PUBLIC REVIEW DRAFT

Delta Ecosystem Stressors: A Synthesis

April 2018

DELTA STEWARDSHIP COUNCIL

A California State Agency

Developed in support of the Delta Plan Chapter 4 Amendment, Last Modified April 2018

For further assistance interpreting the content of this document, please contact Delta Stewardship Council staff.

accessibility@deltacouncil.ca.gov

Phone: 916-445-5511

Table of Contents

List of Figures

List of Tables

1. Introduction

The Delta Reform Act of 2009 requires that the Delta Stewardship Council (Council) adopt a Delta Plan (the Plan) to achieve the coequal goals of providing a more reliable water supply for California and protecting, restoring, and enhancing the Sacramento – San Joaquin Delta (Delta) ecosystem. The Delta Reform Act states that the coequal goals shall be achieved in a manner that protects and enhances the unique cultural, recreational, natural resource, and agricultural values of the Delta as an evolving place (Water Code Section 85000). The Plan was adopted in 2013. The Council will review the Delta Plan at least once every five years and may revise it, as the Council deems appropriate (Water Code Section 85300).

In the time since 2013, a significant shift in State planning for Delta ecosystem protection, restoration, and enhancement has occurred, prompting review of the Delta Plan approach to ecosystem restoration, and examination of whether its policies and recommendations are still suited to achieve the ecological goals of the Delta Reform Act. Specifically, the Delta Reform Act of 2009 directed the Delta Stewardship Council to consider the Habitat Conservation Plan (HCP) and Natural Community Conservation Plan (NCCP), which were under development by State and Federal agencies to address permitting requirements associated with State Water Project (SWP) and Central Valley Project (CVP) facility upgrades. The combined HCP/NCCP was to consist of comprehensive, broad-based ecosystem planning, including protection and restoration of plant, fish, and wildlife communities, in an effort to achieve comprehensive biodiversity protection. However, in April 2015, State and Federal agencies selected an alternative approach to meeting environmental permitting requirements that focused on offsetting project impacts but did not include the comprehensive biodiversity protection originally envisioned with the comprehensive HCP/HCCP. In addition, new science and other information on the Delta ecosystem has become available since the Delta Plan was adopted in 2013. As a result, the Council is developing an amendment of the Plan's Chapter 4, *Protect, Restore, and Enhance the Delta Ecosystem* to reflect these changes.

Council staff are reviewing the best available science to inform an amendment of Chapter 4 of the Delta Plan. To support this effort, Council staff have developed three science synthesis papers. This paper focuses on the form and function of the Delta's aquatic and terrestrial ecosystems, and identifies implications and considerations for restoration and management. Two additional papers synthesize science related to climate change and sea-level rise (Climate Change Paper), and approaches to ecosystem protection, restoration, and enhancement (Restoration Paper), including the human dimension of restoration and societal benefits of a healthy ecosystem.

The Delta is recognized as one of a handful of large and important estuaries globally that provide significant riparian and wetland resources and support significant biodiversity. Multiple stressors including flow impairment and floodplain disconnection, large-scale loss of wetlands and native vegetation communities, water quality degradation, and non-native species introductions have affected species populations and overall ecosystem health within the watershed. Climate change and sea-level rise will continue to further stress the Delta ecosystem. Despite constraints from urbanization, land subsidence, and non-native species, substantial opportunities exist to protect, restore, and enhance the Delta ecosystem.

The Delta Reform Act defines restoration as "*the application of ecological principles to restore a degraded or fragmented ecosystem and return it to a condition in which its biological and structural components achieve a close approximation of its natural potential, take into consideration the physical changes that have occurred in the past and the future impact of climate change and sea level rise*" (Water Code Section 85066).

The Delta Reform Act also provides specific guidance for the Delta Plan, directing the inclusion of the following measures that promote all of the following characteristics of a healthy Delta ecosystem (Water Code Section 85302(c)):

1. Viable populations of native resident and migratory species.
2. Functional corridors for migratory species.
3. Diverse and biologically appropriate habitats and ecosystem processes.
4. Reduced threats and stresses on the Delta ecosystem.
5. Conditions conducive to meeting or exceeding the goals in existing species recovery plans and state and federal goals with respect to doubling salmon populations.

Furthermore, the Delta Plan also includes the following sub-goals and strategies for restoring a healthy ecosystem (Water Code Section 85302(e)):

1. Restore large areas of interconnected habitats within the Delta and its watershed by 2100.
2. Establish migratory corridors for fish, birds, and other animals along selected Delta river channels.
3. Promote self-sustaining, diverse populations of native and valued species by reducing the risk of take and harm from invasive species.
4. Restore Delta flows and channels to support a healthy estuary and other ecosystems.
5. Improve water quality to meet drinking water, agriculture, and ecosystem long-term goals.
6. Restore habitat necessary to avoid a net loss of migratory bird habitat and, where feasible, increase migratory bird habitat to promote viable populations of migratory birds.

Using the measures, sub-goals and strategies of the Delta Reform Act as guidance, this synthesis paper identifies implications for policy and practice related to restoration and management of the Delta ecosystem, and provides considerations for a planned amendment to Chapter 4. Following this Introduction (Section 1), Section 2 provides a summary overview of the topics addressed in this synthesis paper. Section 3 discusses the historical and current geomorphic setting of the Delta, including a description of landforms, flows and sediment, and the process of land subsidence. Section 4 provides a similar level of review of the Delta ecosystem, including vegetation communities, fish and wildlife, the food web, and environmental water quality. Section 5 describes primary stressors acting on the Delta ecosystem. Section 6 provides examples of restoration actions that target ecological resilience. Section 7 describes the key findings of the review and associated implications for restoration and management of the Delta ecosystems. Section 8 provides a summary of considerations for the amendment of Chapter 4 of the Delta Plan. Section 9 contains the references cited.

For the purposes of this paper, "the Delta" refers to the statutory legal Delta and Suisun Marsh collectively, consistent with the Delta Plan (see Figure 1).

