

Chapter 4

Other Aquatic Ecosystem Stressors

This chapter was included in the 2023 draft Staff Report, and some of the original text has since been modified to reflect evolving science and for consistency with information provided in the Scientific Basis Report Supplement and other sections of this Staff Report. Some specific updates include discussion of floodplain and wetland habitat restoration, ammonia/ammonium, harmful algal blooms, water temperature, fish predators and nonnative species, and climate change.

4.1 Introduction

The factors that harm native species are broadly referred to as *stressors*. Stressors affect populations by altering the growth, reproduction, and mortality rate of individual organisms. Stressors may also interact with each other in an additive or synergistic fashion (^Sommer et al. 2007). These stressors occur both within the Delta and upstream in the greater watershed and are unfavorable and unnatural attributes of the ecosystem, leading ultimately to diminished populations and, in the worst case, extinction of native species (^Mount et al. 2012). The precise effect of non-flow stressors on the abundance and distribution of native species is not known. The presumption is that these stressors have negatively affected native taxa (^Moyle 2002; ^Mount et al. 2012); however, it is difficult to determine how much each stressor affects native species in isolation because stressors interact and may act in conjunction with each other.

The State Water Board recognizes that ecosystem recovery in the Delta depends on more than just adequate flows. Many scientific studies have identified the involvement of other aquatic ecosystem stressors, such as reduced habitat, pollutants, nonnative invasive and predatory species, and abiotic factors, as contributing factors in species declines (^Sommer et al. 2007; Moyle et al. 2012; ^Mount et al. 2012). The recognition that many factors stress the Delta's ecosystem also is reflected in *The Delta Plan: Ensuring a Reliable Water Supply for California, a Healthy Delta Ecosystem, and a Place of Enduring Value* (^DSC 2013), a long-term enforceable plan for the Delta that calls for consideration of multiple stressors to improve ecosystem restoration success. Projects and programs to address these other stressors are often referenced generically as *non-flow actions*. However, that term is something of a misnomer as it fails to capture both how inadequate flows have contributed to the pervasiveness and severity of other stressors and the need for adequate flows to successfully implement many *non-flow* or *other aquatic ecosystem* measures. The benefits of flows are enhanced when implemented in concert with habitat restoration, control of waste discharges, control of invasive species, fisheries management, and other efforts. A multifaceted approach is needed to address Delta concerns and reconcile an altered ecosystem (^Sommer et al. 2007; Moyle et al. 2012).

This chapter organizes other aquatic ecosystem stressors into five categories: physical habitat loss or alteration, water quality, nonnative species, fisheries management, and climate change. No one category is independent of the others, and significant interactions can amplify or suppress the negative effects of each on the aquatic ecosystem. The following sections describe generally how stressors negatively affect the aquatic ecosystem and the interactions between stressors. This chapter also describes how flow management interacts with other stressors, indicating the need for including flow considerations in strategies for reducing the effects of stressors as a whole.

The State Water Board recognizes that addressing these stressors will amplify the ecological benefit of new and existing flows beyond what the State Water Board can require through flow and water project operations alone. In addition to flow actions, the proposed program of implementation describes habitat restoration and other ecosystem actions that are being, or should be, taken to address these aquatic ecosystem stressors (Chapter 5, *Proposed Changes to the Bay-Delta Plan for the Sacramento/Delta*, Chapter 9, *Proposed Voluntary Agreements*, and further refined in the project description in Chapter 13, *Revised Proposed Plan Amendments*). Many of those actions are within the purview of other agencies and entities and should appropriately be further developed and implemented by those agencies and entities. The State Water Board will help to facilitate those efforts in a coordinated fashion with the flow actions. Section 7.21, *Habitat Restoration and Other Ecosystem Projects*, addresses physical habitat restoration and other complementary ecosystem measures that entities may undertake toward achieving the overall goal of improving conditions for fish and wildlife in the Sacramento/Delta.

4.2 Physical Habitat Loss or Alteration

For fish, flow is habitat. The hydraulic structural conditions (depth, velocity, substrate, or cover) define the actual living space of the organism (USFWS 2010). However, in the Delta watershed, there also has been a dramatic loss in other aspects of physical habitat suitable for native fish species. For example, the channels of the Delta have been significantly modified by raising of levees and armoring of the levee banks with stone and concrete riprap. This reduces the complexity and functionality of habitat for native species, including reducing the incorporation of woody debris and vegetative material into the nearshore area, minimizing and reducing local variations in water depth and velocities, and simplifying the community structure of the nearshore environment (NMFS 2009 BiOp). Habitat loss exacerbates the effects of other stressors, especially in ecosystems with low freshwater flows (Mount et al. 2012). Increased habitat complexity and hydrologic connectivity is needed to maximize the effectiveness of increased flows in supporting native fishes (Mount et al. 2012).

A reconciliation strategy has been proposed for the Delta “that blends the needs of humans and the ecosystem in a landscape and hydrology that has irreversibly changed” (Hanak et al. 2011). Reconciliation includes actions to create better conditions to support native species, recognizing that a return to pristine or historical conditions is not possible, particularly in areas that have been transformed by farming and urbanization. A multi-agency collaboration among government, academia, and non-government entities, guided by best available science and adaptive management, is needed to implement actions to restore and preserve marsh, riparian, and upland habitat in the Delta and its tributaries (Mount et al. 2012) in a coordinated fashion between upstream and downstream actions accounting for the effects of existing and future climate change. Actions may include land acquisition to prepare tidal marshes and other habitats for higher sea level, acquisition and preservation of riparian and floodplain habitat, removing or breaching levees to increase connectivity between floodplains and open water, and periodic flooding to encourage establishment and preservation of native riparian habitat.

Federal, state, and local agencies, as well as non-governmental organizations, have made and are making significant investments in habitat restoration to benefit native species. Some of the major efforts are discussed below and in the specific habitat sections that follow, though many smaller projects are also being undertaken.

The Ecosystem Restoration Program (ERP), a multi-agency effort primarily between the California Department of Fish and Wildlife (CDFW), U.S. Fish and Wildlife Service (USFWS), and National Marine Fisheries Service (NMFS), was formed to improve and increase aquatic and terrestrial habitats and ecological function in the Delta and its tributaries. The ERP has implemented restoration projects through grants administered by the ERP Grants Program, with more than \$700 million dedicated as of 2014 for more than 500 restoration projects. ERP projects include enhancement or restoration of more than 9,000 acres of habitat as well as protection of more than 48,000 acres of existing habitat, including non-tidal perennial aquatic, riparian and riverine aquatic, freshwater emergent wetland, and seasonal wetland habitats on the Sacramento River, Feather River, and Big Chico, Butte, Clear, and Mill Creeks (ERP 2014).

In 2014, the Water Quality, Supply, and Infrastructure Improvement Act was enacted allocating significant additional funding for restoration and related projects in the Bay-Delta watershed, including nearly \$1.5 billion for ecosystem and watershed protection and restoration projects (CNRA 2015). California EcoRestore, a California Natural Resources Agency initiative implemented in coordination with state and federal agencies to advance restoration and enhancement of at least 30,000 acres of habitat in the Delta, Suisun Marsh, and Yolo Bypass, is proposed to be funded in part by Proposition 1. EcoRestore restoration targets include 3,500 acres of managed wetlands, 9,000 acres of tidal and subtidal habitat, and 17,500 acres of floodplain restoration, as well as fish passage improvements (^CNRA 2016).

In addition to the above efforts, in 1992, Congress passed the Central Valley Project Improvement Act (CVPIA) (Title 34 of Public Law 102-575) to address impacts of the CVP on fish, wildlife, and associated habitats. Included among the purposes of the CVPIA is to “contribute to the State of California’s interim and long-term efforts to protect the San Francisco Bay/Sacramento-San Joaquin Delta Estuary.” To date, significant funding has been provided for restoration efforts in the Bay-Delta watershed. The 2019 federal budget included \$62 million for the CVPIA Restoration Fund for projects such as American River spawning and rearing habitat, Clear Creek spawning gravels and channel restoration, and Sacramento River salmonid habitat restoration (Reclamation and USFWS 2018). These CVPIA Restoration Fund projects were consistent with the conservation priorities identified by the ERP.

To help guide restoration efforts in the Delta, the San Francisco Estuary Institute and the Aquatic Science Center through the Delta Landscapes Project has produced an instructive report titled: *A Delta Renewed: A Guide to Science-Based Ecological Restoration in the Sacramento-San Joaquin Delta*. The report emphasizes process-based recovery of landscape functions that integrate natural and cultural processes and maximize resilience to climate change, invasive species, and other challenges (^SFEI-ASC 2016). The report includes regional recommendations and on-the-ground strategies and discusses the potential for establishing smaller, modified landscapes that are resilient, productive, sustainable, and supportive of people and native wildlife.

The habitat within the Bay-Delta can be divided into distinct segments: tidal marsh in the north and south Delta and Suisun Marsh, riparian habitat and open channels throughout the Delta and its tributaries, and floodplain and wetland habitat in the north and south Delta and its tributaries (^Mount et al. 2012; ^Whipple et al. 2012). Each habitat is discussed in more detail in the following subsections.

4.2.1 Riparian Habitat and Open Channels

Riparian vegetation is a critical resource for native aquatic species, providing numerous important habitat features, including shade, refugia, habitat structure, food resources, and other functions. Historically, the Sacramento River system and surrounding tributaries included significant vegetated riparian areas, including stands of oak, cottonwood, and other deciduous and coniferous trees (^Rood et al. 2003), as well as vines, shrubs, and grasses that sprung up when fluvial and alluvial sediments and their associated flows were more prevalent (^Roberts et al. 1980; ^Whipple et al. 2012).

The Sacramento River had 800,000 acres of riparian vegetation in 1848, but only 12,000 acres, or about 1 percent, remained by 1972 (Sands and Howe 1977). The conversion of forests to orchard and field crops, logging, streambank stabilization, channelization, and freshwater flow reduction due to dams and irrigation all contributed to this loss of riparian habitat (^Whipple et al. 2012). Channelization, leveeing, and riprapping of river reaches and sloughs now are common in the Sacramento River system and typically create channels with minimal habitat complexity, which results in low food availability and little protection from either fish or avian predators (USACE and CDFG 2010). In addition, the proliferation of nonnative submerged and floating aquatic vegetation significantly decreases open water habitat quantity and quality for native fishes.

A combination of land use restoration actions coordinated with flow actions are needed to address the ecological degradation caused by the loss of riparian forests and construction of levees and channelized waterways. Those actions include riparian reforestation, channel modifications, and levee design and management actions (setback levees and other actions) that produce more natural hydrologic and geomorphic processes that promote natural ecological processes. Flow actions are needed that support and promote riparian processes, including the establishment and maintenance of native riparian vegetation and other natural hydrologic and geomorphic processes through perennial and periodic storm flows that overtop channel banks, saturate soils, and encourage seed regeneration and other functions.

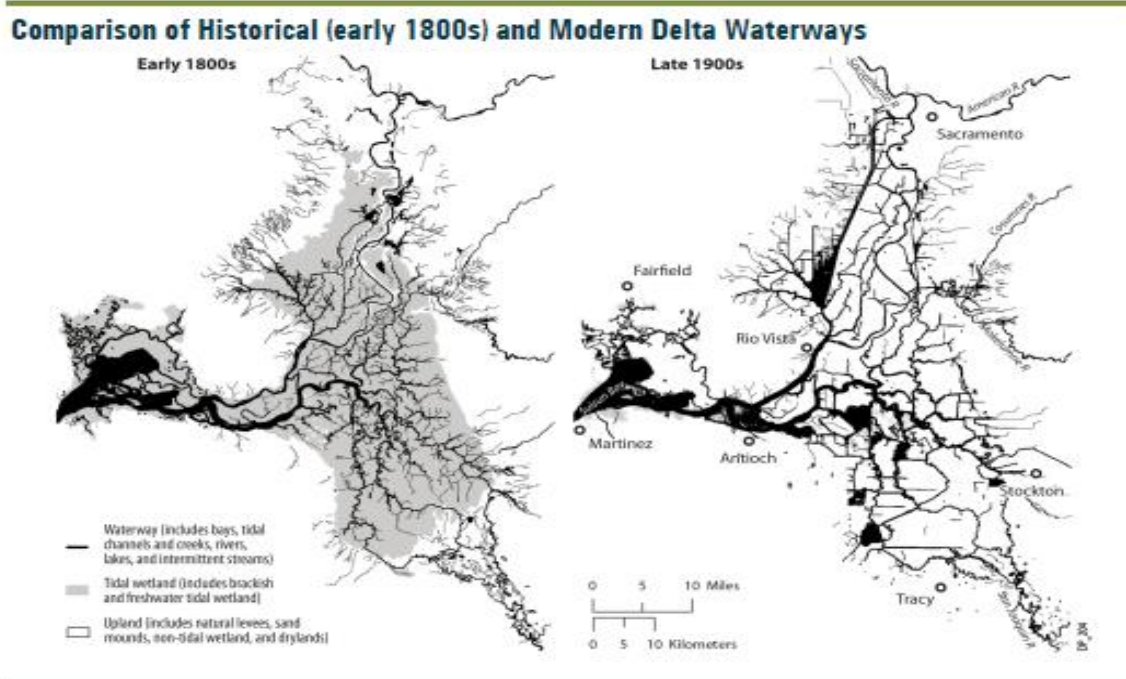
Federal, state, and local agencies and non-governmental organizations have made and are making significant investments in riparian restoration projects to benefit native species, including through the ERP, CVPIA, and other programs and projects. For example, a significant effort has been made to restore habitat on Battle Creek, one of the more ecologically valuable tributaries to the Delta, through the Battle Creek Salmon and Steelhead Restoration Project (Battle Creek Restoration Project). The Battle Creek Restoration Project seeks to reestablish approximately 42 miles of prime salmon and steelhead habitat on Battle Creek, a tributary to the Sacramento River, by improving fish passage and restoring ecological processes through modifications of facilities and operations associated with Pacific Gas and Electric Company's (PG&E) Battle Creek Hydroelectric Project (Reclamation 2016a). As of May 2018, over \$140 million has been invested in the Battle Creek Restoration Project (Greater Battle Creek Watershed Working Group 2018). However, in April 2019, PG&E withdrew its application to the Federal Energy Regulatory Commission for the Battle Creek Restoration Project Phase 2. (PG&E 2019)

4.2.2 Tidal Marsh Habitat

Extensive freshwater tidal marshes in the Bay-Delta watershed historically provided critical habitat for many native species. Tidal marsh habitat supports many native plant species and sustains diverse food webs and ecosystem processes (^Atwater et al. 1979). Networks of sloughs provide

habitat structure and cool water refugia during summer heat spells (^Mount et al. 2012). Tidal marshes also influence the recycling and retention of nutrients.

Tidal marshes have changed dramatically over the past 150 years, largely due to filling and diking (Figure 4.2-1) (^Atwater et al. 1979; Nichols et al. 1986; ^Moyle 2002; ^Whipple et al. 2012). The Delta currently supports less than 10,000 acres of tidal wetland, all of which is small and fragmented (^USFWS 2008 BiOp). This represents about 3 percent of the acreage of tidal wetland before the gold rush (^Whipple et al. 2012) and less than 30 percent of tidal mudflats and wetland originally present in San Francisco Bay (Callaway et al. 2011). Landscape changes of this magnitude suggest comparable changes in the magnitude, transport, and fate of estuarine-derived organic matter and primary production (Brown et al. 2016). The conversion of tidal wetlands to diked seasonal wetlands resulted in habitat loss for many native species, including Delta smelt and longfin smelt.



Source: ^Whipple et al. 2012

Figure 4.2-1. Comparison of Historical and Modern Delta Waterways, Tidal Wetland, and Upland Areas

Altered tidal marsh habitat may be restored by growing tules, cordgrass, and cattails to reverse subsidence (Zedler 1988; Miller et al. 2008). Alternatively, breaching or removal of levees along with better flow management may restore hydrologic connectivity and improve tidal marsh habitats in anticipation of sea level rise (^Mount et al. 2012). Brown et al. (2016) recommend that tidal wetland restoration in the Delta be conducted as an experimental program because there are still many unanswered questions about the outcome of planned restoration actions. Adoption of an experimental adaptive management approach may achieve the most for native species in the long run with the limited resources available.

Effectiveness monitoring of restoration activities is important to determine the capacity, opportunity, and realized functioning of tidal wetlands to meet the needs of native fish and other aquatic species. The Interagency Ecological Program (IEP), a multiagency collaborative monitoring,

research, modeling, and synthesis effort to inform planning and regulatory decisions, has formed a Tidal Wetland Monitoring Project Work Team (Team). The purpose of the Team is to collaborate on the design of monitoring programs for fish and foodweb resources in restored tidal wetlands in the Bay-Delta system. In this effort, the Team has developed a monitoring framework that includes effectiveness monitoring tools and project-specific monitoring plans to inform adaptive management and planning for future projects. The Delta Restoration Network has also been developed by the Sacramento-San Joaquin Delta Conservancy as a forum for information sharing and coordination to ensure an integrated and accountable restoration program in the Delta. The purpose of the network is to coordinate and integrate restoration actions to ensure integrated performance tracking among governmental and non-governmental entities engaged in restoration and habitat management in the Delta and Suisun Marsh (^Delta Conservancy 2015).

Suisun Marsh is the largest expanse of tidal marsh in the Bay-Delta and is the largest remaining brackish wetland in western North America (^O'Rear and Moyle 2009). The marsh provides important habitat for many birds, mammals, and reptiles, and more than 40 fish species (^O'Rear and Moyle 2009; ^Reclamation et al. 2013). It also provides important tidal rearing areas for juvenile salmonids. Suisun Marsh currently consists of a variety of habitats, including managed diked wetlands, unmanaged seasonal wetlands, tidal wetlands, sloughs, and upland grasslands. It encompasses more than 10 percent of California's remaining natural wetlands (^Whipple et al. 2012), with 6,300 acres of its total 116,000 acres in tidal wetlands. As a result of diminished freshwater inflow in Suisun Marsh (^Feyrer et al. 2011), increased salinity intrusion has reduced primary productivity and biodiversity (Reclamation and USFWS 2018).

The 2014 Suisun Marsh Habitat Management, Preservation, and Restoration Plan (SMP) is a 30-year plan to address habitats and ecological processes, public and private land use, levee system integrity, and water quality through tidal restoration and managed wetland activity in Suisun Marsh. An objective of the SMP is to implement the CALFED Ecosystem Restoration Program Plan restoration target of 5,000 to 7,000 acres of tidal marsh and protection and enhancement of over 40,000 acres of managed wetlands. The SMP proposes that Reclamation and DWR implement a Preservation Agreement Implementation Fund. The Preservation Agreement Implementation Fund is a single cost-share funding mechanism that would contribute to funding of some activities needed to improve managed wetland facility operations and to implement restoration actions (Reclamation and USFWS 2018).

4.2.3 Floodplain and Wetland Habitat

Functioning floodplains are important components of the aquatic ecosystem, providing abundant food and refugia, spawning grounds, and other critical habitat functions (^Jeffres et al. 2008; ^Sommer et al. 2001b; ^Li et al. 1994). Healthy floodplains are morphologically complex and include backwaters, wetlands, sloughs, and connected channels that carry and store floodwater. Floodplain areas can constitute islands of biodiversity within semi-arid landscapes, especially during dry seasons and extended droughts (^ERP 2014).

A significant amount of floodplain habitat in the Delta has been lost through the channelization of rivers, including construction of levees and channel straightening, deepening, and lining (Mount 1995). Since the early 1800s, freshwater emergent wetlands have been reduced by more than 70 percent in the Delta due to land conversion for agricultural and urban uses (^Whipple et al. 2012). At the same time, water storage and conveyance, flood control, and navigation activities have impaired the amount and timing of flows onto the floodplain. Further, hydraulic mining, especially

in the Yuba and Feather Rivers, and other activities have caused changes in sediment deposition within channels and floodplains, loss of channel capacity, and aggradation of river courses (Mount 1995).

Some complex, productive habitats with floodplains remain in the system (e.g., Sacramento River reaches with setback levees [primarily located upstream of the City of Colusa] and flood bypasses [Yolo and Sutter Bypasses]). Juvenile life stages of salmonids are dependent on the function of this habitat for successful survival and recruitment (NMFS 2009 BiOp). Native salmonids that rear on floodplain habitat in the Delta watershed grow larger and faster than fish that do not due to higher food production. In one study, zooplankton biomass was found to be 10 to 100 times higher on the floodplain than in open river habitat (Jeffres et al. 2008). Efforts are underway through EcoRestore and other efforts to restore floodplain habitat in the Delta watershed in a collaborative fashion with agricultural practices. Included among these projects is The Knaggs Ranch Agricultural Floodplain Study in the Yolo Bypass, which seeks to emulate highly productive salmon rearing habitat through a collaborative effort between farmers and researchers to help restore salmon populations by reintroducing them during winter to inundated floodplains that are farmed with rice during the summer (California Trout 2017; Holmes et al. 2021).

While zooplankton produced in floodplains or flooded agricultural lands could provide food for juvenile salmon, water quality monitoring is also needed to avoid exposing fish to additional stressors such as pesticides and methylmercury. Agricultural drainage has been shown to increase pesticide concentrations in the Yolo Bypass (Orlando et al. 2020), and juvenile Chinook salmon in the Yolo Bypass have been shown to have higher concentrations of current-use pesticides than salmon rearing in the Sacramento River (Anzalone et al. 2022; Anzalone et al. 2024). Monitoring suggests that habitat restoration and flooding of tributary and bypass floodplains are also associated with higher bioaccumulation of methylmercury in fish, exceeding the water quality objective for methylmercury in fish tissue established by the Delta Methylmercury total maximum daily loads (TMDL) (Davis et al. 2025).

Uncertainties remain in the foodweb benefits of wetland and floodplain restoration. Tidal wetland habitats in the Bay-Delta have been hypothesized to export resources and food into adjacent open water habitats; however, available evidence has not supported this, and the elucidation of such benefits would require further research (Yelton et al. 2022). Similarly, the benefits of floodplain and other shallow water habitat restoration for native fish species in the Delta are still not fully understood, and the mediation of any such benefits by factors such as flow and fisheries management are areas of active research. For example, the efficacy of restoration efforts for juvenile salmon in the Bay-Delta depends on flow and spawner abundance (Munsch et al. 2020). Additionally, studies indicate that Sacramento River flood bypasses exhibit higher invertebrate productivity compared to channelized sections of the river, and salmonids access and use this biomass during high flow conditions (Sommer et al. 2001; Goertler et al. 2018; Cordoleani et al. 2022; Sturrock et al. 2022), suggesting that increasing inundation of the flood bypasses can increase productivity and support juvenile salmon growth for individuals that can access these habitats. However, for tributary floodplain and instream habitat restoration, there is more uncertainty surrounding foodweb benefits due to limited tributary foodweb monitoring in the system. One monitoring study found higher densities of macroinvertebrates in restored side channels on the Sacramento River compared to baseline unrestored sites, but the highest densities of macroinvertebrates were found in the main channel (Banet et al. 2021). Further research into how juvenile salmon growth rate, size, and habitat utilization affects the survival, adult returns, and fitness of individual salmon is needed. Without reliable estimates of juvenile salmon production or

foodweb productivity, it is difficult to determine whether food limitation, if it exists, is currently a significant stressor that prevents salmon population growth. The limitation of salmon population growth by food limitation appears unlikely because of consistent scientific findings that flow and temperature are the key explanatory variables for salmon emigration survival (Zeug et al. 2014; Michel 2018; Henderson et al. 2018; Michel et al. 2021; Nobriga et al. 2021; Hassrick et al. 2022). In addition, the connectivity between rivers and floodplains may be inhibiting successful use of floodplain habitat (Feyrer et al. 2006; DWR and Reclamation 2012; Reclamation and DWR 2019; Opperman et al. 2010) rather than the amount of floodplain habitat serving as a limiting factor. Restoration of these shallow water habitats can be beneficial if connectivity issues are addressed in restoration designs.

4.2.4 Upper Watershed Forest and Meadow Habitat

The Sacramento/Delta watershed contains forests, meadows, and waters in the Cascade Range and Sierra Nevada that provide a variety of ecological services. Upper watershed forests store carbon, provide habitat for native species, provide recreational opportunities, produce a large portion of California's timber supply, and provide water for hydroelectric power generation (Sierra Nevada Watershed Improvement Program 2018). Headwater areas in the Bay-Delta watershed also provide a vital water source for downstream ecosystems and consumptive uses.

Several Sacramento/Delta tributaries originate at high elevations in the Cascade Range and the Sierra Nevada and are fed primarily by snowmelt. The Sierra Nevada snowpack, which produces an estimated average annual water supply of approximately 11 million acre-feet (2013 Water Plan V2, Mountain Counties), accumulates at higher mountain elevation areas during the winter months. During the late spring and summer, the Sierra Nevada snowpack melts and runs off into rivers and reservoirs, providing a crucial and high-quality water supply during the drier months and cold water for Chinook salmon and steelhead and other native species. Protection of the Sierra Nevada snowpack is identified as a critical part of any long-term solution to ecosystem health and water supply reliability (2013 Water Plan V2, Mountain Counties).

Many California forests evolved with low-intensity fire as an ecosystem process that provided forest health benefits (Forest Climate Action Team 2018). However, management practices, including fire suppression and intensive logging activities, have resulted in overgrown forests in many areas (Sierra Nevada Watershed Improvement Program 2018; 2013 Water Plan V2, Mountain Counties). It is estimated that Sierra Nevada forest density has increased from 50 to 70 trees per acre in the nineteenth century to 400 trees per acre in 2010 (2013 Water Plan V2, Mountain Counties). As a result, upper watershed forests have become susceptible to large, high-severity fires (Forest Climate Action Team 2018; 2013 Water Plan V2, Mountain Counties), which can result in erosion, reduce the cover for snowpack, degrade water quality, and alter the predictability of the water supply. In addition, forests planted as even-aged stands to replace logged areas are often overgrown and can leave forests susceptible to disease, insects, and the impacts of drought (2013 Water Plan V2, Mountain Counties). Drought exacerbates the risk of wildfire in the Bay-Delta watershed's forest habitat. For example, it is estimated that approximately 130 million trees died as a result of California's 2012 to 2016 drought, the majority of which are located in the Sierra Nevada (CALFIRE 2017).

Multiple management and restoration efforts are currently underway to support upper watershed ecosystem health and resiliency. For example, in 2018, the multi-agency Forest Climate Action Team produced a Forest Carbon Plan that provides strategies to promote healthy and resilient forests and

considers opportunities to establish forests as a more reliable and resilient long-term carbon sink (Forest Climate Action Team 2018). In addition, the 2020 Water Resilience Portfolio identifies multiple actions that would help to protect and enhance upper watersheds and forests, including encouraging investment in upper watersheds to protect water quality and supply (Water Resilience Portfolio Action 15) and working toward accomplishing the goals of the California Forest Carbon Plan (Water Resilience Portfolio Action 15.2). Efforts are also underway to address meadow restoration and protection. For example, the National Fish and Wildlife Foundation's Sierra Nevada Meadow Restoration Program supports meadow restoration and protection efforts in the Sierra Nevada. Since 2009, over 3,000 acres of meadow and associated hydrology have been directly supported; and an additional 6,700 acres of meadow are in restoration planning, design, and permitting phases (NFWF 2018).

4.3 Water Quality

Water quality conditions, including contaminants and associated toxicity, nutrients, low dissolved oxygen, increased temperature, and reduced turbidity, can adversely affect native fish and other aquatic organisms in the Bay-Delta watershed. In addition to affecting aquatic organisms, various contaminants may affect terrestrial wildlife, including birds, and may bioaccumulate in edible fish tissue to become a human health concern. Dissolved oxygen concentrations, turbidity, and temperatures are all parameters directly influenced by flow management that are discussed individually in the following subsections and in the context of flow elsewhere in this Staff Report. Contaminants are also affected by flows but are primarily discussed in this chapter.

4.3.1 Contaminants

Contaminants are introduced into Bay-Delta waterways by publicly owned wastewater treatment works (POTW), agricultural and industrial discharges, and urban storm water runoff. Herbicides and insecticides are also applied directly to Bay-Delta waterways for aquatic plant and mosquito control. Other contaminants already exist in the environment naturally or are legacy contaminants that are no longer in use but still present in the environment. Many of these contaminants can affect the survival and fitness of organisms and alter foodwebs and ecosystem dynamics. Some contaminants may enter public drinking water sources and bioaccumulate in edible fish tissue to become a human health concern (Davis et al. 2013). Other trace metals and organic compounds bind strongly with sediment, making the movement of sediment a mechanism for their transport (Schoellhamer et al. 2007).

