

RESEARCH

Climate Change Effects on San Francisco Estuary Aquatic Ecosystems: A Review

Bruce Herbold¹, Eva Bush², Gonzalo Castillo³, Denise Colombano⁴, Rosemary Hartman⁵, Peggy Lehman⁶, Brian Mahardja⁷, Ted Sommer⁸

ABSTRACT

Climate change is intensifying the effects of multiple interacting stressors on aquatic ecosystems worldwide. In the San Francisco Estuary, signals of climate change are apparent in the long-term monitoring record. Here we synthesize current and potential future climate change effects on three main ecosystems (floodplain, tidal marsh, and open water) in the

upper estuary and two representative native fishes that commonly occur in these ecosystems (anadromous Chinook Salmon, *Oncorhynchus tshawytscha* and estuarine resident Sacramento Splittail, *Pogonichthys macrolepidotus*). Based on our review, we found that the estuary is experiencing shifting baseline environmental conditions, amplification of extremes, and restructuring of physical habitats and biological communities. We present priority topics for research and monitoring, and a conceptual model of how the estuary currently functions in relation to climate variables. In addition, we discuss four tools for management of climate change effects: regulatory, water infrastructure, habitat development, and biological measures. We conclude that adapting to climate change requires fundamental changes in management.

SFEWS Volume 20 | Issue 2 | Article 1

<https://doi.org/10.15447/sfew.2022v20iss2art1>

* Corresponding author: bherbold@gmail.com

- 1 Private consultant, subcontracted to AECOM
Oakland, CA 94610 USA
- 2 Delta Stewardship Council
Delta Science Program
Sacramento, CA 95814 USA
- 3 US Fish and Wildlife Service
Sacramento, CA 95825 USA
- 4 University of California, Berkeley
Department of Environmental Science,
Policy, and Management
Berkeley, CA 94720 USA
- 5 California Department of Water Resources
Sacramento, CA 95814 USA
- 6 California Department of Fish and Wildlife
Stockton, CA 95206 USA
- 7 US Bureau of Reclamation
Sacramento, CA 95825 USA
- 8 California Department of Water Resources (retired)
Davis, CA 95616 USA

KEY WORDS

Chinook Salmon, Sacramento Splittail, tidal marsh, floodplain, open water, drought, flood

INTRODUCTION

Climate change is reshaping biological communities worldwide and estuaries are no exception (Cloern et al. 2016; Lauchlan and Nagelkerken 2020). The San Francisco Estuary (estuary) is subjected to extreme seasonal and

annual variation from regional and global atmospheric and oceanic forcing (Cloern and Jassby 2012) that contribute to difficult problems for management (Luoma et al. 2015). Increasing trends in climate-related variables (e.g., water temperature, sea level, drought duration) and climatic extremes (e.g., strong atmospheric rivers, record heat waves), are creating estuarine conditions outside the historic range of conditions (Cloern et al. 2011). As a result, understanding the ecology of the estuary is now inextricably linked to understanding the cumulative effect of multiple interacting stressors (Orr et al. 2020)—resulting from both climate change and management—on environmental and biological processes.

Environmental conditions have been monitored in the estuary since the early 20th century, and consistent monitoring of fishes goes back to the 1950s. These data show that since the 1980s:

1. Peak flows and floodplain inundations occur earlier in the year, are shorter in duration, and are more intense than historically (Cloern et al. 2011; Wang et al. 2018; He et al. 2019).
2. An uptrend in salinity intrusion is greater in the Spring than in the Summer–Fall (July–October vs. February–June; Hutton et al. 2021).
3. Water temperature is rising, primarily during the late Fall to Winter and mid-Spring (Bashevkin et al. 2022).
4. Changes in environmental conditions are concordant with a decline in many native species and an increase in many alien species (Cloern 2007; Winder and Jassby 2011).

To identify the effects of these changes on ecosystems and species in the estuary, we reviewed the literature and the environmental data for climate and climate-related effects. We focused the review on two representative fish species—the anadromous Chinook Salmon (*Oncorhynchus tshawytscha*) and the resident Sacramento Splittail (*Pogonichthys macrolepidotus*)—and on three aquatic ecosystems in the upper estuary that are used by those

species: floodplain, tidal marsh, and open water. This work builds on an extensive literature review of climate effects on the estuary by the Interagency Ecological Program (IEP) Climate Change Team (CC MAST 2022). We also build on recent climate-related discussions about effects and adaptation (Ghalambor et al. 2021; Norgaard et al. 2021). Our goal is to identify priority topics for research and monitoring that can facilitate sound management of the estuary under climate change.

FINDINGS

Effects of Climate Change

Global warming significantly increased air temperature in California during the 20th century (Figure 1A and 1B), a trend expected to increase by an additional 1.5 °C to 4.5 °C by 2100 (Cayan et al. 2008; Knowles et al. 2018; Pierce et al. 2018; IPCC 2021). In the estuary, air temperature is a key driver of water temperature, which has increased by approximately 0.85 °C in the past 50 years (Bashevkin et al. 2022). However, the rate of temperature change exhibits considerable seasonal and regional variability, with the highest rates detected during winter and spring and in the northern Sacramento–San Joaquin Delta (Delta) (Bashevkin et al. 2022). Warmer temperature not only directly affects organisms by altering physiological processes but can interact with other environmental factors, such as contaminants, to increase effects on aquatic organisms (Brooks et al. 2012; DeCourten et al. 2017, 2019; Kolomijeca 2020).

The Mediterranean climate of California consists of an extremely variable wet season from October through March, and a dry season the rest of the year (Knowles et al. 2018). Warming air temperature in the winter increases the amount of precipitation arriving as rain rather than snow (Stewart et al. 2005; Reich et al. 2018; Knowles et al. 2018) and leads to a decrease in the snowpack (Knowles et al. 2006; Mote et al. 2018). Warmer air temperatures reduce the moisture content of the snowpack (Cayan et al. 2008), shift the timing of snowmelt to earlier in the year, and decrease its duration (Huang et al. 2020).

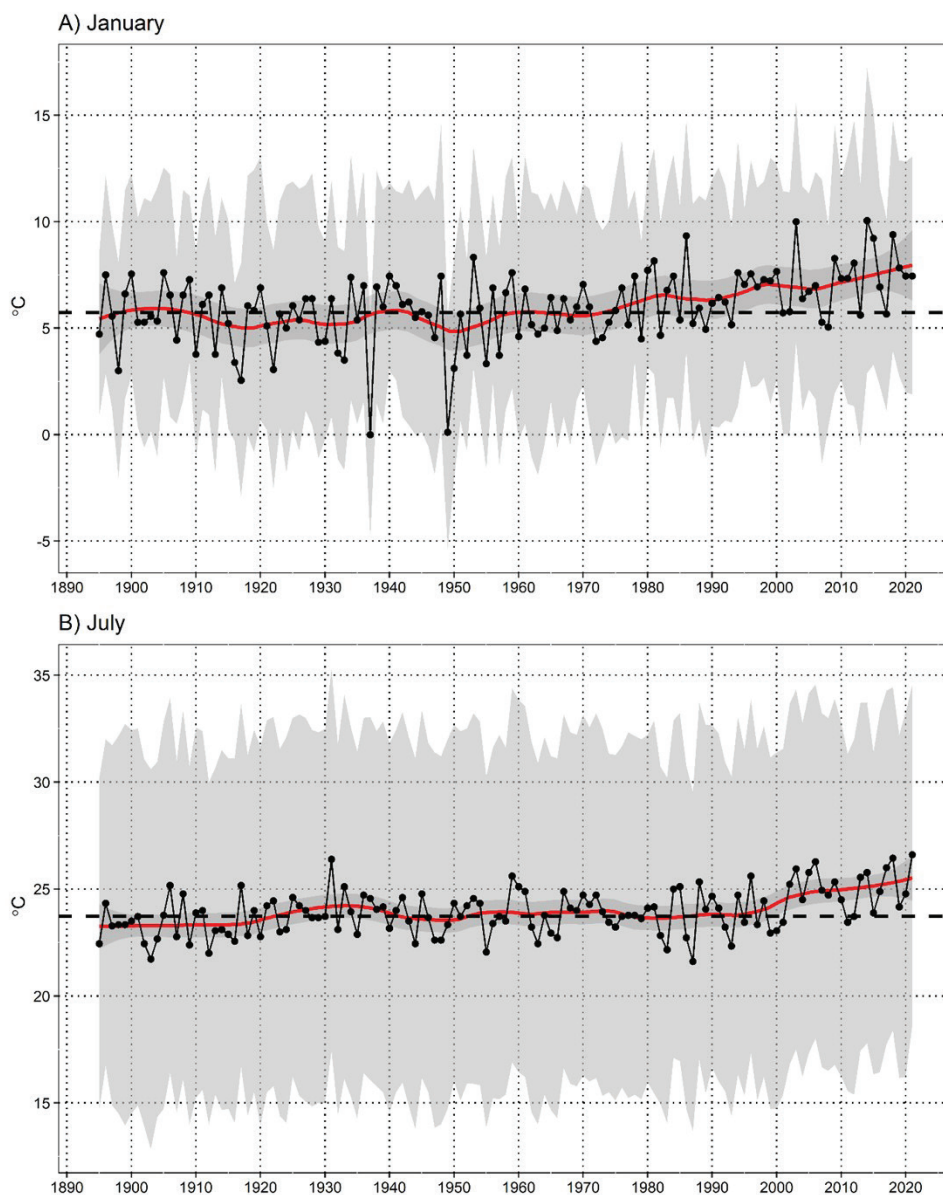


Figure 1 California statewide air temperature time series from US Climate Divisional Database (<https://www.ncdc.noaa.gov/cag/statewide/time-series>) for January (i.e., the coldest month of the year) and July (i.e., the warmest month of the year). *Points* represent average temperature for the month and year, *black dashed line* represents the average temperature for the month between 1901 and 2000, and *outer grey shading* represents the maximum and minimum temperatures. The *red line* and *darker grey shading* represent the LOESS smooth line for average temperature points and the 95% confidence intervals, respectively (fraction of points used to fit local regression = 0.25).

Winter precipitation as rain, reduced retention of precipitation as snow, and low moisture content of the snowpack (Dettinger et al. 2016; Luković et al. 2021)—in combination with an increase in the frequency and intensity of severe storms (Das et al. 2013; Knowles et al. 2018; Swain et al. 2018)—creates a new hydrologic regime. Daily rainfall totals are projected to increase by 5% to 20% (Pierce et al. 2018). This increase in storm frequency and intensity leads to record floods in California, where storms are already more variable and extreme than in the rest of the United States (Ralph and Dettinger 2012). Patterns

of freshwater flow from 1906 to 2020, the longest record available in the estuary, show strong seasonal and annual variation driven by winter and spring precipitation and wet and dry regimes (Figure 2A and 2B). Consecutive wet years have not occurred in the estuary since 1996-1999, while consecutive dry and critical years have occurred three times. Overall, rising regional temperatures are expected to further intensify changes in the timing and magnitude of freshwater flow into the estuary, including “weather whiplash” scenarios characterized by rapid transitions between

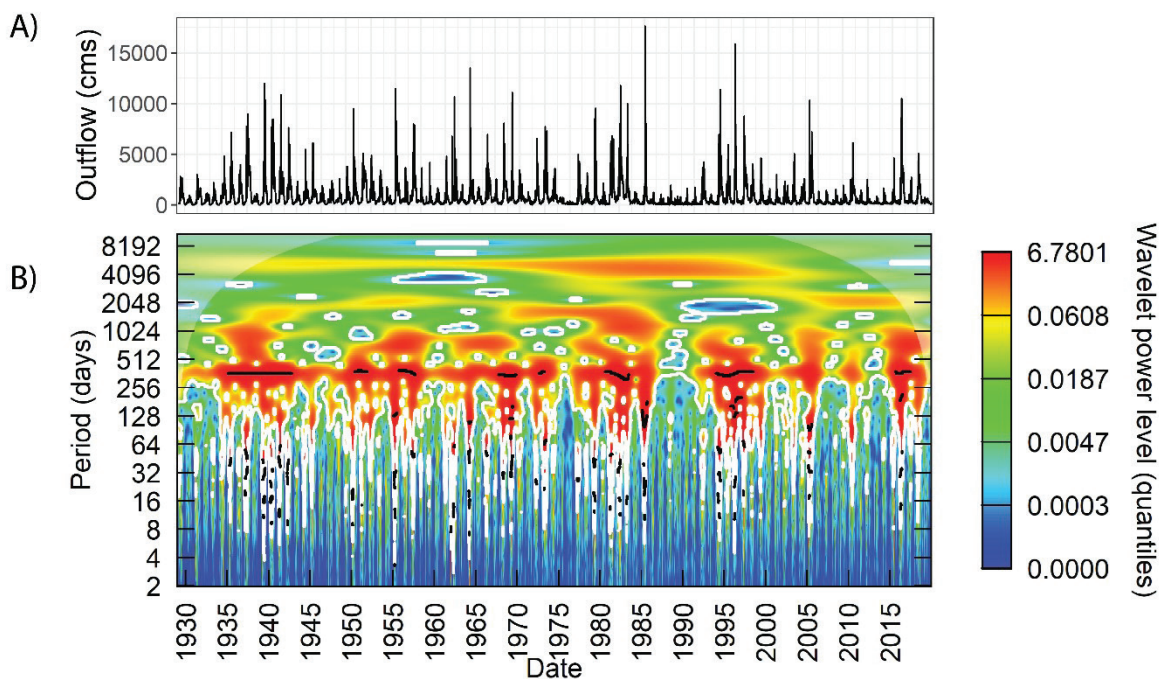


Figure 2 (A) Daily net Delta outflow (m^3s^{-1}) estimated for Chipps Island from 1929 to 2020. (B) A wavelet plot for estuary outflow (Roesch and Schmidbauer 2018). Wavelet power levels (*color scale*) represent the strength (amplitude) of periodicity in outflow across the different scales (*y-axis*, in days) and over the years (*x-axis*). For example, the annual scale (period = ~ 365 days) shows variation in wavelet power that was often strong (*color = red*; *line = black*), reflecting annual fluctuations in flow that are characteristic of California's Mediterranean climate. Transitions from *red* to *non-red* areas represent hydrologic regime shifts (e.g., a shift to extreme drought in the late 1980s and early 1990s). Data source: CDWR 2021.

extreme wet and dry conditions (Swain et al. 2018).

The high decadal-scale variability that has characterized climate in the eastern Pacific over the past 4 centuries (Biondi et al. 2001) also includes drought. Drought is not new to California (Stahle et al. 2011), but increasing temperatures increase the likelihood of precipitation deficits co-occurring with warm conditions (Diffenbaugh et al. 2015). Drought is three to four times more likely today than in pre-industrial times in California (Swain et al. 2018), and anthropogenic warming intensifies recent droughts (Williams et al. 2020). Future droughts are likely to be longer, warmer, and drier than the recent extreme drought of 2012-2016 (Meko et al. 2014; Dettinger et al. 2016). Extreme drought will further influence ecosystems in the estuary through the effect of salinity intrusion (Ghalambor et al. 2021). Sea level rose 20 cm over the 20th century, and

conservative estimates indicate it will rise by another 20 to 170 cm by 2100 (Flick et al. 2003; NRC 2012). Paleoclimatic data, when combined with climate change projections, suggest a sea level rise of several meters over 50 to 150 years is possible (Hansen et al. 2016). Modeling studies suggest a sea level rise of 140 cm could shift the estuary's salinity field landward by 7 km (MacWilliams and Gross 2010).