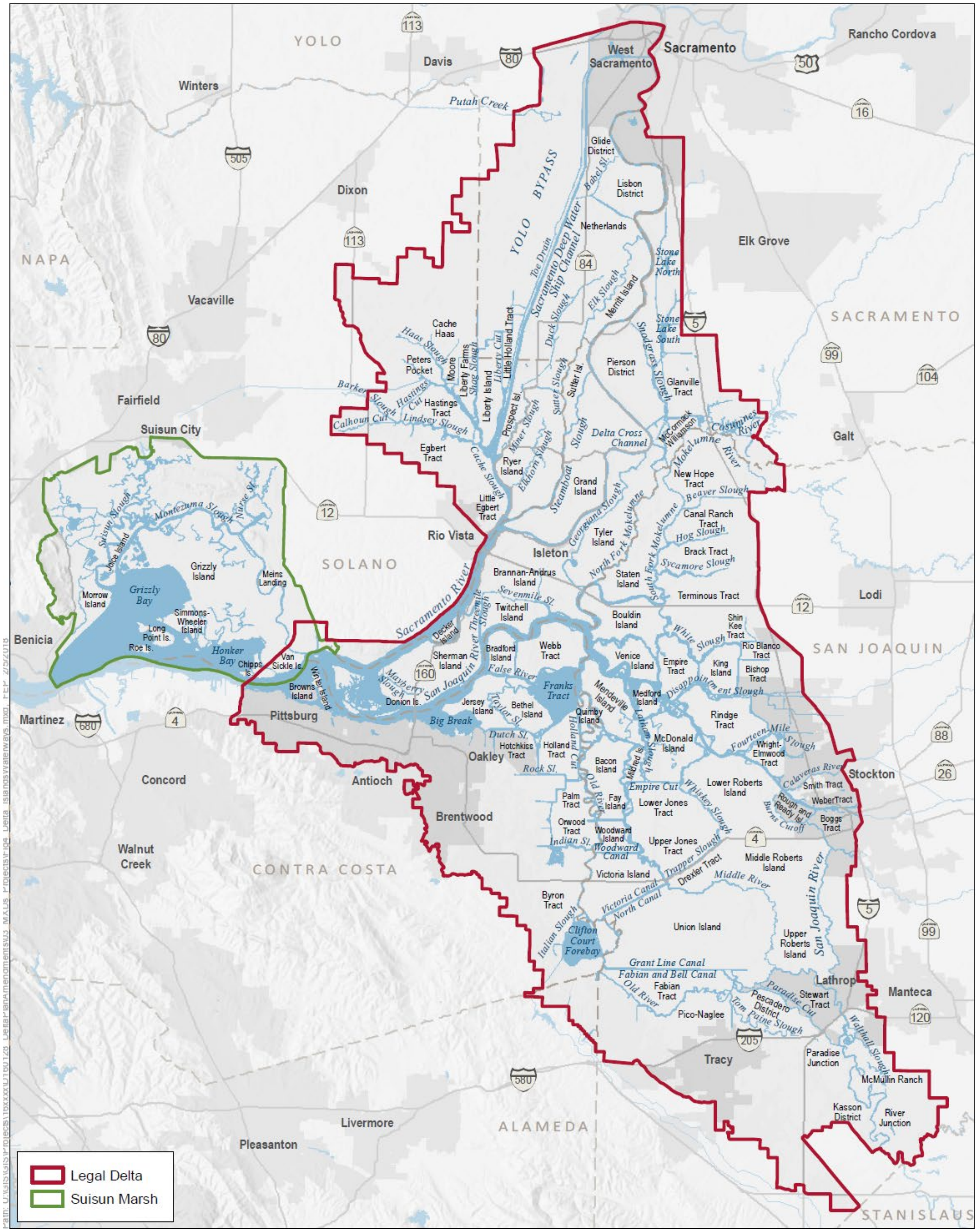


Figure 1. Sacramento – San Joaquin Delta Planning Area

2. The Delta Ecosystem

The Delta and its watershed once supported a dynamic food web and rich array of native plant and animal species that contributed to exceptional biological diversity at regional, state, continental, and global scales (Myers et al. 2000). This included diverse fish community that included Delta Smelt (*Hypomesus transpacificus*) and Longfin Smelt (*Spirinchus thaleichthys*), multiple large runs of Chinook Salmon (*Oncorhynchus tshawytscha*), numerous other freshwater, estuarine, and anadromous fish, as well as a diverse suite of wildlife, including waterbirds, mammals, reptiles, and amphibians (Bay Institute 1998; Moyle 2002; Whipple et al. 2012). However, since the start of the Gold Rush in the middle of the 19th century, the ecosystem has undergone a dramatic transformation due to flow alterations, large-scale landform modifications associated with changes in land use, degradation of water quality, and the introduction of numerous non-native species (Bay Institute 1998; Whipple et al. 2012; SFEI-ASC 2014, 2016).

A multitude of stressors has acted on the Delta ecosystem (Healy et al. 2008, 2016; Luoma et al. 2015). Construction of dams for water supply and flood control have substantially altered the natural hydrograph. Small impoundments and water diversions occur throughout the freshwater portion of the estuary, but the largest facilities are associated with the CVP and the SWP. These facilities impound water at several locations in the Sacramento and San Joaquin river basins, divert water upstream of the Delta, and export water from the southwestern Delta to agricultural and urban areas to the south and the San Francisco Bay Area. Levee construction and land conversion has reduced the vast wetlands that once covered and surrounded the Delta to small remnants. There has been an 80-fold decrease in the ratio of wetland to open water area in the Delta, from a historical ratio of 14:1 to a current ratio of 1:6 (Whipple et al. 2012; Herbold et al. 2014; SFEI-ASC 2016). Levee construction and dredging have also led to a substantial reconfiguration of the bays, sloughs, and channels, while large-scale water diversions and discharge of contaminants have altered water quantity and quality. Construction of levees has largely disconnected rivers from floodplain terraces, resulting in substantial loss of riparian vegetation communities. Water quality is impaired, largely because of urban and agricultural inputs within the watershed (Preece et al. 2017). In addition, a wide variety of non-native plants and animals have established in the Delta (Cohen and Carlton 1998; Light et al. 2005; Winder et al. 2011; Carlton et al. 1990). These species are modifying a number of ecological processes in the Delta by altering physically processes (e.g., non-native vegetation establishment and changes to hydrodynamics, water quality, light, turbidity), and disrupting the food web through bottom-up (e.g., Asian clam grazing, zooplankton species shifts) and top-down (e.g., predation by non-native predatory fish species) effects (Mount et al. 2012).

Despite these impaired conditions, significant opportunities exist to 1) restore geomorphic and ecological processes through reconnection of tidal marsh plain and flood plain, 2) re-establish native vegetation communities, and 3) improve water quality. These actions are critical steps in supporting the ecological needs of fish and wildlife species, providing increases in currently limited marsh and floodplain for both habitat and primary production (i.e., food web function). Further these actions can work in step with active management of non-native invasive species by reducing non-native habitat suitability and contributing to the health of native species such that effects may be more compensatory (Dybala et al. 2014; Mordecai et al. 2015). In sub-regions of the Delta where subsidence has limited the potential for hydrologic reconnection, subsidence reversal activities can halt and reverse continued loss of land elevation, and limit the impacts of sea-level rise. The following sections synthesize best available science related to key stressors acting on ecosystem function within the Delta, focusing on the geomorphic and ecological aspects of the Delta that support ecosystem function.