In general, contaminant effects vary based on the magnitude and duration of exposure and species-specific sensitivity, with insecticides and heavy metals being more likely to affect zooplankton and other small-bodied invertebrates. At higher trophic levels, toxic effects from these contaminants may not be lethal, but sub-lethal effects may reduce ecological fitness through impaired growth, reproduction, or behavior, or increase the organism's susceptibility to disease (Davis et al. 2013). Moreover, the consequences of sub-lethal pollutant effects on keystone species that play a disproportionate role in controlling ecosystem function may manifest throughout the entire ecosystem (Clements and Rohr 2009).

The level and degree to which a species is exposed to different contaminants varies based on a number of factors, including the species' life cycle, geographic range of the species, and contaminant

loading. Reduced freshwater inflow from the Sacramento-San Joaquin River system may also reduce the estuary's capacity to dilute, transform, or flush contaminants (Nichols et al. 1986). Aquatic organisms may be simultaneously exposed to contaminants present in water, sediment, and/or food depending on the species, life stage, life history, trophic level, and feeding strategy. For example, early life stages of many Delta fish species inhabit the system during late winter and spring, a time when storm water runoff from agricultural and urban areas can transport contaminants (e.g., dormant spray pesticides, metals) into the Delta. Early life stages are generally far more sensitive to contaminants than adults, and the toxic effects of these contaminants may be far more serious seasonally for that reason (Werner et al. 2010b; Weston et al. 2014). Bottom-feeding fish or sediment-dwelling invertebrates may also be more likely to be exposed to sediment-associated contaminants (via diet and interstitial water), while pelagic (open water) organisms are mostly exposed to dissolved and suspended particle-associated contaminants in the water column.

The Bay-Delta Plan operates in conjunction with the *Water Quality Control Plan for the Sacramento River and San Joaquin River Basins* adopted and implemented by the Central Valley Regional Water Quality Control Board (Central Valley Water Board) and the San Francisco Bay Regional Water Quality Control Board (San Francisco Bay Water Board), addressing point source and nonpoint source discharges and other controllable water quality factors. (See also Water Boards' 2008 Strategic Workplan for Activities in the Bay-Delta [and 2014 update by the Central Valley Water Board].) The Water Boards have regulatory programs that control discharges of wastes from wastewater treatment facilities, industrial facilities, urban areas, irrigated agricultural lands, dredging operations, and other sources of wastewater to the Bay-Delta and tributaries. Water Code section 13260, subdivision (a) requires that any person discharging waste or proposing to discharge waste that could affect the quality of the waters of the state, other than into a community sewer system, shall file with the appropriate regional water board a report of waste discharge, containing such information and data as may be required by the regional water board, unless the regional water board waives such requirement. Waste discharge requirements (WDRs) prescribe requirements, such as limitations on temperature, toxicity, or pollutant levels, as to the nature of any discharge. (Wat. Code § 13260, subd. (a).) WDRs may also include monitoring and reporting requirements. (See *id.* § 13267; Cal. Code Regs., tit. 23, § 2230.)

The Water Boards address water quality impairments that are caused by multiple dischargers by developing TMDLs that set water quality objectives or targets and allocate allowable loads to sources of contaminants. TMDLs have been adopted and are in the process of being implemented for various constituents in the Delta and the Bay as discussed below. Over the years, the contaminants and discharge sources have changed, and there have been significant improvements in controlling most types of contaminants. Nevertheless, additional efforts are still needed. Some contaminants pose a concern for some Delta beneficial uses and there is also concern for an emerging list of new contaminant categories (pharmaceuticals and endocrine disruptors), discussed in more detail in Section 4.3.1.3, *Endocrine Disruptors*, and the need for comprehensive monitoring and assessment activities to ensure that the occurrence and effects of contaminants are understood and addressed.

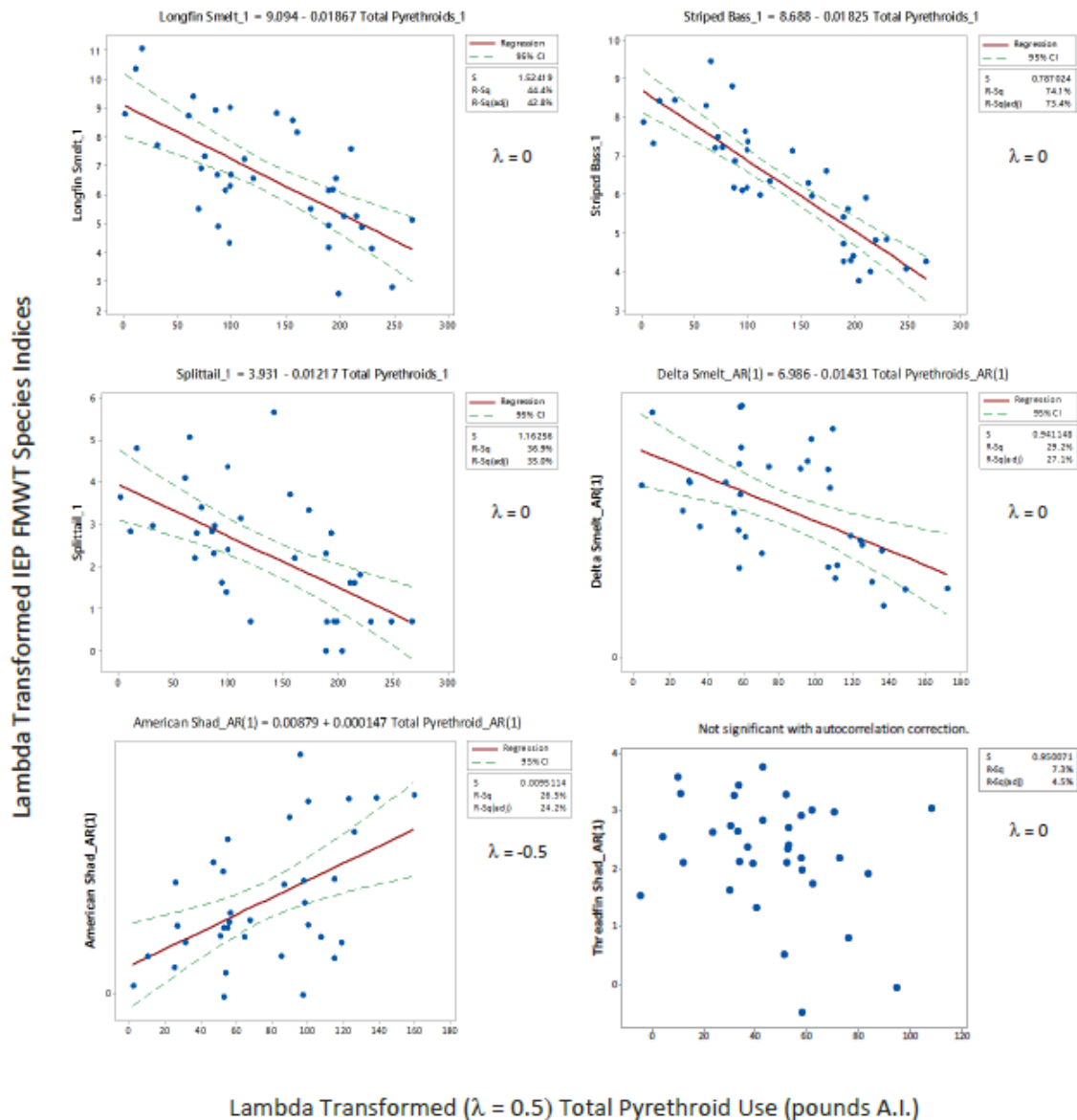
4.3.1.1 Pesticides and Other Pollutants

Water samples have detected the widespread occurrence of pesticides currently used throughout the Central Valley and Bay-Delta estuary (Orlando et al. 2013). The U.S. Geological Survey measured 26 to 27 pesticides or their primary degradation products in samples collected from the Sacramento and San Joaquin Rivers in 2011 and 2012 (Orlando et al. 2013). The average number of detections was six and nine pesticides per sample, respectively. The toxicity of most of these pesticides to

aquatic life, singly or in combination, is largely unknown (Orlando et al. 2013; ^Fong et al. 2016). However, pyrethroid insecticides have been detected in the Delta at toxic concentrations (Holmes et al. 2008; Weston et al. 2008), and pyrethroids and other insecticides have been implicated as one of the factors in the decline in the population of Delta smelt and other pelagic fishes (^Sommer et al. 2007; Orlando et al. 2013; ^Fong et al. 2016).

Negative relationships were found between total pyrethroid insecticide use in the six Delta counties and annual fall midwater trawl indices (1978–2014) of longfin smelt, Delta smelt, Sacramento splittail, American shad, threadfin shad, and striped bass (Figure 4.3-1) (^Fong et al. 2016). Associations between fish abundance and pyrethroid use suggest that pyrethroids may be a contributor to fish population declines in the Delta (^Fong et al. 2016), though there is a strong relationship between pesticide concentrations and flow. The toxicological mechanisms responsible for reduced fish recruitment are not known, although pyrethroid insecticides have been documented to induce nervous, immune, muscular, and osmoregulatory impacts at the genetic level in Delta smelt (Jeffries et al. 2015). Pyrethroid insecticides have also elicited histopathological lesions, stress responses, and abnormalities in splittail larvae (Teh et al. 2005). Salmonids may also be negatively affected by insecticides at the neurophysiological level as suggested by a recent study that showed that the effects of pyrethroids led to decreased feeding behavior in juveniles (Baldwin et al. 2009). Pyrethroid insecticides also may negatively affect food resources for native fishes. Weston and Lydy measured toxic effects leading to death or reduced swimming ability in the amphipod *Hyalella azteca* in samples containing urban runoff collected from the cities of Sacramento and Vacaville (^Weston and Lydy 2010). Toxic concentrations of pyrethroid insecticides have also been detected in sediment samples collected from waterbodies draining agricultural and urban areas in the Central Valley (Weston et al. 2014), including those with wastewater effluent (^Weston and Lydy 2010). At some locations, peak pesticide concentrations during runoff events coincided with high population densities of Delta smelt (^Bennett 2005; Kuivila and Moon 2004).

In 2017, the Central Valley Water Board adopted a Basin Plan Amendment for the Control of Pyrethroid Pesticide Discharges that established measurable pyrethroid concentration goals and a program of implementation for the control of pyrethroid pesticides that are affecting or could affect aquatic life uses in surface waters in the Sacramento and San Joaquin River watersheds. It also established TMDLs for waterbodies that are listed as impaired by pyrethroids on the Clean Water Act Section 303(d) list, and established provisions to address or prevent future pyrethroid listings.



Source: ^Fong et al. 2016.

FMWT = fall midwater trawl

IEP = Interagency Ecological Program

Figure 4.3-1. Least Squares Regressions with 95 Percent Confidence Intervals for Fall Midwater Trawl Species Abundances as a Function of Annual Pyrethroid Pesticide Use in Six Delta Counties (1978–2014)

In 2023, NMFS determined that the continued use of two insecticides, carbaryl and methomyl, would likely jeopardize the continued existence of 37 and 30 aquatic species, respectively, including Central Valley spring-run Chinook salmon, Sacramento River winter-run Chinook salmon, California Central Valley steelhead, and the Southern Resident distinct population segment (DPS) of killer whales (NMFS 2023). Juvenile salmonid growth rates are negatively affected by these insecticides through two pathways. The first path is the reduction of feeding success and subsequent reduced

growth rates. The second path is the reduction in densities of sensitive aquatic invertebrates and other prey species for salmonids. Salmon are often food limited in freshwater habitats, and results showed that all Central Valley salmonids and steelhead can be severely affected by changes in juvenile growth driven by reduced prey availability and feeding success. Central Valley salmonids are the primary prey for the Southern Resident DPS of killer whales, and negative impacts on the salmon populations would cascade to the population of the Southern Resident DPS of killer whale.

Herbicide applications for control of invasive aquatic plants may also have negative effects on native fish and invertebrates. The California Department of Parks and Recreation's Division of Boating and Waterways (CDBW) applies glyphosate, 2,4-D, and Imazamox herbicides directly to waterbodies to control invasive aquatic weeds (CDBW 2017). Close to 4,300 acres of waterways were treated in 2016 for control of water hyacinth, Brazilian waterweed, and curly leaf pondweed (CDBW 2017). Like insecticides, little is known about the toxic effect of these herbicides singly and in combination on aquatic life. The herbicides may decrease the health of Delta fish species and their prey (Fong et al. 2016; Hasenbein et al. 2017). Sub-lethal effects, such as decreased condition factors and energy reserves, were measured in Delta smelt in response to mixtures containing Imazamox (Hoffman et al. 2017). Similarly, Imazamox, glyphosate, 2,4-D, and fluridone herbicides were found to induce sub-lethal effects in Delta smelt embryos and larvae and cause mortality to *E. affinis* at concentrations measured in the estuary (Stillway et al. 2016).

Mosquito and Vector Control Districts use Integrated Pest Management (IPM) to control mosquito populations in counties surrounding the Delta (Sacramento-Yolo Mosquito and Vector Control District 2014). IPM includes biological, physical, and, as a last resort, chemical/microbial control. The chemical and microbial agents used are organophosphate and pyrethroid insecticides, *Bacillus thuringiensis* and *B. sphaericus* (two bacterial extracts), and the insect growth regulator methoprene. Chemical applications include direct applications on stagnant surface water, including seasonally flooded wetlands. These chemicals are applied at toxic concentrations to kill mosquito larvae and likely also injure other small invertebrates.

The State Water Board administers statewide general National Pollutant Discharge Elimination System permits for pesticides, including aquatic animal invasive species control, spray applications, vector control, and weed control. These permits require compliance with applicable water quality standards, application of best management practices, and compliance with relevant federal and state law (including California Department of Pesticide Regulation). The permits do not authorize discharges of chemicals in waterbodies listed as impaired for that specific chemical. The permits include monitoring and reporting provisions and contain requirements for corrective action in the event of any adverse effect on a federally listed threatened or endangered species or its federally designated critical habitat that may have resulted from the chemical application.

Fong et al. (2016) and Healey et al. (2016) recommended that a dedicated contaminant monitoring and assessment program be established in the Delta to better understand the biological effects of pesticide applications on native fish and wildlife.

4.3.1.2 Legacy Contaminants

Several legacy contaminants that are no longer in use are still present in the Bay-Delta watershed. Organochlorine (OC) pesticides like dichlorodiphenyltrichloroethane (DDT), chlordane, and dieldrin are now banned but were used extensively in agriculture in the Central Valley half a century ago (Lee and Jones-Lee 2002). Like OCs, polychlorinated biphenyls (PCBs), and polycyclic aromatic

hydrocarbons (PAHs) are legacy contaminants that were used for industrial purposes and were banned in the late 1970s. OCs and PCBs are linked to thyroid and endocrine disorders, genital malformities, and cancer in humans; they also have led to reproductive declines in birds and wildlife (Bergman et al. 2012). Fish and aquatic organisms can absorb these chemicals through sediment, resulting in fish kills and harm to lower food chain aquatic invertebrates (USGS 2012; Vivekanandhan and Duraisamy 2012).

Presence of legacy pesticides in fish tissue collected from Central Valley rivers and the Delta has resulted in the issuance of advisories recommending limited human consumption of some fish species (^De Vlaming 2008). OC and PCB pesticide concentrations have declined and were significantly lower in fish caught in 2005 than during the 1970s; however, some individual fish still had concentrations above levels of concern for human health (^De Vlaming 2008). PCB concentrations in San Francisco Bay sport fish have also declined but are still more than 10 times higher than the threshold of concern for human health and may adversely affect wildlife (Lee and Jones-Lee 2002; Davis et al. 2007).

There are no control programs for reducing OC, PCB, or PAH concentrations in the Central Valley or Delta. The San Francisco Bay Water Board, however, adopted a PCB TMDL in 2007 (San Francisco Bay Water Board 2007). The TMDL for PCBs became effective in 2010, and key implementation actions are carried out through permits issued to dischargers.

4.3.1.3 Endocrine Disruptors

Endocrine-disrupting chemicals (EDCs) are substances found in pesticides, personal care products and pharmaceuticals (PCPP), household cleaning products, and industrial chemicals that disrupt the endocrine (hormone) system of fish and wildlife (Brander et al. 2016; ^Fong et al. 2016). At the organismal level, EDCs impair reproductive health and development and can cause tumors and malformities. At the population level, EDCs can lead to skewed sex ratios (^Fong et al. 2016; Bergman et al. 2012), resulting in declines in population abundance of aquatic organisms (Bergman et al. 2012).

Special studies in the Bay-Delta estuary have shown that EDC substances are present and may be causing organismal and population-level effects (Brander et al. 2013; Tadesse 2016; Riar et al. 2013). Skewed sex ratios were documented in Mississippi silverside (*Menidia audens*) at sites with high urban runoff in Suisun Marsh (Brander et al. 2013). Sacramento splittail and other fish have shown evidence of feminization through high levels of female egg yolk protein expression in males. Water samples with EDC mixtures were collected in the same areas that feminization occurred (Tadesse 2016). Impacts of EDCs were also observed in invertebrate salmon prey in the American River. However, the chemicals did not appear to be at concentrations that affected the reproductive health of local salmonids (Weston et al. 2014; Riar et al. 2013; De Vlaming et al. 2006).

Common EDC substances in the Bay-Delta estuary include pesticides such as pyrethroids and fipronil, and PCPPs such as latent birth control hormones and microplastics. Urban and agricultural runoff are sources of EDC substances, as are discharges from POTWs (^Weston and Lydy 2010; ^Fong et al. 2016). PCPPs may be hard to detect (^Fong et al. 2016). Because of detection difficulties, EDCs are also defined as a subset of a group of chemicals called *contaminants of emerging concern* (CECs) (^Anderson et al. 2010). Generally, CECs are not commonly monitored in the environment but have the potential to cause adverse ecological or human health impacts (Klosterhaus et al.

2013). The Water Boards have various monitoring programs and special studies for drinking water and recycled water for CECs, including endocrine disruptors.

The State Water Board convened the Science Advisory Panel in 2010 to identify strategies and methods for regulating CECs, including EDC substances, in recycled water. The panel's primary recommendations were to develop analytical methods to measure chemical concentrations and to identify trigger levels for biological assessment (Anderson et al. 2010).

4.3.1.4 Ammonia/Ammonium

Ammonia is a toxic chemical with the potential at elevated concentrations to reduce growth, reproduction, and survival of aquatic organisms (USEPA 2013). Ammonia exists in two forms in water: un-ionized ammonia (NH_3) and ammonium (NH_4^+). The equilibrium between NH_3 and NH_4^+ depends primarily on pH and to a lesser extent on temperature and salinity (USEPA 2013). NH_3 is the more toxic of the two forms. Both NH_3 and NH_4^+ are present in effluent from POTWs and confined animal facilities. Additional sources of NH_4^+ to the Delta include agricultural and urban runoff, atmospheric deposition, and internal nutrient cycling (Novick and Senn 2013).

Toxicity has been observed in bioassays at ammonia concentrations comparable to those measured in the Sacramento River and Delta. The USEPA criteria summary of ammonia toxicity found that unionid mussels were the most sensitive warm freshwater aquatic organisms evaluated, while juvenile salmonids were the most sensitive cold water fish species tested (USEPA 2013). Surface water monitoring in the Delta determined that ammonia concentrations were lower than values reported to be toxic to freshwater unionid mussels and juvenile salmonids (Foe et al. 2010). Acute 7-day larval Delta smelt bioassay testing was conducted with ambient surface water from the Delta amended with ammonia, though no toxicity was detected (Werner et al. 2010b). However, Delta smelt exposed to ammonia at concentrations measured in the Delta exhibited immune and muscular system, developmental, and behavioral abnormalities (Connon et al. 2011; Hasenbein et al. 2014). Ammonia concentrations comparable to values measured in the Sacramento River were toxic to *Pseudodiaptomus forbesi* and *Hyallela azteca*, important food resources for native larval fishes, including Delta smelt, but additional analyses are needed to fully understand the effects of ammonia on Delta invertebrates (Teh et al. 2011; Werner et al. 2010a, 2010b).

Ammonia concentrations may also negatively affect algal primary production, standing biomass, and species composition in the Delta. The effect of ammonia concentrations on algal primary production and species composition in the Delta is controversial (Dahm et al. 2016; Cloern et al. 2014a). Some studies show that elevated NH_4^+ levels reduce algal primary production rates in water samples collected from Suisun Bay and the Delta by suppressing nitrate uptake (Wilkerson et al. 2006; Dugdale et al. 2007; Parker et al. 2012). However, more recent experimental research suggests that phytoplankton growth in the Sacramento River and Delta is unlikely to be impaired by ammonia concentrations (Strong et al. 2021; Esparza et al. 2014; Kraus et al. 2017). High filtration rates by the invasive overbite clam, *Potamocorbula*, and high turbidity levels are additional factors responsible for reducing primary production and standing algal biomass in Suisun Bay. Elevated NH_4^+ levels have also been hypothesized to contribute to the observed shift in algal species composition from diatoms to blue-greens and greens (Brown 2010) by selecting for species less sensitive to NH_4^+ (Glibert 2010; Glibert et al. 2011). However, investigations using IEP Environmental Monitoring Program data (1975–2009) suggest that diatom decreases were more closely aligned with the establishment of the invasive clam *P. amurensis* than the gradual increase in ammonium concentrations, while cyanobacteria and green algae abundances have not changed significantly

(Cloern et al. 2014b). The shift in phytoplankton community composition reported in Glibert (2010) and Glibert et al. (2011) has also been questioned because of data quality issues with the initial algal cell count data on which they were based (Senn et al. 2016). A non-peer-reviewed reanalysis of the cell count data does not support the observation that the shift in algal species composition reported by those papers has occurred (Senn et al. 2016).

The Sacramento Regional Wastewater Treatment Plant (SRWTP; renamed to EchoWater Resource Recovery Facility in 2023), located at Freeport on the Sacramento River, is the largest POTW discharging into the Delta and historically contributed about 90 percent of the Delta's annual ammonia load (Jassby 2008). In 2010, the Central Valley Water Board issued the SRWTP an updated discharge permit (National Pollutant Discharge Elimination System Permit No. CA0077682) that required SRWTP to upgrade to a tertiary treatment system to eliminate up to 95 percent of the ammonia load to the Sacramento River and approximately 65 percent of the total nitrogen. The required construction and upgrades to facilities were completed in 2023, substantially reducing nutrient loads to the Sacramento River. The new treatment processes remove 99 percent of ammonia and 89 percent of nitrogen from SRWTP effluent, resulting in cleaner wastewater discharge (SWRCB 2023). Healey et al. (2016) and Brown et al. (2016) observed that the upgrade to the SRWTP provides a unique opportunity to evaluate the effect of nutrient reductions, including ammonia, on algal primary production rates and community composition and the overall health of the Delta ecosystem. Low flows in the estuary and Delta accentuate the effects of degraded water quality, such as high NH_3 and NH_4^+ levels. Thus, increased Sacramento River flows would dilute any remaining nutrients and enhance water quality by flushing the estuary more often. Similarly, enhanced flows in winter and spring may decrease indirect effects of excess nutrients, such as summer and fall blue green algal blooms (Preece et al. 2025).

The primary control and monitoring programs for ammonia are through the Central Valley Water Board and San Francisco Bay Water Board. The regional boards regulate ammonia in discharge permits through application of effluent limits that implement narrative and numeric water quality objectives. In addition, the Irrigated Lands Regulatory Program regulates waste discharge, including nitrogen-based fertilizers, from irrigated lands to prevent discharges from causing or contributing to exceedances of water quality objectives. Monitoring of ammonia is conducted by the IEP, National Pollution Discharge Elimination System permit holders, and the U.S. Geological Survey. The Central Valley Water Board is also evaluating the need to add or revise water quality objectives for ammonia to the *Water Quality Control Plan for the Sacramento River and San Joaquin River Basins* and the *Water Quality Control Plan for the Tulare Lake Basin*.

4.3.1.5 Selenium and Mercury

Selenium is an essential micronutrient at low levels but toxic at higher concentrations (Chapman et al. 2009). The most lethal forms of selenium are selenomethionine and selenocysteine (Chapman et al. 2009). Both organic forms of selenium are produced by microorganisms and biomagnify in aquatic food chains, with diet being the primary route of exposure (Lemly 1985; Chapman et al. 2009). At high concentrations, selenium is a reproductive toxicant (Chapman et al. 2009). It has been shown to biomagnify in the invasive clam, *Potamocorbula*, which is a food source for bottom-feeding fish such as sturgeon (Linville et al. 2002). High selenium concentrations were shown to cause reproductive harm to sturgeon (Linares-Casenave et al. 2015; Stewart et al. 2004). Historically, the primary controllable sources of selenium to the San Francisco estuary were subsurface agricultural drainage from the west side of the San Joaquin Valley and discharge of oil processing waste from refineries in the North Bay (81 FR 46030). TMDLs were adopted to control

loads from both sources. Over the last decade, the loads from agricultural and refinery sources have been significantly reduced. In recent years, the average selenium water concentrations in the Bay have been ~0.1 part per billion in 2011, much lower than the existing water quality objective of 5 parts per billion. Ambient water column concentrations and selenium levels in fish are generally below the targets established by the North San Francisco Bay TMDL adopted in 2015. Only bottom-feeding species with a high proportion of *Potamocorbula* in their diet, such as white sturgeon, show selenium concentrations that are occasionally higher than the TMDL target of 11.3 micrograms per gram (Baginska 2015). Selenium concentrations in all other sport fish are well below levels of concern for human health.

Mercury was mined in the California Coast Ranges and used in gold mining in the Sierra Nevada (Churchill 2000). The mining resulted in widespread inorganic mercury contamination in water courses in the Coast Ranges, valley floor, and Sierra Nevada. Methylmercury is the most toxic form of the element and is produced by sulfate reducing bacteria in anaerobic sediment (Compeau and Bartha 1985; Gilmour et al. 1992). As described in Section 4.2, *Physical Habitat Loss or Alteration*, restoration and reconnection of floodplains benefit ecosystems and native species in a variety of ways; however, elevated flows increase environmental methylmercury by flooding riparian habitat and seasonal wetlands, which are the primary sources of methylmercury production in northern California (Wood et al. 2010). Control measures exist for sources of inorganic mercury. For example, improving the sediment-trapping efficiency of the Cache Creek Settling Basin would reduce the loads of mercury that enter the Yolo Bypass from the Cache Creek watershed.

Like selenium, methylmercury bioaccumulates in the aquatic food chain with the primary route of exposure being through consumption of mercury-contaminated fish (USEPA 1997). At greatest risk are human and wildlife fetuses and young (NRC 2000). Mercury has also been implicated in tissue accumulation causing gill, liver, kidney, and gastrointestinal tract damage to higher trophic-level species like sturgeon and splittail (Huang et al. 2012; Deng et al. 2008). Fish advisories were issued recommending limited human consumption of several fish species caught in the Central Valley and Bay-Delta estuary (OEHHA 2009). The San Francisco Bay and Central Valley Water Boards adopted mercury TMDL control programs for San Francisco Bay and the Delta. ^Fong et al. (2016) recommended that monitoring be conducted to characterize long-term trends in bioaccumulative substances in fish. The trend analysis would serve as a performance measure to evaluate the effectiveness of ongoing mercury and selenium control programs.

4.3.2 Harmful Algal Blooms

Harmful algal blooms (HABs) have become a regular occurrence in the Delta since 1999 (Lehman et al. 2005, ^2013; Kurobe et al. 2013). In freshwater systems like the Delta, HABs are mostly attributable to cyanobacteria (^Kudela et al. 2023). In the Delta, *Microcystis aeruginosa* is the most common cyanobacteria species although the invasive toxin-producer *Cylindrospermopsis raciborskii* also has been detected, as well as other genera such as *Anabaenopsis*, *Aphanizomenon*, *Dolichospermum*, *Lyngbya*, *Phormidium*, *Planktolynghya*, *Planktothrix*, and *Oscillatoria* (^Kudela et al. 2023). Cyanobacterial species secrete hepato and central nervous system toxins, which can be toxic to humans and aquatic wildlife (Lehman et al. 2008; ^Berg and Sutula 2015).

The full toxicological effect of HAB species on aquatic life in the Delta is not known. Recent research has measured microcystin in zooplankton, amphipods, and fish in the Delta (^Lehman et al. 2010, ^2017; UC Santa Cruz 2015). Striped bass and Mississippi silversides collected from the Delta had liver lesions consistent with sub-lethal exposure to microcystin (^Lehman et al. 2010). Laboratory

studies with threadfin shad and Sacramento splittail fed *Microcystis*-contaminated food developed similar liver and gonadal lesions (Acuña et al. 2012a, 2012b). The survival of *E. affinis* and *P. forbesi* was reduced in laboratory bioassays with increasing concentrations of dissolved microcystin, although the levels inducing toxicity were higher than commonly measured in the Delta (Ger et al. 2009). Survival of both copepod species was reduced when *Microcystis* exceeded 10 percent of their diet (Ger et al. 2010). Dissolved microcystin concentrations in the Delta occasionally have exceeded both the Office of Environmental Health and Hazard Assessment's action level for human health and the World Health Organization's recreational use guideline (^Berg and Sutula 2015).