Human activities have transformed the estuary landscape over the last 150 years, eliminating most of the natural habitats and drastically altering the hydrodynamics (Whipple et al. 2012). Upstream dams, infrastructure, water diversion, and land use substantially alter the hydrograph, water quality, and the distribution and abundance of native species (Brown et al. 2010; Moyle et al. 2010). For example, in low-precipitation years, upstream and Delta diversions take a large proportion of available water, which increases

salinity intrusion (Moyle et al. 2010; Castillo et al. 2018). In high-precipitation years after droughts, replenishing water in depleted reservoirs becomes a priority, which can reduce the amount of water released downstream from dams (Reis et al. 2019). The increased frequency of drought under climate change is likely to enhance other stressors with a variety of synergistic interactions (Bennett and Moyle 1996; Brook et al. 2008; Castillo 2019). As climate change progresses, untangling and anticipating these multiple interacting stressors will be essential to management (Orr et al. 2020; Carrier-Belleau et al. 2021).

In addition to the direct effect of environmental stressors on species, climate change also affects species interactions and foodweb structure. The estuary has been invaded by hundreds of non-native species at every trophic level (Cohen and Carlton 1998), resulting in an unprecedented combination of species and fundamentally altered food-web dynamics (Winder and Jassby 2011; Moyle 2014). Many of these non-native species have had unpredictable, usually harmful, consequences to Delta fish communities and ecosystems described as the “Frankenstein effect” (Moyle 1999). Climate change may continue to favor invaders that are highly tolerant of warm temperatures (Moyle et al. 2013), such as Largemouth Bass (*Micropterus salmoides*), Inland Silverside (*Menidia beryllina*), and Brazilian waterweed (*Egeria densa*) (Brown and Michniuk 2007; Conrad et al. 2016; Mahardja et al. 2016, 2017). In addition, more non-native species are expected to invade the estuary, with uncertain consequences to ecosystem function and native species persistence (Moyle et al. 2013).

The effects of climate change on the estuary thus occur within an array of interacting anthropogenic and natural factors. We do not address the likely, but indeterminate, effects of climate change on levee stability and water project operations. The linkages in the estuary between global climate change and regional physical effects and local ecosystem processes are illustrated in [Figure 3](#).

Biota of Interest

We focus on two management-relevant and ecologically distinct native fish species that can be found in all three ecosystems: the anadromous Chinook Salmon and the estuarine resident Sacramento Splittail. Anadromous species migrate from rivers to the ocean and back and are thus only exposed to estuarine conditions for part of the year. Variation in their overall abundance may be partially determined by conditions elsewhere. Resident species are exposed to environmental conditions in the estuary year-round so fluctuations in their abundance reflect conditions in the estuary.

Chinook Salmon

The Central Valley contains the southernmost populations of Chinook Salmon, which were exceptionally abundant before the mid-20th Century. Fish would mature in the ocean for up to 5 years before migrating into rivers of the Central Valley to spawn and die in the cold water their eggs require. Young grow in their natal streams for weeks, or as much as a year before migrating through the Delta to the ocean. Dams blocked access to most traditional spawning grounds, and agriculture and urban development eliminated much of the habitat used by growing and migrating young fish (Moyle 2002). All runs are now seriously depleted.

Four different runs of Chinook Salmon are found in the Central Valley, named for the season when the adults migrate from the ocean through the Delta on their way to riverine spawning grounds (Moyle 2002; Yoshiyama et al. 2011). Fall-run and late-fall-run fish spawn shortly after their upstream migration, and the young move out during the subsequent spring. Spring-run and winter-run adults hold for various lengths of time after migrating to their spawning grounds, and their young hold for various lengths of time before outmigrating (Moyle 2002). Spring run and winter run are currently listed as threatened and endangered (81 FR 33468 and 70 FR 37160), respectively, under the federal Endangered Species Act (USFWS 2003). As climate change continues, the decline of Chinook Salmon abundance is accelerating (Munsch et al. 2019;

Climate change alterations to the timing, frequency, magnitude, and spatial extent of environmental drivers, and impacted ecosystems

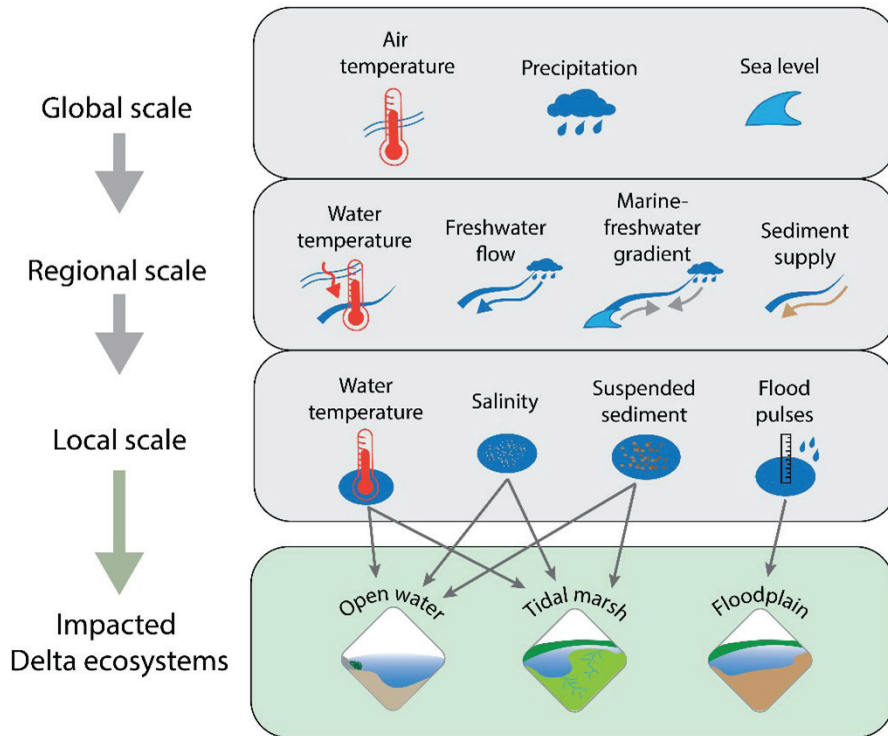


Figure 3 Schematic of the key climate change impacts on Delta ecosystems. Spatial down-scaling is represented with arrows from global, regional, and local scales (grey arrows and panels) to open water, tidal marsh, and floodplain ecosystems (green arrow and panel).

Cordoleani et al. 2021), as predicted in climate change vulnerability assessments nearly a decade ago (Katz et al. 2013; Moyle et al. 2013; Quiñones and Moyle 2014).

Sacramento Splittail

Sacramento Splittail is a large, long-lived, cyprinid fish that is endemic to the estuary although some movement upstream is common; years in which the bypasses flood are associated with large production of young (Moyle et al. 2004). Splittail consist of two genetically distinct populations: one that spawns in the Central Valley and another that spawns in the Petaluma and Napa rivers around San Pablo Bay (Baerwald et al. 2007). Although the two populations are largely reproductively isolated from one another, spatial overlap occurs during wetter years when salinity is low throughout the upper estuary (Feyrer et al. 2015; Mahardja et al. 2015). Sacramento Splittail is a California Species of Special Concern (Moyle et al. 2015) and was listed as a threatened

species by the U.S. Fish and Wildlife Service from 1995 to 2003 (USFWS 2003; Sommer et al. 2007). More recently, climate change vulnerability assessments determined that Splittail populations are vulnerable to extinction from climate change effects on the estuary (Moyle et al. 2013).

Aquatic Ecosystems of Interest

We examine three contrasting ecosystems—floodplains, tidal marshes, and open water—to provide insights into effects of climate change. Historically, the upper estuary was an expansive habitat mosaic featuring rivers, floodplains, tidal sloughs, tidal marshes, and deep and shallow bays (Whipple et al. 2012). Starting with the California Gold Rush and the annexation of California by the United States in 1850, rapid development via urbanization, agriculture, commerce, and water conveyance transformed the estuary into an open-water-dominated system (Nichols et al. 1986). Currently, there is a large emphasis on improving the ecological conditions of the upper estuary

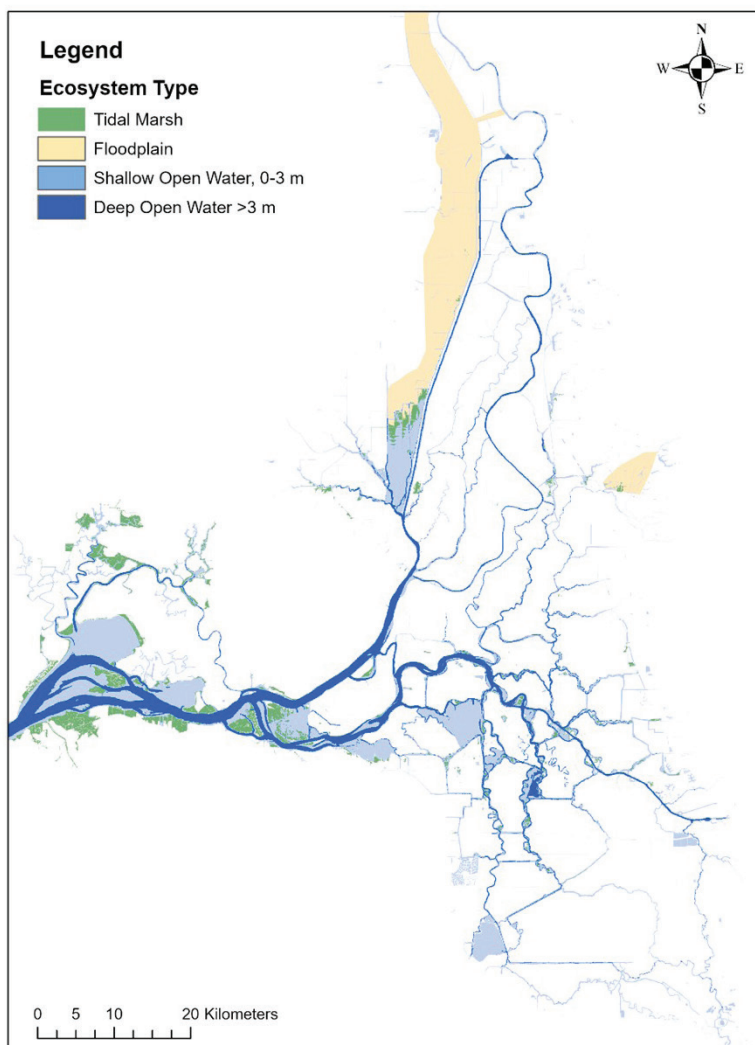


Figure 4 Map of three aquatic ecosystem types in the upper San Francisco Estuary: floodplain (*yellow*), tidal marsh (*green*), and open water (*blue*). Data sources: SFEI 2017, 2020; Fregoso et al. 2017.

by restoring habitat complexity and variability (Moyle et al. 2010; EcoRestore 2021; Sherman et al. 2017; Young et al. 2018; Cloern et al. 2021). However, the extent to which climate change affects floodplains, tidal marshes, and open-water ecosystems and their current distribution (Figure 4) warrants further investigation because each is the target of major management actions.

Floodplain

Levees and water management block inundation of much of the historic floodplain habitat in the upper estuary and Central Valley (Opperman et al. 2017). However, remnant floodplains such as the Yolo Bypass and Cosumnes River floodplains provide benefits to a variety of native aquatic species (Sommer, Harrell, and Nobriga et al. 2001;

Sommer, Nobriga, Harrell et al. 2001; Crain et al. 2004). The magnitude, frequency, duration, and seasonal timing of floodplain inundation is changing with climate. Floods are more likely to occur in the winter months (December through February) than in the spring (March through April), as precipitation from local rainfall—rather than snowmelt from the mountains—becomes the source of water (Dettinger et al. 2016). Although the magnitude and frequency of floods will increase, the duration of floods will decrease (DSC 2021). A decrease in the duration of floods can lead to an increase in flood intensity, making extreme flood events like the “Great Flood of 1862” more common (Swain et al. 2018). Extreme flood events larger than those in recent history are possible based on tree-ring chronologies

that date back 2,000 years (Meko et al. 2014) in the western region, and 1,000 years in the San Francisco Estuary (Hutton et al. 2021).

Floodplains and the species dependent on them are sensitive to the frequency, timing, duration, and intensity of floods (e.g., Takata et al. 2017; Zischg and Bermúdez 2020). Climate change alters the timing and duration of inundation. Inundation in the late winter and early spring enhances production at the base of the food web by stimulating the growth of phytoplankton, particularly diatoms (Lehman et al. 2008). Diatoms grow within a few days in the low light and cooler conditions of late winter and thrive in the high-flow conditions that promote vertical mixing in the floodplain (Lehman et al. 2008; Glibert et al. 2014). In contrast, insect larvae such as chironomids, an important macroinvertebrate food for juvenile fish, require 2 weeks or more of inundation to achieve maximum abundance (Benigno and Sommer 2008). Co-occurrence of the lower food-web production with fish abundance is essential to fish production in the floodplain (Grosholz and Gallo 2006; Moyle et al. 2007). As a result, shifts in the timing of seasonal flooding may pose a problem for energy transfer through the food web (Jardine et al. 2012).

The frequency and severity of droughts may also affect the resilience of the floodplain ecosystem. Severe or prolonged drought as we have seen in the last 20 years can damage the invertebrate egg bank on the floodplain, so that when inundation occurs, invertebrate populations are low (Bond et al. 2008). Few periods of inundation may limit the export of nutrients and phytoplankton that is needed to stimulate downstream food webs (Frantzich et al. 2018). In addition, fluctuation from drought to flood may affect the persistence of floodplain vegetation (Greet et al. 2011).

All four runs of outmigrating Chinook Salmon use floodplains in the estuary. In years when floodplains are inundated, juvenile salmon enter floodplains to feed on zooplankton and insect larvae, which are larger and more abundant than those in adjacent river channels (Jeffres et al. 2008; Limm and Marchetti 2009; Bellmore et al.

2013). As a result, juvenile Chinook Salmon that feed in floodplains during high-flow years have a high growth rate and enter the ocean at a larger size than those which only feed in river channels during low-flow years (Sommer, Nobriga, Harrell et al. 2001; Takata et al. 2017). Large fish tend to have high survival rates in the ocean, which can result in larger returns of spawning adults to rivers in subsequent years (Woodson et al. 2013; Willmes et al. 2018). Shorter durations of floodplain inundation from climate change may limit foraging opportunities for outmigrating juveniles or result in a temporal mismatch whereby flooding occurs too early for them to access floodplain resources (Jardine et al. 2012). Elevated air temperature can make the water in floodplains too warm for salmon; however, cooling of water with tide and evaporative cooling may contribute to the development of more favorable water temperature in the floodplain than in nearby sloughs (Enright et al. 2013; Aha et al. 2021).

Similar to Chinook Salmon, Splittail abundance is linked to floodplain inundation (Sommer et al. 1997), but climate-related effects on seasonal flooding can have a greater effect on Splittail populations. Adult Splittail migrate upstream into the floodplain during high-flow events in January and February (Sommer et al. 2014) and lay their eggs on flooded vegetation in March and April (Caywood 1974; Moyle et al. 2004). Early and/or short floodplain inundation periods adversely affect spawning success (Sommer et al. 1997; Sommer, Nobriga, Harrell et al. 2001). Inundated floodplains also provide safe migration corridors between spawning and rearing habitats, as well as brackish-shallow-water rearing habitat (Moyle et al. 2004).