3. Geomorphic Setting

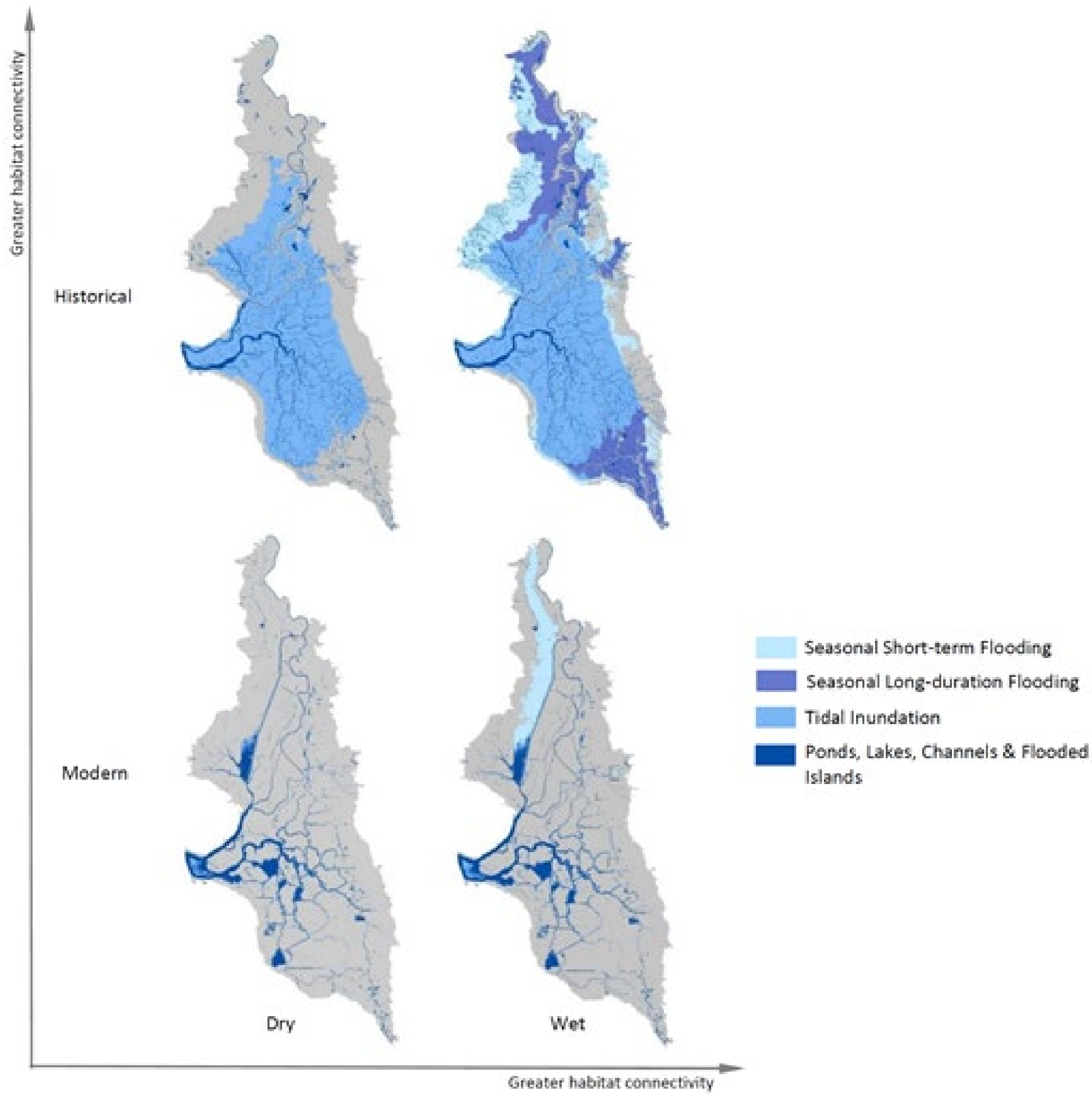
The inland position of the Delta is unique among other coastal deltas (Atwater and Belknap 1980). The Delta lies at the confluence of the Sacramento and San Joaquin rivers and is constrained by the Coast Range along the western extent. The Delta connects to the ocean through a series of bays and associated intertidal plains. The inland Delta formed sometime between 10,000 and 6,000 years ago when the rising sea level inundated a broad valley (Atwater et al. 1979; Atwater and Belknap 1980). The landscape maintained its elevation over the past 10,000 years through a balance between tectonic subsidence, sea-level rise, watershed sediment input and wetland organic (i.e., plant detritus) deposits (Atwater et al. 1979; Atwater and Belknap 1980). Surficial geology indicates that the Delta landscape consisted of marsh plains, channel network systems, flood basins, and natural levees that supported freshwater emergent and riparian vegetation, ponds, and salt pannes over the millennia (Shlemon and Begg 1975; Atwater and Belknap 1980; Whipple et al. 2012).

Landscape-scale reclamation, levee construction, and land cover conversion has reduced wetland extent and limited the interaction of water and sediment over the majority of the Delta landscape, as has occurred in many similar ecosystems (Pethick and Crook 2000; Reed 2002; SFEI-ASC 2014). Exposure of the Delta's peat soils to oxidation, compaction, and wind erosion have caused widespread subsidence, with ongoing regional subsidence rates ranging from <0.3 to >1.8 cm yr-1 (Deverel and Rojstaczer 1996; Deverel and Leighton 2010; Deverel et al. 2016; Sharma et al. 2016). Because of subsidence over the past century, island elevations throughout the Delta are substantially below mean sea level, with some islands being as low as eight meters (26 feet) below sea level (Deverel and Rojstaczer 1996; Ingebritsen et al. 2000; Mount and Twiss 2005; California Department of Water Resources [DWR] 2007). Levee failure in this context poses a number of dire consequences including effects on tidal and flow forcing, water quality (e.g., salinity intrusion), loss of agricultural lands, and the potential for the development of deep-water lakes similar to Franks Tract (Durand 2017).

Runoff from more than 40 percent of California's land area drains through the Delta, and out to San Francisco Bay and the Pacific Ocean (Ingebritsen et al. 2000) (see Figure 2). California's two largest river systems—the Sacramento and San Joaquin rivers—along with other major tributaries on the east and west sides of the Delta deliver freshwater, coarse and fine sediment, nutrients, and other materials to the tidally-influenced Delta. The river systems of the Central Valley and Delta experience large intra- and inter-annual flow variations due to California's Mediterranean climate. Tidal forcing modulates these flows, having a greater influence during dry periods (Moyle et al. 2010). These hydrologic variations lead to a dynamic estuarine salinity gradient. The construction of dams and diversions has reduced and altered in-flows, outflows, and in-Delta hydrodynamics (Fleenor et al. 2010; National Research Council [NRC] 2012; Swanson 2015; SWRCB 2017). These changes have implications for geomorphic processes, species habitat conditions and migration, and water quality and food web function (Poff et al. 2010; Moyle et al. 2011). Coupled with the disconnection of floodplains and tidal marsh plains, dams and diversions have reduced and altered sediment dynamics throughout the Delta watershed (Schoellhamer et al. 2013). This reduction has affected multiple aspects of the Delta ecosystem, including erosion and depositional processes that affect tidal marsh accretion and long-term stability, vegetation dynamics, water quality (e.g., turbidity, salinity) and food web function. Figure 3 illustrates the extent of flood and marsh plain disconnection within the Delta.

Seasonal and inter-annual variability of the flow and sediment inputs drive physical processes that support a range of ecosystems and ecological processes (Poff 1997; Bolger et al. 2011; Fox et al. 2015; SFEI-ASC 2016). Ecosystem processes include vegetation recruitment and succession, movement of organisms across ecosystem types, and food web productivity (Nilsson and Berggren 2000; Greco et al. 2007). In the winter and spring, fresh water often extends into San Pablo Bay, while in the summer and fall brackish water can intrude into the western Delta. In addition, inter-annual precipitation (i.e., rain and snow) varies unpredictably with extremely dry years with little precipitation and very wet years with widespread flooding (Kirby et al. 2005, 2010). Climate change is altering precipitation and runoff patterns within the Delta watershed (Dettinger and Cayan 1995; Null et al. 2010; Dettinger 2011). This could affect both magnitudes and frequencies of floods by increasing the intensity of large storms and rain and snowmelt-generated runoff events (Das et al. 2011). These changes will also result in lower summertime flows, with reduced snow pack, increasing stresses on ecosystems, and potentially increasing the risk of fire (Dettinger et al. 2004; Moyle et al. 2013) (see Climate Change Paper).