The magnitude and frequency of HABs are influenced by several environmental factors that are becoming more common in the Delta. These include higher water temperature, longer water residence time, increased water clarity, salinity, and high nutrient concentrations. *Microcystis* blooms occur now during summer and fall in the south and central Delta and are associated with water temperature above 19°C, long water residence time, intensification of water column stratification, high irradiance, and elevated nutrient (nitrogen and phosphorous) concentrations (Jacoby et al. 2000; ^Berg and Sutula 2015; ^Kudela et al. 2023; ^Lehman et al. 2013). Although a temperature threshold of 19°C has been documented for initiating *Microcystis* blooms in the Delta, optimal growth often occurs above 25°C when cyanobacteria begin to outcompete other phytoplankton (^Lehman et al. 2013; ^Kudela et al. 2023). Site-specific factors such as tidal and net flows, which influence water residence time and disperse phytoplankton, can also affect the occurrence of HABs in the Delta depending on the local physical environment. For example, dead-end channels and marinas, characterized by weaker stream flow and mixing, may experience higher primary productivity and less dilution of HAB species whereas main channels, characterized by stronger streamflow and tidal forcing, may experience lower growth rates and biomass accumulation (Preece et al. 2024b).

While ammonium has been identified as a preferred nitrogen source for *Microcystis*, it also can utilize all forms of nitrogen, and elevated nitrogen of any form has been linked to increased toxicity (^Kudela et al. 2023). However, nutrients are generally high in the Delta, and other factors such as low flows (in part by increasing residence time) and high temperatures are thought to be more important in driving HABs (^Kudela et al. 2023). Many of these environmental factors become increasingly common and more important during drought years which may, at least partially, explain some of the increase in HAB reports throughout the Delta given that 15 of the last 20 years have been classified as below normal, dry, or critical water years. Climate change is associated with these factors and may result in increasing the frequency and magnitude of HABs in the future (^Lehman et al. 2017). However, climate change also is associated with sea level rise and increasing salinities in the Bay-Delta. Salinities greater than 10 parts per thousand (ppt) suppress *Microcystis* growth (^Berg and Sutula 2015), which could occur in Suisun and inhibit *Microcystis* blooms in that region.

Cyanobacterial HABs benefit from slow-moving water, where mixing is weak and the potential for water column stratification is high. *Microcystis*, a slow-growing genus of cyanobacteria, is well suited to these conditions as stagnant water allows for the accumulation of *Microcystis* colonies. However, when mixing is strong, other faster-growing phytoplankton can outcompete *Microcystis* and *Microcystis* blooms are less likely to establish (^Kudela et al. 2023). *Microcystis* abundance in the Delta is correlated with low flow in the San Joaquin River, Sacramento River, and central Delta (^Lehman et al. 2013). Although research has shown that the position of X2 is correlated with HABs in the Delta (Lehman et al. 2022), more recent research demonstrates that X2 is not a strong predictor of HABs in the south-central Delta where HABs are most abundant. In those regions, water

residence time is more influenced by lower San Joaquin River inflow and exports (Preece and Hartman 2024). Summer-fall flow thresholds limiting *Microcystis* blooms were identified for the upper San Joaquin River (approximately 2,825 cubic feet per second [cfs]) and lower Sacramento River near Rio Vista (approximately 10,594 cfs) (^Lehman et al. 2013), but recent research suggests that flows above these levels limit bloom severity but do not prevent bloom formation when temperature and other conditions are right for *Microcystis* growth (Lehman et al. 2022).

Flow is one of many drivers that may influence *Microcystis* bloom formation and severity in addition to other factors, including annual hydrologic context, nutrient concentrations, light availability, and temperature (Preece and Hartman 2024; Preece et al. 2024a). These individual factors may interact to drive or inhibit blooms. For example, research investigating drought impacts on HABs found that SWP and CVP exports, temperature, and Secchi depth (a measure of water clarity) together best explained the probability of *Microcystis* observations in the South Delta, Franks Tract, Lower San Joaquin River, and Old River regions, demonstrating that several environmental factors affect HAB formation (Bouma-Gregson et al. 2024). Additional research demonstrates that although higher San Joaquin River inflow and higher Sacramento Valley index values for water year type are correlated with decreased bloom magnitude, increasing summertime flows may be less effective at controlling HABs when temperatures are high (Preece and Hartman 2024). Accordingly, climate change is expected to increase the duration of the bloom season as temperatures increase (^Lehman et al. 2013), and climate change is a primary factor contributing to increasing frequency and severity of HABs in the Delta and globally (^Kudela et al. 2023). Although the specific manners in which drivers interact remain to be quantified in scientific literature, the consideration of interrelated drivers can provide a better understanding of the environmental conditions that may enable or promote bloom formation.

Cyanobacteria and their toxin levels are not routinely measured in the Delta despite their regular occurrence at potentially toxic concentrations. Brown et al. (2016) recommend that “quantitative monitoring should be developed and implemented so blooms and their effect on food webs can be better understood.” Kudela et al. (^2023) had a similar recommendation for HABs monitoring that is coordinated across the whole estuary; uses multiple approaches such as in situ sampling and remote sensing targeted toward multiple beneficial uses, including recreational contact and fishery harvesting; and measures all relevant and potential toxins. The Central Valley Water Board commissioned a white paper to review the biological and ecological factors that influence the prevalence of cyanobacteria and cyanotoxin production; summarize observations of cyanobacterial blooms and associated toxin levels in the Delta; and synthesize the literature to provide an understanding of the factors, including nutrients, promoting cyanobacterial blooms in the Delta (^Berg and Sutula 2015). This report, along with several other white paper reports describing the state of the science and current information needs, formed the foundation of the Central Valley Water Board’s *Delta Nutrient Research Plan*. The *Delta Nutrient Research Plan* established a framework and actions to generate information to determine whether numeric nutrient objectives are needed and whether nutrient reductions will decrease existing water quality concerns in the Delta (^Central Valley Water Board 2018a). In addition, to improve understanding of cyanobacteria, the Surface Water Ambient Monitoring Program (SWAMP) has developed a framework and a strategy to develop and implement a Freshwater and Estuarine Harmful Algal Bloom (FHAB) Monitoring Program for California (^Smith et al. 2021.). The responsibilities of the FHAB Monitoring Program include event response, statewide assessment and monitoring, risk assessment, research, outreach and education, and reporting. Lastly, the Delta Science Program led an effort to develop a Delta HABs

Monitoring Strategy.¹ Released in 2024, the Delta Cyanobacterial Harmful Algal Blooms(CHAB) Monitoring Strategy identifies additional monitoring, data, and knowledge gaps related to HABs including a lack of coordinated monitoring in areas of the Delta known for experiencing low flows and exhibiting the most severe HABs such as dead-end sloughs and backwater areas. The Delta CHAB Monitoring Strategy also suggests additional special studies to fill key knowledge gaps, further inform monitoring needs, and identify practicable Delta HAB mitigation options (Preece et al. 2024b). The USGS has prepared a Delta CHAB Monitoring Designs Report, recommending possible monitoring designs that could be implemented as part of a coordinated Delta-wide CHAB monitoring program, consistent with recommendations of the Delta CHAB Monitoring Strategy (Bouma-Gregson et al. 2025).

4.3.3 Dissolved Oxygen

Dissolved oxygen is critical to the health and survival of aquatic organisms. Low dissolved oxygen concentrations or hypoxia reduces the growth, swimming ability, and survival of aquatic organisms (USEPA 1986). Dissolved oxygen concentrations in waterways are affected by many environmental factors, including flow, temperature, salinity, and discharge of oxygen-requiring substances. Dissolved oxygen levels fluctuate diurnally, with oxygen levels typically being highest during daylight hours when photosynthesis produces oxygen as a by-product. Dissolved oxygen levels also fluctuate seasonally, with oxygen concentrations typically being lowest in summer during nighttime when freshwater flows are low and water temperature is high (Spence et al. 1996; Newcomb et al. 2010). Warm water holds less dissolved oxygen than cold water and higher water temperatures also increase the metabolic and associated oxygen consumption rates of aquatic organisms, making warm water conditions potentially stressful for aquatic life (Myrick and Cech 2000). Cold water species, such as developing salmonid embryos and larvae, are among the most sensitive organisms to low dissolved oxygen concentrations (USEPA 1986). Temperature and oxygen requirements of salmonids are discussed in Chapter 3, *Scientific Knowledge to Inform Fish and Wildlife Flow Recommendations*.

Several locations in the Bay-Delta periodically experience low dissolved oxygen concentrations, which may have negative impacts on native fish. Seven creeks and sloughs in the southern and eastern Delta and the lower Calaveras, Middle, Mokelumne, and Old Rivers in the central Delta are listed as impaired because of low dissolved oxygen concentrations. Low dissolved oxygen also occurs in low-flow channels and dead-end sloughs in Suisun Marsh (^O'Rear and Moyle 2009). Fish mortality has been observed when managed wetlands in Suisun Marsh are flooded and subsequently drained, releasing large loads of organic-rich matter and water with low dissolved oxygen concentrations into adjacent channels (^O'Rear and Moyle 2009; Tetra Tech and WWR 2013). In 2018, the San Francisco Bay Water Board amended the *Water Quality Control Plan for the San Francisco Bay Basin* to establish site-specific water quality objectives and a TMDL for dissolved oxygen in Suisun Marsh.

Since the 1930s, near the city of Stockton, the San Joaquin River and the Stockton Deep Water Ship Channel (DWSC) have experienced regular periods of low dissolved oxygen. These low dissolved oxygen conditions occurred year-round and have resulted in fish kills and delayed the upstream

¹ <https://deltacouncil.ca.gov/pdf/science-program/information-sheets/2022-10-21-draft-delta-harmful-algal-bloom-monitoring-strategy.pdf>.

migration of fall-run adult Chinook salmon (^McConnell et al. 2015). In 2005, the State Water Board approved a dissolved oxygen TMDL that included, as part of its implementation requirements, reductions in point and nonpoint sources of oxygen-demanding substances and a requirement to assess the feasibility of operating an experimental aeration facility in the Stockton DWSC. In 2011, the assessment of the experimental aeration demonstration project was successfully completed and showed that aeration improved water quality with no redirected detrimental effects. A 5-year voluntary agreement was finalized in 2012 that provided funding for operation and maintenance and amended aeration agreements provided extensions after 2016. An upgrade of the City of Stockton's Regional Wastewater Control Facility and operation of the aeration facility have contributed to significant improvements in dissolved oxygen conditions in the DWSC. The dissolved oxygen water quality objective has been violated less than 1 percent of the time since 2013, when both the upgrade to the City of Stockton's Regional Wastewater Control Facility and the aeration facility were operational (^McConnell et al. 2015).

4.3.4 Sediment and Turbidity

Turbidity is a measure of water clarity related to suspended sediment that is important for estuarine species in the Bay-Delta estuary (^Bennett 2005; ^USFWS 2001). The Sacramento River is the largest source of suspended sediment to the Delta and is estimated to have provided about 85 percent of sediment between 1999 and 2005 (^Wright and Schoellhamer 2004). Most of the sediment enters the Delta between December and April and is carried in first-flush events and in high winter storm flows. Sediment from the Sacramento basin has declined by about 50 percent since stream gaging began in 1957 (^Wright and Schoellhamer 2004). Construction of dams is thought to be the primary reason for the decrease (^Schoellhamer et al. 2016). Dams reduce sediment supply because large reservoirs trap the incoming sediment behind the dam and discharge clear water downstream below the dam. Other factors affecting the sediment supply and turbidity in the Sacramento River include hydraulic mining, levee construction and isolation of floodplains, land use change, logging, and invasive aquatic submerged vegetation (^Wright and Schoellhamer 2004; Hestir et al. 2016a). The primary source of suspended sediment in the Sacramento basin is now from unregulated tributaries that discharge below rim reservoirs on the valley floor (^Schoellhamer et al. 2016).

Turbidity in the estuary has declined by about 40 percent over the last half century (^Cloern et al. 2011). The decline is attributed to reduced sediment input from reservoirs and from the spread of submerged aquatic vegetation (SAV) in the Delta (^Schoellhamer et al. 2016). Areas in the Delta with the largest expanse of SAV have the greatest decrease in suspended sediment (Hester et al. 2016a). SAV slows water movement, promoting increased sedimentation and reductions in turbidity. Between 20 and 70 percent of the increase in clarity in the Delta may have resulted from the expansion in SAV coverage (Hester et al. 2016a).

Turbidity affects multiple important biological processes in the Bay-Delta estuary. For example, turbidity influences the amount of food available for the entire food web. Phytoplankton production in the estuary is light limited (Cloern 1999). Decreasing turbidity levels increase algal production and phytoplankton biomass, assuming that primary consumers are unable to keep up with the increasing algal supply (^Dahm et al. 2016). Several native fish species and their invertebrate prey are food limited (see Chapter 3, *Scientific Knowledge to Inform Fish and Wildlife Flow Recommendations*; Brown et al. 2016; ^Moyle et al. 2016). Phytoplankton are an important food resource for these organisms, and increasing food levels are likely to increase population

abundance. However, higher water clarity may lead to phytoplankton blooms, eutrophication, and harmful cyanobacteria blooms (^Dahm et al. 2016). Reductions in turbidity are also associated with declines in estuarine habitat for Delta smelt, striped bass, and threadfin shad. These fish are found in high abundance near X2, an area of high turbidity (^Hasenbein et al. 2013).

The reasons for the fish distributions are not entirely clear, but laboratory studies have shown that Delta smelt require turbidity for successful feeding (Baskerville-Bridges et al. 2004) and for refuge from predators (^Nobriga et al. 2008). The Delta Smelt Resiliency Strategy is assessing the feasibility of adding suspended sediment to the low-salinity zone for the benefit of Delta smelt (CNRA 2016). Another example of the importance of turbidity is the positive feedback loop between reductions in turbidity and expansion of SAV coverage. Nonnative SAV, like *Egeria densa*, are light limited. An expansion in their range promotes additional sedimentation, further reductions in turbidity, and further range expansion (Hester et al. 2016b). Increasing sediment loads with sea level rise could help maintain tidal wetlands at an optimal elevation for plant establishment and growth (^Schoellhamer et al. 2016).

Improved reservoir management and SAV control may increase sediment loading and turbidity in the Delta. Currently, reservoirs capture peak flood flows and their associated suspended sediment loads for flood control, irrigation, and water supply.

4.3.5 Temperature

Water temperature is a key factor in defining habitat suitability for aquatic organisms. High water temperature can be stressful for many aquatic organisms (^Kammerer and Heppell 2012), particularly fish that are near the southern edge of their distribution (^Matthews and Berg 1997). High water temperature also increases the growth and distribution of many nonnative species, increasing their ability to successfully compete for limited food and habitat with native organisms (^Moyle 2002; ^Kiernan et al. 2012). Major factors that increase water temperature and negatively affect the health of the Bay-Delta ecosystem include disruptions of historical streamflow patterns due to water diversions and reservoir impoundments, loss of riparian forest vegetation, reduced flows, discharges from agricultural drains, and climate change (^USFWS 2001). Many of these factors occur in unregulated Sacramento River tributaries and negatively affect salmonid spawning and rearing. The effect of elevated temperature on juvenile and adult salmonids in tributaries is discussed in Chapter 3, *Scientific Knowledge to Inform Fish and Wildlife Flow Recommendations*.

Exposure of Chinook salmon and steelhead populations to elevated water temperature is a major factor contributing to their decline (see Section 3.4 in Chapter 3, *Scientific Knowledge to Inform Fish and Wildlife Flow Recommendations*; ^Myrick and Cech 2001). Dams and reservoirs now block Chinook salmon, steelhead, and sturgeon access to much of the historical higher elevation habitat for these species, with consistently colder water temperatures. In the Central Valley, dams block Chinook salmon and steelhead from the majority of their historical spawning habitat (NMFS 2014), and spawning and rearing habitat is now restricted to river reaches below rim dams. Reductions in cold water storage impede reservoirs from meeting their downstream water temperature requirements, especially during critically dry years (^NMFS 2009 BiOp, ^2014a). Physical and operational measures, including temperature control devices and seasonal storage targets, are employed at Central Valley reservoirs to improve the reliability of cold water discharge during

critical summer and fall spawning and rearing periods.² Increasing water demand and climate change are expected to further limit the effectiveness of reservoir flow and water temperature management in protecting anadromous fish populations below reservoirs (^Lindley et al. 2007; ^Cloern et al. 2011). These conditions occurred in 2014 and 2015 when a lack of sufficient inflow and cold water storage in Shasta Reservoir resulted in sub-lethal to lethal water temperatures in the downstream Sacramento River, contributing to very low egg-to-fry survival for winter-run Chinook salmon (^NMFS 2016c). Similar temperature conditions also occurred in the 2021 and 2022 drought years when water supplies, especially in the cold water pool of Shasta Reservoir, were extremely limited and affected winter-run Chinook salmon (NOAA Fisheries 2022, 2023).

There is recognition of the need to improve data collection and modeling at Shasta Reservoir and other rim reservoirs to better understand the physical processes affecting thermal dynamics and determine the most effective strategies for meeting the downstream temperature requirements of salmonids (^Anderson et al. 2015). The U.S. Bureau of Reclamation (Reclamation) is currently utilizing a reservoir and river temperature model called HEC-5Q to forecast water temperature conditions in the Sacramento River for seasonal operations planning. The model domain includes the Trinity and Shasta Divisions of the CVP and the Sacramento River from Keswick Dam to below the American River, along with Clear Creek from Whiskeytown Reservoir to the Sacramento River (Reclamation 2016b). The model is not publicly available, and Smith (2016) lists several known limitations with HEC-5Q. Reclamation is currently developing a modeling framework that will provide for seasonal temperature planning that incorporates information from new and additional models in conjunction with other reservoir and watershed analysis tools in the future.

In addition to Reclamation's current modeling efforts, NMFS models Sacramento River temperatures below Shasta Reservoir using the River Assessment for Forecasting Temperature (RAFT) model and a survival model that shows the probability of temperature-dependent egg-to-fry survival for winter-run Chinook salmon redds downstream from Keswick Dam (Daniels et al. 2018). NMFS has also developed a Central Valley Temperature Mapping and Prediction (CVTEMP) website that displays modeled and observed water temperature and flow data for the Sacramento River associated with Shasta Reservoir, Shasta Dam operations, and meteorological conditions. Flow and temperature data continue to be collected in Shasta and Keswick Reservoirs and downstream in the river to calibrate, validate, and refine the suite of linked models in CVTEMP to determine potential biological effects (Reclamation 2019).

Further downstream, the effect of Delta inflow on water temperatures in the Delta is limited because water generally has warmed considerably by the time it reaches the Delta, approaching maximum values dictated by meteorologically driven equilibrium values. As a result, substantial changes in flow would be needed to alter Delta inflow temperatures. In one study of Delta water temperatures, flow was not needed to produce accurate estimates of water temperature with statistical modeling, although the study noted that particularly high flows such as occurred during the winter of 1997–1998 could affect model accuracy (^Wagner et al. 2011). Other studies indicate that water temperatures within the Delta may reach equilibrium values farther inland under low flow conditions as a result of increased atmospheric forcing (i.e., longer residence time allows more time for meteorological conditions to affect water temperature) (^Vroom et al. 2017; ^Gleichenhauf 2015), and that Delta water temperatures tend to be lower under average or high inflow conditions as

² Temperature control devices have been installed for thermal regulation at Shasta, Folsom, and Whiskeytown Reservoirs as mitigation for the lack of access to higher elevation habitat.

compared to low inflow conditions (^Jeffries et al. 2016; ^Gleichauf 2015). Effects of flow on Delta water temperature are complex; while lower flow may allow water temperatures to reach equilibrium farther inland, lower flow also may allow the cold ocean water to reach within the Delta (^Gleichauf 2015).

Bashevkin and Mahardja (^2022) found that Delta water temperature is positively or negatively correlated with Delta inflow depending on time of year and location within the Delta. These relationships are mediated by meteorology (^Vroom et al. 2017; ^Bashevkin and Mahardja 2022) and snowmelt (^Knowles and Cayan 2002). The summer period, when local precipitation is minimal, appears to be most influenced by upstream factors, whereas local precipitation and other meteorological conditions may influence much of the winter patterns (^Bashevkin and Mahardja 2022).

4.4 Nonnative Species

The Sacramento River, Bay-Delta, and major tributaries to both Suisun Bay and Suisun Marsh are home to a diverse assemblage of native and nonnative species. While native species evolved and adapted to the unique hydrology of the area, nonnatives were introduced over time deliberately and accidentally by government agencies and others, ship ballast water releases and other vessel introductions, releases of aquarium species, and bait bucket releases (^Kimmerer 2004). Species were deliberately introduced for several reasons, including (1) improving fishing and aquaculture; (2) providing bait for anglers; and (3) providing biological control of aquatic pests or disease vectors (^Moyle 2002). There are over 250 introduced species, including fish, invertebrates, and plants, in the Bay-Delta (Cohen and Carlton 1995; USFWS 2004).

When nonnative species are introduced to an ecosystem, they can have direct and indirect effects on native species and affect ecosystem processes. Nonnative species can reduce ecosystem biodiversity by placing additional stress on native species through competition, predation, hybridization, habitat interference, and disease (^Moyle 2002; ^Mount et al. 2012). Regions in the Bay-Delta watershed with the greatest alteration in flow are most dominated by nonnative species (^Brown and May 2006; ^Brown and Michniuk 2007). Nonnative fish are known to occur in many locations in the Bay-Delta watershed; and invasive species dominate the fish assemblage in some locations, such as the interior Delta (^Brown and May 2006). The presence of so many nonnative species is considered a major impediment to recovery of native taxa (^Healey et al. 2016).

Nonnative species include fish, invertebrates, and aquatic plants, as discussed in more detail in the following subsections. Invasive species are very difficult to eradicate once introduced; however, various efforts have been and continue to be made to address the problem. The California Natural Resources Agency recognizes the importance of controlling aquatic invasive species and has developed the *California Aquatic Invasive Species Management Plan*, which proposes management actions for addressing aquatic invasive species threats in California (^CDFG 2008b). Objectives of the plan are to encourage state, federal and local collaboration, prevent new introductions, develop early detection and monitoring programs, ensure rapid response and eradication when invasions are detected, and develop effective, long-term control and management measures for established species. The plan also promotes education, outreach, and research to evaluate the efficacy of management actions and annual evaluations and adaptive management to ensure that the program is managed in an effective manner.

4.4.1 Fishes

The Bay-Delta alone has roughly 51 nonnative freshwater fish species that have become part of the ecosystem (^Moyle 2002). It has been acknowledged by the scientific community that the Bay-Delta estuary has become a novel ecosystem given all the nonnative introductions (Moyle et al. 2012). Many are considered to be recreationally or commercially important, such as striped bass, largemouth bass, and threadfin shad—all of which interact with native species but some of which are also in decline (^Sommer et al. 2007; Moyle et al. 2012). The altered hydrology creates more competitively favorable conditions for spawning and rearing of nonnative species than for native organisms (^Brown and Bauer 2009) and the long term success of nonnatives is facilitated by altered flow regimes (^Bunn and Arthington 2002). These conclusions suggest that a return to a more natural hydrology may be one of the few ways of favoring native species at the expense of introduced ones.

NMFS considers predation by nonnative species an important factor affecting Sacramento River winter-run Chinook salmon, Central Valley spring-run Chinook salmon, Central Valley fall- and late-fall-run Chinook salmon, and Central Valley steelhead (CDFG 2011a). Native predators of salmon and steelhead include pikeminnow (*Ptychocheilus grandis*), several avian species (BPA 2010) in the Delta, and the occasional marine mammal (CDFG 2011a; ^Grossman et al. 2013). Invasive fishes may either eat or compete with smelts and other natives for food (^Sommer et al. 2007; ^Moyle 2002), most notably centrarchids such as bass species (^DSC 2013). Centrarchids interfere with native species through predation and competition (^Grossman et al. 2013).

Silversides (*Menidia beryllina*) are an example of a nonnative species that both preys upon and competes with native species for limited food resources. Silversides school in large numbers over sand and gravel bottoms and are the most abundant fish in many shallow areas of the estuary (Chernoff et al. 1981; Kramer et al. 1987; ^Moyle 2002). Their distribution overlaps that of native species like Delta smelt, juvenile salmonids, and Sacramento splittail (^Moyle 2002). Silversides may outcompete other small planktivorous fish for limited food resources (^Moyle 2002). They are also voracious predators on larval fish and are abundant in shallow areas where Delta smelt spawn, especially during low-flow years (Swanson et al. 2000; ^Moyle 2002). Silversides also prey heavily on Delta smelt eggs and larvae (Baerwald et al. 2012). The introduction of silversides coincided with and may have contributed to the decline of Delta smelt populations. The continued abundance of silversides may inhibit the recovery of Delta smelt (Swanson et al. 2000; ^Moyle 2002). Other important nonnative predators include striped bass, white and channel catfish, and largemouth bass. These species also better tolerate highly altered environments characterized by low flow and low dissolved oxygen conditions than native species (^Moyle 2002; ^Feyrer 2004).

Predation by nonnative fish on Chinook salmon larvae remains a controversial issue in the Bay-Delta estuary (^Grossman et al. 2013). Removal of striped bass or other predacious fish species has been suggested as a method to improve juvenile Chinook salmon survival. Predator removal experiments improved juvenile Chinook salmon survival in small areas of the Delta for a short time (^Cavallo et al. 2012) but did not increase salmon survival in the long run (^Grossman 2016). The majority of fish predators in the Bay-Delta are nonnative species (more than 20 taxa), and many consume juvenile Chinook (^Grossman 2016). Removing a single species increases the number of other nonnative competitors (^Grossman 2016). For example, a field study found that predator removal only provided a temporary increase in juvenile salmon survival since, within a week, predator populations had rebounded, and survival had returned to pre-removal levels (^Cavallo et al. 2012). Bridges, water infrastructure facilities, unnatural bends, and gravel removal pits in river channels

have been identified as predator hotspots (Sabal et al. 2016). Identification and modification of these structures to eliminate hiding and ambush sites for nonnative predators may be a limited but more effective predator control method than predator removal.

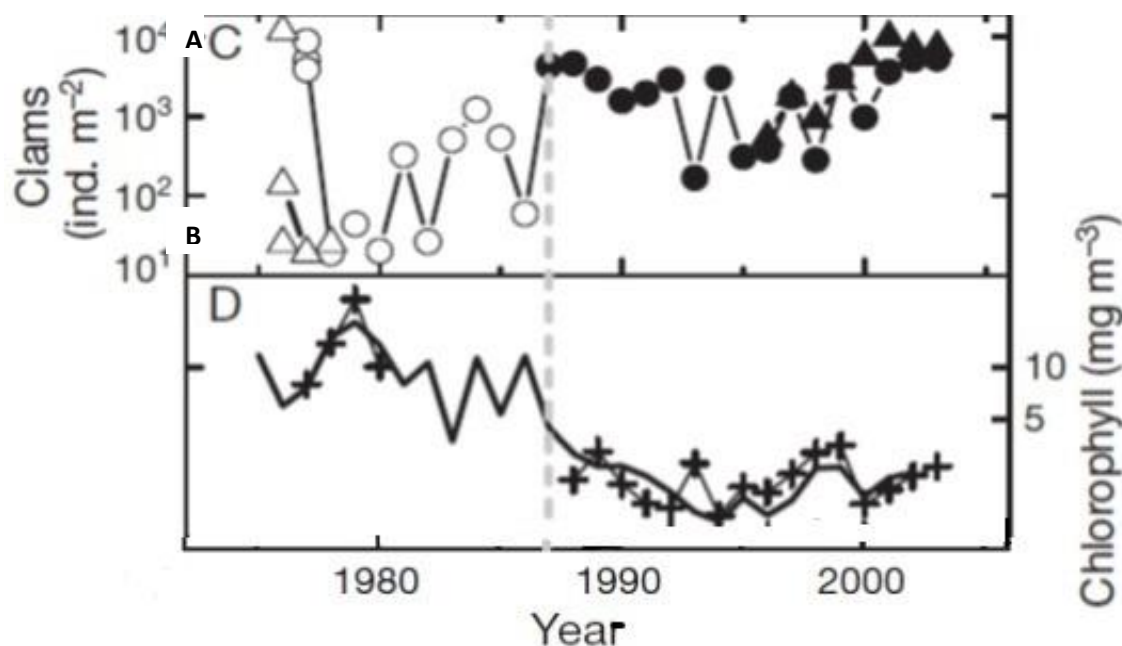
The extent of predation by nonnative fish on native populations remains largely unknown due to the lack of available monitoring data on fish predators. The Bay-Delta system supports a variety of nonnative predators, and as environmental conditions change over time predator abundance, prey abundance, and prey selection by predators may all shift. To gain a better understanding of how nonnative fish predators affect native fish populations, more information is needed on predator and prey abundance in addition to estimates of predation mortality on specific life stages of prey populations. Drought and climate change may also facilitate alterations in predator-prey relationships and additional studies and monitoring to examine long-term dietary trends in nonnative predators are needed (^Grossman 2016). While predator-prey relationships within the Bay-Delta system require further investigation, evidence indicates that more flow of a more natural pattern from major Sacramento/Delta tributaries may be a better solution for recovery of native species than predator removal. This is consistent with the observation that more permanent, or more constant, flows created by damming and diverting river flows favor introduced species (^Moyle and Mount 2007; ^Poff et al. 2007). For example, the reestablishment of more natural flow regimes in Putah Creek provided higher spring flows, cooler water temperatures, and more shaded habitat, which improved native fish spawning and rearing at the expense of nonnative species (^Marchetti and Moyle 2001; ^Kiernan et al. 2012). Studies may be warranted that examine the consequences if nonnative fish are not salvaged at the CVP and SWP. The CVP and SWP salvaged more than 32 million striped bass, 3 million silversides, half a million largemouth bass, and 5 million white catfish between 1992 and 2005 (^Grimaldo et al. 2009). More than 95 percent of the fish salvaged at the CVP and SWP facilities were nonnative species (Aasen 2016). Not salvaging these fish may be a cost-effective way to reduce the population size of nonnatives without having a negative impact on native organisms.