Tidal Marsh

Tidal marsh was a dominant landscape feature in the historic estuary; however, extensive diking, draining, and conversion to agriculture (e.g., farmland, pasture) in the 19th and 20th centuries eliminated up to 98% of tidal marsh area and nearly all associated aquatic primary production (Cloern et al. 2021). The remaining tidal marshes are sparsely distributed throughout

the upper estuary and have received less attention from long-term aquatic monitoring programs (Brown 2003). Nevertheless, there is a growing recognition of the role that tidal marsh plays in the estuary food web and as key habitat for species of concern (Davis et al. 2019; Hammock et al. 2019; Colombano, Handley, O’Rear et al. 2021). Because of the various ecosystem services that tidal marsh can provide, extensive marsh restoration planning and implementation throughout the estuary is now underway (Herbold et al. 2014; Sherman et al. 2017).

Tidal marsh ecosystems face multiple interacting stressors from climate change (Colombano, Litvin, Ziegler et al. 2021), including rising sea level (Stralberg et al. 2011; Schile et al. 2014), shifting sediment dynamics (Barnard et al. 2013), and elevated temperature and salinity (Ghalambor et al. 2021; Bashevkin et al. 2022). While shading and evapotranspiration, nighttime flooding of the marsh plain, and Delta breezes may help maintain cool water temperatures in tidal marshes (Enright et al. 2013), the extent to which marshes can provide adequate thermal refugia and thus ameliorate the effects of warming on thermally sensitive fish species remains unclear.

Rising sea level increases the duration of tidal inundation of the marsh plain and, thus, the rates of sediment and organic matter accumulation. The capacity for marshes to resist and recover from disturbance (e.g., storm surges, drought) and to maintain elevation (i.e., relative position of the marsh surface with respect to tidal heights) depends on whether the annual rate of sediment and organic matter accumulation keeps pace with sea level rise (Cahoon and Gunterspergen 2010). How much sediment is delivered to marshes under different climate change scenarios remains uncertain. High flows as a result of strong atmospheric rivers in winter and spring may mobilize large amounts of sediment in pulses, which could increase the annual sediment supply to the estuary (Schoellhamer et al. 2018; Stern et al. 2020). Alternatively, sediment capture and flow regulation by dams, dredging, and other human effects influences will continue

to deprive the estuary of some of its upstream sediment supply (Wright and Schoellhamer 2004; Schoellhamer et al. 2013). Salinity intrusion and increased hydroperiod could further exacerbate physiological stress to freshwater and brackish vegetation (Ghalambor et al. 2021) and, with reduced sediment delivery, could ultimately result in marsh edge erosion, channel expansion, ponding, and drowning (e.g., sudden peat collapse and conversion to open water) (Cahoon et al. 2021). Under the latter scenario, marsh islands surrounded by water in the low-salinity zone (e.g., Sherman Island, Browns Island, Ryer Island) may be most vulnerable to sea level rise and drought. In contrast, interior marshes adjacent to upland transition zones (e.g., Rush Ranch in Suisun Marsh) may be able to migrate if there is sufficient upland connectivity and accommodation space (Kirwan et al. 2010; Knowles 2010; Buffington et al. 2021).

Marsh restoration and managed retreat are considered the primary mechanisms for marsh persistence in the estuary under climate change (Goals Project 2015). However, uncertainties surround tidal amplification vs. attenuation, and different areas will likely respond differently. Where shorelines remain armored with levees for flood control, sea level rise may increase tidal amplitude; however, if widespread marsh restoration occurs and/or low-lying areas flood with tidal waters, then tidal amplitude may decrease (Holleman and Stacey 2014). Because tidal forcing is critical to site-level marsh geomorphology, habitat availability, and food production and transport, changes in tidal amplitude have profound ecological implications (Ganju et al. 2013; Lehman et al. 2015), particularly whether freshwater tidal marshes in the interior Delta are at risk of drowning (Swanson et al. 2015).

Despite their limited areal extent, tidal marshes provide critical refuge, foraging, and rearing habitat for resident and transient fishes (Brown 2003; Colombano et al. 2020). Juvenile Splittail rely on tidal marshes upon arrival to the low-salinity zone in late spring and early summer (Moyle et al. 2004). Shallow, dendritic tidal channels lined with

emergent vegetation support seasonally diverse food webs (e.g., detrital and algal pathways; Feyrer et al. 2003; Schroeter et al. 2015; Young et al. 2021) and provide ample cover for young fish seeking refuge from predators (Colombano, Handley, O'Rear et al. 2021). Widespread loss of tidal marsh via drowning would likely create a bottleneck for Splittail recruitment to adult populations by reducing optimal nursery habitat.

In contrast, the degree to which juvenile Chinook Salmon use tidal marshes in this estuary is poorly understood. Outmigrating Chinook Salmon are commonly found in near-shore areas adjacent to emergent marsh, including tidal slough complexes in the North Delta (McLain and Castillo 2009; Takata et al. 2017). Similarly, they are regularly captured in springtime beach seine samples in Montezuma Slough, a migratory corridor that connects the Sacramento River to Suisun Marsh (O'Rear et al. 2020). However, the frequency and extent to which outmigrants rear in tidal marshes (as is commonly observed in the Pacific Northwest; e.g. Roegner et al. 2010; Davis et al. 2016), remains unknown (Aha et al. 2021), in part from the challenge of capturing them in existing sampling programs (Perry et al. 2016). At the very least, tidal marsh may enhance juvenile salmon survival by providing vegetated cover, velocity refuge, and foraging habitat along migration corridors from the Delta to the ocean. Overall, as climate change progresses, the capacity for remnant and restored tidal marshes to provide refuge and rearing habitat depends on their capacity to either keep pace with sea level rise or to migrate into upland transition zones.

Open Water

Currently, the upper estuary is primarily a sub-tidal, open-water ecosystem (Whipple et al. 2012). While much of the tidal marshes and floodplains in the estuary have been lost since the mid-19th century, the open-water area has more than doubled (Cloern et al. 2021). In the Delta, the open-water ecosystem now consists mostly of straightened, web-like channels with shallow-water-edge habitat at levee margins. Large expanses of shallow-water habitat (i.e., tidal lakes) are also present because of unrepaired levee

failures that flooded agricultural tracts. More westerly open waters (e.g., Suisun Bay, Suisun Marsh, and San Pablo Bay) typically have a mix of embayments and channels that experience a wide range of salinity (e.g., freshwater and brackish) as a result of increased ocean influence (Hutton et al. 2016).

The deep open-water areas of the estuary have received the most monitoring and research attention over the past 60 years (Stompe et al. 2020). Here, freshwater flow interacts with tidal currents and wind, producing a dynamic environment that changes considerably across hours, days, seasons, years, and decades (Figure 4). Before the late 20th century, the estuary's open waters were sparsely vegetated (e.g., with native *Stuckenia* spp.; Whipple et al. 2012) and therefore dependent on *in situ* production of photosynthetic microplankton to provide new organic matter to the food web. However, proliferation of the filter-feeding overbite clam (*Potamocorbula amurensis*), which was introduced in 1987, has reduced the abundance of many photosynthetic microplankton and zooplankton species (Kimmerer et al. 1994; Lehman 2004; Winder and Jassby 2011). Another large shift occurred in the early 2000s, when several native and introduced species of fish and invertebrates experienced sharp population declines (e.g., the endemic Delta Smelt, *Hypomesus transpacificus*; Sommer et al. 2007; Mac Nally et al. 2010; Thomson et al. 2010). While pelagic productivity has declined in the estuary's bays and channels over the years (Kimmerer et al. 1994; Mac Nally et al. 2010; Thomson et al. 2010), productivity in the shallow littoral areas (e.g., near-shore habitats such as levee margins) within the Delta appears to have increased. Submerged and floating aquatic vegetation have become more widely distributed over the past few decades, and the abundances of non-native fishes associated with this vegetations have also increased (Brown and Michniuk 2007; Conrad et al. 2016; Mahardja et al. 2017; Ta et al. 2017).

Reduced outflow and warmer temperatures in late-spring and early summer months produce

favorable habitat for many invasive fish, invertebrates, and aquatic vegetation (Mac Nally et al. 2010; Kimmerer et al. 2019; Michel et al. 2021). Harmful algal blooms also thrive under conditions of warm water and high residence times (Lehman, Kurobe, and Teh 2022). These same conditions are detrimental to most, though not all, native fishes (Brown et al. 2016; Young et al. 2018; Munsch et al. 2019). Intervening years of high outflow reset the salinity regime, but the increased frequency of drought conditions may not allow adequate time for native fish populations to recover (Mahardja et al. 2021).

Salinity intrusion from sea level rise, in combination with reduction in snowpack, is expected to shift species' phenology and increase the prevalence of salt-tolerant species in the upper estuary. More saline conditions may favor some native fishes and aquatic vegetation over their invasive counterparts, though it may come at the cost of freshwater-associated species (Moyle et al. 2010; CC MAST 2022). These changes may incur management responses such as reconfigurations of the Delta, as seen in the emergency drought barriers of 2015 and 2021 (Kimmerer et al. 2019), as well as the proposed Franks Tract redesign, which would reduce salinity intrusion permanently (CDFW 2020; see "[Management Options](#)").

Chinook Salmon are at the warmest end of their natural range in California. Rising temperatures will pose additional challenges to up-migrating adults and outmigrating juveniles in the estuary's open water (Herbold et al. 2018). Higher water temperature increases the metabolic demand of salmon as they migrate and increases their susceptibility to diseases (Richter and Kolmes 2005; Rhodes et al. 2011; Lehman et al. 2020). Juvenile mortality may increase with higher temperature and can be exacerbated by the likely further spread of invasive aquatic vegetation and the piscivorous predators associated with such habitat (Nobriga et al. 2021; Zeug et al. 2021).

The higher frequency of extreme floods and droughts affect Chinook Salmon in diverse ways. Chinook Salmon typically benefit from

wetter years and suffer in drought years (Munsch et al. 2019, 2020). However, Chinook Salmon demonstrate high life-history diversity and phenotypic plasticity (e.g., Crozier et al. 2008; Goertler et al. 2018), which buffer the species from various detrimental conditions (Cordoleani et al. 2021). Nevertheless, human actions have weakened the overall complexity of Chinook Salmon populations in the Central Valley, though efforts are underway to mitigate such effects (Carlson and Satterthwaite 2011).

Splittail adults are often found near the bottom where they predominantly feed (Caywood 1974; Meng and Moyle 1995; Sommer et al. 1997). Adult Splittail have broad thermal and salinity tolerances that may buffer them from the dominant effects of climate change in the open-water ecosystem (Moyle 2002). The largest direct climate change effect on Splittail in the open water may be on the connectivity between the species' two distinct geographic populations (Baerwald et al. 2007). Because Splittail reside mostly in low- to moderate-salinity waters, salinity intrusion may compress their distribution and possibly lead to less frequent interactions between the two populations (Ghalambor et al. 2021). Extreme flood years may lead to higher overlap between the two populations, while more numerous and intense drought years may more effectively isolate the populations (and likely also of individuals within each population, such as those in Petaluma and Napa rivers) (Feyrer et al. 2015; Mahardja et al. 2015). Because of the lack of access to floodplain in dry years and the projected increase in the frequency of droughts, Splittail spawning at river margins may become more common.

Summary

The estuary is rapidly changing in response to changes in climate-related variables (Cloern et al. 2011; Dettinger et al. 2016). Multiple interacting stressors are shifting baseline environmental conditions, amplifying extremes, restructuring physical habitats and biological communities, and, ultimately, causing scientists and managers to rethink conservation strategies. From the ocean, climate change will affect the estuary

primarily through salinity intrusion and sea level rise, which will inundate low-elevation habitats, facilitating levee breaches, and changing salinity distributions. From the terrestrial side, increased temperatures and altered hydrologic conditions affect both the quantity and quality of aquatic habitat. The total amount of Delta inflow may not change radically on a decadal scale, but an increase in the frequency of extreme wet and dry years will amplify the already high hydrologic variability in the system (Dettinger et al. 2016). Rising salinities (Ghalambor et al. 2021), warmer temperatures (Bashevkin et al. 2022), and newly inundated areas will shift suitable habitat for some species (CC MAST 2022).

Major environmental changes force species to “*adapt, move, or die*” (e.g., Habary et al. 2017; Johansen et al. 2017). *Adaptation* for species depends on the rate of environmental change and the ability of species to change in response. *Moving* may be an option for mobile species at the expense of range contractions both within the estuary or through regional range contraction (e.g., non-endemic anadromous or semi-anadromous fish shifting to northern marine and estuarine habitats). *Dying* (extinction) is not a desirable outcome in most cases. Therefore, we expect that *adaptation* by humans and aquatic organisms will be necessary.

Management options in the context of climate change can be viewed as “*resist, adapt, or direct*” (Thompson et al. 2021; Rahel 2022). We can *resist* change and attempt to keep our familiar and desirable ecosystems, we can *adapt* our management to accommodate climate change effects while maintaining desirable ecosystem services, or we can *direct* expected changes into more desirable configurations. Our management activities, our institutions, and our science enterprise face unprecedented challenges, making innovation vital to cope with these extreme changes.

Management in the face of climate change requires a fundamental re-thinking of how we manage and study the estuary. Climate change interacts with other stressors, further

complicating monitoring and management (Lauchlan and Nagelkerken 2020; Orr et al. 2020). We have described some of the major effects of climate change on key estuarine ecosystems and identified some of the needed management and science approaches. At the very least, we need to consider our science and management in the context of environmental extremes as the new normal.

To help understand the breadth of change, we recap how climate change will affect three major ecosystems in the Delta: floodplain, tidal marsh, and open water. While each of the three has very different responses to climate change, these responses are likely to scale up to significant population-level effects on resident and migratory fishes that rely on the estuary.

- **Floodplain** ecosystem dynamics vary with the frequency, timing, duration, and intensity of floods, which are all affected by climate change. Extended dry periods between inundation events are increasing, which in turn influences environmental conditions and food webs. Flood characteristics control floodplain access for Chinook Salmon rearing and for Splittail spawning and rearing.
- **Tidal marshes** are threatened by rising sea level and altered upstream sediment inputs. Tidal marshes with insufficient elevation will not be able to keep pace with sea level rise and will ultimately drown and transition to open-water habitats. Sacramento Splittail (and possibly Chinook Salmon) will likely be severely affected by widespread loss of this productive nursery habitat.
- **Open-water ecosystems** are particularly vulnerable to the short-term effects of extreme warming and salinity intrusion. These changes, combined with uncertainty of whether the estuary will experience increased or decreased turbidity, are expected to greatly alter habitat suitability for Chinook Salmon and Sacramento Splittail during dispersal and migration, particularly for more sensitive juvenile life stages.

MANAGEMENT OPTIONS

Given the extreme conditions that can occur with climate change, there is an urgent need to consider what management options are available to reduce effects on the estuary. On the positive side, the estuary has an unusually broad suite of aquatic management tools that have been used both at the pilot scale and for routine management (Sommer 2020). However, application of these tools so far has not prevented sharp declines for many species (e.g., Quiñones and Moyle 2014; Hobbs et al. 2017). At least four general categories of tools can be used to address habitat management: regulatory; water infrastructure; habitat; and other biological measures. Below, we summarize some of the potential management tools that could be used to mitigate the effects of climate change. For each of these actions, we recommend strong science support to guide management, based on sound adaptive management and precautionary principles (e.g., Allen and Gunderson 2011; Dark and Burgin 2017).