Figure 2. Delta and Watershed Planning Area

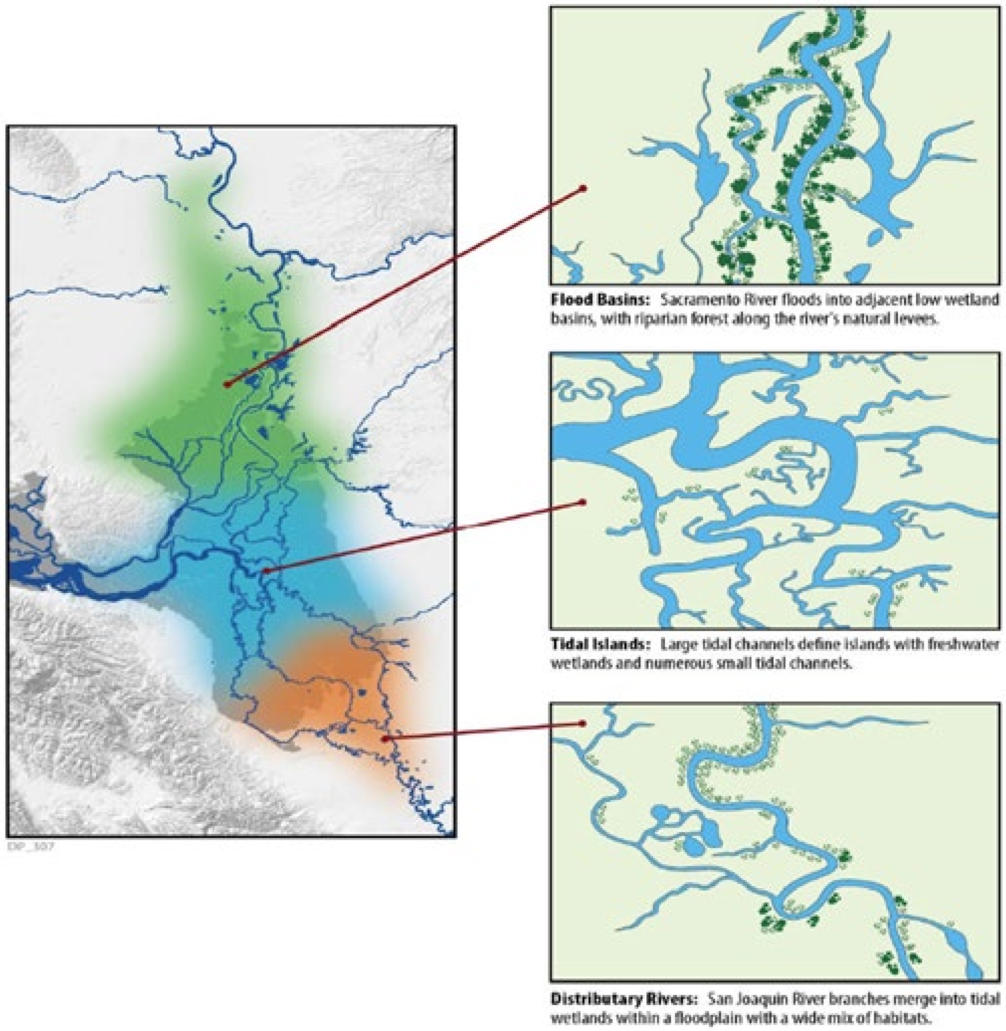


Source: SFEI-ASC 2014

Figure 3. Changes in Flooding Patterns in the Historical and Modern Delta

The historical Delta landscape consisted of three primary sub-regions based on physical characteristics: flood basins in the north Delta, tidal islands in the central Delta and distributary rivers (rivers with multiple branches flowing away from main channels) in the south Delta (Atwater and Belknap 1980; Whipple et al. 2012) (see Figure 4). Historically the flood basins of the north Delta were adjacent to the rivers, accommodating large-magnitude floods occurring regularly on the Sacramento River and other tributaries. These connections have been lost due to the construction of levees. Prior to 1850, this sub-region contained broad zones of non-tidal freshwater emergent wetlands relatively free of dendritic channel networks, which transitioned into tidal freshwater emergent wetlands of the central Delta. The central Delta sub-region was tidally influenced, with little topographic relief, and flooded during spring tides and riverine flooding (Atwater et al. 1979; Bay Institute 1998; Whipple et al. 2012). Large tidal sloughs with low banks intersected to form islands. Channel density and sinuosity in the central Delta appears to have been greater than in the less tidally dominated northern and southern parts of the Delta (but lower than the brackish and saline marshes of the estuary downstream in the Suisun region that has greater tidal energy). The physical landscape of the modern Delta has been disconnected from tidal connection, simplified, and channelized (Bay Institute 1998; ASC-SFEI 2014). Within the central Delta, exposure of peat soils in impounded islands has led to the most significant instances of subsidence (Mount and Twiss 2005; Bates and Lund 2013). In the western extent of the central Delta, sand mounds (i.e., small dunes) extended above the marsh plains, providing dry land forms in an otherwise wet landscape. These dune complexes have been stabilized by non-native invasive stands of Arundo donax. The south Delta was shaped by the three distributary branches of the San Joaquin River. These branches produced numerous secondary overflow channels that seasonally inundated floodplain terraces, which broadened downstream and merged gradually with tidal wetlands. This complex network of distributary channels with associated natural levees of variable height along the margins intersected the fluvial-tidal transition zone, conveying floodwaters toward the more heavily tidal central Delta (Atwater et al. 1979).

Transitions between these sub-regions occur gradually and across broad areas. Sub-regional differences in landscape form, watershed input, and tidal dynamics all affect the geomorphic processes and resulting ecosystem structure and function (Atwater et al. 1979; Bay Institute 1998; Whipple et al. 2012). These sub-regional characteristics are fundamental considerations in evaluating current and future restoration strategies in the Delta, (Moyle et al. 2012; SFEI-ASC 2016).