4.4.2 Invertebrates

The value of the Bay-Delta estuary as a nursery area for native species has been compromised by the successful invasion of nonnative invertebrates, including several species of bivalves, crustaceans, and jellyfish. These organisms now dominate both the benthic and planktonic environments of the estuary and disrupt the base of the estuarine foodweb (Jassby et al. 2002; ^Sommer et al. 2007; ^Mount et al. 2012). Complex trophic interactions make it difficult to predict the biological effect of these invasions on the native invertebrate community, including its composition and abundance (York et al. 2013). However, observed changes in the Bay-Delta suggest that a shift has occurred in energy flow from a phytoplankton-based pelagic foodweb to a detritus-derived benthic foodweb (^Winder and Jassby 2011).

Potamocorbula and *Corbicula fluminea* are two common introduced bivalves in the Bay-Delta estuary. A long-term decline in phytoplankton biomass (chlorophyll-a) occurred in Suisun Bay after the introduction of *Potamocorbula* in 1987 (Figure 4.4-1) (Jassby et al. 2002; Lucas et al. 2002; ^Kimmerer 2006; ^Jassby 2008). *Corbicula fluminea* is native to Asia and was first reported in the Bay-Delta in 1945 (Cohen and Carlton 1995). As filter feeders, the two clam species consume large quantities of phytoplankton, bacterioplankton, and small zooplankton (e.g., rotifers, copepod nauplii) (Greene et al. 2011; ^Durand 2010), which decreases food availability for larger zooplankton and mysids that serve as prey for fish species in the Bay-Delta (^Mount et al. 2012).

Invasive bivalves have affected native fish species in the Bay-Delta. Soon after the *Potamocorbula* invasion, there was a large decline in the carrying capacity of the estuary for Delta smelt, longfin smelt, and starry flounder (^Bennett 2005; ^Moyle et al. 2016; see discussion in Chapter 3, *Scientific Knowledge to Inform Fish and Wildlife Flow Recommendations*). Recruitment per unit of Delta outflow for longfin smelt and starry flounder decreased by 4.3 ± 1.4 and 3.9 ± 1.5 fold (mean $\pm$ standard error), respectively, and has not recovered (see Figure 3.5-2 and Figure 3.9-2 in Chapter 3). Today *Potamocorbula* dominates the entire brackish transition zone of the estuary. *Corbicula fluminea* is widely dispersed as the most abundant bivalve species in the freshwater portion of the Delta (Lucas et al. 2002). Because of the widespread distribution of these two invasive clams, there are very few locations in the estuary where phytoplankton assemblages can develop as occurred prior to the two invasions. Reduced standing chlorophyll levels are considered a major factor in controlling secondary production and fish abundance in the estuary (^Kimmerer 2002b; Brown et al. 2016). As a result, the capacity of the system to produce food for fish is now more limited. Studies are needed to determine whether physical or biological control of *Potamocorbula* is practical and feasible. Biological controls might include encouraging more predation by diving ducks. Diving ducks (*Aythya marila*, *Aythya affinis*, and *Melanitta perspicillata*) prey on *Potamocorbula* in winter and, when not hunted, significantly reduce clam densities (Poulton et al. 2002; Richman and Lovvorn 2004; Lovvorn et al. 2013).



Source: ^Kimmerer 2006.

Figure 4.4-1. Clam Abundance and Chlorophyll Concentrations in the Low-Salinity Zone before and after the Invasion of the Clam *Potamocorbula* in 1987 (vertical dashed line)

Between the early 1960s and mid-1990s, eight East Asian pelagic copepods invaded the Bay-Delta estuary where they replaced native species and disrupted the aquatic food chain. Those species included *Acartiella sinensis*, *Limnoithona sinensis*, *Limnoithona tetraspina*, *Oithona davisae*, *Pseudodiaptomus forbesi*, *Pseudodiaptomus marinus*, *Sinocalanus doerri*, and *Tortanus dextrilobatus* (^Orsi and Ohtsuka 1999). During the late 1980s and early 1990s, the nonnative copepod *P. forbesi* largely replaced the native *Eurytemora affinis* as *Potamocorbula* became abundant in the low-

salinity reaches of the estuary (^Winder and Jassby 2011). *Eurytemora affinis* still achieves high population levels during spring, but it is replaced by *P. forbesi* in summer and fall. Although small native fishes such as smelts can switch between the two prey types, they may not benefit consuming the nonnative copepod, *P. forbesi*, which is a faster swimmer than *E. affinis* and may be more difficult to catch and not as cost-efficient a prey item to consume (Meng and Orsi 1991; Morgan et al. 1997; ^Slater and Baxter 2014; ^Moyle et al. 2016). Some of these nonnative copepods are also generally less nutritious for native fish. *P. forbesi*, *Acartiella* spp., and *Limnoithona* are smaller than native copepods such as *Eurytemora* spp. and *Acartia* spp., take more energy to capture, and are less available to predators (Meng and Orsi 1991; ^Winder and Jassby 2011; ^Mount et al. 2012).

Historically, the native mysid, *Neomysis mercedis*, and the *Crangonid* shrimp, *Crangon franciscorum*, were common species in the Bay-Delta estuary. Native mysid populations, which are the preferred and more nutritious prey for both juvenile and adult native fish species, have declined (^Winder and Jassby 2011) and have been replaced by nonnatives including *Gammarus daiberi* (^Kimmerer 2004). A recent unpublished analysis of the outflow requirements of important introduced and native zooplankton is summarized in Chapter 3, *Scientific Knowledge to Inform Fish and Wildlife Flow Recommendations*. The analysis suggested that increasing net Delta outflow between March and September will increase the abundance of *E. affinis*, *P. forbesi*, and *N. mercedis* (^Hennessy and Burris 2017).

Two species of jellyfish (*Maeotias marginata*, *Moerisia* spp.) are now established in Suisun and San Pablo Bays (Rees and Gershwin 2000; Wintzer et al. 2011). Not much is known about these species, but there is concern that these predatory jellyfish will further alter the aquatic community by capturing and consuming zooplankton, larvae, and juvenile fish (Rees and Gershwin 2000).

4.4.3 Aquatic Plants

A suite of nonnative plants has colonized the Delta (^Boyer and Sutula 2015) and is now a permanent part of the Bay-Delta ecosystem. These plants include Brazilian waterweed (*Egeria densa*), water hyacinth (*Eichhornia crassipes*), water primrose (*Ludwigia* spp.), curly leaf pondweed (*Potamogeton* spp.), and Eurasian watermilfoil (*Myriophyllum spicatum*) (^Ferrari et al. 2013; ^CDBW 2016; ^DSC 2013; ^Boyer and Sutula 2015). Native submerged and floating aquatic vegetation also occurs in the Delta. Common native species are pondweed (*Stuckenia* spp.) and coontail (*Ceratophyllum demersum*). The most problematic nonnative aquatic plants are Brazilian waterweed and water hyacinth because of their ability to spread rapidly under the right environmental conditions, displacing native species, clogging waterways, altering turbidity, and negatively affecting other aquatic species. These invasive species are sometimes called *ecosystem engineers* because of their ability to affect food chains and other aquatic species by modifying the surrounding physical environment (^Mount et al. 2012).

Brazilian waterweed has detrimental effects on the Bay-Delta ecosystem (^Boyer and Sutula 2015). Brazilian waterweed is native to South America, was introduced to the United States in 1893, and became established in shallow littoral areas of the freshwater Delta during the 1980s. From 2004 to 2006, the distribution of Brazilian waterweed increased by more than 10 percent per year and continued to increase during the subsequent drought (Conrad et al. 2016). Brazilian waterweed covers 60 percent of central Delta channels (Santos et al. 2011) and from 5 to 10 percent of all Delta waterways (Santos et al. 2016). These estimates are approximate because no regular monitoring program exists to determine biomass and coverage of aquatic vegetation (^Boyer and Sutula 2015). Brazilian waterweed occurs in dense canopies that shade the understory and reduce phytoplankton

growth, exclude other submerged native aquatic plants, decrease oxygen levels at night, and increase water temperature and water clarity by reducing water circulation and promoting sedimentation. Brazilian waterweed also provides cover for large nonnative fish predators that prey on smaller native fish. USFWS (^2016) considers predation in SAV a limiting factor for Delta smelt survival. Brazilian waterweed does not occur in Suisun Bay because of its intolerance of salinities greater than 5 ppt (Borgnis and Boyer 2015). Colonization of the Delta by SAV established a new food web. Brazilian waterweed provides structural complexity and surface area for attached epiphytic algae and invertebrates and a refuge for fish (^Brown and Michnick 2007; Schultz and Dibble 2012; Brown et al. 2016). A stable isotope diet study found that centrarchids ate amphipods that were consuming epiphytic algae attached to SAV (Grimaldo et al. 2009). Some open water fishes—juvenile Chinook salmon and silversides—also may have entered the SAV canopy at high tide and consumed attached food organisms.

Water hyacinth also has detrimental effects on the Bay-Delta ecosystem (^Boyer and Sutula 2015). Water hyacinth is native to South America and was introduced to the United States in 1884 (^DSC 2013). Since its introduction into the Delta, water hyacinth has proliferated, and eradication is no longer an option (CDBW 2012). The results of sampling efforts indicate that water hyacinth coverage in the Delta increased four-fold from 2004-2007 and 2014, and now covers about 800 hectares in the Delta (^Boyer and Sutula 2015). Negative issues associated with water hyacinths are similar to those caused by Brazilian waterweed. Water hyacinth now covers the entire water surface of many back sloughs, blocking sunlight for phytoplankton and other submersed autotrophs, decreasing dissolved oxygen, creating barriers to navigation, changing turbidities in the water column, and affecting fish feeding and passage (Villamagna and Murphy 2010). Water hyacinths are sensitive to salinity and exhibit stress at 2.5 ppt (Haller et al. 1974) and mortality above 6 to 8 ppt (as summarized in ^Boyer and Sutula 2015). Little is known about the foodweb effect of water hyacinths on native fishes and the aquatic ecosystem (Brown et al. 2016).

Climate change may increase the abundance and distribution of invasive aquatic plants in the Delta (^Boyer and Sutula 2015). Climate change is predicted to result in warmer water temperatures and an increased frequency of droughts. These factors will favor the increased dominance of Brazilian waterweed and water hyacinth. However, sea level rise and increased saltwater intrusion into the western Delta could slow the spread of these salt intolerant plants.

CDBW is the lead state agency for water hyacinth control and coordinates with other state, local, and federal agencies in controlling water hyacinth. CDBW administers the Aquatic Invasive Plant Control Program (AIPCP), which covers 11 counties: Alameda, Contra Costa, Fresno, Madera, Merced, Sacramento, San Joaquin, Solano, Stanislaus, Tuolumne, and Yolo. The purpose of the AIPCP “is to keep waterways safe and navigable by controlling the growth and spread of aquatic invasive plants in the Sacramento-San Joaquin Delta (Delta), its surrounding tributaries, and Suisun Marsh.” The AIPCP also “balances potential impacts of aquatic invasive plant management while (1) minimizing non-target species impacts and (2) preventing environmental degradation in Delta waterways and tributaries” (^CDBW 2017). All previous aquatic invasive plant programs in the Delta have been incorporated into the AIPCP, which includes water hyacinth, water primrose, South American spongeplant (*Limnobium laevigatum*), Brazilian waterweed, curly leaf pondweed, Eurasian watermilfoil, coontail, and fanwort (*Cabomba caroliniana*).

CDBW routinely applies chemical herbicides to control the spread of multiple invasive aquatic plant species, including Brazilian waterweed and water hyacinth. CDBW also conducts mechanical shredding operations on invasive floating aquatic vegetation (^Boyer and Sutula 2015; ^CDBW

2006). Sub-lethal effects on aquatic organisms have been documented from these herbicide applications (see Section 4.3, *Water Quality*). Mechanical shredding of water hyacinth can measurably affect water quality and local effects of mechanical shredding may occur. In one study, mechanical shredding resulted in low dissolved oxygen levels and a localized fish kill in one Delta agricultural slough because of decomposition of the shredded organic material, but dissolved oxygen concentrations increased following hyacinth shredding in a Delta wetland (Greenfield et al. 2007). The U.S. Department of Agricultural Research Services and the California Department of Food and Agriculture are investigating the potential introduction of biological control agents for control of aquatic weeds (reviewed in Boyer and Sutula 2015). Recently, the Central Valley Water Board assembled a Science Work Group to review factors that may control the abundance and distribution of nonnative macrophytes (Central Valley Water Board 2014) and commissioned a literature review of the factors that may be controlling the prevalence of floating and submerged aquatic vegetation in the Delta. Major findings and major science recommendations resulting from the literature review was summarized in a white paper (Boyer and Sutula 2015). The white paper, along with several other white papers describing the state of science and current information needs, formed the foundation of the Central Valley Water Board's *Delta Nutrient Research Plan* (Central Valley Water Board 2018a). The purpose of the *Delta Nutrient Research Plan* is to identify research and modeling needed to determine whether water quality objectives for nutrients are needed in the Delta. In addition, a more variable flow pattern that allows periodic low Delta outflow and some saltwater intrusion into the western Delta could naturally restrict the distribution of nonnative aquatic plants, such as Brazilian waterweed and water hyacinth, which are sensitive to salinity.

Additional efforts are underway to address nonnative aquatic vegetation control in the Delta. Two groups, the Delta Region Areawide Aquatic Weed Project and the IEP Aquatic Vegetation Project Work Team are carrying out efforts to better understand the effects of nonnative aquatic plants on the aquatic ecosystem and to develop control strategies. The Delta Region Areawide Aquatic Weed Project, a collaboration among National Aeronautics and Space Administration, U.S. Department of Agriculture-Agricultural Research Service, University of California-Davis, and local agencies, was formed in 2011 and is evaluating the use of remote sensing-based geospatial information to determine aquatic weed distributions and is conducting research on more effective herbicides and biocontrol methods. The IEP Aquatic Vegetation Project Work Team, composed of federal and state scientists, was formed in 2016 and is investigating the impacts of nonnative aquatic vegetation and treatment efforts on Bay-Delta habitats and wildlife. In 2018, the IEP Aquatic Vegetation Project Work Team produced a Framework for Aquatic Vegetation Monitoring in the Delta, which describes potential frameworks for aquatic vegetation monitoring in the Delta and Suisun Marsh to inform resource management needs.

4.5 Fisheries Management

This section focuses on the effects of fisheries management activities on the aquatic ecosystem in the Delta and its tributaries such as harvest, hatchery operations, and fish passage barriers.

4.5.1 Harvest

The Delta and its tributaries currently support recreational and commercial fisheries. Recreational fisheries include a marine and freshwater fishery for striped bass, largemouth bass, black bass, white sturgeon, Chinook salmon, steelhead, catfish, and American shad (CDFG 2011b). The only commercial fisheries in the Delta are for threadfin shad and crayfish, although the Delta and its

tributaries also support a commercial ocean salmon fishery (Water Science and Technology Board et al. 2012; ^Mesick 2001; ^Moyle 2002). As discussed in Chapter 3, *Scientific Knowledge to Inform Fish and Wildlife Flow Recommendations*, there has been a substantial decline in population abundance of salmonids, sturgeon, splittail, starry flounder, and California bay shrimp over the past 50 years. A number of factors contribute to these declines, including loss of flow and physical habitat, along with the effects of other stressors (^Sommer et al. 2007; ^Fong et al. 2016). An additional factor may be a potentially unsustainable take of adult breeding stock in commercial and recreational fisheries. Loss of adult breeding stock can reduce recruitment, future population abundance, and the viability of the fishery.

The California Fish and Game Commission (CFG), Pacific Fishery Management Council (PFMC), and NMFS have evaluated the effect of take and recommended more stringent fishing regulations to the CFGC for native and special-status Bay-Delta species (CDFW 2016). Some of these regulations are summarized in Table 4.5-1. In addition, PFMC conducts a dynamic annual regulatory setting process to adjust salmonid harvest rates based on stock size and distribution. For example, PFMC implemented a near full closure of the ocean salmon fishery from 2008 through 2009, full closure of the California ocean salmon fishery in 2023 and 2024, and a full commercial and partial recreational closure of the California ocean salmon fishery in 2025 because of reduced stock size. Reductions in the recreational take of sturgeon and Sacramento splittail have also occurred. Finally, poaching represents an illegal form of harvest and has been a continuing problem in the Delta, especially for sturgeon (^Mount et al. 2012). CDFW uses wardens and other surveillance methods to discourage and prosecute illegal poaching.

Table 4.5-1. Summary of Recent Take Regulations to Reduce the Impact of Commercial and Recreational Harvest on Native Fish Species

Effective Year	Regulation Change	Intended Impact
Salmonids		
2008–2009	Near-full closure of ocean salmon fisheries	Protection of collapsed fall-run Chinook salmon population
2023–2024	Full closure of California ocean salmon fisheries	Protection of collapsed fall-run Chinook salmon population
2025	Full commercial and partial recreational closure of California ocean salmon fisheries	Protection of collapsed fall-run Chinook salmon population
>1989	Winter-run Chinook salmon: Since winter-run Chinook salmon were listed as federally threatened in 1989, various ocean area and river reach fishing closures and reduced size limits, and truncated seasons have been used to reduce the catch of winter-run Chinook salmon in commercial and recreational fisheries.	Reduced winter-run Chinook salmon harvest rates (which has been successful)
Sturgeon		
2006	Green sturgeon: zero bag limit	No legal harvest
2007	White sturgeon: 1 fish daily, 3-fish annual bag limits	Reduced adult harvest rate
2007	White sturgeon: Reduced maximum legal size	Improved survival of older/larger spawners

Effective Year	Regulation Change	Intended Impact
>2006	Sturgeon general: Various fishing restrictions, including substantial river-reach closures, weir basin closures, and gear restrictions	Reduced catch of non-legal sizes, reduced legal and illegal harvest in vulnerable areas
Other Species		
2010	Splittail: 2-fish daily bag limit	Reduction in total annual harvest

4.5.2 Hatcheries

Hatchery production is recognized as an important component of salmon and steelhead conservation and recovery efforts but historically has posed a threat to wild Chinook salmon and steelhead stocks through genetic, ecological, and management impacts (Waples 1991; ^California Hatchery Scientific Review Group 2012; ^NMFS 2014a). Most hatcheries in California are operated as production hatcheries to mitigate the loss of habitat (lost access to spawning and rearing habitat above dams), with the primary goal of supporting ocean commercial and recreational salmon fisheries and in-river recreational salmon and steelhead fisheries (^California Hatchery Scientific Review Group 2012). Annual production from salmon and steelhead hatcheries in California approaches 50 million juveniles, with more than 32 million fall-run Chinook salmon produced at five Central Valley hatcheries in most years (^California Hatchery Scientific Review Group 2012). Currently, hatchery-origin Chinook salmon make up a substantial proportion of Central Valley salmon runs, and spawning escapement of fall-run Chinook salmon in some of the major tributaries is now dominated by hatchery-origin fish (Yoshiyama et al. 2000; ^Barnett-Johnson et al. 2007).

Hatcheries can have positive effects on salmonid populations. Artificial propagation has been shown to be effective in bolstering the numbers of naturally spawning fish, conserving genetic resources, and guarding against catastrophic loss of naturally spawned populations at critically low abundance levels, as was the case for the winter-run population during the 1990s (^NMFS 2014a). The Livingston Stone National Fish Hatchery was established as a conservation hatchery program to augment the naturally spawning winter-run Chinook salmon population in the Sacramento River; the hatchery is currently managed to maintain genetic diversity and minimize potential adverse effects associated with artificial propagation. However, an increasing proportion of hatchery fish among returning adults in recent years has raised concerns about potential effects on the genetic integrity and fitness of the population (^NMFS 2016a).

Fish produced in hatcheries can also have detrimental genetic, ecological, and management effects on natural salmonid populations (Kostow 2009; Araki et al. 2008; ^California Hatchery Scientific Review Group 2012). Hatcheries can cause unintentional evolutionary change in populations that can lead to loss of local adaptations and reductions in genetic diversity and fitness of wild populations (Reisenbichler and Rubin 1999; Bisson et al. 2002). For example, evidence exists that large off-site releases of fall-run Chinook salmon from Central Valley hatcheries and resulting high levels of straying of hatchery adults to natural spawning areas have genetically homogenized the evolutionarily significant unit, contributing to losses in biodiversity and reduced resilience and viability (^Williamson and May 2005; ^Lindley et al. 2009). In addition, high levels of straying of hatchery fish can adversely affect natural stocks through ecological interactions, including disease transmission, predation, and competition for spawning habitat or other resources (^California

Hatchery Scientific Review Group 2012). Large-scale hatchery production and historically high harvest rates in mixed-stock fisheries has also contributed to reductions in natural diversity through overharvest of naturally produced stocks (^Lindley et al. 2009). The California Hatchery Scientific Review Group identified current harvest rates on naturally produced Sacramento River fall-run Chinook salmon as a continued concern because of degraded conditions for downstream migration throughout the basin (^California Hatchery Scientific Review Group 2012).

Along with habitat loss and degradation, hatchery management was identified as an important factor contributing to the listings of Central Valley spring-run Chinook salmon and steelhead (^NMFS 2014a). Most of the spring-run Chinook salmon production in the Central Valley is of hatchery-origin, and introgression of spring- and fall-run and significant straying of adults from Feather River Hatchery have posed a significant threat to the genetic integrity of natural spawning fall- and spring-run Chinook salmon in other watersheds (^NMFS 2014a). Over the past several decades, the genetic integrity of Central Valley steelhead has been diminished by increases in the proportion of hatchery fish relative to naturally produced fish, use of out-of-basin stocks for hatchery production, and straying of hatchery-produced fish (^NMFS 2014a).

Recent reviews and evaluations of these hatchery programs (^California Hatchery Scientific Review Group 2012 and Hatchery Genetic Management Plans) have led to a number of proposed strategies or recommended changes in hatchery policies and management to address these impacts and assist in the conservation and recovery of listed evolutionary significant units and distinct population segments and other naturally spawning Chinook salmon populations. These recommendations include marking hatchery-produced fish to distinguish them from naturally spawned individuals, examining the role and contribution of existing hatchery production to overall population abundance, and maintaining genetic diversity and integrity of different runs. Strategies for improving the husbandry and survival of hatchery fish include evaluations of diet and prerelease condition and the size, location, and timing of release.

4.5.3 Fish Passage Barriers

There are many known and potential barriers to anadromous fish passage in the Sacramento/Delta watershed. Fish passage barriers generally are defined as any human-made, instream, channel-wide infrastructure that reduces ecosystem connectivity and increases habitat fragmentation by restricting or impeding the migration of fish and other aquatic organisms. Fish passage barriers include road crossings, bridges, culverts, flood control channels, pumping plants, and borrow and gravel mining pits. Ongoing restoration and passage improvement efforts are occurring in the Sacramento/Delta watershed to address the issue of barriers, including screening of unscreened water diversions, fish passage improvements at instream water structures, and planning efforts for passage at large dams.

The loss of juvenile salmonids at unscreened water diversions in the Sacramento River and Delta has been identified as a reason for the listing of winter- and spring-run Chinook salmon and steelhead (^NMFS 2014a). The potential for entrainment of young fish at unscreened or poorly screened diversions for agricultural, municipal, and industrial use and managed wetlands continues to be recognized as a major stressor for these species and other special-status fish (^USFWS 1996; ^NMFS 2014a). While entrainment losses have likely increased with increases in water withdrawals, the role of this stressor in the historical declines and current status of these populations remains largely unquantified (Moyle and Israel 2005). As part of the CVPIA's fish restoration efforts, the Anadromous Fish Screen Program (AFSP) was established in 1994 to address this issue and provide

technical guidance and cost-share funding for fish screen projects. The AFSP also supports activities and studies to assess the potential benefits of fish screening, determine the highest priority diversions for screening, improve the effectiveness and efficiency of fish screens, encourage dissemination of information related to fish screening, and reduce the overall costs of fish screens. Many of the large water diversions (greater than 150 cubic feet per second) on the Sacramento River are screened or are currently proposed for screening (NMFS 2014a). However, there are more than 3,700 water diversions on the Sacramento and San Joaquin Rivers, their tributaries, and in the Delta; most of these are unscreened (Mussen et al. 2013). From 2009 through 2012, the AFSP and CALFED ERP conducted fish entrainment monitoring at 12 agricultural diversion sites on the Sacramento River and Steamboat Slough to evaluate site-specific physical, hydraulic, and habitat characteristics to assist with future fish screening prioritization efforts. This monitoring program, like past studies, indicated that entrainment of salmon was low relative to other fish species (Vogel 2013). In general, the factors affecting fish entrainment at unscreened diversions are complex and poorly understood because of the many site-specific variables that influence the exposure and vulnerability of fish to entrainment (Vogel 2013). Laboratory experiments using a large river-simulation flume indicate that entrainment losses of juvenile salmon are likely related to several factors, including the numbers of unscreened diversions to which the fish are exposed, the proximity of individual fish to the diversion intake structure as they pass the site, water velocity (sweeping velocities), water diversion rates, turbidity, and light levels (Mussen et al. 2013). The 2009 through 2012 study monitoring results indicate that some of the most important determinants of salmon entrainment likely include the initial timing of irrigation diversions in the spring, hydrologic conditions preceding the onset of irrigation diversions, and the natural emigration timing of salmon in relation to the timing of diversions. For example, a major factor contributing to the low incidence of salmon entrainment in these years appears to be the timing of emigration (as influenced by the timing of peak flow events) relative to the timing of diversions (Vogel 2013).

Fish passage improvement projects can help reduce the risk of juvenile salmonid entrainment and migration through the interior Delta during the critical periods of the migration window. Multiple studies have shown that juvenile salmonid outmigration routes through the interior Delta have lower survival rates compared to outmigration routes that use the north Delta (Perry and Skalski 2009; Brandes and McLain 2001; Dekar et al. 2013; Newman 2008). In recent years, DWR has experimented with the use of non-physical barriers and physical barriers and has assessed these structures' effectiveness at reducing the percentage of salmonids that migrate from the Sacramento River in the northern Delta to Georgiana Slough and the interior Delta. In 2011 and 2012, DWR experimented with the use of a bio-acoustic fish fence, a non-physical barrier that used sounds and flashing lights to deter juvenile anadromous salmonids from entering Georgiana Slough. In 2014, DWR experimented with the use of a floating fish guidance structure, a physical barrier to reduce salmonid passage into Georgiana Slough.

In addition to unscreened water diversions, many other instream structures such as culverts, low weirs, bridges, road crossings, and gravel mining pits can be fish passage barriers that impede or delay migrating fish. Barriers can be partial, total, or temporary depending on the weather, hydrologic conditions, sediment loads, and other factors. During low-flow conditions, instream structures can temporarily be total barriers to migration because of inadequate water depth. However, the structure may become partially or entirely passable at higher flows and increasing water depths. Other considerations, such as water velocity, water quality, and fish swim speed and leaping ability, also influence fish passage at a barrier.

New culverts must be designed to meet the criteria of either an active channel, stream simulation, or a hydraulic design option for upstream passage. The suitability of each design option depends on several factors, such as the species of fish expected to utilize the passage and whether the culvert is a new or replacement installation. Undersized culverts generally need to be entirely replaced, while other culverts can be significantly improved with minor modifications or retrofits (CDFG 2002). CDFW has developed multiple documents to assist in evaluating fish passage at existing culverts, such as the *California Salmonid Stream Habitat Restoration Manual* and *Culvert Criteria for Fish Passage* (CDFG 2010, 2002). Furthermore, the California Department of Transportation has developed an engineering document that can assist designers in planning projects that achieve the resource agency goal for fish passage within the state highway system (Caltrans 2007).