This evolving environment is characterized by greater extremes than seen historically. As a result, management tools used in the past will likely have reduced efficacy in the future. We therefore agree with Norgaard et al. (2021) that policy and management likely need to move into a forward-looking mode of scenario planning and rely less on historical conditions to address the rapidly evolving issue of climate change. Below, we briefly describe some of the ways that these management tools might be implemented.

Regulatory

Since the 1990s, environmental regulations such as water rights decisions and endangered species laws have played an increasing role in the management of the estuary, although not as much as depicted in public forums (Reis et al. 2019). Hence, agencies such as the State Water Resources Control Board, California Department of Fish and Wildlife, National Marine Fisheries Service, US Fish and Wildlife Service, and Army Corps of Engineers have a major role in the regulatory response to climate change. However, many of these agencies rely on historical conditions

to evaluate the need for remedial actions. The Clean Water Act (1973; §131.12) requires that all the beneficial uses of all bodies of water must be protected and not be degraded further than they were when the act was adopted in 1973. Listing of endangered species requires identification of the habitat critical to survival of every taxon, often defined by historical data (ESA 1973; §4). Climate change may require changes in the beneficial uses associated with water bodies and the nature and location of habitats that support listed species.

Water Infrastructure

Water infrastructure—including dams, gates, barriers, and diversions—was designed around historical hydrology and landscapes. A primary use of dam releases has been to control salinity in the estuary; rising sea level will make this task more difficult. Historical dam operation strategies may not be sustainable as hydrology vacillates between extreme flood and drought. This, in turn, affects Delta inflow and corresponding salinity intrusion, influencing a broad suite of habitats. Improved weather forecasting combined with better hydrologic models may improve efficiency of operation.

One of the highest-profile issues will be sustainable water diversion for urban and agricultural uses, which is vulnerable to salinity intrusion from levee collapse because of high tide and flood, earthquake, and/or sea level rise (Lund et al. 2010). Alteration in the timing and location of diversions will likely require adaptations to reduce fish entrainment and to offset reductions in habitat quality associated with water diversion (e.g., Grimaldo et al. 2009; Moyle et al. 2010).

Infrastructure such as dams and weirs could be tools to respond to climate-induced changes. One recent example is the novel use of the Suisun Marsh Salinity Control Gates to limit salinity intrusion and improve habitat conditions for Delta Smelt and other species in Suisun Marsh (Sommer, Hartman, Koller 2020; Beakes et al. 2021). Infrastructure such as the proposed Fremont Weir Notch project (USBR and CDWR 2019; see "[Habitat](#)") can enable floodplain inundation at

lower river stages to support floodplain ecosystem processes.

Habitat

Habitat restoration is perhaps the single most important management tool to mitigate some of the effects of climate change. Restoration can buffer climate effects by expanding the area of suitable habitat, supporting broader species distribution (e.g., “bet hedging”), and increasing food production. The three ecosystems support very different values for species and provide strikingly different management options.

Floodplains are of great importance for Sacramento Splittail and Chinook Salmon, and they provide food-web subsidies for downstream regions (Sommer, Harrell, and Nobriga et al. 2001; Feyrer et al. 2006a, 2006b; Jeffries et al. 2007). The Yolo Bypass has been well-studied over the past 2 decades, resulting in a robust understanding of some of the necessary habitat improvements (USBR and CDWR 2019). The single most important modification is the construction of a notch in Fremont Weir at the north end of Yolo Bypass to improve connectivity with the Sacramento River. This notch has the potential to substantially buffer some of the expected changes in flood timing, frequency, and duration. Moreover, greater access to food-rich floodplain habitats can help species such as Chinook Salmon deal with the increased bioenergetic costs of warmer temperatures (unless temperatures exceed acute or lethal levels). A related management approach is to make better use of existing floodplain habitats (Katz et al. 2017; Sommer, Schreier, Conrad et al. 2020). As an example, agricultural areas could be modified in several ways to improve their value for juvenile salmon rearing (e.g., Herbold et al. 2018). Managed flooding has also been examined on a pilot scale for other species such as Sacramento Splittail (Sommer et al. 2002, 2008).

In addition to the targeted fish-management improvements above, major changes in the flood-management system are likely (CDWR 2017). Specifically, to deal with increased frequency and intensity of extreme floods, there is a

clear need to increase the area of floodplain. Enlarged floodplains provide a unique and major opportunity to increase ecological value, while simultaneously helping to mitigate the higher flood risk. As a recent example, the planned Lookout Slough project will substantially increase the size of Yolo Bypass, providing more floodplain habitat as well as expanded flood conveyance (CDWR 2020).

Tidal marsh restoration represents a similar and critical complement to floodplain management. The science behind this activity is expanding rapidly, with an increased understanding of the potential benefits of restoration to at-risk species (Sherman et al. 2017). As summarized in previous sections, this habitat type could provide resilience to climate change in several ways. A major focus of ecosystem management is to increase the amount of tidal marsh habitat, with much of the effort in the upper estuary concentrated in the North Delta and Suisun Marsh (USFWS 2019). A key challenge for these habitats is that sea level rise may inundate low-elevation projects; still, new marsh habitats, especially those with the potential for upland transgression, could provide an important buffer for planned retreat under sea level rise.

The concept of habitat restoration is much more complicated for open-water regions, which are more expansive than under historical conditions (Whipple et al. 2012). Climate change will likely mediate the creation of large new areas of open-water habitat that may have benefits for some species (Moyle et al. 2013; Young et al. 2018). Management of these areas must focus more on the quality—rather than quantity—of habitats. For example, aquatic weed management could help maintain suitable open-water areas for target species (Ta et al. 2018). Moreover, efforts such as the Franks Tract project could generate benefits for fish habitat, water quality, and recreation in this large, flooded island (CDFW 2020). Planning a response to flooded island based on aquatic community patterns (e.g., Young et al. 2018) and levee maintenance costs (Suddeth et al. 2010) could greatly ameliorate the environmental and

economic effects of levee breaches because of climate change.

Other Biological Measures

Example tools in this category include population supplementation and predator control (Sommer 2020). Predation will increase under climate change as warmer temperatures increase the metabolic needs of some consumers, increasing mortality rates of prey. Unfortunately, predator removal remains largely conceptual; pilot evaluations have not shown sustained, measurable benefits (e.g., Cavallo et al. 2012; Michel et al. 2020). Numerous predator “hot spots” occur throughout the Delta (Lehman et al. 2020; Grossman 2016), so some targeted efforts may be useful. However, unintended consequences of predator control on predator-prey dynamics are not uncommon (Pine et al. 2009; Shephard et al. 2019) and are more likely under climate change (e.g., Grossman 2016; Davis et al. 2019).

Supplementation of desirable species has historically been an important tool to sustain salmonid populations, particularly Chinook Salmon and Steelhead Trout (*Oncorhynchus mykiss*), whose populations are particularly sensitive to raised temperatures throughout their ranges and the loss of upstream habitats via dam construction. Hatchery populations will, therefore, continue to be a critical part of salmonid management in the Central Valley. Major changes may be necessary in response to climate extremes. For example, transporting juvenile Chinook Salmon for release past the Delta instead of in their natal stream has been used as tool during extreme low-flow conditions (e.g., Sturrock et al. 2019). Increasing the use of hatcheries to maintain refuge populations of salmonids as well as a variety of other species may also be needed. Supplementation of Splittail seems unlikely in the foreseeable future because better management of floodplain inundation, via the notch and reservoir reoperations, more directly addresses the needs of the species. However, a new fish refuge and research center has been proposed to help house other at-risk species such as Delta Smelt and Longfin Smelt (*Spirinchus thaleichthys*) (CDWR and USFWS 2017).

To be useful, however, supplementation must be integrated with effective flow- and non-flow habitat-restoration actions (e.g., Moyle et al. 2010; Hobbs et al. 2017).

In addition, these management actions should consider the amount of toxins present in the environment in which they are done. Global warming has increased the abundance of harmful blooms in the estuary, particularly cyanobacteria (Lehman et al. 2017, 2021). Through the production of hepatotoxins and neurotoxins, these blooms affect the survival of species from bacteria to fish (Ger et al. 2018; Acuña et al. 2020; Lehman et al. 2021). The blooms can also decrease the dissolved oxygen concentration in the water column (Sutula et al. 2017). Management actions are needed to control the major nutrients, water temperature, and residence time that enable large blooms to develop (Paerl and Otten 2013).

SCIENCE NEEDS

Beyond the suite of management approaches described above, science support is needed to monitor and diagnose climate effects. The central pillar of science support is maintaining core long-term monitoring programs to evaluate changes in ecological processes (Stompe et al. 2020; Cloern et al. 2021). These long-term changes are different from the current priorities that focus more on daily operational issues such as fish entrainment into water export facilities (Grimaldo et al. 2009; USFWS 2019). Consequently, monitoring may need to change to address some aspects of climate change. Below, we note two urgent areas.

Marsh Habitat

Tidal marshes are historically under-sampled yet are some of the habitats most vulnerable to sea level rise and salinity intrusion. As more tidal marsh habitats are constructed and mature, their value to target species must be assessed to guide restoration designs. More robust and coordinated tidal marsh monitoring and research is a top priority for science support (Sherman et al. 2017; Hartman et al. 2019).

Extreme Events

Major floods, sustained drought, record heat waves, major levee breaks, and harmful blooms are all examples of climate-related events that can have major effects on the estuary. Long-term monitoring provides a good baseline of information but evaluating the effect of extreme events will require more focused sampling and habitat management. For example, levee breaks can create entirely new open-water habitats. Advanced planning for monitoring such extreme events can provide valuable and timely information.

CONCLUSIONS

Climate change is the gravest threat facing humans and ecosystems over the coming decades. We review relevant literature for the estuary to give insight into the current and potential effects of climate change on three estuarine ecosystems and processes affecting two native fish species with very different life-history strategies. Global warming is changing hydrodynamics in California by altering the timing and magnitude of streamflow, particularly during the late winter and spring. Altered streamflow will affect the migration and feeding success of the two very different fish species we considered. Through its effects on water temperature and the salinity field, climate change will also significantly affect most aquatic species of conservation concern. We identify some of the management and science approaches needed to adapt to these changes in the estuary and conclude that a fundamental rethinking of how we manage and study the estuary is needed.

ACKNOWLEDGMENTS

We dedicate this article to Dr. Larry Brown from the US Geological Survey who helped to spearhead this project and was a friend, mentor, and role model to many of us. The findings and conclusions of this study are those of the authors and do not necessarily represent the views of the California Department of Water Resources, US Bureau of Reclamation, US Fish and Wildlife Service, the Delta Stewardship Council, or the Interagency Ecological Program. We thank

Daphne Gille, Steve Culberson, and anonymous reviewers for comments that significantly improved the manuscript.

Funding. BH was supported by CDWR through a contract with AECOM. DC was supported by a Delta Science Fellowship administered by the Delta Stewardship Council and California Sea Grant (Award No. 62034). GC was supported by US Bureau of Reclamation (Agreement No. R20PG00036).

Funding Sources and Collaborating Agencies. California Department of Water Resources, California Department of Fish and Wildlife, Delta Stewardship Council Delta Science Program, US Bureau of Reclamation, US Fish and Wildlife Service.

REFERENCES

- Acuña S, Baxa D, Lehman PW, Teh F-C, Deng D-F, Teh SJ. 2020. Determining the exposure pathway and impacts of *Microcystis* on Threadfin Shad, *Dorosoma petenense*, in San Francisco Estuary. *Environ Toxicol Chem.* [accessed 2022 Apr 06];39(4):787–798. <https://doi.org/10.1002/etc.4659>
- Aha NM, Moyle PB, Fangue NA, Rypel AL, Durand JR. 2021. Managed wetlands can benefit juvenile Chinook Salmon in a tidal marsh. *Estuaries Coasts.* [accessed 2022 Apr 06];44:1440–1453. <https://doi.org/10.1007/s12237-020-00880-4>
- Allen CR, Gunderson LH. 2011. Pathology and failure in the design and implementation of adaptive management. *J. Environ Manag.* [accessed 2022 Apr 06];92:1379–1384. <https://doi.org/10.1016/j.jenvman.2010.10.063>
- Baerwald M, Bien V, Feyrer F, May B. 2007. Genetic analysis reveals two distinct Sacramento splittail (*Pogonichthys macrolepidotus*) populations. *Conserv Genet.* [accessed 2022 Mar 10]; 8(1):159–167. <https://doi.org/10.1007/s10592-006-9157-2>
- Barrett J, Rose JM, Pagach J, Parker M, Deonaraine S. 2015. Development of an estuarine climate change monitoring program. *Ecol Indicators.* [accessed 2022 Apr 06];53:182–186. <https://doi.org/10.1016/j.ecolind.2015.01.039>

- Barnard, PL, Schoellhamer DH, Jaffe BE, McKee LJ. 2013. Sediment transport in the San Francisco Bay coastal system: an overview. *Marine Geol.* [accessed 2022 Apr 06];345:3-17. <https://doi.org/10.1016/j.margeo.2013.04.005>
- Bashevkin SM, Mahardja B, Brown LR. 2022. Warming in the upper San Francisco Estuary: patterns of water temperature change from five decades of data. *Limnol Oceanogr.* [accessed 2022 Apr 06]; <https://doi.org/10.1002/lno.12057>
- Beakes MP, Graham C, Conrad JL, White JR, Koohafkan M, Durand J, and Sommer T. 2021. Large-Scale Flow Management Action Drives Estuarine Ecological Response. *N Am J Fish Manag.* [accessed 2022 Mar 10];41(1):64-77. <https://doi.org/10.1002/nafm.10529>
- Bellmore JR, Baxter CV, Martens K, Connolly PJ. 2013. The floodplain food web mosaic: a study of its importance to salmon and steelhead with implications for their recovery. *Ecol Appl.* [accessed 2022 Apr 06];23(1):189-207. <https://doi.org/10.1890/12-0806.1>
- Benigno GM, Sommer TR. 2008. Just add water: sources of chironomid drift in a large river floodplain. *Hydrobiologia.* [accessed 2022 Apr 06];600(1):297-305. <https://doi.org/10.1007/s10750-007-9239-2>
- Bennett WA, Moyle PB. 1996. Where have all the fishes gone? interactive factors producing fish declines in the Sacramento-San Joaquin estuary. In: Hollibaugh JT, editor. *The San Francisco Bay: the ecosystem; further investigations into the natural history of San Francisco Bay and Delta with reference to the influence of man.* [accessed 2022 Jun 20]. San Francisco (CA): AAAS, Pacific Division. p. 519-542. Available from: https://books.google.com/books/about/San_Francisco_Bay.html?id=zOASAAAAYAAJ
- Biondi F, Gershunov A, Cayan DR. 2001. North Pacific decadal climate variability since 1661. *J Climate.* [accessed 2022 Mar 10];14(1):5-10. [https://doi.org/10.1175/1520-0442\(2001\)014<0005:NPD CVS>2.0.CO;2](https://doi.org/10.1175/1520-0442(2001)014<0005:NPD CVS>2.0.CO;2)
- Bond NR, Lake PS, Arthington AH 2008. The impacts of drought on freshwater ecosystems: an Australian perspective. *Hydrobiologia.* [accessed 2022 Apr 06];600(1):3-16. <https://doi.org/10.1007/s10750-008-9326-z>
- Brook B, Sodhi WN, Bradshaw CJ. 2008. Synergies among extinction drivers under global change. *Trends Ecol Evol.* [accessed 2022 Apr 06];23:453-460. <https://doi.org/10.1016/j.tree.2008.03.011>
- Brooks ML, Fleishman E, Brown LR, Lehman PW, Werner I, Scholz N, Mitchelmore C, Lovvorn JR, Johnson ML, Schlenk D, van Drunick S. 2012. Life histories, salinity zones, and sublethal contributions of contaminants to pelagic fish declines illustrated with a case study of San Francisco Estuary, California, USA. *Estuar Coasts.* [accessed 2022 Mar 10];35(2):603-621. <https://doi.org/10.1007/s12237-011-9459-6>
- Brown LR. 2003. An introduction to the San Francisco Estuary tidal wetlands restoration series. *San Franc Estuary Watershed Sci.* [accessed 2022 Apr 06];1(1). <https://doi.org/10.15447/sfews.2003v1iss1art1>
- Brown LR, Bauer ML. 2010. Effects of hydrologic infrastructure on flow regimes of California's Central Valley rivers: implications for fish populations. *River Res Applications.* [accessed 2022 Apr 06];26(6):751-765. <https://doi.org/10.1002/rra.1293>
- Brown LR, Komoroske LM, Wagner RW, Morgan-King T, May JT, Connon RE, Fangue NA. 2016. Coupled downscaled climate models and ecophysiological metrics forecast habitat compression for an endangered estuarine fish. *PloS ONE.* [accessed 2022 Apr 06];11(1):e0146724. <https://doi.org/10.1371/journal.pone.0146724>
- Brown LR, Michniuk D. 2007. Littoral fish assemblages of the alien-dominated Sacramento-San Joaquin Delta, California, 1980-1983 and 2001-2003. *Estuaries Coasts.* [accessed 2022 Apr 06];30(1):186-200. <https://doi.org/10.1007/BF02782979>
- Buffington KJ, Janousek CN, Dugger BD, Callaway JC, Schile-Beers LM, Borgnis Sloane E, Thorne KM. 2021. Incorporation of uncertainty to improve projections of tidal wetland elevation and carbon accumulation with sea-level rise. *PLoS ONE.* [accessed 2022 Apr 06];16(10): e0256707. <https://doi.org/10.1371/journal.pone.0256707>
- Cahoon DR, Guntenspergen GR. 2010. Climate change, sea-level rise, and coastal wetlands. *Natl Wetlands Newsl.* [accessed 2022 Mar 10];32(1):8-12. Available from: <https://pubs.er.usgs.gov/publication/70003388>