Source: Whipple et al. 2011

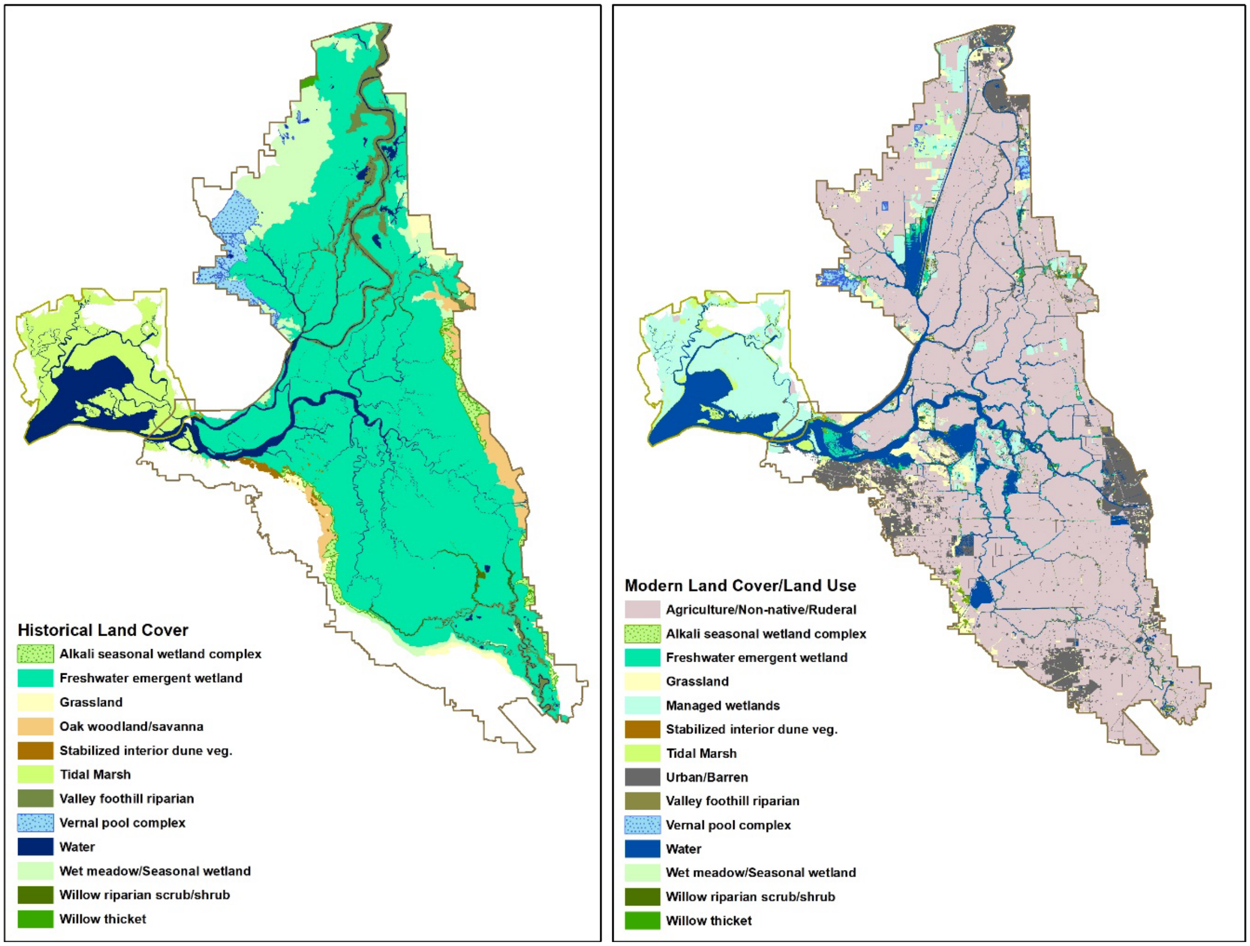
Figure 4. Primary Landscapes in the Historical Delta

4. Ecological Setting

4.1 Land Cover and Vegetation Communities

The flood basins, tidal marsh plain and channel networks, and natural levees within the three sub-regions of the Delta once supported a diverse array of riparian, wetland, and upland land cover types (Figure 5). Table 1 describes the extent of dominant land cover types, including the pre-1850 and modern areal extent of each. Within the north Delta, dense stands of tules over ten feet (three meters) tall were present. Complex multi-layered riparian forest and scrub existed on natural levees, and upland margins supported grasslands and vernal pool complexes wetlands (Geographic Information Center [GIC] 2003; Whipple et al. 2012). The dominant land cover of the tidal plains and channel networks of the central Delta was a matrix of tules, willows, and other freshwater wetland plant species (Whipple et al. 2012). Dune complexes in the western-central Delta hosted unique plant communities adapted to dynamic conditions (Pickart and Barbour 2007). The flood plains of the south Delta included heterogeneous distributions of emergent wetland, willow thickets, and peripheral upland areas with alkali wetlands, oaks, and grassland (GIC 2003; Whipple et al. 2012). These vegetation communities were affected by physical processes including tidal action, shifting seasonal salinity, and flooding regimes; vegetation also interacted with sediment erosion and deposition, creating complex community composition and structure (Vaghti and Greco 2007; Grewell et al. 2007). The riparian and wetland ecosystems of the Delta and its watershed supported a significant amount of the biodiversity on the Central Valley landscape (Thompson 1957; Bay Institute 1998; Lund et al. 2007; Whipple et al. 2012; Robinson et al. 2016).

Shaded riverine aquatic cover is an important component of the riparian ecosystems that are typically found upstream of tidal marshes, and is defined as the nearshore aquatic area occurring at the interface between a river and adjacent woody riparian habitat (DeHaven 1989). The principal attributes of this valuable cover type include: (a) the adjacent bank being composed of natural, eroding substrates supporting riparian vegetation that either overhangs or protrudes into the water, and (b) the water containing variable amounts of woody debris, such as leaves, logs, branches and roots, as well as variable depths, velocities, and currents. These attributes provide high-value feeding areas, burrowing substrates, escape cover, and reproductive cover for numerous regionally important fish and wildlife species, including Chinook Salmon, Steelhead (Oncorhynchus mykiss), and bank swallow. However, this cover-type on the Sacramento and San Joaquin rivers and their major tributaries has been substantially lost over the past several decades, primarily due to bank protection projects (USFWS 1992; DeHaven 1989; Whipple et al. 2012; Moyle et al. 2012).



Source: Expanded from Whipple et al. (2012) and SFEI-ASC (2014) using VegCAMP (Hickson and Keeler-Wolf 2007) to include Suisun Marsh and missing regions of the legal Delta.

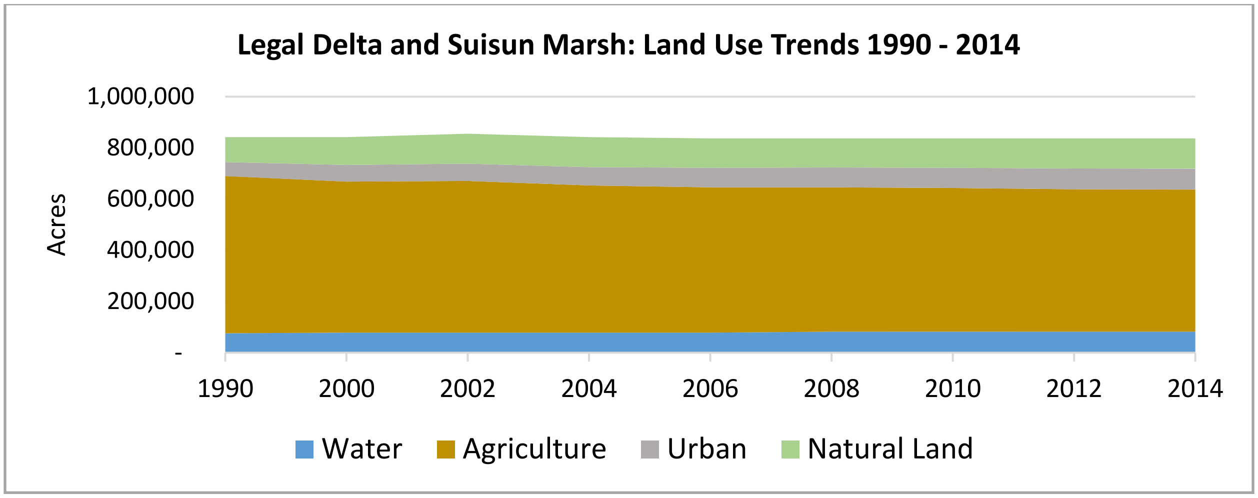
Figure 5. Land Cover and Vegetation Community Types within the Delta and Suisun Marsh

Table 1. Summary of Land Cover and Land Use Extent (Acres) for the Historical and Modern Delta and Suisun Marsh

Land Cover/Land Use Type	Historical Acres	Modern Acres	Percent Change
Agriculture/Non-native/Ruderal	-	508,938	-
Managed wetlands	-	73,400	-
Urban/Barren	-	63,731	-
Willow thicket	826	372	-55%
Willow riparian scrub/shrub	2,332	6,906	196%
Stabilized interior dune veg	2,550	19	-99%
Grassland	7,792	32,994	323%
Alkali seasonal wetland complex	13,607	698	-95%
Vernal pool complex	16,935	4,240	-74%
Oak woodland/savanna	17,331	-	-100%
Valley foothill riparian	28,439	6,889	-76%
Tidal Marsh/Freshwater emergent (hydraulically connected, includes fresh/brackish/saline)	506,562	19,892	-96%
Wet meadow/Seasonal wetland (fluvial, hydraulically connected)	57,671	5,029	-91%
Water	64,697	92,532	43%
Total Natural Land Cover Acres (does not include agriculture, managed wetlands, urban/barren, water)	**654,045**	**77,039**	**-88%**

Source: Expanded from Whipple et al. (2012) and SFEI-ASC (2014) using VegCAMP (Hickson and Keeler-Wolf 2007) to include Suisun Marsh and missing regions of the legal Delta.