4.5.3.1 Dams and Reservoirs

The impacts of large dams in the Central Valley are well documented (^Yoshiyama et al. 1998). Currently, large dams restrict access to the majority of historical holding and spawning habitat for Chinook salmon (^Moyle 2002). Dams not only block or delay the migration of fish to critical habitat but also adversely affect important biological components of river ecosystems, including instream flow, water temperature, and habitat structure and function. Reservoir releases from the major dams in the Central Valley do not typically correspond with the natural flow regime of the watershed; instead, reservoirs are more likely to be individually operated to meet various demands. It is well understood that altered flow regimes can reduce native species richness, composition, and abundance, while also adversely affecting habitat suitability and foodweb productivity by restricting connectivity to floodplain and side-channel habitat (^American Rivers 2002). Reservoirs and reservoir releases can also affect water temperatures. Chapter 3, *Scientific Knowledge to Inform Fish and Wildlife Flow Recommendations*, and Section 4.3.4, *Temperature*, provide additional information on the impact of water temperature on aquatic resources.

Dams also alter the physical and chemical composition of river ecosystems by disrupting natural sediment processes, which increases bank erosion and limits the transfer of nutrients to the downstream environment. For example, it is estimated that many reservoirs in California store over 90 percent of the sediment load of a watershed (^DWR 2013a). The rate at which sediment is trapped in a reservoir depends on watershed size, topography, geology, the size of the reservoir, and reservoir management operations (McCartney 2000). The downstream reaches of a river often are able to regain sediment only through erosion of the existing stream bank and channel.

Volitional and non-volitional passage facilities can provide for upstream fish passage to cold water habitat above large dams. The goal of a passage facility is to attract migrating fish to a specific spot below the dam where they either volitionally move upstream through a fish ladder or are collected below the dam and transported upstream (FAO 2001). Ideally, a fish passage facility would provide volitional passage to fish by providing constant hydraulic connectivity from the reservoir to the river. These types of passage facilities include fishways and fish ladders for upstream migrants and fish bypasses for downstream migrants. The design of a volitional passage facility must consider hydraulic criteria such as flow, velocity, turbulence, and drop height, as well as environmental factors such as water temperature, dissolved oxygen, noise, light, and odor. These criteria must be especially investigated if there are significant differences in water quality between the upstream and downstream reaches of the reservoir (Larinier 2000). However, volitional passage facilities often are applicable only for passage at smaller dams and weirs and must also undergo routine maintenance to clear the facility of debris and sediment.

Non-volitional passage facilities rely on human or machine intervention to provide upstream fish passage. Non-volitional technologies can reduce the physical demand on fish and usually require less space, construction costs, and flow velocity compared to volitional facilities. Fish lifts and locks and collection and transport operations are two common types of non-volitional fish passage facilities. Fish lifts mechanically operate to move fish up and over a barrier, while collection and transport operations collect fish at one location and transport them around a barrier such as a large dam. Currently, collection and transport programs are being evaluated as a method to reintroduce salmon into the upper reaches of the Yuba River and the McCloud River.

Large dams are also an obstacle to juvenile fish migrating downstream from the upstream reaches of the reservoir. Nonnative piscivorous predators are usually abundant in reservoirs in which the water column is deep and slower moving compared to the river. In addition, the complex shape of reservoirs can lead to migration delays. At the dam, turbines and spillways can cause direct injury or mortality to juvenile fish, while turbulence can increase exposure of juvenile fish to predation immediately downstream of the dam. Several options are available for downstream passage, including bypass flumes and pipes and collection and transport operations. In addition, screening and guidance technologies, such as physical and behavioral barriers, can lead fish away from turbine intakes, water diversions, and spillways. Two-way trap and haul operations are also an option for providing downstream fish passage.

Dam removal projects can restore access to historical habitat for anadromous salmonids. In recent years, several dam removal projects have undergone environmental review, and some have been implemented in California. For example, in 2014, the Hammer Diversion Dam was removed from South Fork Cottonwood Creek, which has restored access to 5 miles of historical upstream anadromous fish holding, spawning, and rearing habitat (USFWS 2014). Several larger dam removal projects in California also have occurred or are in the planning stages. For example, the San Clemente Dam on the Carmel River was removed in 2015, restoring over 25 miles of spawning and rearing habitat to the threatened South-Central California Coast Steelhead DPS. In addition, four dams and associated facilities have been removed from the Klamath River, restoring nearly 400 miles of habitat for salmon and other species. Dam removal projects are underway or have been completed in other western states; for example, the Elwha and Glines Canyon Dams were removed from the Elwha River in Washington between 2011 and 2014.

4.5.4 Thiamine Deficiency

Thiamine deficiency has emerged as a new stressor to California Central Valley Chinook salmon, resulting in significant impacts on early life stage mortality of salmon stocks. It is estimated that, in 2021, 44 percent of endangered winter-run Chinook salmon suffered from thiamine-dependent mortality in the river (NOAA Fisheries 2022), and several of the other stocks suffered from low and critically low levels. Thiamine deficiency complex (TDC) was first discovered in California's Central Valley in early 2020 when hatcheries reported an increase in mortality of fall-run Chinook fry as well as unusual behaviors, such as loss of appetite, lethargy, corkscrew swimming, impaired coordination, inability to remain upright and excitability. Prior to 2020, TDC had not been diagnosed in California salmon; however, there is some evidence it may have gone undetected in the past (Mantua et al. 2021).

Thiamine (also called vitamin B1) is an essential vitamin necessary for converting food into energy. Salmon cannot produce thiamine on their own and must acquire the compound through diet.

Thiamine deficiency, or a lack of thiamine, occurs when an organism cannot retain or take in enough

of this vitamin through its typical diet to power vital body functions. In addition to the behavioral aberrations attributed to TDC, other physical abnormalities seen in fry include hydrocephalus (build up of fluid in the ventricles deep within the brain), vascular congestion, diminished yolk sac conversion efficiency, large yolk sacs with opacities, edema, and hemorrhaging. (Fisher et al. 1995; Fitzsimmons et al. 2005; Harder et al. 2018). The impacts of these physical and behavioral defects lead to reduced disease resistance (Ottinger et al. 2012), growth (Fitzsimons et al. 2009), prey capture (Fitzsimons et al. 2009), and predator avoidance (Fitzsimons et al. 2009) that all influence survival. Fry with TDC can replenish their thiamine levels via their diet; however, survivors may have these ongoing sub-lethal effects. Lethal and sub-lethal effects of TDC have also been identified in adult salmonids, which may cause unusual swimming patterns (Amcoff et al. 1998), reduced fitness (Houde et al. 2015), or reduced ability to ascend cascades during migration (Ketola et al. 2005).

In addition to being caused by a lack of thiamine in the diet, TDC can also be caused by a diet of fishes high in thiaminase, an enzyme that destroys or inactivates thiamine in the gut of consumers, such as those in the Herring family (Clupeidae) (Lepak et al. 2013). Thiaminase was identified as the primary cause for the onset of TDC in Great Lakes and Baltic Sea salmonids (Brown et al. 1998). It is hypothesized that TDC in California's Central Valley Chinook salmon is caused by consumption of prey fish with thiaminase I (NMFS 2021). Surveys off the West Coast in 2019 and 2020 found record high abundances of northern anchovy (*Engraulis mordax*) off the southern and central California coast, a species that produce thiaminase I in their tissue (NMFS 2021).

While increased consumption of anchovies is currently thought to be the proximate cause, other factors like environmental thiamine or climate change also may be involved. For example, environmental conditions in the marine food web could be producing less thiamine (Sañudo-Wilhelmy et al. 2012; Suffridge et al. 2018, 2020), adults could be experiencing conditions of oxidative stress (Vuori and Nikinmaa 2007), diets rich in fats can cause peroxidation (Mikkonen et al. 2011; Keinänen et al. 2018), or additional toxicants (Lundström et al. 1999) could be influencing thiamine pathways for salmon. Early results suggest that Chinook salmon in 2019 to present had narrow diets dominated by anchovies that were high in thiaminase and lipids, and low in thiamine relative to other prey species—all of which are known to reduce thiamine in consumers (Mantua et al. 2021).

Since the diagnosis of TDC in Central Valley hatcheries, thiamine treatments have been used at different life stages to increase egg thiamine concentrations that reduce both direct mortality and latent development effects. Thiamine injection treatments are given to returning adults before spawning and at fertilization, and eggs and fry are soaked in thiamine baths. For the spring-run Chinook salmon program at Feather River Hatchery, returning fish are tagged as spring-run Chinook salmon and released back into the river. This tagging period provides an opportunity to inject these fish with thiamine prior to their spawning. Female winter-run have also been treated with thiamine prior to spawning, which has resulted in significant improvements to egg thiamine concentration and survival of progeny (Bell 2022). Central Valley fall-run Chinook salmon hatchery fish are spawned almost immediately upon entering the hatcheries, so thiamine treatments have been given to eggs at fertilization to elevate egg thiamine levels.

Although treatments are now available to remedy and even prevent TDC in hatcheries, research into the causes of low overall thiamine levels for Chinook salmon is ongoing (Mantua et al. 2021). Samples of eggs collected at the Central Valley hatcheries over the past few years have found that the impacts of TDC seem to vary between stocks (NMFS 2021), and potentially between years. There

are currently little data on TDC presence in natural-origin Central Valley salmonid fry. Some fry collected in rotary screw traps have shown signs of TDC; however, mortality would likely occur in early life stages before fry would reach the traps (NMFS 2022). Studies are ongoing to assess TDC in natural-origin fish in the ocean as well as the potential for treatment. In addition, studies of adult Chinook in the ocean could provide some insight in the future of thiamine levels for returning adults (NOAA Fisheries 2020).

4.5.5 Disease

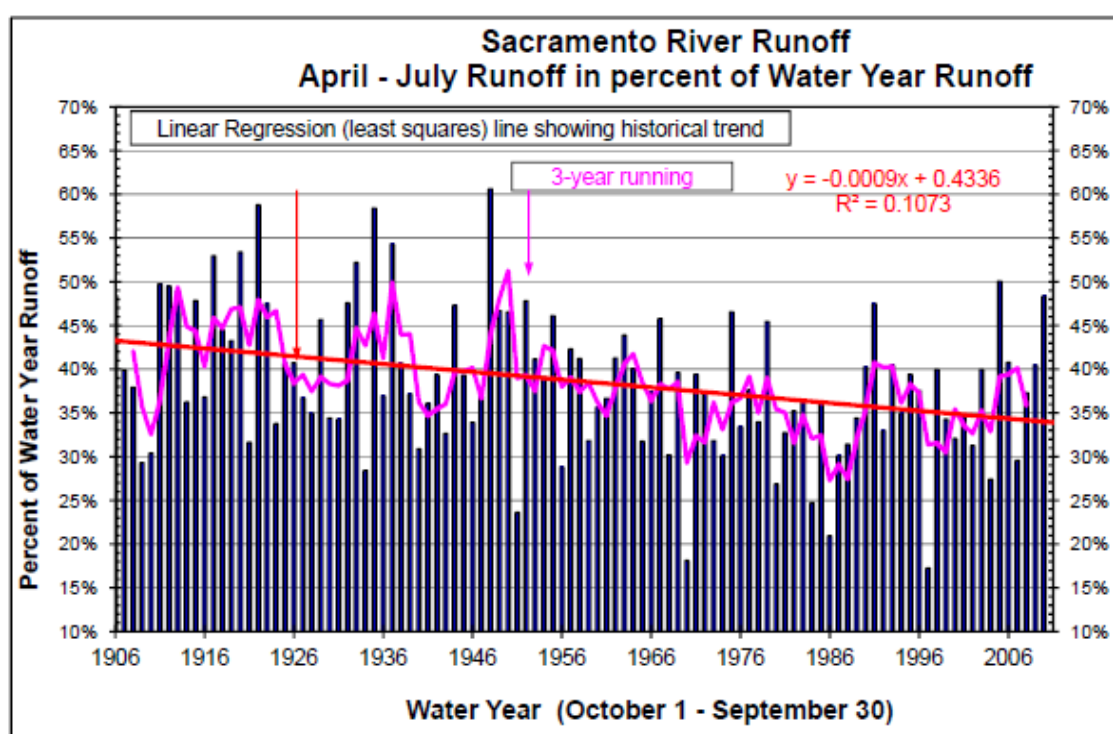
Disease is a growing concern in the Sacramento River and its tributaries, particularly for Chinook salmon (Atkinson et al. 2014; Foott 2016; Foott et al. 2017; Lehman et al. 2020). Pathogens are regarded as a major cause of mortality in juvenile salmonids, mostly during their migration to the ocean (Lehman et al. 2020). Susceptibility of fishes to disease is related to several factors that occur in the environment, including fish species and their densities, water quality conditions, decreased flows, and the amount of pathogens in the environment (Foott et al. 2017). Increasing water temperatures is another concern for the prevalence of these pathogens (Ray et al. 2012). Although pathogens occur naturally in the environment, the operations of dams may have produced environmental conditions where fish are more susceptible to disease (NMFS 2016d). Impediments to upstream migration and lack of sufficient flow can delay upstream migration and increase residence time, therefore increasing pathogen exposure and decreasing survival.

The National Wild Fish Health Survey is a program conducted by the USFWS Fish Health Center to assess the prevalence and distribution of major fish pathogens in wild fish populations. One focus of the California/Nevada Fish Health Center's National Wild Fish Health Survey efforts was with juvenile fall-run Chinook pathogens (particularly *Ceratomyxa shasta* and *Parvicapsula minibicornis*), smolt development (gill Na-KATPase activity), and response to organophosphates (Brain AChE activity) in the Sacramento River. In 2013, 2014, 2015, and 2016, *Ceratomyxa shasta* infection was detected in juvenile Chinook salmon collected from the lower Sacramento River. In 2014, 74 percent of Chinook juveniles examined were infected with *Ceratomyxa shasta* (Foott 2014). Research in the Klamath River has documented significant juvenile Chinook mortality in some years (Foott et al. 2004) as well as a better understanding of the complex interaction of the parasite's life cycle (fish and polychaete worm hosts) with environmental factors such as temperature, flow, and nutrients (Stocking et al. 2006). The prognosis of myxosporean infections in natural Chinook and their effect on survival should be evaluated further.

4.6 Climate Change

Climate change can exacerbate stressors, particularly through increased water temperatures, changing patterns of runoff, and salinity intrusion (Knowles and Cayan 2002, 2004). In the Bay-Delta, climate change impacts are predicted to include higher ambient temperatures, increased salinity intrusion, and reduced water supply reliability. The trend of increasing temperature through the twentieth century has decreased the controllable water supply, raised flood risk, and contributed to the severity of recent droughts (Roos 2005; DWR 2015). Since 1900, the global average temperature has risen by 1.5°F and may increase an additional 2.5–10.4°F by the end of the century (IPCC 2001; Mirchi et al. 2013). Future temperature increases of 1 to 3 degrees are expected to decrease the magnitude of the snowpack and cause up to 40 percent more of winter precipitation to fall as rain (Knowles and Cayan 2002, 2004; DSC 2013). The shift in precipitation from

snow to rain may result in larger runoff events prior to April and less snowmelt-driven runoff in the spring and summer. This shift may also lead to higher flooding risks in spring (Knowles and Cayan 2004; Knowles et al. 2006) and lower Sacramento River runoff from April through July (Figure 4.6-1). Figure 4.6-1 shows the percent of April through July (spring snowmelt) contribution to annual runoff demonstrating a declining trend since the early 1900s (red line). While median annual freshwater inflow to the Bay-Delta estuary has not significantly changed over the last 100 years, seasonal patterns have shifted, and the variability of Delta outflow has increased (Hutton et al. 2021). Climate change may alter the magnitude and timing of future unimpaired flow. Reduced snowfall will also diminish the volume of water held in the snowpack and the inter-annual water carry-over capacity of the system, negatively affecting the state's water supply reliability and maintenance of cold water habitat below reservoirs for salmonids (DSC 2013; Mirchi et al. 2013).



Source: Roos 2012.

Figure 4.6-1. Declining Trend in April–July Contribution to Total Water Year Runoff in the Sacramento River System, 1907–2010

Warmer water temperature because of less runoff from snowmelt in spring and summer may directly affect the life cycle of many fish species. Increased water temperature will negatively affect cold water-dependent fish species, including salmonids and smelt species, and will likely increase the range of invasive species (Healey et al. 2008; Villamanga and Murphy 2010). Climate-induced increases in ambient water temperature in Sierra Nevada streams could be from 1 to 5°C (Ficklin et al. 2013). Water temperature increases of 2 to 2.5°C will result in a 10-percent reduction of dissolved oxygen (Ficklin et al. 2013). A continued rise in stream temperatures, warmer atmospheric temperatures, diminished snowpack resulting in altered streamflow volume and

timing, lower late-summer flows, and increased sea-surface temperature and ocean acidity all contribute to climate-driven changes in the larger San Francisco estuary, resulting in alterations to the marine and freshwater food-chain dynamics on which native species depend (Herbold et al. 2022). Increasing Bay-Delta water temperatures have already been observed over the past 50 years, with the degree of warming varying spatially and seasonally (Bashevkin et al. 2022). Though resilient to historic flood and drought sequences in the climate record, present-day salmon now encounter more stressful conditions than those in which they evolved (Herbold et al. 2018). Higher temperature and lower dissolved oxygen levels will favor nonnative species that are better adapted to those conditions than native fish (^Kiernan et al. 2012; Moyle et al. 2013). While many of California's native species have survived drought and floods of the past, native species must now confront the effects of climate change in a drastically altered landscape, where centuries of post-colonial land conversion and water system engineering have left drying floodplains, lower river baseflows, and opportunities for the proliferation of invasive, predatory species (Power et al. 2024). Moreover, warmer water and more extreme events will decrease cold water habitats for native fisheries. The projected effects of climate change are particularly problematic for species like Delta smelt because of their low temperature tolerances (^Wagner et al. 2011). By the end of the twenty-first century, warming temperatures are projected to compress Delta smelt maturation windows by 15 to 25 percent, leading to declines in growth and egg production (^Brown et al. 2016). Similar reductions in habitat quality may occur for other native species. Elevated ambient water temperatures can stimulate growth of nuisance aquatic plants and HABs, which also can lead to decreases in dissolved oxygen and increases in organic carbon (^DSC 2013). Warming temperatures are particularly impactful in the central and south Delta, where temperature thresholds for listed species such as juvenile salmonids are frequently exceeded during summer and early fall, translating into longer periods and higher levels of thermal stress (Pien et al. 2024). In this same region, *Microcystis*, a cyanobacteria known to cause HABs, experiences the lowest average number of thermal stress days, defined as the number of days when environmental temperatures exceed the organism's thermal tolerance threshold (Pien et al. 2024), meaning that high temperatures in the Delta normally do not limit *Microcystis* growth. Increasing temperatures due to climate change contribute to the increased frequency and severity of HABs in the Delta (^Kudela et al. 2023). Higher evaporation rates from warmer temperatures, particularly during the hot summer months, contribute to reduced streamflows that lead to drier soils, reduced groundwater infiltration, higher evaporative losses of water from surface reservoirs, increased urban and agricultural demand for irrigation water, and less water available for ecosystem and habitat protection (DWR 2008).

Sea level rise, predicted to increase by as much as 55 inches by 2100 (OPC 2011; ^DSC 2013), is already occurring in the San Francisco Bay (Grenier 2016). Sea level rise will create greater salinity intrusion into the interior Delta, which can impair water quality for agricultural and municipal uses, and has already changed habitat for fish species (^Feyrer et al. 2011; ^Moyle et al. 2010; Grenier 2016). Increased salinity intrusion may also change the distribution, range, and abundances of organisms because X2 may move upstream of Suisun Bay and into habitat that is less ideal for growth and reproduction of native fishes (see Section 3.2 in Chapter 3, *Scientific Knowledge to Inform Fish and Wildlife Flow Recommendations*). Rising sea level also increases the risk of levee failure and disruption of water exports, particularly in the interior Delta where substantial Delta island subsidence has already occurred (^Mount and Twiss 2005; DWR 2008). Increased salinity intrusion into the Delta may require higher freshwater releases from upstream reservoirs to repel saltwater (DWR 2009). This may result in a 10-percent reduction in available freshwater by mid-century and a 25-percent reduction by the end of the century (DWR 2009). Rising sea level inundates freshwater marshes and other freshwater aquatic habitats with brackish water, reducing

habitat for native plants and wildlife, shifting intertidal to subtidal habitat, and shifting low-lying upland areas to intertidal habitat (^Mount and Twiss 2005; ^Whipple et al. 2012; ^DSC 2013). Additionally, adjacent higher elevation habitat will be necessary for wildlife to escape flooding (^ERP 2014; Grenier 2016).

As climate patterns change, California is poised to experience an increasing number of more severe and lengthy droughts (Swain et al. 2018). While low precipitation can be considered the primary driver of droughts, anthropogenic warming also contributes to droughts, causing previously improbable prolonged mega-droughts to become substantially more likely in North America, with California's Central Valley being especially vulnerable (Williams et al. 2015; Williams et al. 2020). The influence of intensive and multi-year droughts has already been observed in the Delta, affecting both water quality and ecosystem responses. Multi-year drought periods in the Delta are characterized by altered water quality parameters including high water temperatures, increased salinity, clearer waters, and elevated nutrient levels, all of which contribute to patchy phytoplankton blooms, varying by region and season (Bosworth et al. 2024.). Drought periods also heavily influence flows in the Delta, resulting in longer residence times, particularly along both the Sacramento and San Joaquin Rivers, and heavily reduced Delta outflow (Hartman et al. 2024). These drought-induced changes may cause changes at higher trophic levels, such as shifts in zooplankton species composition and distribution, an increase in the incidence of HABs, and changes in phytoplankton community composition of the Delta (Hartman et al. 2024). Changes in water quality conditions can also impact larger fish and aquatic organisms, potentially leading to mismatches in life histories or traits and abiotic conditions as species experience temperatures, flows, and salinities for which they are not adapted. The occurrence of pelagic fish species such as Delta smelt and longfin smelt tends to decline during multi-year droughts, and while they often recover quickly, they do not fully recover in wet years that follow a drought (^Mahardja et al. 2021).

Actions to prepare and mitigate the effects of climate change may include acquisition of additional higher elevation wetland habitat for wildlife to escape flooding in the estuary (^ERP 2014; Grenier 2016; Goals Project 2015). In the upper basin, fish passages may need to be built around dams to facilitate upstream migration of salmonids above reservoirs to cooler habitats. Additionally, operators may need to change water temperature controls from dams and other infrastructure to adjust for climate change effects. However, the extent and magnitude of climate change is uncertain, making planning and management difficult.

In 2017, the State Water Board adopted a resolution requiring a comprehensive response to climate change in all State Water Board actions, including drinking water regulation, water quality protection, water rights administration, and financial assistance (Resolution No. 2017-0012). The 2017 resolution builds on the previous and ongoing work to mitigate greenhouse gas emissions and support implementation of the California Global Warming Solutions Act of 2006 (Assembly Bill [AB] 32³). The 2017 resolution directs the State Water Board and encourages regional water boards to update their policies, plans, and permits to enhance ecosystem resilience and prepare for and adapt to the impacts of climate change (^SWRCB 2017a).

³ Nunez, Statutes of 2006, added Division 25.5 (commencing with section 38500) to the California Health and Safety Code.

4.7 References Cited

4.7.1 Common References

- ^2013 Water Plan V2, Mountain Counties: California Department of Water Resources (DWR). 2014. *California Water Plan Update 2013*. Volume 2, Regional Reports.
- ^American Rivers. 2002. *The Ecology of Dam Removal: A Summary of Benefits and Impacts*. February. Washington, DC.
- ^Anderson, P., N. Denslow, J. E. Drewes, A. Olivieri, D. Schlenk, and S. Snyder. 2010. Monitoring Strategies for Chemicals of Emerging Concern (CECs) in Recycled Water: Recommendations of a Science Advisory Panel. State Water Resources Control Board Final Report.
- ^Anderson, J. J., J. Gore, R. Kneib, N. Monsen, G. Schladow, and J. Van Sickle. 2015. *Independent Review Panel (IRP) Report for the 2015 Long-Term Operations Biological Opinions (LOBO) Annual Science Review*. A report to the Delta Science Program. December.
- ^Atwater, B. F., S. F. Conrad, J. N. Dowden, C. W. Hedel, R. L. MacDonald, and W. Savage. 1979. History, Landforms, and Vegetation of the Estuary's Tidal Marshes. Pages 347–385 In T. J. Conomos (ed.). *San Francisco (CA): San Francisco Bay, the Urbanized Estuary*. American Association for the Advancement of Science.
- ^Barnett-Johnson, R., B. G. Churchill, C. F. Royer, and C. J. Donohoe. 2007. Identifying the Contribution of Wild and Hatchery Chinook Salmon (*Oncorhynchus tshawytscha*) to the Ocean Fishery Using Otolith Microstructure as Natural Tags. *Canadian Journal of Fisheries and Aquatic Sciences* 64:1683–1692.
- ^Bashevkin, S. M., and B. Mahardja. 2022. Seasonally Variable Relationships between Surface Water Temperature and Inflow in the Upper San Francisco Estuary. *Limnology and Oceanography*. 67:684–702. January.
- ^Bennett, W. A. 2005. Critical Assessment of the Delta Smelt Population in the San Francisco Estuary, California. *San Francisco Estuary and Watershed Science* 3(2):1–71.
- ^Berg, M. and M. Sutula. 2015. *Factors Affecting the Growth of Cyanobacteria with Special Emphasis on the Sacramento–San Joaquin Delta*. Southern California Coastal Water Research Project. Technical Report 869. August.
- ^Boyer, K. and M. Sutula. 2015. *Factors Controlling Submersed and Floating Macrophytes in the Sacramento–San Joaquin Delta*. Southern California Coastal Water Research Project. Technical Report 870. Costa Mesa, CA.
- ^Brown, L. R. and M. L. Bauer. 2009. Effects of Hydrologic Infrastructure on Flow Regimes of California's Central Valley Rivers: Implications for Fish Populations. *River Research and Applications* 26(6):751–765.
- ^Brown, L. R. and J. T. May. 2006. Variation in Spring Nearshore Resident Fish Species Composition and Life Histories in the Lower Sacramento-San Joaquin Watershed and Delta. *San Francisco Estuary Watershed and Science* 4(2).

- ^Brown, L. R. and D. Michniuk. 2007. Littoral Fish Assemblages of the Alien-Dominated Sacramento–San Joaquin Delta, California, 1980–1983 and 2001–2003. *Estuaries and Coasts* 30(1):186–200.
- ^Brown, L. R., L. M. Komoroske, R. W. Wagner, T. Morgan-King, J. T. May, R. E. Connon, and N. A. Fanguie. 2016. Coupled Downscaled Climate Models and Ecophysiological Metrics Forecast Habitat Compression for an Endangered Estuarine Fish. *PloS ONE* 11(1), e0146724.
- ^Bunn, S. E. and A. H. Arthington. 2002. Basic Principles and Ecological Consequences of Altered Flow Regimes for Aquatic Biodiversity. *Environmental Management* 30(4):492–507.
- ^California Department of Fish and Game (CDFG). 2008b. *California Aquatic Invasive Species Management Plan*. January.
- ^California Department of Parks and Recreation, Division of Boating and Waterways (CDBW). 2006. *Egeria densa Control Program: Second Addendum to 2001 Environmental Impact Report with Five-Year Program Review and Future Operations Plan*. December 8. Sacramento, CA.
- ^California Department of Parks and Recreation, Division of Boating and Waterways (CDBW). 2016. *Frequently Asked Questions: Water Hyacinth*.
- ^California Department of Parks and Recreation, Division of Boating and Waterways (CDBW). 2017. DBW Begins Herbicide Treatment in the Delta for Water Hyacinth and *Egeria densa*. News Release.
- ^California Department of Water Resources (DWR). 2013a. *Technologies for Passing Fish at Large Dams*. Draft. June. R. Beckwith, S. Denzler, L. Pierce, and T. Greene (eds.). FloodSAFE Environmental Stewardship and Statewide Resources Office. June.
- ^California Hatchery Scientific Review Group. 2012. *California Hatchery Review Report*. Prepared for the U.S. Fish and Wildlife Service and Pacific States Marine Fisheries Commission. June.
- ^California Natural Resources Agency (CNRA). 2016. *Restoring the Sacramento-San Joaquin Delta Ecosystem*.
- ^Cavallo, B., J. Merz, and J. Setka. 2012. Effects of Predator and Flow Manipulation on Chinook Salmon (*Oncorhynchus tshawytscha*) Survival in an Imperiled Estuary. *Environmental Biology of Fishes* 96(2-3):393–403.(DOI: 10.1007/s10641-012-9993-5).
- ^Central Valley Regional Water Quality Control Board (Central Valley Water Board). 2018a. *Delta Nutrient Research Plan*.
- ^Cloern, J. E., N. Knowles, L. R. Brown, D. Cayan, M. D. Dettinger, T. L. Morgan, D. H. Schoellhamer, M. T. Stacey, M. Van Der Wegen, R. W. Wagner, and A. D. Jassby. 2011. Projected Evolution of California’s San Francisco Bay-Delta: River System in a Century of Climate Change. *Climate Change and San Francisco Estuary-Watershed* 6:9.
- ^Dahm, C. A. Parker, A. Adelson, M. Christman, and B. Bergamaschi. 2016. Nutrient Dynamics of the Delta: Effects on Primary Producers. *San Francisco Estuary and Watershed Science* Special Issue: State of the Bay-Delta Science 2016, Part 3 14 (4).
- ^Delta Stewardship Council (DSC). 2013. *The Delta Plan: Ensuring a Reliable Water Supply for California, a Healthy Delta Ecosystem, and a Place of Enduring Value*. May. Sacramento, CA.