- Cahoon DR, McKee KL, Morris JT. 2021. How plants influence resilience of salt marsh and mangrove wetlands to sea-level rise. *Estuar Coas.* [accessed 2022 Mar 10];44(4):883–898.
<https://doi.org/10.1007/s12237-020-00834-w>
- Carlson SM, Satterthwaite WH. 2011. Weakened portfolio effect in a collapsed salmon population complex. *Can J Fish Aquat Sci.* [accessed 2022 Apr 06];68(9):1579–1589.
<https://doi.org/10.1139/f2011-084>
- Carrier-Belleau C, Drolet D, McKindsey CW. 2021. Environmental stressors, complex interactions and marine benthic communities' responses. *Sci Rep.* [accessed 2022 Apr 06];(11)4194.
<https://doi.org/10.1038/s41598-021-83533-1>
- Castillo G. 2019. Modeling the influence of outflow and community structure on an endangered fish population in the upper San Francisco Estuary. *Water.* [accessed 2022 Apr 06];11(6):1162.
<https://doi.org/10.3390/w11061162>
- Castillo G, Damon L, Hobbs J. 2018. Community patterns and environmental associations for pelagic fishes in a highly modified estuary. *Mar Coast Fish.* [accessed 2022 Apr 06];10(5):508–524.
<https://doi.org/10.1002/mcf2.10047>
- Cavallo B, Merz J, Setka J. 2012. Effects of predator and flow manipulation on Chinook Salmon (*Oncorhynchus tshawytscha*) survival in an imperiled estuary. *Environ Biol Fish.* [accessed 2022 Apr 06];96:393–403.
<https://doi.org/10.1007/s10641-012-9993-5>
- Cayan DR, Maurer EP, Dettinger MD, Tyree M, Hayhoe K. 2008. Climate change scenarios for the California region. *Climatic Change.* [accessed 2022 Mar 10];87(1):21–42.
<https://doi.org/10.1007/s10584-007-9377-6>
- Caywood ML. 1974. Contributions to the life history of Splittail. *Pogonichthys macrolepidotus* (Ayers). [master's thesis]. [Sacramento (CA)]: California State University. 77 p.
- [CC MAST] Climate Change Management, Analysis and Synthesis Team. 2022. Synthesis of data and studies related to the effect of climate change on the ecosystems and biota of the Upper San Francisco Estuary. IEP Technical Report 99. Interagency Ecological Program, Sacramento, CA
- [CDFW] California Department of Fish and Wildlife. 2020. Franks Tract reimaged. [accessed 2022 Jun 01] Available from:
<https://franks-tract-futures-ucdavis.hub.arcgis.com/>
- [CDWR] California Department of Water Resources. 2017. Central Valley flood protection plan 2017 update. August 2017. [accessed 2020 Sep 03]. Sacramento (CA): CDWR. 210 p. [accessed 2022 June 17]. https://water.ca.gov/-/media/DWR-Website/Web-Pages/Programs/Flood-Management/Flood-Planning-and-Studies/Central-Valley-Flood-Protection-Plan/Files/2017-CVFP-Update-FINAL_a_y19.pdf
- [CDWR] California Department of Water Resources. 2020. Final Environmental Impact Report: Lookout Slough Tidal Habitat Restoration and Flood Improvement Project. State Clearinghouse No. 2019039136. Available from: https://water.ca.gov/-/media/DWR-Website/Web-Pages/Programs/Environmental-Services/Restoration-Mitigation-Compliance/Files/Lookout-Slough-FEIR_DES_v1_11032020_ay11.pdf
- [CDWR] California Department of Water Resources. 2021. Dayflow: net Delta outflow at Chipps Island. [accessed 2020 Jun 01]. Available from:
<https://data.cnra.ca.gov/dataset/dayflow>
- [CDWR and USFWS] California Department of Water Resources and US Fish and Wildlife Service. 2017. Delta Research Station Project: Estuarine Research Station and Fish Technology Center Final Environmental Impact Report/ Environmental Impact Statement. February 2017. [accessed 2022 Jun 17]. <https://www.federalregister.gov/documents/2019/08/13/2019-17225/delta-research-station-project-estuarine-research-station-and-fish-technology-center-final>
- Clean Water Act. 1973. Title 40 Protection of Environment, Chapter 1 Environmental Protection Agency, Subchapter D Water Programs, Part 131 Water quality standards, Subpart B Establishment of water quality standards, §131.12 Antidegradation policy and implementation methods. [accessed 2022 Jun 01]. Available from:
<https://www.ecfr.gov/current/title-40/chapter-I/subchapter-D/part-131>
- Cloern JE. 2007. Habitat connectivity and ecosystem productivity: Implications from a simple model. *Am Nat.* [accessed 2022 Mar 10];169(1):E21–E33.
<https://doi.org/10.1086/510258>

- Cloern, JE, Abreu PC, Carstensen J, Chauvaud L, Elmgren R, Grall J, Greening H, Johansson JOR, Kahru M, Sherwood ET, et al. 2016. Human activities and climate variability drive fast-paced change across the world's estuarine-coastal ecosystems. *Global Chang Biol.* [accessed 2022 Apr 06];22(2):513-529. <https://doi.org/10.1111/gcb.13059>
- Cloern JE, Jassby, AD. 2012. Drivers of change in estuarine-coastal ecosystems: discoveries from four decades of study in San Francisco Bay. *Rev Geophys.* [accessed 2022 Apr 06];50(RG4001). <https://doi.org/10.1029/2012RG000397>
- Cloern JE, Knowles N, Brown LR, Cayan D, Dettinger MD, Morgan TL, Schoellhamer DH, Stacey MT, Van der Wegen M, Wagner RW, Jassby AD. 2011. Projected evolution of California's San Francisco Bay-Delta-River system in a century of climate change. *PLoS ONE.* [accessed 2022 Apr 06];6(9):e24465. <https://doi.org/10.1371/journal.pone.0024465>
- Cloern JE, Safran SM, Smith VL, Robinson A, Whipple AA, Boyer KE, Drexler JZ, Naiman RJ, Pinckney JL, Howe ER. 2021. On the human appropriation of wetland primary production. *Sci Total Environ.* [accessed 2022 Apr 06];785:147097. <https://doi.org/10.1016/j.scitotenv.2021.147097>
- Cohen AN, Carlton JT. 1998. Accelerating invasion rate in a highly invaded estuary. *Science.* [accessed 2022 Apr 06];279(5350):555-558. <https://doi.org/10.1126/science.279.5350.555>
- Colombano DD, Manfree AD, Teejay AO, Durand JR, Moyle PB. 2020. Estuarine-terrestrial habitat gradients enhance nursery function for resident and transient fishes in the San Francisco Estuary. *Mar Ecol Prog Ser.* [accessed 2022 Apr 06];637:141-157. <https://doi.org/10.3354/meps13238>
- Colombano DD, Handley TB, O'Rear TA, Durand JR, Moyle PB. 2021. Complex tidal marsh dynamics structure fish foraging patterns in the San Francisco Estuary. *Estuaries Coasts.* [accessed 2022 Apr 06];44(6):1604-1618. <https://doi.org/10.1007/s12237-021-00896-4>
- Colombano DD, Litvin SY, Ziegler SL, Alford SB, Baker R, Barbeau MA. 2021. Climate change implications for tidal marshes and food web linkages to estuarine and coastal nekton. *Estuaries Coasts.* [accessed 2022 Apr 06];44:1637-1648. <https://doi.org/10.1007/s12237-020-00891-1>
- Conrad JL, Bibian AJ, Weinersmith KL, De Carion D, Young MJ, Crain P, Hestir EL, Santos MJ, Sih A. 2016. Novel species interactions in a highly modified estuary: association of Largemouth Bass with Brazilian Waterweed *Egeria densa*. *Trans Am Fish Soc.* [accessed 2022 Apr 06];145:249-263. <https://doi.org/10.1080/00028487.2015.1114521>
- Cordoleani F, Phillis CC, Sturrock AM, FitzGerald AM, Malkasian A, Whitman GE, Weber PK, Johnson RC. 2021. Threatened salmon rely on a rare life history strategy in a warming landscape. *Nat Clim Change.* [accessed 2022 Apr 06];(11)982-988. <https://doi.org/10.1038/s41558-021-01186-4>
- Crain PK, Whitener K, Moyle PB. 2004. Use of a restored central California floodplain by larvae of native and alien fishes. *Am Fish Soc Symp.* [accessed 2022 Jun 01];(39):125-140. Available from: https://watershed.ucdavis.edu/pdf/crg/reports/crain_et_al2004.pdf
- Crozier LG, Hendry AP, Lawson PW, Quinn TP, Mantua NJ, Battin J, Shaw RG, Huey RB. 2008. Potential responses to climate change in organisms with complex life histories: evolution and plasticity in Pacific Salmon. *Evol Appl.* [accessed 2022 Apr 06];1:252-270. <https://doi.org/10.1111/j.1752-4571.2008.00033.x>
- Dark S, Burgen S. 2017. An examination of the efficacy of the precautionary principle as a robust environmental planning and management protocol. *J Environ Plan Manag.* [accessed 2022 Apr 06];60(12):1-11. <https://doi.org/10.1080/09640568.2016.1276436>
- Das T, Maurer EP, Pierce DW, Dettinger MD, Cayan DR. 2013. Increases in flood magnitudes in California under warming climates. *J Hydrol.* [accessed 2022 Mar 10];501:101-110. <https://doi.org/10.1016/j.jhydrol.2013.07.042>
- David AT, Simenstad CA, Cordell JR, Toft JD, Ellings CS, Gray A, Berge HB. 2016. Wetland loss, juvenile salmon foraging performance, and density dependence in Pacific Northwest estuaries. *Estuaries Coasts.* [accessed 2022 Apr 06];39:767-780. <https://doi.org/10.1007/s12237-015-0041-5>

- Davis BE, Cocherell DE, Sommer T, Baxter RD, Hung TC, Todgham AE, Fangue NA. 2019. Sensitivities of an endemic, endangered California Smelt and two non-native fishes to serial increases in temperature and salinity: implications for shifting community structure with climate change. *Conservation Physiol.* [accessed 2022 Apr 06];7(1):65–76. <https://doi.org/10.1093/conphys/coy076>
- DeCourten, BM, Brander SM. 2017. Combined effects of increased temperature and endocrine disrupting pollutants on sex determination, survival, and development across generations. *Sci Rep.* [accessed 2022 Apr 06];7:9310. <https://doi.org/10.1038/s41598-017-09631-1>
- DeCourten BM, Connon RE, Brander SM. 2019. Direct and indirect parental exposure to endocrine disruptors and elevated temperature influences gene expression across generations in a euryhaline model fish. *Peer J.* [accessed 2022 Apr 06];7:e6156. <https://doi.org/10.7717/peerj.6156>
- [DSC] Delta Stewardship Council 2021. Delta adapts: creating a climate resilient future. Sacramento (CA): State of California. Available from: <https://deltacouncil.ca.gov/delta-plan/climate-change>
- Dettinger M, Anderson J, Anderson M, Brown LR, Cayan D, Maurer E. 2016. Climate change and the Delta. *San Franc Estuary Watershed Sci.* [accessed 2022 Apr 06];14(3). <https://doi.org/10.15447/sfews.2016v14iss3art5>
- Diffenbaugh N, Swain DL, Touma D. 2015. Anthropogenic warming has increased drought risk in California. *Proc Natl Acad Sci.* [accessed 2022 Apr 06];112(13):3931–3936. <https://doi.org/10.1073/pnas.1422385112>
- EcoRestore. 2021. [website]. [accessed 2022 Mar 10]. Available from: <https://water.ca.gov/Programs/All-Programs/EcoRestore>
- Endangered Species Act. 1973. 16 U.S. Code §1533. Determination of endangered species and threatened species. [accessed 2022 Jun 01]. Available from: <https://www.govinfo.gov/app/details/USCODE-2011-title16/USCODE-2011-title16-chap35-sec1533/summary>
- Enright C, Culberson SD, Burau JR. 2013. Broad timescale forcing and geomorphic mediation of tidal marsh flow and temperature dynamics. *Estuar Coas.* [accessed 2022 Mar 10];36(6):1319–1339. <https://doi.org/10.1007/s12237-013-9639-7>
- Feyrer F, Healey M. 2003. Fish community structure and environmental correlates in the highly altered southern Sacramento-San Joaquin Delta. *Environ Biol Fishes.* [accessed 2022 Apr 06];66:123–132. <https://doi.org/10.1023/A:1023670404997>
- Feyrer F, Herbold B, Matern SA, Moyle PB. 2003. Dietary shifts in a stressed fish assemblage: consequences of a bivalve invasion in the San Francisco Estuary. *Environ Biol Fishes.* [accessed 2022 Mar 10];67(3):277–288. <https://doi.org/10.1023/A:1025839132274>
- Feyrer F, Sommer T, Harrell W. 2006a. Managing floodplain inundation for native fish: production dynamics of age-0 Splittail in California's Yolo Bypass. *Hydrobiologia.* [accessed 2022 Apr 06];573:213–216. <https://doi.org/10.1007/s10750-006-0273-2>
- Feyrer F, Sommer T, Harrell W. 2006b. Importance of flood dynamics versus intrinsic physical habitat in structuring fish communities: evidence from two adjacent engineered floodplains on the Sacramento River, California. *N Am J Fish Manag.* [accessed 2022 Apr 06];26:408–417. <https://doi.org/10.1577/M05-113.1>
- Feyrer F, Cloern JE, Brown LR, Fish MA, Hieb KA, Baxter RD. 2015. Estuarine fish communities respond to climate variability over both river and ocean basins. *Global Change Biol.* [accessed 2022 Apr 06];21:3608–3619. <https://doi.org/10.1111/gcb.12969>
- Flick RE, Murray JF, Ewing LC. 2003. Trends in United States tidal datum statistics and tide range. *J. Waterw. Port Coast Ocean Eng.* [accessed 2022 Mar 10];129(4):155–164. [https://doi.org/10.1061/\(ASCE\)0733-950X\(2003\)129:4\(155\)](https://doi.org/10.1061/(ASCE)0733-950X(2003)129:4(155))
- Frantzich J, Sommer T, Schreier B. 2018. Physical and biological responses to flow in a tidal freshwater slough complex. *San Franc Estuary and Watershed Sci.* [accessed 2022 Apr 06];16(1). <https://doi.org/10.15447/sfews.2018v16iss1/art3>
- Fregoso T, Wang R-F, Ateljevich E, Jaffe BE. 2017. San Francisco Bay–Delta bathymetric/topographic digital elevation model (DEM). US Geological Survey data release. <https://doi.org/10.5066/F7GH9G27>

