been introduced since 1941, representing a substantial effort. Over time, there has been increased trucking of young salmon to downstream release locations, particularly during drought periods (Sturrock et al. 2019). The purpose of this change in introduction methods was to increase survival of out-migrating salmon. However, trucking has contributed to increased straying of returning adult salmon in the tributaries, and a narrowing in the timing of ocean arrival, the possible consequence of which is a reduced ability to deal with higher variability in coastal conditions under climate change.

Salmonids are the only Bay-Delta fishes regularly supplemented with hatchery stock, but it is likely that there will be some level of supplementation with Delta Smelt in the near future in response to requirements of the new federal Biological Opinion (USFWS 2019). As a first step, a public workshop was held in 2017 to identify major scientific uncertainties and to guide future studies (Lessard et al. 2018). A team of agency and university scientists has been using this input to determine methods to manage Delta Smelt releases from the refuge population to benefit the wild. A key product of this effort will be the development of a Hatchery and Genetic Management Plan. In the meantime, efforts continue to maintain a refuge population in Byron, CA, with a smaller back-up population at Livingston Stone Hatchery in Shasta Lake, CA. Currently, free-swimming hatchery fish have not been released into the Delta, except as part of a predation study in Clifton Court Forebay (Castillo et al. 2012).

Invasive Species Detection

The Bay-Delta has an extreme invasion rate, with growing problems from invasive plants, invertebrates, fishes, and mammals (Cohen and Carlton 1998). The most cost-effective ways to deal with these species is early detection, to help avoid successful introductions and allow a rapid response (Mehta et al. 2007). There are many types of detection tools including visual surveys, remote sensing, and modern genetic methods (eDNA).

One of the best examples of this approach is the current effort to prevent introduction of dreissenid mussels into the Bay-Delta (<https://www.wildlife.ca.gov/Conservation/Invasives/Quagga-Mussels>). Benthic grazing by other invasive bivalves is already well known to affect primary production in the Bay-Delta very negatively (Alpine and Cloern 1992), which in turn limits higher trophic levels (Sommer et al. 2007; Kimmerer 2006). Zebra and Quagga mussels are therefore the target of a major detection and education program at state borders and boating recreation areas.

Once invasive bivalves are established, management options are limited. There is currently no feasible approach to remove established invasive bivalves (i.e., *Potamocorbula*; *Corbicula*) from Bay–Delta habitats, so potential options remain at the conceptual level. Although outflow has some effect on invasive clams, high flows mainly result in a change in species composition rather than reducing overall biomass (Baxter et al. 2015). Restoration may be a potential tool to make some habitats less suitable for invasive bivalves. For example, smaller sloughs in Suisun Marsh tend to have lower densities of invasive clams than downstream areas (Baumsteiger et al. 2017); therefore, creating more small tidal channels could be beneficial. Similarly, clam densities are lower in San Pablo Bay, where there is heavy grazing pressure from diving ducks (Poulton et al. 2004), so perhaps there are ways to create open-water habitats that enhance invasive clam mortality.

Another high-profile example of detection as a Bay–Delta management tool is the current effort to locate and eradicate an invasive rodent *Nutria Myocastor coypus* (CDFW: <https://www.wildlife.ca.gov/Conservation/Invasives/Species/Nutria/detection>). Unfortunately, the species has been detected in the southern part of the Delta and appears to be expanding in distribution. The main concern is that *Nutria* damage levees and other habitats through burrowing, overgraze vegetated habitats, and carry pathogens and parasites. Current activities include trapping by wildlife professionals, and an extensive public outreach program to help detect new introductions.

Summary

The Bay–Delta can be considered an estuary of superlatives. It is one of the most invaded estuaries in the world (Cohen and Carlton 1998), drains a high percentage of California (46%), provides water to 8% of the population of the US, supports the world’s fifth-largest economy (Moyle et al. 2018), and has very long list of special-status species. Based on this review article, I propose that we add “most heavily-managed estuary” as an additional remarkable aspect of the Bay–Delta. This claim is based on the relatively long list of resource-management tools (Table 1; Figure 2) and the high degree to which each is being used. In particular, several of these tools in the Water Infrastructure category are used virtually daily to manage different aspects of the ecosystem.

A primary rationale for this article was to provide guidance for researchers wishing to conduct “actionable science.” A high priority in this region is for agencies to support projects that lead to improvements in resource management. For this reason, most of the major agency funding sources (e.g., the Delta Science Program; the Interagency Ecological Program) rank proposals, in part, based on management relevance—essentially a statement on the degree to which the proposed research is likely to be actionable. Hence, scientists wanting to maximize the management relevance of their research (or proposal) might consider asking themselves a simple question: “If my study is successful, is there a way that the results could be used for management?” The list of tools I have provided therefore helps researchers to examine whether there is currently a management tool that might incorporate their findings. I fully acknowledge that research can lead to

new tools that were not addressed in my review; as a consequence, understanding the current management options and their limitations can help to fuel innovation.

A related goal of my review was to better inform resource managers about the full suite of tools used in the Bay-Delta. Managers are often faced with individual or multi-faceted problems that may be difficult to address without an understanding of all the options. This does not mean, however, that there are easy answers to natural-resource issues. Figuring out which tools are appropriate depends on multiple factors including cost, political feasibility, socio-economic concerns, resource availability, regulatory constraints, and level of urgency. Most of these are relevant not only to the Bay-Delta, but also to the broader watershed where many of the issues can originate. Moreover, I expect it is rare for only one of the previously described management tools to be the only solution to a given problem. As a starting point, conceptual models can help to identify some of the candidate management tools. For example, conceptual models for species (e.g., Baxter et al. 2015; Johnson et al. 2017) or habitats (e.g., Sherman et al. 2017) illustrate many of the drivers and landscape pathways that should be considered. Other decision-support tools such as structured decision-making (Gregory et al. 2013) can then provide a platform to incorporate the most promising management options for testing in the light of the numerous social, environmental, and economic factors that need to be considered.

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