- ^De Vlaming, V. 2008. *Organochlorine Pesticides and Polychlorinated Biphenyls (PCB) Concentrations in Muscle Tissue of Fish Collected from the San Joaquin River and Sacramento River Watersheds and Delta during 2005*. Prepared for the Regional Water Quality Control Board, Central Valley Region.
- ^Durand, J. R. 2010. *Determinants of Seasonal Abundance of Key Zooplankton of the San Francisco Estuary*. M.S. thesis. San Francisco State University, San Francisco, CA.
- ^Ecosystem Restoration Program (ERP). 2014. *Conservation Strategy for Restoration of the Sacramento-San Joaquin Delta, Sacramento Valley and San Joaquin Valley Regions*. May.
- ^Ferrari, M. C. O., L. Ranaker, K. L. Weinersmith, M. J. Young, A. Sih, and J. L. Conrad. 2013. Effects of Turbidity and an Invasive Waterweed on Predation by Introduced Largemouth Bass. *Environmental Biology of Fishes* 97(1):79–90.
- ^Feyrer, F. 2004. Ecological Segregation of Native and Alien Larval fish assemblages in the southern Sacramento-San Joaquin Delta. *American Fisheries Society Symposium* 39:67–79.
- ^Feyrer, F., K. Newman, M. Nobriga, and T. Sommer. 2011. Modeling the effects of future outflow on the abiotic habitat of an imperiled estuarine fish. *Estuaries and Coasts* 34(1):120–128.
- ^Fong, S., S. Louie, I. Werner, J. Davis, and R. E. Connon. 2016. Contaminant Effects on California Bay-Delta Species and Human Health. *San Francisco Estuary and Watershed Science* 14(4):1–34.
- ^Gleichauf, K.T. 2015. *Temperature and Tidal River Junction Dynamics in the Sacramento-San Joaquin Delta, California*. Ph.D. Dissertation, Stanford University.
- ^Goals Project. 2015. *The Baylands and Climate Change: What We Can Do*. Baylands Ecosystem Habitat Goals Science Update 2015 prepared by the San Francisco Bay Area Wetlands Ecosystem Goals Project. California State Coastal Conservancy, Oakland, CA.
- ^Greenfield, B. K., G. S. Siemering, J. C. Andrews, M. Rajan, S. P. Andrews Jr., and D. F. Spencer. 2007. Mechanical shredding of water hyacinth (*Eichhornia crassipes*): Effects on water quality in the Sacramento-San Joaquin River Delta, California. *Estuaries and Coasts* 30:627–640.
- ^Grimaldo, L. F., T. Sommer, N. Van Ark, G. Jones, E. Holland, P. Moyle, P. Smith, and B. Herbold. 2009. Factors affecting fish entrainment into massive water diversions in a freshwater tidal estuary: can fish losses be managed? *North American Journal of Fisheries Management* 29:1253–1270. <https://doi.org/10.1577/M08-062.1>.
- ^Grossman, G. D. 2016. Predation on Fishes in the Sacramento–San Joaquin Delta: Current Knowledge and Future directions. *San Francisco Estuary and Watershed Science* 14(2).
- ^Grossman, G. D., T. Essington, B. Johnson, J. Miller, N. E. Monsen, and T. N. Pearsons. 2013. *Effects of Fish Predation on Salmonids in the Sacramento River–San Joaquin Delta and Associated Ecosystems*. September 25.
- ^Hasenbein, M., L. M. Komoroske, R. E. Connon, J. Geist, and N. Fangue. 2013. Turbidity and salinity Affect Feeding Performance and Physiological Stress in the Endangered Delta Smelt. *Integrative and Comparative Biology* 53(4):620–634.
- ^Healey, M., M. Dettinger, and R. Norgaard. 2016. Perspectives on Bay-Delta Science and Policy. *San Francisco Estuary and Watershed Science: The State of Bay-Delta Science 2016, Part 3*.

- ^Hennessy, A. and Z. Burris. 2017. *Preliminary Analysis of Current Relationships between Zooplankton Abundance and Freshwater Outflow in the Upper San Francisco Estuary*. California Department of Fish and Wildlife Memorandum.
- ^Jassby, A. D. 2008. Phytoplankton in the Upper San Francisco Estuary: Recent Biomass Trends, Their Causes and Their Trophic Significance. *San Francisco Estuary and Watershed Science* 6(1).
- ^Jeffres, C. A., J. J. Opperman, and P. B. Moyle. 2008. Ephemeral Floodplain Habitats Provide Best Growth Conditions for Juvenile Chinook Salmon in a California River. *Environmental Biology of Fishes* 83:449–458.
- ^Jeffries, K. M, R. E. Cannon, B. E. Davis, L. M. Komoroske, M. T. Britton, T. Sommer, A. E. Todgham, and N. A. Fangue. 2016. Effects of High Temperatures on Threatened Estuarine Fishes During Period of Extreme Drought. *Journal of Experimental Biology* 219 (11):1705–1716.
- ^Kammerer, B. D. and S. A. Heppell. 2012. Individual condition indicators of thermal habitat quality in field populations of redband trout (*Oncorhynchus mykiss gairdneri*). *Environmental Biology of Fishes* 96:823–835.
- ^Kiernan, J. D., P. B. Moyle, and P. K. Crain. 2012. Restoring Native Fish Assemblages to a Regulated California Stream Using the Natural Flow Regime Concept. *Ecological Applications* 22(5):1472–1482.
- ^Kimmerer, W. J. 2002b. Effects of Freshwater Flow on Abundance of Estuarine Organisms: Physical Effects or Trophic Linkages? *Marine Ecology Progress Series* 243:39–55.
- ^Kimmerer, W. J. 2004. Open Water Processes of the San Francisco Estuary: from Physical Forcing to Biological Responses. *San Francisco Estuary and Watershed Science* 2(1):Article 1.
- ^Kimmerer, W. J. 2006. Response of Anchovies Dampens Effects of the Invasive Bivalve *Corbula amurensis* on the San Francisco Estuary Foodweb. *Marine Ecology Progress Series* 324:207–218.
- ^Knowles, N. and D. R. Cayan. 2002. Potential Effects of Global Warming on the Sacramento/San Joaquin Watershed and the San Francisco Estuary. *Geophysical Research Letters* 29(18):38-1–38-4.
- ^Knowles, N. and D. R. Cayan. 2004. Elevational Dependence of Projected Hydrologic Changes in the San Francisco Estuary and Watershed. *Climate Change* 62:319–336.
- ^Kudela, R. M., M. D. A. Howard, S. Monismith, and H. W. Paerl. 2023. Status, Trends, and Drivers of Harmful Algal Blooms along the Freshwater-to-Marine Gradient in the San Francisco Bay–Delta System. *San Francisco Estuary and Watershed Science* 20(4):6.
- ^Lehman, P. W., K. Marr, G. L. Boyer, S. Acuna, and S. J. Teh. 2013. Long-Term Trends and Casual Factors Associated with Microcystis Abundance and Toxicity in San Francisco Estuary and Implications for Climate Change Impacts. *Hydrobiologia* 718(1) 141–158.
- ^Lehman, P. W., T. Kurobe, S. Lesmeister, D. Baxa, A. Tung, and S. J. Teh. 2017. Impacts of the 2014 Severe Drought on the *Microcystis* Bloom in San Francisco Estuary. *Harmful Algae* 63:94–108.
- ^Li, H., G. A. Lamberti, T. N. Pearsons, C. K. Tait, and J. L. Li. 1994. Cumulative Effects of the Riparian Disturbances along High Desert Trout Streams of the John Day Basin, Oregon. *Transactions of the American Fisheries Society* 123:627–640.

- ^Lindley, S. T., R. Schick, E. Mora, P. B. Adams, J. J. Anderson, S. Greene, C. Hanson, B. P. May, D. R. McEwan, R. B. MacFarlane, C. Swanson, and J. G. Williams. 2007. Framework for Assessing Viability of Threatened and Endangered Chinook Salmon and Steelhead in the Sacramento–San Joaquin Basin. *San Francisco Estuary and Watershed Science* [online serial] 5(1): Article 4.
- ^Lindley, S. T., C. B. Grimes, M. S. Mohr, W. Peterson, J. Stein, J. T. Anderson, L. W. Botsford, D. L. Bottom, C. A. Busack, T. K. Collier, J. Ferguson, J. C. Garza, A. M. Grover, D. G. Hankin, R. G. Kope, P. W. Lawson, A. Low, R. B. MacFarlane, K. Moore, M. Palmer-Zwahlen, F. B. Schwing, J. Smith, C. Tracy, R. Webb, B. K. Wells, and T. H. Williams. 2009. *What Caused the Sacramento River Fall Chinook Stock Collapse?* Pacific Fishery Management Council. March 18.
- ^Mahardja, B., V. Tobias, S. Khanna, L. Mitchell, P. Lehman, T. Sommer, L. Brown, S. Culberson, and J. L. Conrad. 2021. Resistance and Resilience of Pelagic and Littoral Fishes to Drought in the San Francisco Estuary. *Ecological Applications* 31(2): e02243.
- ^Marchetti, M. P. and P. B. Moyle. 2001. Effects of Flow Regime on Fish Assemblages in a Regulated California Stream. *Ecological Applications* 11:530–539.
- ^Matthews, K. and N. Berg. 1997. Rainbow Trout Responses to Water Temperature and Dissolved Oxygen Stress in Two Southern California Stream Pools. *Journal of Fish Biology* 50:50–67.
- ^McConnell, S., C. Joab, R. Rai, and J. Simi 2015. *San Joaquin River Dissolved Oxygen Control Program Implementation Staff Report*. Report prepared for the Central Valley Regional Water Quality Control Board, Sacramento CA.
- ^Mesick, C. F. 2001. *Factors that Potentially Limit the Populations of Fall-Run Chinook Salmon in the San Joaquin Tributaries*. Stanislaus Fish Group, Stockton, CA.
- ^Mount, J. and R. Twiss. 2005. Subsidence, Sea Level Rise, Seismicity in the Sacramento–San Joaquin Delta. *San Francisco Estuary and Watershed Science* 3(1).
- ^Mount, J., W. Bennett, J. Durand, W. Fleenor, E. Hanak, J. Lund, and P. Moyle. 2012. *Aquatic Ecosystem Stressors in the Sacramento–San Joaquin Delta*. San Francisco: Public Policy Institute of California. pp. 1–22.
- ^Moyle, P. B. 2002. *Inland Fishes of California*. University of California Press, Berkeley, CA.
- ^Moyle, P. B. and J. F. Mount. 2007. Homogenous Rivers, Homogenous Faunas. *Proceedings of the National Academy of Science* 104(14):5711–5712.
- ^Moyle, P. B., J. R. Lund, W. A. Bennett, and W. E. Fleenor. 2010. Habitat Variability and Complexity in the Upper San Francisco Estuary. *San Francisco Estuary and Watershed Science* 8(3).
- ^Moyle, P. B., L. R. Brown, and J. A. Hobbs. 2016. Delta Smelt: Life History and Decline of a Once-Abundant Species in the San Francisco Estuary. *San Francisco Estuary and Watershed Science* 14(2).
- ^Myrick, C. A. and J. J. Cech, Jr. 2001. *Temperature Effects on Chinook Salmon and Steelhead: a Review Focusing on California's Central Valley Populations*. Bay-Delta Modeling Forum Technical Publication 01-1:1–57.

- ^National Marine Fisheries Service (NMFS). 2009. *Biological Opinion and Conference Opinion on the Long-Term Operations of the Central Valley Project and State Water Project*. June 4. Endangered Species Act Section 7 Consultation. Southwest Region.
- ^National Marine Fisheries Service (NMFS). 2014a. *Recovery Plan for the Evolutionarily Significant Units of Sacramento River Winter-Run Chinook Salmon and Central Valley Spring-Run Chinook Salmon and the Distinct Population Segment of California Central Valley Steelhead*. West Coast Region, Sacramento, CA.
- ^National Marine Fisheries Service (NMFS). 2016a. *Central Valley Recovery Domain 5-Year Review: Summary and Evaluation California Central Valley Steelhead Distinct Population Segment*.
- ^National Marine Fisheries Service (NMFS). 2016c. *California Central Valley Recovery Domain 5-Year Status Review: Summary and Evaluation of Sacramento River Winter-Run Chinook Salmon ESU*. December 2016.
- ^National Marine Fisheries Service (NMFS). 2016d. *Endangered Species Act Section 7(a)(2) Biological Opinion, and Magnuson-Stevens Fishery Conservation and Management Act Essential Fish Habitat Response and Fish and Wildlife Coordination Act Recommendations for Relicensing the Oroville Facilities Hydroelectric Project, Butte County California (FERC Project No. 2100-134)*. NOAA Fisheries West Coast Region.
- ^ Newman, K. B. 2008. *An Evaluation of Four Sacramento–San Joaquin River Delta Juvenile Salmon Survival Studies*. Project SCI-06-G06-299. U.S. Fish and Wildlife Service, Stockton, CA.
- ^Nobriga, M. L., T. R. Sommer, F. Feyrer, and D. Fleming. 2008. Long-Term Trends in Summertime Habitat Suitability for Delta Smelt (*Hypomesus transpacificus*). *San Francisco Estuary and Watershed Science* 6(1):1–13.
- ^O’Rear, T. A. and P. B. Moyle. 2009. *Trends in Fish Populations of Suisun Marsh, Jan. 2008–Dec. 2008*. California Department of Water Resources, Annual Report SAP 4600001965.
- ^Orsi, J. J. and S. Ohtsuka. 1999. Introduction to the Asian Copepods *Acartiella sinensis*, *Tortanus dextrilobatus* (Copepoda: Calanoida), and *Limnoithona tetraspina* (Copepoda: Cyclopoidia) to the San Francisco Estuary, California, USA. *Plankton Biology and Ecology* 46(2):128–131.
- ^Poff, N. L., J. D. Olden, D. M. Merritt, and D. M. Pepin. 2007. Homogenization of Regional River Dynamics by Dams and Global Biodiversity Implications. *Proceedings of the National Academy of Sciences* 104(14):5732–5737.
- ^Roberts, W. G., J. G. Howe, and J. Major. 1980. A Survey of Riparian Forest Flora and Fauna in California. In Sands, A. (ed). *Riparian Forests in California: Their Ecology and Conservation*. University of California, Davis Press, Institute of Ecology.
- ^Rood, S. B., C. R. Gourley, E. M. Ammon, L. G. Heki, J. R. Klotz, M. L. Morrison, D. Mosley, G. G. Scoppetone, S. Swanson, and P. L. Wagner. 2003. Flows for Floodplain Forests: a Successful Riparian Restoration. *Bioscience* 53(7):647–656.
- ^Sacramento-San Joaquin Delta Conservancy (Delta Conservancy). 2015. *Delta Restoration Network*. Available: <http://deltaconservancy.ca.gov/delta-restoration-network-0/>. Accessed: April 14, 2017.

- ^San Francisco Estuary Institute Aquatic Science Center (SFEI-ASC). 2016. *A Delta Renewed – a Guide to Science-Based Ecological Restoration in Sacramento-San Joaquin Delta*. Prepared for the California Department of Fish and Wildlife and Ecosystem Restoration Program. A Report of SFEI-ASC's Resilient Landscapes Program, Publication #799, San Francisco Estuary Institute-Aquatic Science Center, Richmond, CA.
- ^Schoellhamer, D. H., S. A. Wright, S. G., Monismith, and B. A. Bergamaschi. 2016. Recent Advances in Understanding Flow Dynamics and Transport of Water-Quality Constituents in the Sacramento-San Joaquin River Delta. *San Francisco Estuary and Watershed Science* Special Issue: The State of the Bay-Delta Science 2016, Part 3 14(4): Article 1.F.
- ^Slater, S. and R. Baxter. 2014. Diet, Prey Selection, and Body Conditions of Age-0 Delta Smelt, *Hypomesus transpacificus*, in the Upper San Francisco Estuary. *San Francisco Estuary and Watershed Science* 12(3):23.
- ^Smith, J., M. Sutula, K. Bouma-Gregson, and M. Van Dyke. 2021. *California State Water Boards' Framework and Strategy for Freshwater Harmful Algal Bloom Monitoring: Full Report with Appendices*. SCCWRP Technical Report #1141.B. Southern California Coastal Water Research Project.
- ^Sommer, T., B. Harrell, M. Nobriga, R. Brown, P. Moyle, W. Kimmerer, and L. Schemel. 2001b. California's Yolo Bypass: Evidence That Flood Control Can Be Compatible with Fisheries, Wetlands, Wildlife, and Agriculture. *Fisheries* 26(8):6–16.
- ^Sommer, T., C. Armor, R. Baxter, R. Breuer, L. Brown, M. Chotkowski, S. Culberson, F. Feyrer, M. Gingras, B. Herbold, W. Kimmerer, A. Mueller-Solger, M. Nobriga, and K. Souza. 2007. The Collapse of Pelagic Fishes in the Upper San Francisco Estuary. *Fisheries Research* 32(6):270–277.
- ^State Water Resources Control Board (SWRCB). 2017a. Resolution No. 2017-0012. Comprehensive Response to Climate Change.
- ^U.S. Bureau of Reclamation (Reclamation), U.S. Fish and Wildlife Service (USFWS) and California Department of Fish and Wildlife (CDFW). 2013. *Suisun Marsh Habitat Management, Preservation, and Restoration Plan Final EIS/EIR*.
- ^U. S. Fish and Wildlife Service (USFWS). 1996. *Sacramento–San Joaquin Delta Native Fishes Recovery Plan*. Portland, OR: U.S. Fish and Wildlife Service, Oregon Fish and Wildlife Office.
- ^U.S. Fish and Wildlife Service (USFWS). 2001. *Final Restoration Plan for the Anadromous Fish Restoration Program: a Plan to Increase Natural Production of Anadromous Fish in the Central Valley of California*. Prepared for the Secretary of the Interior by the US Fish and Wildlife Services with the assistance of the Anadromous Fish Restoration Program Core Group. Stockton, CA.
- ^U.S. Fish and Wildlife Service (USFWS). 2008. *Formal Endangered Species Act Consultation on the Proposed Coordinated Operations of the Central Valley Project (CVP) and State Water Project (SWP)*. Biological Opinion. December. Sacramento Fish and Wildlife Office, Sacramento, CA.
- ^U.S. Fish and Wildlife Service (USFWS). 2016. Species Assessment and Listing Priority Assignment Form. *Hypomesus transpacificus*.

- ^Vroom, J., M. van der Wegen, R. C. Martyr-Koller, and L. V. Lucas. 2017. What Determines Water Temperature Dynamics in the San Francisco Bay-Delta System? *Water Resources Research* 53:9901-9921.
- ^Wagner, R. W., M. Stacey, L. R. Brown, and M. Dettinger. 2011. Statistical Models of Temperature in the Sacramento–San Joaquin Delta under Climate-Change Scenarios and Ecological Implications. *Estuaries and Coasts* 34:544–556.
- ^Weston, D. P. and M. J. Lydy. 2010. Urban and Agricultural Sources of Pyrethroid Insecticides to the Sacramento–San Joaquin Delta of California. *Environmental Science and Technology* 44(5):1833–1840.
- ^Whipple, A. A., R. M. Grossinger, D. Rankink, B. Stanford, and R. A. Askevold. 2012. *Sacramento-San Joaquin Delta Historical Ecology Investigation: Exploring Pattern and Process*. Prepared for the California Department of Fish and Game and Ecosystem Restoration Program. A Report of the San Francisco Estuary Institute-Aquatic Science Center’s (SFEI-ASC) Historical Ecology Program, SFEI-ASC Publication #672, San Francisco Estuary Institute-Aquatic Science Center, Richmond, CA.
- ^Williamson, K. S. and B. May. 2005. Homogenization of Fall-Run Chinook Salmon Gene Pools in the Central Valley of California, USA. *North American Journal of Fisheries Management* 25:993–1009.
- ^Winder, M. and A. D. Jassby. 2011. Shifts in zooplankton community structure: Implications for Food Web Processes in the Upper San Francisco Estuary. *Estuaries and Coasts* 34:675–690.
- ^Wright, S. A. and D. H. Schoellhamer. 2004. Trends in the Sediment Yield of the Sacramento River, California, 1957–2001. *San Francisco Estuary and Watershed Science* 2(2).
- ^Yoshiyama, R. M., F. W. Fisher, and P. B. Moyle. 1998. Historical Abundance and Decline of Chinook Salmon in the Central Valley Region of California. *North American Journal of Fisheries Management* 18:487–521.
- ^Zeug, S. C., S. Sellheim, and C. Watry. 2014. Response of Juvenile Chinook Salmon to Managed Flow: Lessons Learned from a Population at the Southern Extent of Their Range in North America. *Fisheries Management and Ecology* 21:155–168.

4.7.2 Section References

- Aasen, G. 2016. Fish Salvage at the State Water Project’s and Central Valley Project’s Fish Facilities during the 2015 Water Year. *IEP Newsletter* 29(1):11–17.
- Acuña, S., D. F. Deng, P. Lehman, and S. Teh. 2012a. Sublethal Dietary Effects of *Microcystis* on Sacramento Splittail, *Pogonichthys macrolepidotus*. *Aquatic Toxicology* 110:1–8.
- Acuña, S., D. Baxa, and S. Teh. 2012b. Sublethal Dietary Effects of Microcystin Producing *Microcystis* on Threadfin Shad, *Dorosoma petenense*. *Toxicon* 60:1191–1202.
- Amcoff, P., H. Borjeson, J. Lindberg, and L. Norrgren. 1998. Thiamine Concentrations in Feral Baltic Salmon Exhibiting the M74 Syndrome. Early Life Stage Mortality Syndrome in Fishes of the Great Lakes and Baltic Sea. *American Fisheries Society, Symposium*. 21:82–89.

- Anzalone, S. E., N. W. Fuller, K. E. H. Hartz, C. A. Fulton, G. W. Whitley, J. T. Magnuson, et al. 2022. Pesticide residues in juvenile Chinook salmon and prey items of the Sacramento River watershed, California—A comparison of riverine and floodplain habitats. *Environmental Pollution* 303:119102.
- Anzalone, S. E., N. W. Fuller, K. E. H. Hartz, G. W. Whitley, J. T. Magnuson, D. Schlenk, S. Acuña, M. R. Whiles, and M. J. Lydy. 2024. The Roles of Diet and Habitat Use in Pesticide Bioaccumulation by Juvenile Chinook Salmon: Insights from Stable Isotopes and Fatty Acid Biomarkers. *Archives of Environmental Contamination and Toxicology* 86:234–248.
- Araki, H., B. A. Berejikian, M. J. Ford, and M. S. Blouin. 2008. Fitness of Hatchery-Reared Salmonids in the Wild. *Evolutionary Applications* ISSN 1752-4571. Journal Compilation Blackwell Publishing Ltd. 1(2008):342–355.
- Atkinson, S. D., J. S. Foott, and J. L. Bartholomew. 2014. Erection of Ceratonova n. gen.(Myxosporea: Ceratomyxidae) to Encompass Freshwater Species C. gasterostea n. sp. from Threespine stickleback (*Gasterosteus aculeatus*) and C. shasta n. comb. from Salmonid Fishes. *The Journal of Parasitology*, 100(5):640–645.
- Baerwald, M. R., B. M. Schreier, G. Schumer, and B. May. 2012. Detection of Threatened Delta Smelt in the Gut Contents of the Invasive Mississippi Silverside in the San Francisco Estuary Using TaqMan Assays. *Transactions of the American Fisheries Society* 141(6):1600–1607.
- Baginska, B. 2015. *Total Maximum Daily Load of Selenium in North San Francisco Bay*. Staff Report for Proposed Basin Plan Amendment for the California Regional Water Quality Control Board, San Francisco Bay Region. November 18. Oakland, CA.
- Baldwin, D. H., J. A. Spromberg, T. K. Collier, and N. L. Scholz. 2009. A Fish of Many Scales: Extrapolating Sublethal Pesticide Exposures to the Productivity of Wild Salmon Populations. *Ecological Applications* 19(8):2004–2015.
- Banet, A. I., S. Tussing, E. A. Roualdes, G. Doolittle, and D. S. Nielsen. 2021. *The Upper Sacramento River Anadromous Fish Habitat Restoration Project: Monitoring of Habitat Restoration Sites in the Upper Sacramento River in 2020-2021*. Annual Monitoring Report.
- Bashevkin, S. M., B. Mahardja, and L. R. Brown. 2022. Warming in the upper San Francisco Estuary: Patterns of water temperature change from 5 decades of data. *Limnology and Oceanography* 67(5):1065–1080.
- Baskerville-Bridges, B., J. Lindberg, and S. I. Doroshov. 2004. The Effect of Light Intensity, Alga Concentration, and Prey Density on the Feeding Behavior of Delta Smelt Larvae. *American Fisheries Society Symposium* 39:219–227.
- Bell, H. N. 2022. *Assessment of the Effects of Thiamine Deficiency on the Survival, Physiology, and Behavior of Early Life-Stage Winter-Run Chinook Salmon*. University of California, Davis.
- Bergman, A., J. J. Heindel, S. Jobling, K. A. Kidd, and R. T. Zoeller. 2012. *State of the Science of Endocrine Disrupting Chemicals: Summary for Decision-Makers*. World Health Organization, Stockholm.

- Bisson, P. A., C. C. Coutant, D. Goodman, R. Gramling, D. Lettenmaier, J. Lichatowich, W. Liss, E. Loudenslager, L. McDonald, D. Philipp, and B. Riddell. 2002. Hatchery Surpluses in the Pacific Northwest. *Fisheries* 27(12):16–27.
- Bonneville Power Administration (BPA). 2010. *Predator Control Helps Salmon*. DOE/BP-4172. September.
- Borgnis, E. and K. E. Boyer. 2015. Salinity Tolerance and Competition Drive Distribution of Native and Invasive Submerged Aquatic Vegetation in the Upper San Francisco Estuary. *Estuaries and Coasts* published online: October. (DOI 10.1007/s12237-015-0033-5).
- Bosworth, D. H., S. M. Bashevkin, K. Bouma-Gregson, R. Hartman, and E. B. Stumpner. 2024. The Anatomy of a Drought in the Upper San Francisco Estuary: Water Quality and Lower-Trophic Responses to Multi-Year Droughts. *San Francisco Estuary and Watershed Science* 22(1).
- Bouma-Gregson, K., D. H. Bosworth, T. M. Flynn, A. Maguire, J. Rinde, and R. Hartman. 2024. Delta Blue(green)s: The Effect of Drought and Drought-Management Actions on Microcystis in the Sacramento–San Joaquin Delta. *San Francisco Estuary and Watershed Science* 22(1).
- Bouma-Gregson, K., L.V. Lucas, A. Jaegge, D. Avouris, E. Richardson, J.A. Zwart, and T.E.C. Kraus. 2025. Designs for Cyanobacterial Harmful Algal Bloom Monitoring in the Sacramento–San Joaquin Delta, California. *ESS Open Archive*.
- Brander, S. M., R. E. Connon, G. He, J. A. Hobbs, K. L. Smalling, S. J. Teh, J. W. White, I. Werner, M. S. Denison, and G. N. Cherr. 2013. From ‘Omics to Otoliths: Responses of an Estuarine Fish to Endocrine Disrupting Compounds across Biological Scales. *PLoS ONE* 8(9):e74251.
- Brander, S. M., M. K Gabler, N. L. Fowler, R. E. Connon, and D. Schlenk. 2016. Pyrethroid Pesticides as Endocrine Disrupters: Molecular Mechanisms in Vertebrates with a Focus on Fishes. *Environmental Science and Technology* 50:8977–8992.
- Brandes, P. L. and J. S. McLain. 2001. Juvenile Chinook Salmon Abundance, Distribution, and Survival in the Sacramento-San Joaquin Estuary. *Fish Bulletin* 179: Contributions to the Biology of Central Valley Salmonids 2:39–138.
- Brown, S. B., D. C. Honeyfield, and L. Vandenbyllaardt. 1998. Thiamine Analysis in Fish Tissues. In *Early Life Stage Mortality Syndrome in Fishes of the Great Lakes and Baltic Sea*. American Fisheries Society, Symposium 21:73–81.
- Brown, T. 2010. Phytoplankton Community Composition: The Rise of the Flagellates. *IEP Newsletter* 22(3):20–28.
- Brown, L., Kimmerer, W., Conrad, J. L., Lesmeister, S., and A. Mueller-Solger. 2016. Food Webs of the Delta, Suisun Bay, and Suisun Marsh: An Update on Current Understanding and Possibilities for Management. *San Francisco Estuary and Watershed Science*, 14(3).
<https://doi.org/10.15447/sfews.2016v14iss3art4>
- California Department of Fish and Game (CDFG). 2002. *Culvert Criteria for Fish Passage*. Revised. May.
- California Department of Fish and Game (CDFG). 2010. *California Salmonid Stream Habitat Restoration Manual*. Fourth Edition. Appendix S. Fish Screen Criteria. Wildlife and Fisheries Division.