- Ganju NK, Nidzieko NJ, Kirwan ML. 2013. Inferring tidal wetland stability from channel sediment fluxes: Observations and a conceptual model. *J Geophysical Res* [accessed 2022 Apr 06];118:1–14. <https://doi.org/10.1002/jgrf.20143>
- Ghalambor CK, Gross ES, Grosholtz ED, Jeffries KM, Largier JK, McCormick SD, Sommer T, Velotta J, Whitehead A. 2021. Ecological effects of climate-driven salinity variation in the San Francisco Estuary: can we anticipate and manage the coming changes? *San Fran Estuary Watershed Sci.* [accessed 2022 Apr 06];19(2). <https://doi.org/10.15447/sfews.2021v19iss2art3>
- Ger KA, Otten, TG, DuMais, R, Ignoffo, T, Kimmerer W. 2018. In situ ingestion of *Microcystis* is negatively related to copepod abundance in the upper San Francisco Estuary. *Limnol Oceanogr.* [accessed 2022 Apr 06];63(6):2394–2410. <https://doi.org/10.1002/lno.10946>
- Glibert PM, Wilkerson FP, Dugdale RC, Parker AE, Alexander J, Blaser S, Murasko S. 2014. Phytoplankton communities from San Francisco Bay Delta respond differently to oxidized and reduced nitrogen substrates—even under conditions that would otherwise suggest nitrogen sufficiency. *Frontiers Marine Sci.* [accessed 2022 Apr 06];1(17). <https://doi.org/10.3389/fmars.2014.00017>
- 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. Oakland (CA): California State Coastal Conservancy. Available from: <https://www.sfei.org/documents/baylandsgoalsreport>
- Greet J, Angus WJ, Cousens RD. 2011. The importance of seasonal flow timing for riparian vegetation dynamics: a systematic review using causal criteria analysis. *Freshwater Biol.* [accessed 2022 Apr 06];56:1231–1247. <https://doi.org/10.1111/j.1365-2427.2011.02564.x>
- Grimaldo LF, Sommer T, Van Ark N, Jones G, Holland E, Moyle PB, Herbold B, Smith P. 2009. Factors affecting fish entrainment into massive water diversions in a tidal freshwater estuary: can fish losses be managed? *N Am J Fish Manag.* [accessed 2022 Mar 10];29(5):1253–1270. <https://doi.org/10.1577/M08-062.1>
- Grosholz E, Gallo E. 2006. The influence of flood cycle and fish predation on invertebrate production on a restored California floodplain. *Hydrobiologia.* [accessed 2022 Mar 10];568(1):91–109. <https://doi.org/10.1007/s10750-006-0029-z>
- Grossman GD. 2016. Predation on fishes in the Sacramento–San Joaquin Delta: current knowledge and future directions. *San Franc Estuary Watershed Sci.* [accessed 2022 Apr 06];14(2). <https://doi.org/10.15447/sfews.2016v14iss2art8>
- Habary A, Johansen JL, Nay TJ, Steffensen JF, Rummer JL. 2017. Adapt, move or die—how will tropical coral reef fishes cope with ocean warming? *Global Change Biol.* [accessed 2022 Apr 06];23(2):566–577. <https://doi.org/10.1111/gcb.13488>
- Hammock BG, Hartman R, Slater SB, Hennessy A, Teh SJ. 2019. Tidal wetlands associated with foraging success of Delta Smelt. *Estuar Coas.* [accessed 2022 Mar 10];42(3):857–867. <https://doi.org/10.1007/s12237-019-00521-5>
- Hansen J, Sato M, Hearty P, Ruedy R, Kelley M, Masson–Delmotte V, Russell G, Tselioudis G, Cao J, Rignot E, et al. 2016. Ice melt, sea level rise and superstorms: evidence from paleoclimate data, climate modeling, and modern observations that 2 °C global warming could be dangerous. *Atmos Chem Phys.* [accessed 2022 Apr 06];16:3761–3812. <https://doi.org/10.5194/acp-16-3761-2016>
- Hartman R, Sherman S, Contreras D, Furler A, Kok R. 2019. Characterizing macroinvertebrate community composition and abundance in freshwater tidal wetlands of the Sacramento–San Joaquin Delta. *PloS ONE.* [accessed 2022 Apr 06];14(11):e0215421. <https://doi.org/10.1371/journal.pone.0215421>
- He M, Anderson M, Schwarz A, Das T, Lynn E, Anderson J, Munévar A, Vasquez J, Arnold W. 2019. Potential changes in runoff of California’s major water supply watersheds in the 21st century. *Water.* [accessed 2022 Mar 10];11(8):1651. <https://doi.org/10.3390/w11081651>
- Herbold B, Baltz DM, Brown L, Grossinger R, Kimmerer W, Lehman P, Simenstad CS, Wilcox C, Nobriga M. 2014. The role of tidal marsh restoration in fish management in the San Francisco Estuary. *San Franc Estuary Watershed Sci.* [accessed 2022 Mar 10];12(1). <https://doi.org/10.15447/sfews.2014v12iss1art1>

- Herbold B, Carlson SM, Henery R, Johnson RC, Mantua N, McClure M, Moyle PB, Sommer T. 2018. Managing for salmon resilience in California's variable and changing climate. *San Franc Estuary Watershed Sci.* [accessed 2022 Mar 10];16(2). <https://doi.org/10.15447/sfews.2018v16iss2art3>
- Hobbs J, Moyle PB, Fangué N, Connon RE. 2017. Is extinction inevitable for Delta Smelt and Longfin Smelt? An opinion and recommendations for recovery. *San Fran Estuary Watershed Sci.* [accessed 2022 Apr 06];15(2). <https://doi.org/10.15447/sfews.2017v15iss2art2>
- Holleman RC, Stacey MT. 2014. Coupling of sea level rise, tidal amplification, and inundation. *J Phys Oceanogr.* [accessed 2022 Apr 06];44(5):1439–1455. <https://doi.org/10.1175/JPO-D-13-0214.1>
- Huang X, Stevenson S, Hall AD. 2020. Future warming and intensification of precipitation extremes: a “double whammy” leading to increasing flood risk in California. *Geophys Res Lett.* [accessed 2022 Apr 06];47:e2020GL088679. <https://doi.org/10.1029/2020GL088679>
- Hutton PH, Meko DM, Roy SB. 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.* [accessed 2022 Apr 06];13:2139. <https://doi.org/10.3390/w13152139>
- Hutton PH, Rath JS, Chen L, Unga MJ, Roy SB. 2016. Nine decades of salinity observations in the San Francisco Bay and Delta: modeling and trend evaluations. *J Water Resour Plan Manag.* [accessed 2022 Apr 06];142:04015069. [https://doi.org/10.1061/\(ASCE\)WR.1943-5452.0000617](https://doi.org/10.1061/(ASCE)WR.1943-5452.0000617)
- Jardine TD, Pusey BJ, Hamilton SK, Pettit NE, Davies PM, Douglas MM, Sinnamon V, Halliday IA, Bunn SE. 2012. Fish mediate high food web connectivity in the lower reaches of a tropical floodplain river. *Oecologia.* [accessed 2022 Apr 06];168(3):829–838. <https://doi.org/10.1007/s00442-011-2148-0>
- Jeffres CA, Opperman JJ, Moyle PB. 2008. Ephemeral floodplain habitats provide best growth conditions for juvenile Chinook Salmon in a California river. *Environmental Biol Fishes.* [accessed 2022 Apr 06];83(4):449–458. <https://doi.org/10.1007/s10641-008-9367-1>
- Johansen JL, Nay TJ, Steffensen JF, Rummer JL. 2017. Adapt, move, or die—how will tropical coral reef fishes cope with ocean warming? *Glob Change Biol.* [accessed 2022 Apr 06];23:566–577. <https://doi.org/10.1111/gcb.13488>
- Katz JVE, Jeffres C, Conrad JL, Sommer TR, Martinez J, Brumbaugh S, Corline N, Moyle PB. 2017. Floodplain farm fields provide novel rearing habitat for Chinook salmon. *PloS ONE.* [accessed 2022 Apr 06];12(6):e0177409. <https://doi.org/10.1371/journal.pone.0177409>
- Katz J, Moyle PB, Quiñones RM, Israel J, Purdy S. 2013. Impending extinction of salmon, steelhead, and trout (*Salmonidae*) in California. *Environmental Biol Fishes.* [accessed 2022 Apr 06];96(10):1169–1186. <https://doi.org/10.1007/s10641-012-9974-8>
- Kimmerer WJ, Gartside E, Orsi JJ. 1994. Predation by an introduced clam as the likely cause of substantial declines in zooplankton of San Francisco Bay. *Mar Ecol Prog Ser.* [Retrieved 2022 Apr 06];113:81–93. <http://www.jstor.org/stable/24849580>
- Kimmerer W, Wilkerson F, Downing B, Dugdale R, Gross ES, Kayfetz K, Khanna S, Parker AE, Thompson J. 2019. Effects of drought and the emergency drought barrier on the ecosystem of the California Delta. *San Franc Estuary Watershed Sci.* [accessed 2022 Apr 06];17(3). <https://doi.org/10.15447/sfews.2019v17iss3art2>
- Kirwan ML, Guntenspergen GR, Alpaos AD, Morris JT, Mudd SM, Temmerman S. 2010. Limits on the adaptability of coastal marshes to rising sea level. *Geophysical Res Lett.* [accessed 2022 Apr 06];37(L23401):1–5. <https://doi.org/10.1029/2010GL045489>
- Knowles N. 2010. Potential inundation due to rising sea levels in the San Francisco Bay region. *San Franc Estuary Watershed Sci.* [accessed 2022 Apr 06];8(1). <https://doi.org/10.15447/sfews.2010v8iss1art1>
- Knowles N, Cronkite–Ratcliff C, Pierce DW, Cayan DR. 2018. Responses of unimpaired flows, storage, and managed flows to scenarios of climate change in the San Francisco Bay-Delta watershed. *Water Resour Res.* [accessed 2022 Mar 10];54(10):7631–7650. <https://doi.org/10.1029/2018WR022852>

- Knowles N, Dettinger MD, Cayan DR. 2006. Trends in snowfall versus rainfall in the western United States. *J Climate*. [accessed 2022 Mar 10];19(18):4545–4559.
<https://doi.org/10.1175/JCLI3850.1>
- Kolomijeca A, Parrott J, Khan H, Shires K, Clarence S, Sullivan C, Chibwe L, Sinton D, Rochman CM. 2020. Increased temperature and turbulence alter the effects of leachates from tire particles on Fathead Minnow (*Pimephales promelas*). *Environmental Sci Technol*. [accessed 2022 Apr 06];54(3):1750–1759.
<https://doi.org/10.1021/acs.est.9b05994>
- [IPCC] Intergovernmental Panel on Climate Change 2021. Masson–Delmotte V, Zhai P, Pirani A, Connors SL, Péan C, Chen Y, Goldfarb L, Gomis MI, Robin Matthews JB, Berger S, et al., editors. *Climate change 2021: the physical science basis. Working group I contribution to the sixth assessment report of the IPCC*. [unknown]: Cambridge University Press. Available from: <https://www.ipcc.ch/report/ar6/wg1/>
- Lauchlan S, Nagelkerken I. 2020. Species range shifts along multistressor mosaics in estuarine environments under future climate. *Fish and Fisheries*. [accessed 2022 Apr 06];21(1):32–46.
<https://doi.org/10.1111/faf.12412>
- Lehman BM, Johnson RC, Adkison M, Burgess OT, Connon RE, Fangué NA, Foott JS, Hallett SL, Martínez-López B, Miller KM, et al. 2020. Disease in Central Valley salmon: status and lessons from other systems. *San Franc Estuary Watershed Sci*. [accessed 2022 Apr 06];18(3).
<https://doi.org/10.15447/sfew.2020v18iss3art2>
- Lehman PW. 2004. The influence of climate on mechanistic pathways that affect lower food web production in northern San Francisco Bay estuary. *Estuaries*. [accessed 2022 Mar 10];27(2):311–324.
<https://doi.org/10.1007/BF02803387>
- Lehman PW, Kurobe T, Huynh K, Lesmeister S, Teh SJ. 2021. Covariance of phytoplankton, bacteria and zooplankton communities within *Microcystis* blooms in San Francisco Estuary. *Frontiers Aquat Microbiol*. [accessed 2022 Apr 06];12:632264.
<https://doi.org/10.3389/fmicb.2021.632264>
- Lehman PW, Kurobe T, Lesmeister S, Baxa D, Tung A, Teh SJ. 2017. Impacts of the 2014 severe drought on the *Microcystis* bloom in San Francisco Estuary. *Harmful Algae*. [accessed 2022 Mar 10];63:94–108.
<https://doi.org/10.1016/j.hal.2017.01.011>
- Lehman PW, Kurobe T, Teh SJ. 2022. Impact of extreme wet and dry years on the persistence of *Microcystis* harmful algal blooms in San Francisco Estuary. *Quat Int*. [accessed 2022 Apr 06];621:16–25.
<https://doi.org/10.1016/j.quaint.2019.12.003>
- Lehman PW, Mayr S, Liu L, Tang A. 2015. Tidal day organic and inorganic material flux of ponds in the Liberty Island freshwater tidal wetland. *Springer Plus*. [accessed 2022 Apr 06];4:273.
<https://doi.org/10.1186/s2Fs40064-015-1068-6>
- Lehman PW, Sommer T, Rivard L. 2008. The influence of floodplain habitat on the quantity and quality of riverine phytoplankton carbon produced during the flood season in San Francisco Estuary. *Aquat Ecology* [accessed 2022 Apr 06];42:363–378.
<https://doi.org/10.1007/s10452-007-9102-6>
- Limm MP, Marchetti MP. 2009. Juvenile Chinook Salmon (*Oncorhynchus tshawytscha*) growth in off-channel and main-channel habitats on the Sacramento River, CA using otolith increment widths. *Environ Biol Fishes*. [accessed 2022 Apr 06];85(2):141–151.
<https://doi.org/10.1007/s10641-009-9473-8>
- Luković J, Chiang JC, Blagojević D, Sekulić A. 2021. A later onset of the rainy season in California. *Geophys Res Lett*. [accessed 2022 Mar 10];48(4):e2020GL090350
<https://doi.org/10.1029/2020GL090350>
- Lund J, Hanak E, Fleenor WE, Bennett WA, Howitt R, Mount JF, Moyle PB. 2010. *Comparing futures for the Sacramento–San Joaquin Delta*. [accessed 2022 Apr 05]. Berkeley (CA): University of California Press. 256 p. Available from: <https://watershed.ucdavis.edu/library/comparing-futures-sacramento-san-joaquin-delta>
- Luoma SN, Dahm CN, Healey M, Moore JN. 2015. Challenges facing the Sacramento–San Joaquin Delta: complex, chaotic, or simply cantankerous? *San Franc Estuary Watershed Sci*. [accessed 2022 Apr 06];13(3).
<https://doi.org/10.15447/sfew.2015v13iss3art7>