Agriculture is now the dominant land use in the Delta, with wetland and riparian vegetation communities lost to land reclamation (Katibah 1984; Bay Institute 1998; Whipple et al. 2012). Land use data from the California Department of Conservation’s (DOC) Farmland Mapping and Monitoring Program (FMMP) (DOC 2017) documents agriculture occupying 73.2 percent (555,807 acres) of the Delta landscape in 2014, despite declining 9.5 percent since 1990. Urban land use occupies 10.7 percent (81,221 acres) and increased 49.4 percent (since 1990). Natural lands occupy 15.5 percent (117,912 acres) and have increased 21.4 percent since 1990 (see Figure 6). Note that “natural lands” as defined by the FMMP include any areas not in agricultural production, rather than necessarily native communities. Such natural lands generally exist in the linear margins of agricultural fields, on levees or leveed channel margins, or on instream islands, and thus may be too small or degraded to be fully functional ecologically.



Source: DOC 2017

Figure 6. Land Use Trends in the Delta and Suisun Marsh from 1990 to 2014

Despite regular human disturbance, some cultivated, or working lands, act as analogue habitats to a limited number of wildlife species. For example, flooded rice fields provide surrogate wetland habitats for species such as giant garter snake (*Thamnophis gigas*). Hay crops and some annually cultivated crops provide important foraging habitat for raptors, including Swainson's hawk (*Buteo swainsoni*), and winter-flooded croplands provide essential foraging and roosting habitat for the greater sandhill crane (*Antigone canadensis tabida*), as well as waterfowl and shore birds (SFEI-ASC 2016; Dybala et al. 2017a; Strum et al. 2017). Agricultural fields can also support other species, including tricolored blackbirds and anadromous fish, under targeted flooding and management regimes (Herzog 1996; Katz et al. 2013).

While not accounted for in Table 1, more than 19 species of non-native invasive aquatic weeds have invaded waterways throughout the Delta (Boyer and Sutula 2015) and are having a significant impact on open water habitats. Submersed and floating aquatic vegetation covered roughly 4,400 hectares (10,872 acres) of the Delta in 2014 (Khanna and Ustin, unpublished data, cited in Robinson et al. 2016). This included 2,880 hectares (7,100 acres) of submersed vegetation, dominated by *Egeria*, and 1,550 hectares (3,800 acres) of floating vegetation, composed of roughly half water hyacinth and half *Ludwigia* spp. (and very little native pennywort, which was previously more common). Importantly, non-native submersed and floating aquatic vegetation provides favorable habitat conditions for non-native predatory fish species that have impacts on the native fish community (Ferrari et al. 2014; Conrad et al. 2016).

4.2 Fish and Wildlife Biodiversity

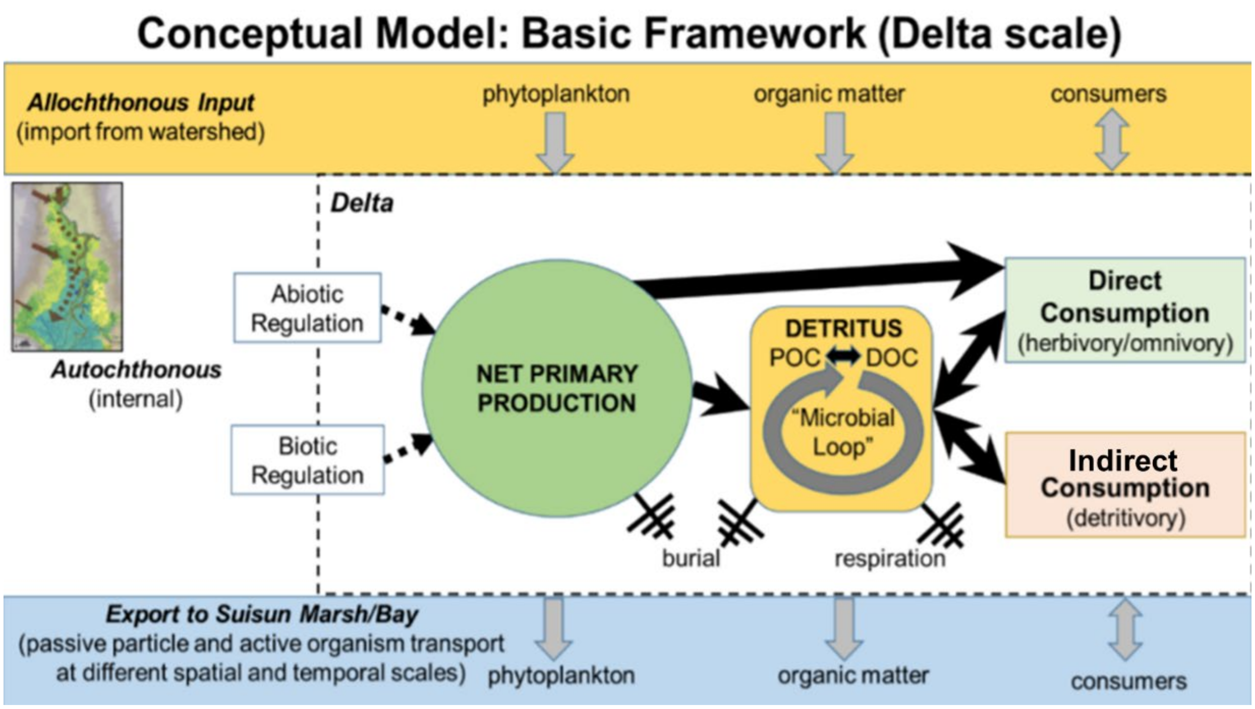
The Delta is of global importance in supporting biological diversity (Myers et al. 2000; Healy et al. 2016). Within the arid and semi-arid regions of the continent, rivers and wetlands (fresh water systems) are critical ecosystems which support more than 80 percent of the terrestrial biodiversity despite their limited spatial distribution on the landscape (<2 percent of the land cover; see Restoration Paper). The historical wetland, riparian, and grassland ecosystems of the Central Valley and Delta supported more than 700 species of plants, fish, and other wildlife (Healy et al. 2008; Healy et al. 2016). Complete documentation of the biodiversity that the Delta supported is limited to anecdotal accounts, but though to be the most species-rich region of the watershed (Bay Institute 1998). Roberts et al. (1977) provide a survey of the riparian forest flora and fauna of the Central Valley riverine ecosystems including plants, birds, mammals, and insects. Gilmer et al. (1982) discuss the importance of the Delta and its watershed as a habitat resource for millions of migratory and resident bird species including waterfowl, shorebirds, waders, raptors, and passerines. More than 200 species of marine and freshwater fish rely on its unique habitat resources for one or more of their life stages. The Delta serves as a migration corridor for all anadromous fish species in the Central Valley as they return to their natal rivers to spawn, and during juvenile outmigration downstream to the ocean. Four runs of adult Chinook Salmon (i.e., fall-, late fall, winter, and spring run), Steelhead, and Green Sturgeon (*Acipenser medirostris*) and White Sturgeon (*Acipenser transmontanus*) move through the Delta during most months of the year. Chinook salmon and steelhead juveniles depend on the Delta as transient rearing habitat while they migrate through the system to the ocean; these juveniles can remain for several months, feeding in marshes, tidal flats, and sloughs. All life stages of the non-native Striped Bass (*Morone saxatilis*) are found in the Delta. Numerous species are year-round Delta residents, such as the native Delta Smelt, Longfin Smelt, Sacramento Splittail, and introduced Threadfin Shad (*Dorosoma petenense*).