- California Department of Fish and Game (CDFG). 2011a. *A Report to the California Fish and Game Commission on Stressors Impacting Delta Related Organisms*.
- California Department of Fish and Game (CDFG). 2011b. *Freshwater Sport Fishing Regulations 2011–2012*.
- California Department of Fish and Wildlife (CDFW) 2016. California Department of Fish and Wildlife comments regarding the Working Draft Scientific Basis Report for New and Revised Flow Requirements on the Sacramento River and Tributaries, Eastside Tributaries, Delta Outflow, and Interior Delta Operations. December.
- California Department of Forestry and Fire Protection (CALFIRE). 2017. *Record 129 Million Dead Trees in California*. News Release. December 12.
- California Department of Parks and Recreation, Division of Boating and Waterways (CDBW). 2012. *Egeria Densa Control Program 2012 Annual Report*.
- California Department of Transportation (Caltrans). 2007. *Fish Passage Design for Road Crossings*. May. Division of Design.
- California Department of Water Resources (DWR) and U.S. Bureau of Reclamation (Reclamation). 2012. *Yolo Bypass Salmonid Habitat Restoration and Fish Passage Implementation Plan*. Department of Water Resources Fish Passage Improvement Program, FloodSAFE Environmental Stewardship and Statewide Resources Office (DWR FESSRO), Sacramento, CA; U.S. Bureau of Reclamation, Mid-Pacific Region (Reclamation), Sacramento, CA.
- California Department of Water Resources (DWR). 2008. *Managing an Uncertain Future: Climate Change Adaptation Strategies for California's Water*. Sacramento, CA.
- California Department of Water Resources (DWR). 2009. *Using Future Climate Projections to Support Water Resources Decision Making in California*. Prepared by the California Department of Water Resources for the California Energy Commission. CEC-500-2009-052-F.
- California Department of Water Resources (DWR). 2015. *Process Guide: California Water Plan Update 2013*. October.
- California Natural Resources Agency (CNRA). 2015. *Proposition 1 Overview*. Available: <http://bondaccountability.resources.ca.gov/p1.aspx>. Accessed: October 10, 2019.
- California Natural Resources Agency (CNRA). 2016. *Delta Smelt Resiliency Strategy*. July.
- California Ocean Protection Council (OPC). 2011. Resolution of the California Ocean Protection Council on Sea-Level Rise. March.
- California Trout. 2017. *Knaggs Ranch Agricultural Floodplain Study*. Available: <http://caltrout.org/our-work/steelhead-salmon/knaggs-ranch-agricultural-floodplain-study/>. Accessed: October 10, 2019.
- Callaway, J. C., V. T. Parker, M. C. Vasey, L. M. Schile, and E. R. Herbert. 2011. Tidal Wetland Restoration in San Francisco Bay: History and Current Issues. *San Francisco Estuary and Watershed Science* 9(3).
- Central Valley Regional Water Quality Control Board (Central Valley Water Board). 2014. *Charge to Macrophyte Science Work Group*.

- Chapman, P., W. Adams, M. Brooks, C. Delos, S. Luoma, W. Maher, H. Ohlendorf, T. Presser, and D. Shaw. 2009. *Ecological Assessment of Selenium in the Aquatic Environment*. Summary of a SETAC Pellston Workshop. February 22–28. Pensacola, FL.
- Chernoff, B. J., J. V. Conner, and C. F. Bryan. 1981. Systematics of *Menidia beryllina* Complex (Pisces: Atherinidae) from the Gulf of Mexico and Its Tributaries. *Copeia* 1981:319–335.
- Churchill, R. 2000. *Contributions of Mercury to California's Environment from Mercury and Goldmining Activities— Insights from the Historical Record*. Manuscript and slides for oral conference presentation at: Assessing and Managing Mercury from Historic and Current Mining Activities, November 28–30. San Francisco, CA. Sponsored by the U.S. Environmental Protection Agency, Office of Research and Development.
- Clements, W. H. and J. R. Rohr. 2009. Community Responses to Contaminants: Using Basic Ecological Principles to Predict Ecotoxicological Effects. *Environmental Toxicology and Chemistry* 28(9):1789–1800.
- Cloern, J. E. 1999. The Relative Importance of Light and Nutrient Limitation of Phytoplankton Growth: a Simple Index of Coastal Ecosystem Sensitivity to Nutrient Enrichment. *Aquatic Ecology* 33:3–16.
- Cloern, J. E., S. Q. Foster, and A. E. Kleckner. 2014a. Phytoplankton Primary Production in the World's Estuarine-Coastal Ecosystems. *Biogeosciences* 11:2477–2501.
- Cloern, J., A. Malkasian, R. Kudela, E. Novick, M. Peacock, T. Schraga, and D. Senn. 2014b. The Suisun Bay problem: Food quality or food quantity? *IEP Newsletter* 27:15–23.
- Cohen, A. N. and J. T. Carlton. 1995. *Nonindigenous Aquatic Species in a United States Estuary: a Case Study of the Biological Invasions of the San Francisco Bay and Delta*. A report for the United States Fish and Wildlife Service, Washington, D.C., and the National Sea Grant College Program Connecticut Sea Grant. December.
- Compeau, G. C. and R. Bartha. 1985. Sulfate-Reducing Bacteria: Principal Methylators of Mercury Anoxic Estuarine Sediment. *Applied and Environmental Microbiology* 50(2):498–502.
- Connon, R., L. Deanovic, E. Fritsch, L. D'Abronzio, and I. Werner. 2011. Sublethal Responses to Ammonia Exposure in the Endangered Delta Smelt; *Hypomesus transpacificus* (Fam. Osmeridae) *Aquatic Toxicology* 105:369–377.
- Cordoleani, F., E. Holmes, M. Bell-Tilcock, R. C. Johnson, and C. Jeffres. 2022. Variability in foodscapes and fish growth across a habitat mosaic: Implications for management and ecosystem restoration. *Ecological Indicators* 136:108681.
- Daniels, M. E., V. Sridharan, S. John, and E. Danner. 2018. *Calibration and Validation of Linked Water Temperature Models for the Shasta Reservoir and the Sacramento River from 2000 to 2015*. NOAA Technical Memorandum NMFS. University of California, Santa Cruz, Institute of Marine Sciences. NOAA Fisheries, SWFSC Fisheries Ecology Division, Santa Cruz, CA.
- Davis, J. A., F. Hetzel, J. J. Oram, and L. J. McKee. 2007. Polychlorinated Biphenyls (PCBs) in San Francisco Bay. *Environmental Research* 105(1):67–86.
- Davis, J. A., J. R. M. Ross, S. N. Bezalel, J. A. Hunt, G. Ichikawa, A. Bonnema, W. A. Heim, D. Crane, S. Swenson, and C. Lamerdin. 2013. *Contaminants in Fish from California Rivers and Streams*,

2011. A Report of the Surface Water Ambient Monitoring Program (SWAMP). California State Water Resources Control Board, Sacramento, CA.
- Davis, J.A., M. Weaver, and W.A. Heim. 2025. *Interpretive Report on Delta RMP Mercury Monitoring: 2016-2022*. March. Delta Regional Monitoring Program.
- Dekar, M., P. Brandes, J. Kirsch, L. Smith, J. Speegle, P. Cadrett, and M. Marshall. 2013. *USFWS Delta Juvenile Fish Monitoring Program Review*. Background Report. June. Prepared for review by the Interagency Ecological Program (IEP) Science Advisory Group. Lodi, CA: U.S. Fish and Wildlife Service, Stockton Fish and Wildlife Office.
- De Vlaming, V., A. Biales, D. Riordan, D. Markiewicz, R. Holmes, P. Otis, C. Leutenegger, R. Zander, and J. Lazorchak. 2006. *Screening California Surface Waters for Estrogenic Endocrine Disrupting Chemicals (EEDC) with a Juvenile Rainbow Trout Liver Vitellogenin mRNA Procedure*. State Water Board, Surface Water Ambient Monitoring Program.
- Deng, D. F., F.-C. Teh, and S. J. Teh. 2008. Effect of Dietary Methylmercury and Seleno-Methionine on Sacramento Splittail Larvae. *Science of the Total Environment* (407):197–203.
- Dugdale, R. C., F. P. Wilkerson, V. E. Hogue, and A. Marchi. 2007. The Role of Ammonium And Nitrate in Spring Bloom Development in San Francisco Bay. *Estuarine, Coastal and Shelf Science* 73:17–29.
- Ecosystem Restoration Program (ERP) 2014. *Ecosystem Restoration Program Highlights Report*. Fall.
- Esparza, M. L., A. E. Farrell, D. J. Craig, C. Swanson, B. S. Dhaliwal, and G. M. Berg. 2014. Impact of Atypical Ammonium Concentrations on Phytoplankton Abundance and Composition in Fresh Versus Estuarine Waters. *Aquatic Biology* 21:191–204.
- Feyrer, F., T. Sommer, and W. Harrell. 2006. Importance of flood dynamics versus intrinsic physical habitat in structuring fish communities: evidence from two adjacent engineered floodplains on the Sacramento River, California. *North American Journal of Fisheries Management* 26(2):408–417.
- Ficklin, D. L., I. T. Stewart, and E. P. Maurer. 2013. Effects of Climate Change on Stream Temperature, Dissolved Oxygen, and Sediment Concentration in the Sierra Nevada in California. *Water Resources Research* 49:2765–2782.
- Fisher, J. P., J. M. Spitsbergen, T. Iamonte, E. E. Little, and A. Delonay. 1995. Pathological and Behavioral Manifestations of the “Cayuga Syndrome,” Thiamine Deficiency in Larval Landlocked Atlantic Salmon. *Journal of Aquatic Animal Health*, 7(4): 269–283.
- Fitzsimons, J. D., S. B. Brown, B. Williston, G. Williston, L. R. Brown, K. Moore, D. C. Honeyfield, and D. E. Tillitt. 2009. Influence of Thiamine Deficiency on Lake Trout Larval Growth, Foraging, and Predator Avoidance. *Journal of Aquatic Animal Health*, 21(4):302–314.
- Foe, C., A. Ballard, and S. Fong. 2010. *Nutrient Concentrations and Biological Effects in the Sacramento-San Joaquin Delta*. Report prepared for the Regional Water Quality Control Board, Central Valley Region.
- Food and Agriculture Organization of the United Nations (FAO). 2001. *Dams, fish and fisheries- opportunities, challenges, and conflict resolution*. FAO Fisheries Technical Paper 219.

- Foott, J. S., R. Harmon, and R. Stone. 2004. Effect of Water Temperature on Non-Specific Immune Function and Ceratomyxosis in Juvenile Chinook Salmon and Steelhead from the Klamath River. *California Fish and Game*, 90(2): 71–84.
- Foott, J. S. 2014. *Sacramento and Feather River Juvenile Chinook Pathogen Survey*. Anderson, CA.
- Foott, J. S., R. Stone, S. Voss, and K. Nichols. 2017. *Ceratonova shasta* and *Parvicapsula minibicornis* (Phylum Cnidaria: Myxosporea) Infectivity for Juvenile Chinook Salmon (*Oncorhynchus tshawytscha*) in the Upper Sacramento River: July–November 2016. Anderson, CA.
- Foott, J. S. 2016. Parasite Infection of Juvenile Late Fall and Winter-Run Chinook in the Sacramento River: September – November 2015 observations in the Balls Ferry to Red Bluff reach. Memorandum to Interested Parties. U.S. Fish and Wildlife Service, California-Nevada Fish Health Center, Anderson, CA.
- Forest Climate Action Team. 2018. *California Forest Carbon Plan: Managing Our Forest Landscapes in a Changing Climate*.
- Ger, K., S. Teh, and C. Goldman. 2009. Microcystin-LR Toxicity on Dominant Copepods *Eurytemora affinis* and *Pseudodiaptomus forbesi* of the Upper San Francisco Estuary. *Science of the Total Environment* 407:4852–4857.
- Ger, K., S. Teh, D. Baxa, S. Lesmeitser, and C. Goldman 2010. The Effects of Dietary Microcystis aeruginosa and Microcystin on Copepods of the San Francisco Estuary. *Freshwater Biology* 55(7):1548–1559.
- Gilmour, C. C., E. A. Henry, and R. Mitchell. 1992. Sulfate Stimulation of Mercury Methylation in Freshwater Sediments. American Chemical Society. *Environmental Science & Technology* 26(11):2281–2287.
- Glibert, P. 2010. Long-Term Changes in Nutrient Loading and Stoichiometry and Their Relationship with Changes in Food Web and Dominant Pelagic Fish Species in the San Francisco Estuary, California. *Reviews in Fishery Science* 18:211–232.
- Glibert, P., D. Fullerton, J. Burkholder, J. Cornwell, and T. Kana. 2011. Ecological Stoichiometry, Biogeochemical Cycling, Invasive Species and Aquatic Food Webs: San Francisco Estuary and Comparative Systems. *Reviews in Fisheries Science* 19(4):358–417.
- Goertler, P., K. Jones, J. Cordell, B. Schreier, and T. Sommer. 2018. Effects of Extreme Hydrologic Regimes on Juvenile Chinook Salmon Prey Resources and Diet Composition in a Large River Floodplain. *Transactions of the American Fisheries Society* 147(2):287–299.
- Greater Battle Creek Watershed Working Group. 2018. Battle Creek Salmon and Steelhead Restoration Project. May.
- Greene, V. E., L. J. Sullivan, J. K. Thompson, and W. J. Kimmerer. 2011. Grazing Impact of the Invasive Clam *Corbula amurensis* on the Microplankton Assemblage of the Northern San Francisco Estuary. *Marine Ecology Progress Series* 431:183–193.
- Grenier, J. L. 2016. Which Way to the Brave New Baylands? *San Francisco Estuary & Watershed Science* 14(1) Article 1.

- Grimaldo, L., A. Steward, and W. Kimmerer. 2009. Dietary Segregation of Pelagic and Littoral Fish Assemblages in a Highly Modified Tidal Freshwater Estuary. *Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science* 1:200–217.
- Haller, W. T., D. L. Sutton, and W. C. Barlowe. 1974. Effects of Salinity on Growth of Several Aquatic Macrophytes. *Ecology* 55(4):891–894.
- Hanak, E., J. Lund, A. Dinar, B. Gray, R. Howitt, J. Mount, P. Moyle, and B. Thompson. 2011. *Managing California's Water from Conflict to Reconciliation*. Public Policy Institute of California.
- Harder, A. M., W. R. Ardren, A. N. Evans, M. H. Futia, C. E. Kraft, J. E. Marsden, C. A. Richter, J. Rinchar, D. E. Tillitt, and M. R. Christie. 2018. Thiamine Deficiency in Fishes: Causes, Consequences, and Potential Solutions. *Reviews in Fish Biology and Fisheries* 28:865–886.
- Hartman, R., E. B. Stumpner, D. H. Bosworth, A. Maguire, C. E. Burdi, and IEP Drought Synthesis Team. 2024. Dry Me a River: Ecological Effects of Drought in the Upper San Francisco Estuary. *San Francisco Estuary and Watershed Science* 22(1).
- Hasenbein M., I. Werner, L. Deanovic, J. Geist, E. Fritsch, and A. Javidmehr. 2014. Transcriptomic Profiling Permits the Identification of Pollutant Sources and Effects in Ambient Water Samples. *Science of the Total Environment* 468–469:688–698.
- Hasenbein, S., S. P. Lawler, and R. E. Connon. 2017. An Assessment of Direct and Indirect Effects of Two Herbicides on Aquatic Communities. *Environmental Toxicology and Chemistry* 36(8):2234–2245.
- Hassrick, J. L., A. J. Ammann, R. W. Perry, S. N. John, and M. E. Daniels. 2022. Factors Affecting Spatiotemporal Variation in Survival of Endangered Winter-Run Chinook Salmon Out-migrating from the Sacramento River. *North American Journal of Fisheries Management* 42:375–395.
- Healey, M., M. Dettinger, R. Norgaard, D. Jones, and R. Ullrey. 2008. *The State of Bay-Delta Science 2008 Summary for Policymakers and the Public November 2007*. CALFED Science Program report.
- Henderson, M. J., I. S. Iglesias, C. J. Michel, A. J. Ammann, and D. D. Huff. 2018. Estimating Spatial-Temporal Differences in Chinook salmon Outmigration Survival with Habitat- and Predation-related Covariates. *Canadian Journal of Fisheries and Aquatic Sciences*. 00:1-13.
- Herbold, B., E. Bush, G. Castillo, D. Colombano, R. Hartman, P. Lehman, B. Mahardja, and T. Sommer. 2022. Climate Change Impacts on San Francisco Estuary Aquatic Ecosystems: A Review. *San Francisco Estuary and Watershed Science* 20(2).
- Herbold, B., S.M. Carlson, R. Henery, R.C. Johnson, N. Mantua, M. McClure, P. Moyle, and T. Sommer. 2018. Managing for Salmon Resilience in California's Variable and Changing Climate. *San Francisco Estuary and Watershed Science* 16(2).
- Hestir, E., D. Schoellhamer, T. Morgan and S. Ustin. 2016. The Effect of Submerged Aquatic Vegetation Expansion on a Declining Turbidity Trend in the Sacramento-San Joaquin River Delta. *Estuaries and Coasts* 39(4):1100–1112.
- Hester, M. W., J. M. Willis, and T. M. Sloey. 2016. Field Assessment of Environmental Factors Constraining the Development and Expansion of *Schoenoplectus californicus* Marsh at a California Tidal Freshwater Restoration Site. *Wetlands Ecology Management* 24:33–44.

- Hoffman, K., M. Stillway, and S. Teh. 2017. *The Toxic Effects of Herbicides and Their Adjuvants on Delta Fish and Plankton*. Interagency Ecological Program presentation abstract.
- Holmes, E. J., P. Saffarinia, A. L. Rypel, M. N. Bell-Tilcock, J. V. Katz, and C. A. Jeffres. 2021. Reconciling Fish and Farms: Methods for Managing California Rice Fields as Salmon Habitat. *PLoS One* 16(2):e0237686.
- Holmes, R. W., B. S. Anderson, B. M. Phillips, J. W. Hunt, D. B. Crane, A. Mekebri, and V. Connor. 2008. Statewide Investigation of the Role of Pyrethroid Pesticides in Sediment Toxicity in California's Urban Waterways. *Environmental Science and Technology* 42(18):7003–7009.
- Houde, A. L. S., P. J. Saez, C. C. Wilson, D. P. Bureau, and B. D. Neff. 2015. Effects of Feeding High Dietary Thiaminase to Sub-Adult Atlantic Salmon from Three Populations. *Journal of Great Lakes Research*, 41(3):898–906.
- Huang, S. S. Y., A. B. Strathe, J. G. Fadel, P. Lin, T. Y. Liu, and S. S. O. Hung. 2012. Absorption, Distribution, and Elimination of Graded Oral Doses of Methylmercury in Juvenile White Sturgeon. *Aquatic Toxicology* 122–123:163–171.
- Hutton, P.H., D.M. Meko, and S.B. Roy. 2021. Supporting Restoration Decisions through Integration of Tree-Ring and Modeling Data: Reconstructing Flow and Salinity in the San Francisco Estuary over the Past Millennium. *Water* 13(15): 2139.
- Intergovernmental Panel on Climate Change (IPCC). 2001. Climate Change 2001: Scientific Basis. In B. Metz et al. (eds.). *Contribution of Working Group III to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: University Press.
- Jacoby, J. M., D. C. Collier, E. B. Welch, F. J. Hardy, and M. Crayton. 2000. Environmental Factors Associated with a Toxic Bloom of *Microcystis aeruginosa*. *Canadian Journal of Fisheries and Aquatic Science* 57:231–240.
- Jassby, A. D., J. E. Cloern, and B. E. Cole. 2002. Annual Primary Production: Patterns and Mechanisms of Change in a Nutrient-Rich Tidal Ecosystem. *Limnology and Oceanography* 47(3):698–712.
- Jeffries, K. M., L. M. Komoroske, J. Truong, I. Werner, M. Hasenbein, S. Hasenbein, N. A. Fangue, and R. E. Connon. 2015. The Transcriptome-Wide Effects of Exposure to a Pyrethroid Pesticide on the Critically Endangered Delta Smelt *Hypomesus transpacificus*. *Endangered Species Research* 28:43–60. (doi: 10.3354/esr00679.)
- Keinänen, M., R. Käkälä, T. Ritvanen, J. Pönni, H. Harjunpää, T. Myllylä, and P. J. Vuorinen. 2018. Fatty Acid Signatures Connect Thiamine Deficiency with the Diet of the Atlantic Salmon (*Salmo salar*) Feeding in the Baltic Sea. *Marine biology*, 165:1–17.
- Ketola, H. G., T. L. Chiotti, R. S. Rathman, J. D. Fitzsimons, D. C. Honeyfield, P. J. Van Dusen, and G. E. Lewis. 2005. Thiamine Status of Cayuga Lake Rainbow Trout and Its Influence on Spawning Migration. *North American Journal of Fisheries Management*, 25(4): 1281–1287.
- Klosterhaus, D. Yee, M. Sedlak, A. Wong, and R. Sutton. 2013. *Contaminants of Emerging Concern in the San Francisco Bay: A Summary of Occurrence Data and Identification of Data Gaps*. San Francisco Estuary Institute final report.
- Knowles, N., M. D. Dettinger, and D. R. Cayan. 2006. Trends in Snowfall vs. Rainfall in the Western United States. *Journal of Climate* 19:4545–4559.

- Kostow, K. 2009. Factors That Contribute to the Ecological Risks of Salmon and Steelhead Hatchery Programs and Some Mitigating Strategies. *Reviews in Fish Biology and Fisheries* 19(1):9–31.
- Kramer, V. L., R. Garcia, and A. E. Colwell. 1987. An Evaluation of the Mosquitofish, *Gambusia affinis*, and the Inland Silverside, *Menidia beryllina*, as Mosquito Control Agents in California Wild Rice Fields. *Journal of the American Mosquito Control Association* 3(4):626–632.
- Kraus, T. E. C., K. D. Carpenter, B. A. Bergamaschi, A. E. Parker, E. B. Stumpner, B. D. Downing, N. M. Travis, F. P. Wilkerson, C. Kendall, and T. D. Mussen. 2017. A river-scale Lagrangian experiment examining controls on phytoplankton dynamics in the presence and absence of treated wastewater effluent high in ammonium. *Limnology and Oceanography* 62:1234–1253.
- Kuivila, K. M. and G. E. Moon. 2004. Potential Exposure of Larval and Juvenile Delta Smelt to Dissolved Pesticides in the Sacramento–San Joaquin Delta, California. *American Fisheries Society Symposium* 39:229–241.
- Kurobe, T., D. V. Baxa, C. E. Mioni, R. M. Kudela, T. R. Smythe, S. Waller, A. D. Chapman, and S. J. Teh. 2013. *Identification of Harmful Cyanobacteria in the Sacramento- San Joaquin Delta and Clear Lake, California by DNA Barcoding*. SpringerPlus 2:491.
- Larinier, M. 2000. *Dams and Fish Migration*. World Commission on Dams. Environmental Issues, Dams, and Fish Migration, Final Draft. June 30.
- Lee, G. F. and A. Jones-Lee. 2002. *Organochlorine Pesticide, PCB and Dioxin/Furan Excessive Bioaccumulation Management Guidance*. California Water Institute Report TP 02-0606 for the State Water Resources and Central Valley Regional Water Quality Control Boards.
- Lehman, B. M., R. C. Johnson, M. Adkison, O. T. Burgess, R. E. Connon, N. A. Fanguie, J. S. Foott, S. L. Hallett, B. Martinez–López, K. M. Miller, and M. K. Purcell. 2020. Disease in Central Valley Salmon: Status and Lessons from Other Systems. *San Francisco Estuary and Watershed Science*, 18(3).
- Lehman, P. W., G. Boyer, C. Hall, S. Waller, and K. Gehrts. 2005. Distribution and Toxicity of a New Colonial *Microcystis aeruginosa* Bloom in the San Francisco Bay Estuary, California. *Hydrobiologia* 541:87–99.
- Lehman, P. W., G. Boyer, M. Satchwell, and S. Waller. 2008. The Influence of Environmental Conditions on the Seasonal Variation of *Microcystis* Cell Density and Microcystins Concentration in San Francisco Estuary. *Hydrobiologia* 600:187–204.
- Lehman, P. W., S. J. Teh, G. L. Boyer, M. L. Nobriga, E. Bass, and C. Hogle. 2010. Initial Impacts of *Microcystis aeruginosa* Blooms on the Aquatic Food Web in the San Francisco Estuary. *Hydrobiologia* 637:229–248.
- Lehman, P. W., T. Kurobe, and S. J. Teh. 2022. Impact of Extreme Wet and Dry Years on the Persistence of *Microcystis* Harmful Algal Blooms in San Francisco Estuary. *Quaternary International* 621: 16–25.
- Lemly, A. 1985. Toxicology of Selenium in a Freshwater Reservoir: Implications for Environmental Hazard Evaluation and Safety. *Ecotoxicology and Environmental Safety* 10:314–338.

- Lepak, J. M., A. L. Houde, P. J. Saez, C. C. Wilson, D. P. Bureau, B. D. Neff. 2013. Effects of Feeding High Dietary Thiaminase to Sub-adult Atlantic Salmon from Three Populations. *Journal of Great Lakes Research*, 41: (2015) 898–906.
- Linares-Casenave, J., R. Linville, J. P. Van Eenanaam, J. B. Muguet, and S. I. Doroshov. 2015. Selenium Tissue Burden Compartmentalization in Resident White Sturgeon (*Acipenser transmontanus*) of the San Francisco Bay Delta Estuary. *Environmental Toxicology and Chemistry* 34(1):152–160.
- Linville R. G., Samuel N. Luoma, Lynda Cutter, and Gregory A. Cutter. 2002. Increased Selenium Threat as a Result of Invasion of the Exotic Bivalve *Potamocorbula amurensis* into the San Francisco Bay-Delta. *Aquatic Toxicology* 57:51–64.
- Lovvorn, J. R., S. E. W. De La Cruz, J. Y. Takekawa, L. E. Shaskey, and S. E. Richman. 2013. Niche Overlap, Threshold Food Densities, and Limits to Prey Depletion for a Diving Duck Assemblage in an Estuarine Bay. *Marine Ecology Progress Series* 476:251–268.
- Lucas, L. V., J. E. Cloern, J. K. Thompson, and N. E. Monsen. 2002. Functional Variability of Habitats within the Sacramento–San Joaquin Delta: Restoration Implications. *Ecological Applications* 12(5):1528–1547.
- Lundström, J., B. Carney, P. AMcoff, A. Pettersson, H. Borjeson, L. Forlin, and L. Norrgren. 1999. Antioxidative Systems, Detoxifying Enzymes and Thiamine Levels in Baltic Salmon (*Salmo salar*) that Develop M. 74. *Ambio* 28(1):24–29.
- Mantua N., R. Johnson, J. Field, S. Lindley, T. Williams, A. Todgham, C. Jeffres, H. Bell, D. Cocherell, J. Rinchar, et al. 2021. Mechanisms, Impacts, and Mitigation for Thiamine Deficiency and Early Life Stage Mortality in California’s Central Valley Chinook Salmon. North Pacific Anadromous Fish Commission Technical Report 17:92–93.
- McCartney, M. P., Sullivan, C., & Acreman, M. C. 2000. Ecosystem impacts of large dams. Washington, DC: United Nation Foundation.
- Meng, L. and J. J. Orsi 1991. Selective Predation by Larval Striped Bass on Native and Introduced Copepods. *Transactions of the American Fisheries Society* 120(2):187–192.
- Michel, C. J., J. J. Notch, F. Cordoleani, A. J. Ammann, and E. M. Danner. 2021. Nonlinear Survival of Imperiled Fish Informs Managed Flows in a Highly Modified River. *Ecosphere* 12(5):e03498.
- Michel, C. J. 2018. Decoupling Outmigration from Marine Survival Indicates Outsized Influence of Streamflow on Cohort Success for California’s Chinook Salmon Populations. *Canadian Journal of Fisheries and Aquatic Sciences* 76:1398–1410.
- Mikkonen, J., M. Keinänen, M. Casini, J. Pönni, and P. J. Vuorinen. 2011. Relationships between Fish Stock Changes in the Baltic Sea and the M74 Syndrome, a Reproductive Disorder of Atlantic Salmon (*Salmo salar*). *ICES Journal of Marine Science*, 68(10):2134–2144.
- Miller, R. L., M. Fram, R. Fuji, and G. Wheeler. 2008. Subsidence Reversal in a Re-Established Wetland in the Sacramento-San Joaquin Delta, California, USA. *San Francisco Estuary and Watershed Science* 6(3).
- Mirchi, A., K. Madani, M. Roos, and D. W. Watkins. 2013. Climate Change Impacts on California’s Water Resources. In *Drought in Arid and Semi-Arid Regions*. Chapter 17, pp. 301–319.