- Mac Nally R, Thomson JR, Kimmerer WJ, Feyrer F, Newman KB, Sih A, Bennett WA, Brown L, Fleishman E, Culberson SD, Castillio G. 2010. Analysis of pelagic species decline in the upper San Francisco Estuary using multivariate autoregressive modeling (MAR). *Ecol Appl*. [accessed 2022 Apr 05];20(5):1417–1430. <https://doi.org/10.1890/09-1724.1>
- MacWilliams ML, Gross ES. 2010. UnTRIM San Francisco Bay–Delta Model sea level rise scenario modeling report, Bay–Delta Conservation Plan. Prepared for Science Applications International Corporation and California Department of Water Resources. [accessed 2022 Mar 10]. Available from: https://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/california_waterfix/exhibits/docs/petitioners_exhibit/dwr/part2/dwr1142/App_5.B_DSM2_Att2_update.pdf
- Mahardja B, May B, Feyrer F, Coalter R, Fangué N, Foin T, Baerwald MR. 2015. Interannual variation in connectivity and comparison of effective population size between two splittail (*Pogonichthys macrolepidotus*) populations in the San Francisco Estuary. *Conserv Genet*. [accessed 2022 Mar 10];16(2):385–398. <https://doi.org/10.1007/s10592-014-0665-1>
- Mahardja B, Conrad JL, Lusher L and Schreier B. 2016. Abundance trends, distribution, and habitat associations of the invasive Mississippi Silverside (*Menidia audens*) in the Sacramento–San Joaquin Delta, California, USA. *San Franc Estuary Watershed Sci*. [accessed 2022 Apr 05];14(1). <https://doi.org/10.15447/sfews.2016v14iss1art2>
- Mahardja B, Farruggia MJ, Schreier B, Sommer T. 2017. Evidence of a shift in the littoral fish community of the Sacramento–San Joaquin Delta. *PLoS ONE*. [accessed 2022 Apr 05];12(1):e0170683. <https://doi.org/10.1371/journal.pone.0170683>
- Mahardja B, Tobias V, Khanna S, Mitchell L, Lehman P, Sommer T, Brown L, Culberson S, Conrad JL. 2021. Resistance and resilience of pelagic and littoral fishes to drought in the San Francisco Estuary. *Ecol Appl*. [accessed 2022 Apr 05];31(2):e02243 <https://doi.org/10.1002/eap.2243>
- McLain J, Castillo G. 2009. Nearshore areas used by fry Chinook Salmon, *Oncorhynchus tshawytscha*, in the northwestern Sacramento–San Joaquin Delta, California. *San Franc Estuary Watershed Sci*. [accessed 2022 Mar 10];7(2). <https://doi.org/10.15447/sfews.2009v7iss2art1>
- Meko DM, Woodhouse CA, Touchan R. 2014. Klamath/San Joaquin/Sacramento hydroclimatic reconstructions from tree rings. Draft Final Report to the California Department of Water Resources; University of Arizona: Tucson, AZ, USA, 117. [accessed 2022 Mar 10]. Available from: <https://cawaterlibrary.net/wp-content/uploads/2017/05/DWR-Tree-Ring-Report.pdf>
- Meng L, Moyle PB. 1995. Status of splittail in the Sacramento–San Joaquin estuary. *Trans Am Fish Soc*. [accessed 2022 Mar 10];124(4):538–549. [https://doi.org/10.1577/1548-8659\(1995\)124<0538:SOSITS>2.3.CO;2](https://doi.org/10.1577/1548-8659(1995)124<0538:SOSITS>2.3.CO;2)
- Michel CJ, Notch JJ, Cordoleani F, Ammann AJ, Danner EM. 2021. Nonlinear survival of imperiled fish informs managed flows in a highly modified river. *Ecosphere*. [accessed 2022 Apr 05];12(5). <https://doi.org/10.1002/ecs2.3498>
- Michel CJ, Smith JM, Lehman BM, Demetras NJ, Huff DD, Brandes PL, Israel JA, Quinn TP, Hayes SA. 2020. Limitations of active removal to manage predatory fish populations. *N Am J Fish Manag*. [accessed 2022 Apr 05];40(1):3–16 <https://doi.org/10.1002/nafm.10391>
- Mote PW, Li S, Lettenmaier DP, Xiao M, Engel R. 2018. Dramatic declines in snowpack in the western US. *NPJ Clim Atmos Sci*. [accessed 2022 Mar 10];(1):1–6. <https://doi.org/10.1038/s41612-018-0012-1>
- Moyle PB. 1999. Effects of invading species on freshwater and estuarine ecosystems. In: Sandeland T, editor. *Invasive species and biodiversity management*. Based on papers presented at the Norway/United Nations (UN) Conference on Alien Species, 2nd Trondheim Conference on Biodiversity, Trondheim, Norway, 1996 July 1–5. [Dordrecht]: Kluwer Academic Publishers. p. 177–191.
- Moyle PB. 2002. *Inland fishes of California*. 2nd ed. Berkeley (CA): University of California Press. 502 p.

- Moyle PB, Baxter RD, Sommer T, Foin TC, and Matern SA. 2004. Biology and population dynamics of Sacramento Splittail (*Pogonichthys macrolepidotus*) in the San Francisco Estuary: a review. *San Franc Estuary Watershed Sci* [accessed 2022 Apr 05];2(2):1–47. <https://doi.org/10.15447/sfew.2004v2iss2art3>
- Moyle P, Bennett W, Durand J, Fleenor W, Gray B, Hanak E, Lund J, Mount J. 2012. Where the wild things aren't. Public Policy Institute of California. [accessed 2022 Mar 10]. Available from: https://www.ppic.org/wp-content/uploads/content/pubs/report/R_612PMR.pdf
- Moyle PB, Crain PK, and Whitener K. 2007. Patterns in the use of a restored California floodplain by native and alien fishes. *San Franc Estuary Watershed Sci*. [accessed 2022 Mar 10];5(3). <https://doi.org/10.15447/sfew.2007v5iss5art1>
- Moyle PB, Kiernan JD, Crain PK, Quiñones RM. 2013. Climate change vulnerability of native and alien freshwater fishes of California: a systematic assessment approach. *PLoS ONE*. [accessed 2022 Apr 05];8(5). <https://doi.org/10.1371/journal.pone.0063883>
- Moyle PB, Lund JR, Bennett WA, Fleenor WE. 2010. Habitat variability and complexity in the upper San Francisco Estuary. *San Franc Estuary Watershed Sci*. [accessed 2022 Apr 05];8(3). <https://doi.org/10.15447/sfew.2010v8iss3art1>
- Moyle PB, Quiñones RM, Katz JV, Weaver J. 2015. Fish species of special concern in California. Sacramento (CA): California Department of Fish and Wildlife. Available from: <https://wildlife.ca.gov/Conservation/SSC/Fishes>
- Munsch SH, Greene CM, Johnson RC, Satterthwaite WH, Imaki H, Brandes PL. 2019. Warm, dry winters truncate timing and size distribution of seaward-migrating salmon across a large, regulated watershed. *Ecol Appl*. [accessed 2022 Apr 05];29(4). <https://doi.org/10.1002/eap.1880>
- Munsch SH, Greene CM, Johnson RC, Satterthwaite WH, Imaki H, Brandes PL, O'Farrell MR. 2020. Science for integrative management of a diadromous fish stock: interdependencies of fisheries, flow, and habitat restoration. *Can J Fish Aquat Sci*. [accessed 2022 Apr 05];77:1487–1504. <https://doi.org/10.1139/cjfas-2020-0075>
- [NRC] National Research Council. 2012. Sea-level rise for the coasts of California, Oregon, and Washington: past, present, and future. National Academies Press. [accessed 2022 Mar 10]. Available from: <https://nap.nationalacademies.org/catalog/13389/sea-level-rise-for-the-coasts-of-california-oregon-and-washington>
- Nichols FH, Cloern JE, Luoma SN, Peterson DH. 1986. The modification of an estuary. *Science*. [accessed 2022 Mar 10];231(4738):567–573. <https://doi.org/10.1126/science.231.4738.567>
- [NOAA] National Oceanic and Atmospheric Administration. 2021. National Centers for Environmental information, Climate at a Glance: Statewide Time Series. [accessed 2021 Jun 16]. Available from: <https://www.ncdc.noaa.gov/cag/>
- Nobriga ML, Michel CJ, Johnson RC, Wikert JD. 2021. Coldwater fish in a warm water world: implications for predation of salmon smolts during estuary transit. *Ecol Evol*. [accessed 2022 Apr 05];11:15. <https://doi.org/10.1002/ece3.7840>
- Norgaard RB, Wiens JA, Brandt SB, Canuel EA, Collier TK, Dale VH, Fernando HJS, Holzer TL, Lumoa SN, Resh VH. 2021. Preparing scientists, policy-makers, and managers for a fast-forward future. *San Fran Estuary Watershed Sci*. [accessed 2022 Apr 05];19(2). <https://doi.org/10.15447/sfew.2021v19iss2art2>
- Opperman JJ, Moyle PB, Larsen EW, Florsheim JL, Manfree AD. 2017. Floodplains: processes and management for ecosystem services. Berkeley (CA): University of California Press. 280 p.
- O'Rear T, Montgomery J, Moyle PB, Durand JR. 2020. Suisun Marsh Fish Study: trends in fish and invertebrate populations of Suisun Marsh, January 2020–December 2020. Annual Report for the California Department of Water Resources. Sacramento (CA): University of California, Davis. [accessed 2022 Apr 05]. Available from: <https://watershed.ucdavis.edu/files/biblio/Suisun%20Marsh%20Fish%20Report%202020%20Final.pdf>
- Orr JA, Vinebrooke RD, Jackson MC, Kroeker KJ, Kordas RL, Mantyka-Pringle C, Van den Brink PJ, De Laender F, Stoks R, Holmstrup M, et al. 2020. Towards a unified study of multiple stressors: divisions and common goals across research disciplines. *Proc Royal Soc B*. [accessed 2022 Apr 05];287(1926):1-10. <https://doi.org/10.1098/rspb.2020.0421>

- Paerl HW, Otten TG. 2013. Harmful cyanobacterial blooms: causes, consequences, and controls. *Environ Microbiol* [accessed 2022 Apr 05];65:995–1010. <https://doi.org/10.1007/s00248-012-0159-y>
- Perry RW, Buchanan RA, Brandes PL, Burau JR, Israel JA. 2016. Anadromous salmonids in the Delta: new science 2006–2016. *San Franc Estuary Watershed Sci.* [accessed 2022 Mar 10];14(2). <https://doi.org/10.15447/sfews.2016v14iss2art7>
- Pierce DW, Kalansky JF, Cayan DR. 2018. Climate, drought, and sea level rise scenarios for California’s fourth climate change assessment. California Energy Commission and California Natural Resources Agency. [accessed 2022 Mar 10]. Available from: https://cawaterlibrary.net/wp-content/uploads/2019/08/Pages-from-Projections_CCCA4-CEC-2018-006.pdf
- Pine III WE, Martell, SJD, Walters CJ, Kitchell JF. 2009. Counterintuitive responses of fish populations to management actions. *Fisheries.* [accessed 2022 Apr 05];34:165-180. <https://doi.org/10.1577/1548-8446-34.4.165>
- Quiñones RM, Moyle PB. 2014. Climate change vulnerability of freshwater fishes of the San Francisco Bay Area. *San Franc Estuary Watershed Sci.* [accessed 2022 Apr 05];12(3). <https://doi.org/10.15447/sfews.2014v12iss3art3>
- Rahel FJ. 2022. Managing freshwater fish in a changing climate: resist, accept, or direct. *Fisheries.* [accessed 2022 Apr 05]. <https://doi.org/10.1002/fsh.10726>
- Ralph FM, Dettinger MD. 2012. Historical and national perspectives on extreme West Coast precipitation associated with atmospheric rivers during December 2010. *Bull Am Meteorol.* [accessed 2022 Mar 10];93(6):783–790. <https://doi.org/10.1175/BAMS-D-11-00188.1>
- Reich KD, Berg N, Walton DB, Schwartz M, Sun F, Huang X, Hall A. 2018. Climate change in the Sierra Nevada: California’s water future. UCLA Center for Climate Science. [accessed 2022 Mar 10]. Available from: <https://www.ioes.ucla.edu/wp-content/uploads/UCLA-CCS-Climate-Change-Sierra-Nevada.pdf>
- Reis GJ, Howard JK, Rosenfield JA. 2019. Clarifying effects of environmental protections on freshwater flows to—and water exports from—the San Francisco Bay Estuary. *San Franc Estuary Watershed Sci.* [accessed 2022 Apr 05];17:1. <https://doi.org/10.15447/sfews.2019v17iss1art1>
- Rhodes LD, Rice CA, Greene CM, Teel DJ, Nance SL, Moran P, Durkin CA, Gezhegne SB. 2011. Nearshore ecosystem predictors of a bacterial infection in juvenile Chinook Salmon. *Mar Ecol Prog Ser.* [accessed 2022 Apr 05];432:161–172. Available from: <https://www.int-res.com/abstracts/meps/v432/p161-172/>
- Richter A, Kolmes SA. 2005. Maximum temperature limits for Chinook, Coho, and Chum Salmon, and Steelhead Trout in the Pacific Northwest. *Reviews Fisheries Sci.* [accessed 2022 Apr 05];13(1):23–49. <https://doi.org/10.1080/10641260590885861>
- Roegner GC, Dawley EW, Russell M, Whiting A, Teel DJ. 2010. Juvenile salmonid use of reconnected tidal freshwater wetlands in Grays River, Lower Columbia River Basin. *Trans Am Fisheries Soc.* [2022 Apr 05];139(4):1211–1232. <https://doi.org/10.1577/t09-082.1>
- Roesch A, Schmidbauer H. 2018. WaveletComp: Computational Wavelet Analysis: wavelet analysis and reconstruction of time series, cross-wavelets and phase-difference (with filtering options), significance with simulation algorithms. <https://CRAN.R-project.org/package=WaveletComp>
- Schile LM, Callaway JC, Morris JT, Stralberg D, Parker VT, Kelly M. 2014. Modeling tidal marsh distribution with sea-level rise: evaluating the role of vegetation, sediment, and upland habitat in marsh resiliency. *PLoS One.* [accessed 2022 Mar 10];9(2):e88760. <https://doi.org/10.1371/journal.pone.0088760>
- Schoellhamer DH, Wright SA, Drexler JZ. 2013. Adjustment of the San Francisco Estuary and watershed to decreasing sediment supply in the 20th century. *Mar Geol.* [accessed 2022 Mar 10];345:63-71. <https://doi.org/10.1016/j.margeo.2013.04.007>