Alterations to flows, loss of connection between land and water, and loss of natural land cover have had significant effects on the native fish and wildlife species within the Delta and its watershed. More than 230 species within the region carry heightened conservation status (ICF 2013:Appendix 1a). Regional populations of many species have been extirpated from the Delta landscape, or are facing functional extinction (e.g., least Bell's vireo, Delta Smelt). Currently more than 34 species have garnered elevated protections through the State and Federal Endangered Species Acts. These changes have also created significant shifts in species composition that is effecting the broader health of the aquatic communities.

Occurrence of non-native invasive species in all trophic levels have been found within the Delta, including phytoplankton, invertebrates, and non-native fishes (Nobriga and Feyrer 2007; Hestir 2011; Lucas and Thompson 2012; Mahardja et al. 2017). Modification of the Delta ecosystem over the last century has resulted in system-wide and localized conditions that favor non-native predatory fish (Moyle et al. 2012; DWR 2015, 2016; Perry et al. 2013, 2015; Buchanan et al. 2013; Conrad et al. 2016). These changes include the disconnection of channels from tidal marsh, channelization and simplification of in-river and riparian vegetation and structure, and introduction and colonization of non-native vegetation and invertebrates. In turn, these changes have modified the ecosystem and resulted in a substantial loss of rearing and foraging habitat, and the reduction in salmonid food resources through alterations in water chemistry and the food web. Grossman et al. (2013) has identified predation hot spots within the Delta where barriers to movement create high mortality. Collectively, these changes have resulted in conditions that favor many non-native predators, and reduce native species productivity, which has resulted in increased predation success and additive effects on native species populations (Grossman 2016; Conrad et al. 2016).

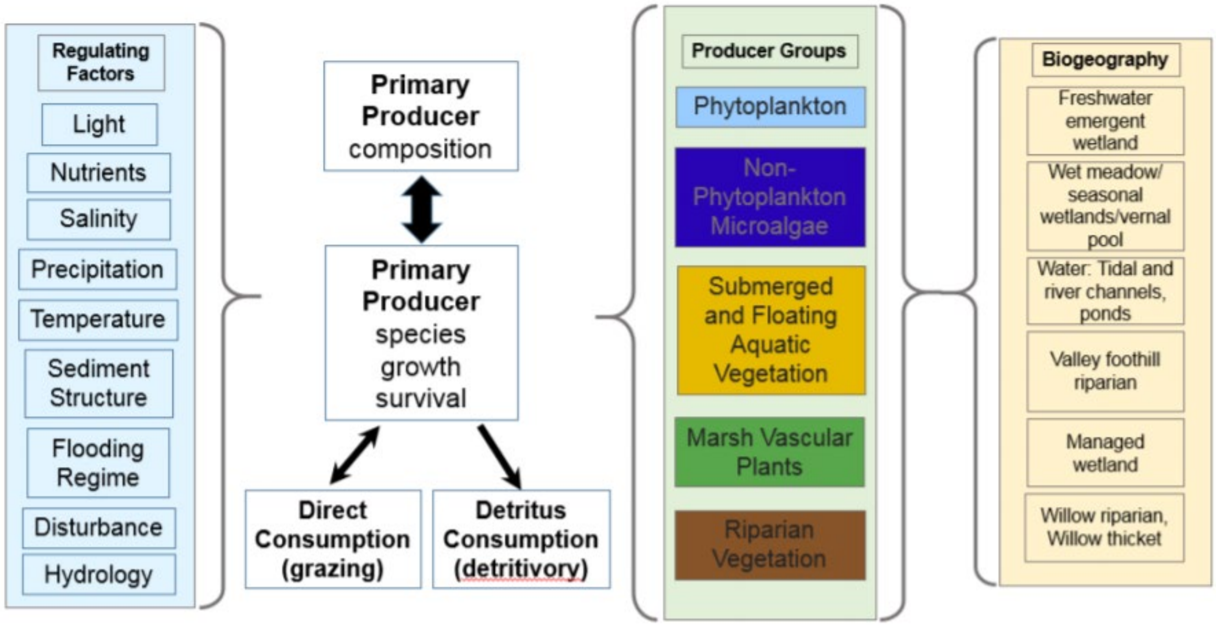
4.3 Food Web

Estuaries are incredibly productive ecosystems, in large part driven by the input of nutrients from the watershed, along with tidal mixing and relatively long residence time of water in the estuary (Schelske and Odum 1962). Primary production is the process by which carbon and nutrients become bio-available in organic compounds (Odum 1971; Day et al. 2013). The capture of carbon and nutrients occurs through photosynthetic or chemosynthetic processes, and forms the base of the food web. Stream channel, floodplain, and tidal marsh connectivity are also critical sources of primary production (Ward 1989; Vannote et al. 1980; also see Restoration Paper). The health and function of ecosystems are dependent on these fundamental processes. Robinson et al. (2016) provides a conceptual model of primary production in the Delta (Figure 7) and a graphic representing the five major producer groups along with environmental regulating factors and the associated land cover types (Figure 8).