- Morgan, C. A., J. R. Cordell, and C. A. Simenstad. 1997. Sink or Swim? Copepod Population Maintenance in the Columbia River. *Marine Biology* 129:309– 317.
- Mount, J. F. 1995. *California Rivers and Streams: The Conflict between Fluvial Process and Land Use*. Berkeley: University of California Press.
- Moyle, P. B. and J. A. Israel. 2005. Untested Assumptions. *Fisheries* 30:5.
- Moyle, P. B., W. Bennett, J. Durand, W. Fleenor, B. Gray, E. Hanak, J. Lund, and J. Mount. 2012. *Where the Wild Things Aren't: Making the Delta a Better Place for Native Species*. San Francisco, CA: Public Policy Institute of California.
- Moyle, P. B., J. D. Kiernan, P. K. Crain, and R. M. Quiñones. 2013. Climate Change Vulnerability of Native and Alien Freshwater Fishes of California: A Systematic Assessment Approach. *PLoS ONE* 8(5): e63883. doi:10.1371/journal.pone.0063883.
- Munsch, S. H., C. M. Greene, R. C. Johnson, W. H. Satterthwaite, H. Imaki, P. L. Brandes, and M. R. O'Farrell. 2020. Science for Integrative Management of Diadromous Fish Stock: Interdependencies of Fisheries, Flow, and Habitat Restoration. *Canadian Journal of Fisheries and Aquatic Sciences* 77:1487–1504.
- Mussen, T. D., D. Cocherell, Z. Hockett, A. Ercan, H. Bandeh, M. Levent Kavvas, J. J. Cech, and N. A. Fangue. 2013. Assessing Juvenile Chinook Salmon Behavior and Entrainment Risk near Unscreened Water Diversions: Large Flume Simulations. *Transactions of the American Fisheries Society* 142:130–142.
- Myrick, C. A. and J. J. Cech, Jr. 2000. Temperature Influences on California Rainbow Trout Physiological Performance. *Fish Physiology and Biochemistry* 22:245–254.
- National Fish and Wildlife Foundation (NFWF). 2018. *Sierra Nevada Meadow Restoration*. Available: <https://www.nfwf.org/sierranevada/Pages/home.aspx>. Accessed: November 27, 2018.
- National Marine Fisheries Service (NMFS). 2014. *Central Valley Chinook Salmon & Steelhead Recovery Plan*. Summer. NOAA Fisheries West Coast Region.
- National Marine Fisheries Service (NMFS). 2021. *Thiamine Deficiency in West Coast Salmon*. Spring. NOAA Fisheries West Coast Region.
- National Marine Fisheries Service (NMFS). 2022. Letter dated January 20, 2022, to Kristin White, U.S. Bureau of Reclamation. Letter provides the U.S. Bureau of Reclamation with the estimated number of juvenile Sacramento River winter Chinook salmon expected to enter the Sacramento–San Joaquin Delta during water year 2022.
- National Marine Fisheries Service (NMFS). 2023. Conference and Biological Opinion on the Environmental Protection Agency's Registration Review of Pesticide Products containing Carbaryl and Methomyl. Office of Protected Resources, Silver Spring, MD. Draft.
- National Oceanic and Atmospheric Administration (NOAA) Fisheries. 2020. Researchers Probe Deaths of Central Valley Chinook, with Possible Ties to Ocean Changes. Available: <https://www.fisheries.noaa.gov/feature-story/researchers-probe-deaths-central-valley-chinook-possible-ties-ocean-changes#:~:text=Scientists%20hypothesize%20that%20female%20Chinook,or%20TDC%2C%20in%20their%20offspring>. Accessed: May 11, 2023.

- National Oceanic and Atmospheric Administration (NOAA) Fisheries. 2022. River Temperatures and Survival of Endangered California Winter-Run Chinook Salmon in the 2021 Drought. Available: <https://www.fisheries.noaa.gov/west-coast/climate/river-temperatures-and-survival-endangered-california-winter-run-chinook-salmon#:~:text=They%20found%20that%2080%20percent,river%20would%20be%20similarly%20affected.> (Accessed: 11 May 2023)
- National Oceanic and Atmospheric Administration (NOAA) Fisheries. 2023. Survival of Endangered California Winter-Run Chinook Salmon in 2022. Available: [https://www.fisheries.noaa.gov/west-coast/climate/survival-endangered-california-winter-run-chinook-salmon-2022#how-many-winter-run-chinook-salmon-eggs-died-due-to-high-temperatures-in-2022?ly%20affected.](https://www.fisheries.noaa.gov/west-coast/climate/survival-endangered-california-winter-run-chinook-salmon-2022#how-many-winter-run-chinook-salmon-eggs-died-due-to-high-temperatures-in-2022?ly%20affected) Accessed: July 14, 2023.
- National Research Council (NRC). 2000. *Toxicological Effects of Methylmercury*. Committee on the Toxicological Effects of Methylmercury, Board of Environmental Studies and Toxicology.
- Newcomb, J., L. Pierce, and H. Spanglet. 2010. *Low Dissolved Oxygen Levels in the Stockton Deep Water Shipping Channel: Adverse Effects on Salmon and Steelhead and Potential Beneficial Effects of Raising Dissolved Oxygen Levels with the Aeration Facility*. October. Fish Passage Improvement Program and Flood Safe Environmental Stewardship and Statewide Resources Office, California Department of Water Resources.
- Nichols, F. H., J. E. Cloern, S. N. Luoma, and D. H. Peterson. 1986. The Modification of an Estuary. *Science* 231:567–573.
- Nobriga, M. L., C. J. Michel, R. C. Johnson, and J. D. Wikert. 2021. Coldwater Fish in a Warm Water World: Implications for Predation of Salmon Smolts during Estuary Transit. *Ecology and Evolution* 11:10381–10395.
- Novick, E. and D. Senn. 2013. *External Nutrient Loads to San Francisco Bay*. Draft. April 9. Prepared by the San Francisco Estuary Institute for the California Regional Water Quality Control Board, San Francisco Bay Region.
- Office of Environmental Health Hazard Assessment (OEHHA). 2009. *Update of California Sport Fish Advisories*. California Environmental Protection Agency. March.
- Opperman, J. J., R. Luster, B. A. McKenney, M. Roberts, and A. W. Meadows. 2010. Ecologically Functional Floodplains: Connectivity, Flow Regime, and Scale. *Journal of the American Water Resources Association (JAWRA)* 46:211–226.
- Orlando, J. L., M. McWayen, C. Sanders, and M. Hladik. 2013. *Dissolved Pesticide Concentrations in the Sacramento-San Joaquin Delta and Grizzly Bay, California, 2011–12*. Prepared in cooperation with the San Luis and Delta Mendota Water Authority. U.S. Geological Survey Data Series 779.
- Orlando, J. L., M. De Parsia, C. Sanders, M. Hladik, and J. Frantzich. 2020. *Pesticide Concentrations Associated with Augmented Flow Pulses in the Yolo Bypass and Cache Slough Complex, California*. U.S. Geological Survey Open-File Report 2020-1076.
- Ottinger, C. A., D. C. Honeyfield, C. L. Densmore, and L. R. Iwanowicz. 2012. Impact of Thiamine Deficiency on T-Cell Dependent and T-Cell Independent Antibody Production in Lake Trout. *Journal of Aquatic Animal Health*, 24(4):258–273.

- Pacific Gas and Electric Company (PG&E). 2019. Notice of Withdrawal of Application for Amendment of License, Project No. 1121-118 (Battle Creek).
- Parker, A., R. Dugdale, and F. Wilkerson. 2012. Elevated Ammonium Concentrations from Wastewater Discharge Depress Primary Production in the Sacramento River and the Northern San Francisco Bay. *Marine Pollution Bulletin* 64(3):574–586.
- Perry, R. W. and J. R. Skalski. 2009. *Survival and Migration Route Probabilities of Juvenile Chinook Salmon in the Sacramento–San Joaquin River Delta during the Winter of 2007–2008*. Final. July. Prepared for U.S. Fish and Wildlife Service, Stockton, CA. Seattle, WA: University of Washington, School of Aquatic and Fishery Sciences.
- Pien, C., R. Hartman, E. Bush, P. Lehman, and B. Davis. 2024. Thermal Stress and Suitability for Aquatic Species in the San Francisco Estuary. *Preprints.org*, <https://doi.org/10.20944/preprints202409.1890.v1>
- Poulton, V. K., J. R. Lovvorn, and J. Y. Takekawa. 2002. Clam Density and Scaup Feeding Behavior in San Pablo Bay, California. *The Condor* 104:218–527.
- Power, M. E., S. Chandra, P. Gleick, and W. E. Dietrich. 2024. Anticipating responses to climate change and planning for resilience in California’s freshwater ecosystems. *PNAS* 121(32): e2310075121.
- Preece, E. P., T. G. Otten, and J. Cooke. 2024a. Use of multiple sampling techniques for cyanobacteria and cyanotoxin monitoring in the Sacramento-San Joaquin Delta under different hydrologic regimes. *Marine Pollution Bulletin* 205:116585.
- Preece, E., M. Berg, T. Lee, K. Odkins, and J. Rinde. 2024b. *Cyanobacterial Harmful Algal Bloom Monitoring Strategy for the Sacramento-San Joaquin Delta*.
- Preece, E. P. and R. Hartman. 2024. Exploring factors that affect *Microcystis* abundance in the Sacramento San Joaquin Delta. Journal Pre-proof. *Harmful Algae*, 102682. <https://doi.org/10.1016/j.hal.2024.102682>.
- Preece, E. P., H.W. Paerl, H.E. Plaas, and J. Cooke. 2025. From Drought to Deluge: Hydrologic Extremes Alter Nutrient-driven Harmful Cyanobacterial Blooms. *Environmental Pollution*, 382, 126731.
- Ray, R. A., R. A. Holt, and J. L. Bartholomew. 2012. Relationship between Temperature and *Ceratomyxa shasta*-Induced Mortality in Klamath River Salmonids. *J Parasitol* 98: 520–526.
- Rees, J. T. and L. A. Gershwin. 2000. Non-Indigenous Hydromedusae in California’s Upper San Francisco Estuary: Life Cycles, Distribution, and Potential Environmental Impacts. *Science Marina* 64:73–86.
- Reisenbichler, R. R. and S. P. Rubin. 1999. Genetic Changes from Artificial Propagation of Pacific Salmon Affect the Productivity and Viability of Supplemented Populations. *ICES Journal of Marine Science* 56:459–466.
- Riar, N., J. Crago, W. Jiang, L. A. Maryoung, J. Gan, and D. Schlenk. 2013. Effects of Salinity Acclimation on the Endocrine Disruption and Acute Toxicity of Bifenthrin in Freshwater and Euryhaline Strains of *Oncorhynchus mykiss*. *Environmental Toxicology and Chemistry* 32(12):2779–2785.

- Richman, S. R. and J. R. Lovvorn. 2004. Relative Foraging Value to Lesser Scaup Ducks of Native and Exotic Clams from San Francisco Bay. *Ecology* 14(4).
- Roos, M. 2005. Accounting for Climate Change. In *California Water Plan Update 2005 Volume 4, Reference Guide: Global Climate Change*. Sacramento, CA: Department of Water Resources.
- Roos, M. 2012. *Snowpack and Snowmelt Changes*. January 3.
- Sabal, M., S. Hayes, J. Merz, and J. Setka. 2016. Habitat Alterations and a Nonnative Predator, the Striped Bass, Increase Native Chinook Salmon Mortality in the Central Valley, California. *North American Journal of Fisheries Management* 36:309–320.
- Sacramento-Yolo Mosquito and Vector Control District. 2014. *2014 Annual Report*. Elk Grove and Woodland, CA.
- San Francisco Bay Regional Water Quality Control Board (San Francisco Bay Regional Water Board). 2007. Resolution R2-2008-0012. *Amending the Water Quality Control Plan to Establish a Total Maximum Daily Load and Implementation Plan for PCBs in the San Francisco Bay*. California Reporting, LLC. Board hearing transcripts.
- Sands, A. and G. Howe. 1977. An Overview of Riparian Forests in California: Their Ecology and Conservation. Pages 98–115 In *Importance, Preservation and Management of Riparian Habitat: A Symposium July 9, 1977, Tuscon, Arizona*. USDA Forest Service General Technical Report RM-43.
- Santos, M., I. Anderson, and S. Ustin. 2011. Effects of Invasive Species on Plant Communities at the Regional Scale. *Biological Invasions* 13(2):443–457.
- Santos, M., S. Khanna. E. Hestir, J. Greenberg, and S. Ustin. 2016. Measuring Landscape-Scale Spread and Persistence of an Invaded Submerged Plant Community from Airborne Remote Sensing. February. *Ecological Applications* 26(6):1733–1744.
- Sañudo-Wilhelmy, S. A., L. S. Cutter, R. Durazo, E. A. Smail, L. Gómez-Consarnau, E. A. Webb, M. G. Prokopenko, W. M. Berelson, and D. M. Karl, 2012. Multiple B-Vitamin Depletion in Large Areas of the Coastal Ocean. *Proceedings of the National Academy of Sciences*, 109(35):4041–14045.
- Schoellhamer, D. H., T. E. Mumley, and J. E. Leatherborrow. 2007. Suspended Sediments and Sediment-Associated Contaminants in San Francisco Bay. *Environmental Research* 105:119–131.
- Schultz, R. and E. Dibble. 2012. Effects of Invasive Macrophytes on Freshwater Fish and Macroinvertebrate Communities: The Role of Invasive Plant Traits. *Hydrobiologia* 684:1–14.
- Senn, D.B., E. Spotswood, and A. Malkassian. 2016. *Synthesis of Current Science: Influence of Nutrient Forms and Ratios on Phytoplankton Production and Community Composition*. San Francisco Estuary Institute Contribution No. 862. November.
- Sierra Nevada Watershed Improvement Program. 2018. *Sierra Nevada Watershed Improvement Program Regional Strategy*.
- Smith, D. J. 2016. Presentation July 11, 2016, to the State Water Resources Control Board.
- Sommer, T. R., M. L. Nobriga, W. C. Harrell, W. Batham, and W. J. Kimmerer. 2001. Floodplain Rearing of Juvenile Chinook Salmon: Evidence of Enhanced Growth and Survival. *Canadian Journal of Fisheries and Aquatic Sciences* 58:325–333.

- Spence, B. C., G. A. Lomnický, R. M. Hughes, and R. P. Novitski. 1996. *An Ecosystem Approach to Salmonid Conservation*. TR-4501-96-6057. Corvallis, OR: ManTech Corp. Funded by National Marine Fisheries Service, U.S. Fish and Wildlife Service and the U.S. Environmental Protection Agency. Available: https://www.westcoast.fisheries.noaa.gov/publications/reference_documents/the_mantech_report.html. Accessed: January 10, 2019.
- State Water Resources Control Board (SWRCB). 2023. *Major State-Funded Sacramento Project to Provide Environmental, Water Recycling Benefits*. Media Release. May 19. Sacramento, CA.
- Stewart A. R., S. N. Luoma, C. E. Schlekot, M. A. Doblin, and K. A. Hieb. 2004. Food Web Pathway Determines How Selenium Affects Aquatic Ecosystems: a San Francisco Bay Case Study. *Environmental Science & Technology* (38):4519–4526.
- Stillway, M., B. Hammock, A. Cruz, D. Hernandez, I. Flores-Avila C. Teh, T. Kurobe, J. Jin, and S. Teh. 2016. *Food Web Impacts of Invasive Aquatic Weed Control in the Sacramento-San Joaquin Delta*. Bay-Delta Science Conference 2016. Oral Presentation.
- Stocking, R. W., R. A. Holt, J. S. Foott, and J. L. Bartholomew. 2006. Spatial and Temporal Occurrence of the Salmonid Parasite *Ceratomyxa shasta* in the Oregon–California Klamath River Basin. *Journal of Aquatic Animal Health*, 18(3):194–202.
- Strong, A. L., M. M. Mills, I. B. Huang, G. L. van Dijken, S. E. Driscoll, G. M. Berg, R. M. Kudela, S. G. Monismith, C. A. Francis, and K. R. Arrigo. 2021. Response of Lower Sacramento River phytoplankton to high-ammonium wastewater effluent. *Elementa: Science of the Anthropocene* 9(1):040.
- Sturrock, A. M., M. Ogaz, K. Neal, N. J. Corline, R. Peek, D. Myers, S. Schluep, M. Levinson, R.C. Johnson, and C.A. Jeffres. 2022. Floodplain trophic subsidies in a modified river network: managed foodscapes of the future? *Landscape Ecology* 37:2991–3009.
- Suffridge, C.P., Bolaños, L.M., Bergauer, K., Worden, A.Z., Morré, J., Behrenfeld, M.J. and Giovannoni, S.J., 2020. Exploring vitamin B1 cycling and its connections to the microbial community in the North Atlantic Ocean. *Frontiers in Marine Science*, 7, p.606342.
- Suffridge, C. P., L. Gómez-Consarnau, D. R. Monteverde, L. Cutter, J. Arístegui, X. A. Alvarez-Salgado, J. M. Gasol, and S. A. Sañudo-Wilhelmy. 2018. B Vitamins and Their Congeners as Potential Drivers of Microbial Community Composition in an Oligotrophic Marine Ecosystem. *Journal of Geophysical Research: Biogeosciences*, 123(9):2890–2907.
- Swain, D. L., B. Langenbrunner, J. D. Neelin, and A. Hall. 2018. Increasing precipitation volatility in twenty-first-century California. *Nature Climate Change* 8:427–433.
- Swanson, C., T. Reid, P. S. Young, and J. J. Cech, Jr. 2000. Comparative Environmental Tolerances of Threatened Delta Smelt (*Hypomesus transpacificus*) and Introduced Wakasagi (*H. nipponensis*) in an Altered California Estuary. *Oecologia* 123:384–390.
- Tadesse, D. 2016. *Constituents of Emerging Concerns (CECs) Statewide Pilot Study Monitoring Plan*. State Water Board, Surface Water Ambient Monitoring Program, Office of Information Management and Analysis.

- Teh, S. J., D. F. Deng, I. Werner, F. C. Teh, and S. S. O. Hung. 2005. Sublethal Toxicity of Orchard Stormwater Runoff in Sacramento Splittail (*Pogonichthys macrolepidotus*) Larvae. *Marine Environmental Research* 59:203–216.
- Teh, S., I. Flores, M. Kawaguchi, S. Lesmeister, and C. Teh. 2011. *Final Report: Full Life-Cycle Bioassay Approach to Assess Chronic Exposure of Pseudodiaptomus forbesi to Ammonia/Ammonium*. University of California Davis.
- Tetra Tech, Inc. and Wetlands and Water Resources (Tetra Tech and WWR). 2013. *Suisun Marsh Conceptual Model— Impairment Assessment Report for Organic Enrichment, Dissolved Oxygen, Mercury, Salinity and Nutrients*. November 26. Prepared for the San Francisco Bay Regional Water Quality Control Board.
- U.S. Army Corps of Engineers and California Department of Fish and Game (USACE and CDFG). 2010. *Newhall Ranch Resource Management and Development Plan and Spineflower Conservation Plan*. SCH No. 20000011025, Final Joint Environmental Impact Statement and Environmental Impact Report prepared by the Newhall Land and Farming Company for the U.S. Army Corps of Engineers and California Department of Fish and Game, Los Angeles.
- U.S. Bureau of Reclamation (Reclamation) and California Department of Water Resources (DWR). 2019. *Yolo Bypass Salmonid Habitat Restoration and Fish Passage Final Environmental Impact Statement/Environmental Impact Report*. May.
- U.S. Bureau of Reclamation (Reclamation) 2016a. *Battle Creek Salmon and Steelhead Restoration Project—about the Project*. Last Updated February 25, 2016. Mid-Pacific Region. Available: <https://www.usbr.gov/mp/battlecreek/about.html>. Accessed: October 23, 2019.
- U.S. Bureau of Reclamation (Reclamation). 2016b. *Draft Workplan for Shasta and Trinity Division Seasonal Operational Water Temperature Modeling*. Mid-Pacific Region.
- U.S. Bureau of Reclamation (Reclamation). 2019. *Temperature-Related Monitoring Priorities: Reclamation 2018 Draft Activities Matrix Monitoring*.
- U.S. Bureau of Reclamation and U.S. Fish and Wildlife Service (Reclamation and USFWS). 2018. *Central Valley Project Improvement Act—2019 Annual Work Plan*. Public Draft. Title XXXIV of Public Law 102-575.
- U.S. Environmental Protection Agency (USEPA). 1986. *Ambient Water Quality Criteria for Dissolved Oxygen*. Office of Water. EPA 440/5-86-003.
- U.S. Environmental Protection Agency (USEPA). 1997. *Mercury Study Report to Congress Vol. 7: Characterization of Human Health and Wildlife Risks from Mercury Exposure in the United States*. Office of Air Quality Planning and Standards and Office of Research and Development.
- U.S. Environmental Protection Agency (USEPA). 2013. *Aquatic Life Ambient Water Quality Criteria for Ammonia—Freshwater*. April. Office of Water, Office of Science and Technology: Washington, D.C.
- U.S. Fish and Wildlife Service (USFWS). 2004. *Reinitiation of Formal and Early Section 7 Endangered Species Consultation on the Coordinated Operations of the Central Valley Project and State Water Project and the Operational Criteria and Plan to Address Potential Critical Habitat Issues*. Biological Opinion. February 15. Sacramento Fish and Wildlife Office, Sacramento, CA.

- U.S. Fish and Wildlife Service (USFWS). 2010. Flow-Habitat Relationships for Juvenile Fall/Spring Run Chinook Salmon and Steelhead/Rainbow Trout Rearing in the Yuba River. Yuba River Rearing Report. Sacramento Fish and Wildlife Office, Sacramento, CA.
- U.S. Fish and Wildlife Service (USFWS). 2014. Diversion Dam Removal Improves Habitat for Migrating Fish in Tehama County. News Release. Red Bluff Fish and Wildlife Office, Red Bluff, CA.
- U.S. Geological Survey (USGS). 2012. *Organochlorine Pesticides and PCBs in Aquatic Ecosystems of the Central Columbia Plateau*. USGS Fact Sheet 170-96.
- University of California, Santa Cruz (UC Santa Cruz). 2015. *Assessing SPATT in San Francisco Bay*. SFEI Contract 1051. Final Report. Submitted to San Francisco Estuary Institute.
- Villamagna, A. M. and B. R. Murphy. 2010. Ecological and Socio-Economic Impacts of Invasive Water Hyacinth (*Eichhornia crassipes*): a review. *Freshwater Biology* 55(2):282–298.
- Vivekanandhan, N. and A. Duraisamy. 2012. Ecological Impact of Pesticides Principally Organochlorine Insecticide Endosulfan: A Review. *Universal Journal of Environmental Research and Technology* 2(5):369–376.
- Vogel, D. 2013. *Evaluation of Fish Entrainment in 12 Unscreened Sacramento River Diversions*. Final Report. Prepared for CVPIA Anadromous Fish Screen Program (U.S. Fish and Wildlife Service and U.S. Bureau of Reclamation) and Ecosystem Restoration Program (California Department of Fish and Wildlife).
- Vuori, K.A. and M. Nikinmaa. 2007. M74 Syndrome in Baltic Salmon and the Possible Role of Oxidative Stresses in Its Development: Present Knowledge and Perspectives for Future Studies. *AMBIO: A Journal of the Human Environment*, 36(2):168–172.
- Waples, R. S. 1991. Pacific Salmon, *Oncorhynchus* spp., and the Definition of “Species” under the Endangered Species Act. *Marine Fisheries Review* 53(3):11–22.
- Water Science and Technology Board, Ocean Studies Board, Division on Earth and Life Studies, and National Research Council. 2012. *Sustainable Water and Environmental Management in the California Bay-Delta*.
- Werner, I., L. A. Deanovic, D. Markiewicz, J. Khamphanh, C. K. Reece, M. Stillway, and C. Reece. 2010a. Monitoring Acute and Chronic Water Column Toxicity in the Northern Sacramento–San Joaquin Estuary, California, USA, Using the Euryhaline Amphipod, *Hyaella azteca*: 2006–2007. *Environmental Toxicology and Chemistry* 29:2190–2199.
- Werner, I., D. Markiewicz, L. Deanovic, R. Connon, S. Beggel, S. Teh, M. Stillway, and C. Reece. 2010b. *Pelagic Organism Decline (POD): Acute and Chronic Invertebrate and Fish Toxicity Testing in the Sacramento–San Joaquin Delta 2008–2010*. Final Report. University of California, Davis–Aquatic Toxicology Laboratory, Davis, CA.
- Weston, D. P., M. Zhang, and M. J. Lydy. 2008. Identifying the Cause and Source of Sediment Toxicity in an Agriculture-Influenced Creek. *Environmental Toxicology and Chemistry* 27(4):953–962.
- Weston, D. P., A. M. Asbell, S. A. Lesmeister, S. J. Teh, and M. J. Lydy. 2014. Urban and Agricultural Pesticide Inputs to a Critical Habitat for the Threatened Delta Smelt (*Hypomesus transpacificus*). *Environmental Toxicology and Chemistry* 33(4):920–929.

- Wilkerson, F., R. C. Dugdale, V. E. Hogue, and A. Marchi. 2006. Phytoplankton Blooms and Nitrogen Productivity in San Francisco Bay. June. *Estuaries and Coasts* 29(3):401–416.
- Williams, A. P., E. R. Cook, J. E. Smerdon, B. I. Cook, J. T. Abatzoglou, K. Bolles, S. H. Baek, A. M. Badger, and B. Livneh. 2020. Large Contribution from Anthropogenic Warming to an Emerging North American Megadrought. *Science* 368:314–318.
- Williams, A. P., R. Seager, J. T. Abatzoglou, B. I. Cook, J. E. Smerdon, and E. R. Cook. 2015. Contribution of Anthropogenic Warming to California Drought During 2012–2014. *Geophysical Research Letters* 42:6819–6828.
- Wintzer, A. P., M. H. Meek, and P. B. Moyle. 2011. Trophic Ecology of Two Non-Native Hydrozoan Medusae in the Upper San Francisco Estuary. *Marine and Freshwater Research* 62(8):952–961.
- Wood, M., C. Foe, J. Cooke, and S. Louie. 2010. *Sacramento–San Joaquin Delta Estuary TMDL for Methylmercury*. Staff Report for the Regional Water Quality Control Board, Central Valley Region. April.
- Yelton, R., A. M. Slaughter, and W. J. Kimmerer. 2022. Diel Behaviors of Zooplankton Interact with Tidal Patterns to Drive Spatial Subsidies in the Northern San Francisco Estuary. *Estuaries and Coasts* 45:1728–1748.
- York, J. K., G. B. McManus, W. J. Kimmerer, A. M. Slaughter, and T. R. Ignoffo. 2013. Trophic Links in the Plankton in the Low Salinity Zone of a Large Temperate Estuary: Top-Down Effects of Introduced Copepods. *Estuaries and Coasts* 37(3):576–588.
- Yoshiyama, R. M., P. B. Moyle, E. R. Gerstung, and F. W. Fisher. 2000. Chinook Salmon in California Central Valley: An Assessment. *Fisheries* 25(2):6–20.
- Zedler, J. B. 1988. Restoring Diversity in Salt Marshes Can We Do It? In National Academy of Sciences. *Biodiversity*. Washington, DC: The National Academies Press.