- Schoellhamer D, McKee L, Pearce S, Kauhanen P, Salomon M, Dusterhoff S, Grenier L, Marineau M, Trowbridge P. 2018. Sediment supply to San Francisco Bay, Water years 1995 through 2016: data, trends, and monitoring recommendations to support decisions about water quality, tidal wetlands, and resilience to sea level rise. Published by San Francisco Estuary Institute (SFEI), Richmond, CA. SFEI Contribution. [accessed 2022 Mar 10];842. Available from: https://www.sfei.org/sites/default/files/biblio_files/Sediment%20Supply%20Synthesis%20Report%202017%20-%202018-06-11_0.pdf
- Schroeter RE, O'Rear TA, Young MJ, Moyle PB. 2015. The aquatic trophic ecology of Suisun Marsh, San Francisco Estuary, California, during autumn in a wet year. *San Franc Estuary Watershed Sci.* [accessed 2022 Mar 10];13(3). <https://doi.org/10.15447/sfews.2015v13iss3art6>
- [SFEI] San Francisco Estuary Institute. 2017. California Aquatic Resource Inventory (CARI). Version 0.3. [accessed 2022 Apr 05]. Available from: <http://www.sfei.org/data/california-aquatic-resource-inventory-cari-version-03-gis-data>
- [SFEI] San Francisco Estuary Institute. 2020. Delta Landscapes Scenario Planning Tool User Guide. Version 1.0.0. Richmond (CA): San Francisco Estuary Institute. [accessed 2022 Apr 05]. Available from: https://www.sfei.org/sites/default/files/biblio_files/DLSPT_User_Guide_v1.0.0_SFEI_5.pdf
- Shephard S, Delanty K, O'Grady M, Kelly F. 2019. Salmonid conservation in an invaded lake: changing outcomes of predator removal with introduction of nonnative prey. *Trans Am Fish Soc.* [accessed 2022 Apr 05];148:219–231. <https://doi.org/10.1002/tafs.10132>
- Sherman S, Hartman R, Contreras D. 2017. Effects of tidal wetland restoration on fish: a suite of conceptual models. Interagency Ecological Program Technical Report 91. Sacramento (CA): Department of Water Resources. [accessed 2022 Apr 05]. Available from: <https://cadwr.app.box.com/v/InteragencyEcologicalProgram/file/571038692179>
- Sommer T. 2020. How to respond? An introduction to current Bay-Delta natural resources management options. *San Franc Estuary Watershed Sci.* [accessed 2022 Apr 05];18(3). <https://doi.org/10.15447/sfews.2020v18iss3art1>
- Sommer T, Baxter R, Feyrer F. 2007. Splittail “delisting”: a review of recent population trends and restoration activities. *Am Fish Soc Symp.* [accessed 2022 Apr 05];3:25–38. Available from: https://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/docs/cmnt091412/sldmwa/sommer_et_al_2007.pdf
- Sommer T, Baxter R, Herbold B. 1997. Resilience of Splittail in the Sacramento–San Joaquin estuary. *Trans Am Fish Soc.* [accessed 2022 Apr 05];126(6):961–976. [https://doi.org/10.1577/1548-8659\(1997\)126%3C0961:ROSITS%3E2.3.CO;2](https://doi.org/10.1577/1548-8659(1997)126%3C0961:ROSITS%3E2.3.CO;2)
- Sommer TR, Harrell WC, Feyrer F. 2014. Large-bodied fish migration and residency in a flood basin of the Sacramento River, California, USA. *Ecol Freshwater Fish.* [accessed 2022 Apr 05];23(3): 414–423. <https://doi.org/10.1111/eff.12095>
- Sommer TR, Harrell WC, Matica Z, and Feyrer F. 2008. Habitat associations and behavior of adult and juvenile Splittail (*Cyprinidae: Pogonichthys macrolepidotus*) in a managed seasonal floodplain wetland. *San Franc Estuary Watershed Sci.* [accessed 2022 Apr 05];6(2). <https://doi.org/10.15447/sfews.2008v6iss2art3>
- Sommer T, Harrell B, Nobriga M, Brown R, Moyle PB, Kimmerer W, Schemel L. 2001. California's Yolo Bypass: evidence that flood control can be compatible with fisheries, wetlands, wildlife, and agriculture. *Fisheries* [accessed 2022 Apr 05];26(8):6-16. [https://doi.org/10.1577/1548-8446\(2001\)026%3C0006:CYB%3E2.0.CO;2](https://doi.org/10.1577/1548-8446(2001)026%3C0006:CYB%3E2.0.CO;2)
- Sommer T, Hartman R, Koller M, Koohafkan M, Conrad JL, MacWilliams M, Bever A, Burdi C, Hennessy A, Beakes M. 2020. Evaluation of a large-scale flow manipulation to the upper San Francisco Estuary: Response of habitat conditions for an endangered native fish. *PLoS One.* [accessed 2022 Mar 10];15(10):e0234673. <https://doi.org/10.1371/journal.pone.0234673>
- Sommer TR, Nobriga ML, Harrell WC, Batham W, Kimmerer WJ. 2001. Floodplain rearing of juvenile Chinook Salmon: evidence of enhanced growth and survival. *Can J Fish Aquat Sci.* [accessed 2022 Apr 05];58:2. <https://doi.org/10.1139/f00-245>

- Sommer T, Schreier B, Conrad JL, Takata L, Serup B, Titus R, Jeffres C, Katz J. 2020. Farm to fish: lessons from a multi-year study on agricultural floodplain habitat. *San Franc Estuary Watershed Sci.* [accessed 2022 Apr 05];18(3). <https://doi.org/10.15447/sfews.2020v18iss3art4>.
- Stahle DW, Griffin RD, Cleveland MK, Edmondson JR, Fye FK, Burnette DJ, Abatzoglou JT, Redmond KT, Meko DM, Dettinger MD. 2011. A tree-ring reconstruction of the salinity gradient in the Northern Estuary of San Francisco Bay. *San Franc Estuary Watershed Sci.* [accessed 2022 Apr 05];9(1). <https://doi.org/10.15447/sfews.2011v9iss1art4>
- Stewart IT, Cayan DR, Dettinger MD. 2005. Changes toward earlier streamflow timing across western North America. *J Climate.* [accessed 2022 Mar 10];18(8):1136–1155. <https://doi.org/10.1175/JCLI3321.1>
- Stompe DK, Moyle PB, Kruger A, Durand JR. 2020. Comparing and integrating fish surveys in the San Francisco Estuary: why diverse long-term monitoring programs are important. *San Franc Estuary Watershed Sci.* [accessed 2022 Mar 10];18(2). <https://doi.org/10.15447/sfews.2020v18iss2art4>
- Stralberg D, Brennan M, Callaway JC, Wood JK, Schile LM, Jongsomjit D, Kelly M, Parker VT, Crooks S. 2011. Evaluating tidal marsh sustainability in the face of sea-level rise: a hybrid modeling approach applied to San Francisco Bay. *PLoS One.* [accessed 2022 Mar 10];6(11):e27388. <https://doi.org/10.1371/journal.pone.0027388>
- Sturrock AM, Satterthwaite WH, Cervantes-Yoshida KM, Huber ER, Sturrock HJW, Nusslé S, Carlson SM. 2019. Eight decades of hatchery salmon releases in the California Central Valley: factors influencing straying and resilience. *Fisheries.* [accessed 2022 Apr 05];44:433–444. <https://doi.org/10.1002/fsh.10267>
- Suddeth R, Mount JF, Lund JR. 2010. Levee decisions and sustainability for the Sacramento-San Joaquin Delta. *San Franc Estuary Watershed Sci.* [accessed 2022 Apr 05];8(2). <https://doi.org/10.15447/sfews.2010v8iss2art3>
- Sutula M, Kudela R, Hagy III JD, Harding Jr. LW, Senn D, Cloern JE, Bricker S, Mineberg G, Beck M. 2017. Novel analyses of long-term data provide a scientific basis for chlorophyll-a thresholds in San Francisco Bay. *Estuar Coast Shelf Sci.* [accessed 2022 Apr 05];197:107–118. <https://doi.org/10.1016/j.ecss.2017.07.009>
- Swain D, Langenbrunner B, David Neelin J, Hall A. 2018. Increasing precipitation volatility in twenty-first-century California. *Nat Climate Change.* [accessed 2022 Apr 05];8:427–433. <https://doi.org/10.1038/s41558-018-0140-y>
- Swanson KM, Drexler JZ, Fuller CC, Schoellhamer DH. 2015. Modeling tidal freshwater marsh sustainability in the Sacramento–San Joaquin Delta under a broad suite of potential future scenarios. *San Franc Estuary Watershed Sci.* [accessed 2022 Apr 05];13(1). <https://doi.org/10.15447/sfews.2015v13iss1art3>
- Ta J, Anderson LW, Christman MA, Khanna S, Kratville D, Madsen JD, Moran, PJ, Viers JH. 2017. Invasive aquatic vegetation management in the Sacramento–San Joaquin River Delta: status and recommendations. *San Franc Estuary Watershed Sci.* [accessed 2021 Jul 31];15(4). <https://doi.org/10.15447/sfews.2017v15iss4art5>
- Takata L, Sommer TR, Conrad JL, Schreier BM. 2017. Rearing and migration of juvenile Chinook salmon (*Oncorhynchus tshawytscha*) in a large river floodplain. *Environmental Biol Fishes.* [accessed 2022 Apr 05];100:1105–1120. <https://doi.org/10.1007/s10641-017-0631-0>
- Thomson JR, Kimmerer WJ, Brown LR, Newman KB, Mac Nally R, Bennett WA, Feyrer F, Fleishman E. 2010. Bayesian change point analysis of abundance trends for pelagic fishes in the upper San Francisco Estuary. *Ecol Appl.* 20(5):1431–1448. <https://doi.org/10.1890/09-0998.1>
- Thompson LM, Lynch AJ, Beever EA, Engman A, Falke JA, Jackson ST, Krabbenhoft T, Lawrence DJ, Limpinsel D, Magill R, et al. 2021. Responding to ecosystem transformation: resist, accept, or direct? *Fisheries.* [accessed 2022 Apr 05];46(1):8–21. <https://doi.org/10.1002/fsh.10506>

- [USBR and CDWR] US Bureau of Reclamation and California Department of Water Resources. 2019. Yolo Bypass Salmonid Habitat Restoration and Fish Passage Project Environmental Impact Report. Sacramento (CA): US Dept. of the Interior, Bureau of Reclamation. Available from: https://www.usbr.gov/mp/nepa/nepa_project_details.php?Project_ID=30484
- [USFWS] US Fish and Wildlife Service. 2003. Endangered and threatened wildlife and plants: notice of remanded determination of threatened status for the Sacramento Splittail (*Pogonichthys macrolepidotus*). Federal Register 68(183):5140–5166.
- [USFWS] US Fish and Wildlife Service. 2019. Biological opinion for the reinitiation of consultation on the coordinated operations of the Central Valley Project and the State Water Project 172 [accessed 2020 Jan 19]. Available from: <https://ecos.fws.gov/ServCat/Reference/Profile/145909>
- Wang J, Yin H, Reyes E, Smith T, Chung F. 2018. Mean and extreme climate change impacts on the State Water Project. California's Fourth Climate Change Assessment, California Energy Commission: Sacramento, CA, USA. [accessed 2022 Mar 10]. Available from: https://www.energy.ca.gov/sites/default/files/2019-12/Water_CCCA4-EXT-2018-004_ada.pdf
- Whipple AA, Grossinger RM, Rankin D, Stanford B, Askevold RA. 2012. Sacramento-San Joaquin Delta historical ecology investigation: exploring pattern and process. Richmond (CA): San Francisco Estuary Institute-Aquatic Science Center. A Report of SFEI-ASC's Historical Ecology Program. Publication #672. [accessed 2022 Apr 05]. <http://www.sfei.org/DeltaHEStudy>
- Williams AP, Cook ER, Smerdon JE, Cook BI, Abatzoglou JT, Bolles K, Baek SH, Badger AM, Livneh B. 2020. Large contribution from anthropogenic warming to an emerging North American megadrought. *Science*. [accessed 2022 Mar 10];368(6488):314-318. <https://doi.org/10.1126/science.aaz9600>
- Willmes M, Hobbs JA, Sturrock AM, Bess Z, Lewis LS, Glessner JJG, Johnson RC, Kurth R, Kindopp J. 2018. Fishery collapse, recovery, and the cryptic decline of wild salmon on a major California river. *Can J Fish Aquat Sci*. [accessed 2022 Apr 05];75:1836–1848. <https://doi.org/10.1139/cjfas-2017-0273>
- Winder M, Jassby AD. 2011. Shifts in zooplankton community structure: implications for food web processes in the upper San Francisco Estuary. *Estuaries Coasts*. [accessed 5 Apr. 2022]; 34(4):675-690. <https://doi.org/10.1007/s12237-10-9342-x>
- Woodson LE, Wells BK, Weber PK, MacFarlane RB, Whitman GE, Johnson RC. 2013. Size, growth, and origin-dependent mortality of juvenile Chinook salmon *Oncorhynchus tshawytscha* during early ocean residence. *Mar Ecol Prog Ser*. [accessed 2022 Apr 05];487:163–175. <https://www.jstor.org/stable/24892117>
- Wright SA, Schoellhamer DH. 2004. Trends in the sediment yield of the Sacramento River, California, 1957–2001. *San Franc Estuary Watershed Sci*. [accessed 2022 Mar 10];2(2). <https://doi.org/10.15447/sfews.2004v2iss2art2>
- Yoshiyama RM, Moyle PB, Gerstung ER, Fisher FW. 2011. Chinook Salmon in the California Central Valley: an assessment. *Fisheries*. [accessed 2022 Apr 04];25(2):6–20. [https://doi.org/10.1577/1548-8446\(2000\)025%3C0006:CSITCC%3E2.0.CO;2](https://doi.org/10.1577/1548-8446(2000)025%3C0006:CSITCC%3E2.0.CO;2)
- Young MJ, Feyrer F, Colombano DD, Conrad LJ, Sih A. 2018. Fish-habitat relationships along the estuarine gradient of the Sacramento-San Joaquin Delta, California: implications for habitat restoration. *Estuaries Coasts*. [accessed 2022 Apr 04];41(8):2389–2409. <https://doi.org/10.1007/s12237-018-0417-4>
- Young M, Howe E, O'Rear T, Berridge K, Moyle P. 2021. Food web fuel differs across habitats and seasons of a tidal freshwater estuary. *Estuaries Coasts*. [accessed 2022 Apr 04];44:286–301. <https://doi.org/10.1007/s12237-020-00762-9>
- Zeug SC, Beakes M, Wiesenfeld J, Greenwood M, Grimaldo L, Hassrick J, Collins A, Acuña S, Johnston M. 2021. Experimental quantification of piscivore density and habitat effects on survival of juvenile Chinook Salmon in a tidal freshwater estuary. *Estuaries Coasts*. [accessed 2022 Apr 04];44:1157–1172. <https://doi.org/10.1007/s12237-020-00836-8>
- Zischg AP, Bermúdez M. 2020. Mapping the sensitivity of population exposure to changes in flood magnitude: prospective application from local to global scale. *Front Earth Sci*. [accessed 2022 Apr 04];8:390. <https://doi.org/10.3389/feart.2020.534735>