Source: Robinson et al. 2016, Figure 4

Figure 7. Conceptual Model of Primary Production

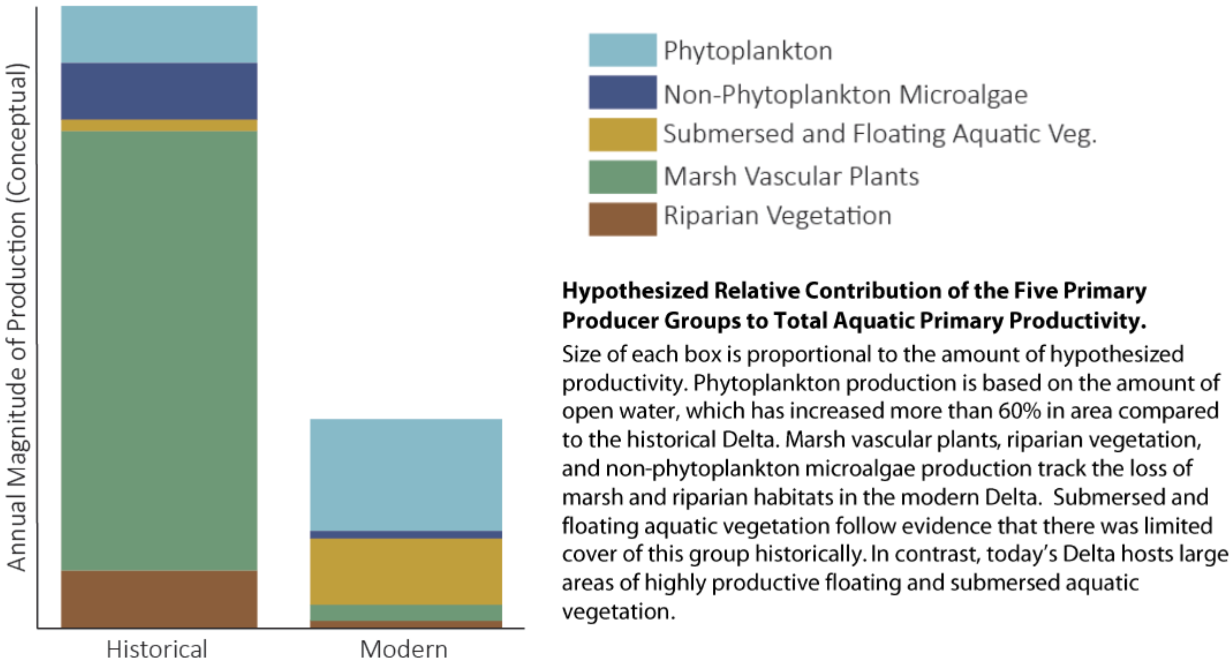


Source: Robinson et al. 2016, Figure 5

Figure 8. Conceptual Representation of the Regulating Factors of Primary Productivity, Including Producer Groups and Corresponding Land Cover Categories

The high rates of primary productivity that are typical of estuarine ecosystems support complex food webs, which also are a function of the variable freshwater-marine interface (Odum 1971; Day et al. 2013; Cloern et al. 2016). The condition and function of the food web in the Delta defines the fundamental capacity of the region to support fish, bird, and other wildlife populations (Robinson et al. 2016). The reduction of flow and land-water connectivity, coupled with the landscape-scale loss of riparian and wetland vegetation communities has significantly reduced the function of the lower trophic levels of the Delta food web (Cloern et al. 2016; Robinson et al. 2016).

The producer groups within the Delta are phytoplankton, non-phytoplankton microalgae, submersed and floating aquatic vegetation, marsh vascular plants, and riparian vegetation. While marsh vascular plants would have historically comprised the dominant primary producer, the loss of tidal marsh has shifted the producer group composition, and the most significant contributor is now phytoplankton (Figure 9; Jassby and Cloern 2000; Jassby et al. 2002; Robinson et al. 2016). It is important to note, however, that phytoplankton productivity in the Delta is ranked among the lowest 15 percent of the world's estuaries – with both productivity processes and resulting bio-available carbon limited by herbivory from non-native clams (Kimmerer et al. 1994; Greene et al. 2011; Cloern et al. 2014). The pre-1850 conditions of the Delta included landscape scale distribution of each of these producer groups (Whipple et al. 2012; Robinson et al. 2016; Cloern et al. 2016). The hydrologically connected nature of the historical condition supported the transfer of energy from primary producers to consumers across these ecosystem types (Cloern 2007; Lehman et al. 2010; Herbold et al. 2014).



Source: Robinson et al. 2016, Figure 1

Figure 9. Historical and Modern Relative Contribution of Primary Producer Groups

It is hypothesized that the historical Delta supported a rich and complex food web given the complex interconnections between in-Delta and upstream ecosystems (Atwater et al. 1979; Robinson et al. 2016; Cloern et al. 2016). The reduction in extent and disconnection of tidal and floodplains from stream channels has significantly reduced the footprint of marsh, riparian and non-phytoplankton microalgal producer groups, and the processes and resources they depend upon (Figure 9; Cloern et al. 2016; Robinson et al. 2016). In addition, the location of floodplains and tidal wetlands is important because local hydrology and water quality have effects on the production and flow of nutrients at the wetland patch scale (Day et al. 2013; Robinson 2016; Cloern et al. 2016). For example, tidally connected areas in the interior Delta would have historically experienced less tidal energy, different salinity gradients, and varying residence times than areas further upstream or downstream (Robinson et al. 2016). Restoring such connectivity throughout the Delta landscape may provide one of the largest beneficial impacts on the Delta food web (Cloern et al. 2016).

While detritus is not a source of primary production, it has a major role in the incorporation of carbon into the aquatic food web. The largest source of detritus in wetlands is highly productive marsh vegetation (Darnell 1967). Detritus-based production was likely an extremely important component of the historical Delta and is important in other estuaries, where it is often the most important carbon source for juvenile out-migrating salmon (Maier and Simenstad 2009). Detrital carbon is not readily consumed by zooplankton, so it must first be processed by microbes before entering the pelagic food web (Muller-Solger et al. 2002; Robinson et al. 2016). A large proportion of detritus may not be bioavailable, and only about 10 percent of what is available will become incorporated into higher trophic levels (Cloern et al. 2016). Decomposition of organic matter, especially detritus from wetland, riparian, and floodplain habitats, is an important consideration related to food web response to future restoration actions in the Delta.

Food web function at trophic levels above primary production varies due to hydrologic conditions (e.g., fluvial vs. tidal), water quality, and multiple aspects of physical and ecological connectivity (Gray et al. 2002; Peterson and Vayssieres 2010; Whitley and Bollens 2014). Howe et al. (2014), and Grimaldo et al. (2009) describe the linkages of primary production and consumers in shallow versus open-water ecosystems. Within floodplains, zooplankton and other invertebrates (e.g., benthic and epi-benthic invertebrates) play an important role as a primary food source for the fish and wildlife species within the Delta ecosystem (Sommer et al. 2004; Sommer and Nobriga 2001). Gray et al. (2002) describes the food web linkages within dead-end sloughs high-residence time creates warm, low dissolved oxygen (DO) conditions. Primary production benefits fish species indirectly through phytoplankton biomass being consumed at intermediate trophic levels (e.g. zooplankton and benthic invertebrates), at which point it becomes available to fish at higher trophic levels (Howe et al. 2014; Grimaldo et al. 2009; Whitley and Bollens 2014). Submerged and aquatic vegetation supports invertebrate consumers important in fish diets, however, can be difficult to access given the substantial structure and impacts to water quality from non-native aquatic weeds (Rozas and Odum 1988; Orsi and Mecum 1996; Simenstad et al. 1999). Productivity pathways exist through proximity (i.e., connectivity) of terrestrial riparian systems and aquatic ecosystems, which can provide trophic connections between fish and terrestrial invertebrates (Bryant and Arnold 2007; Grimaldo et al. 2009; and Whitely and Bollens 2014).

Loss of primary production from hydrologic disconnection, land conversion, and poor water quality limit the food web potential across multiple pathways. Given limited primary resources, competition across consumer groups can become an additive and an important stressor (Kimmerer et al. 1994; Feyrer et al. 2003; Kimmerer and Lougee 2014). Non-native invasive species such as *Potamocorbula amurensis* and *Corbicula fluminea* can greatly reduce phytoplankton biomass and have been implicated in associated reductions in zooplankton biomass (Kimmerer et al. 1994; Feyrer et al. 2003; Kimmerer and Lougee 2014). Declines of aquatic fish species, including non-native species, have been attributed to the additive effects of food web decline, lower trophic level non-native species (e.g., Asian overbite clam -*Potamocorbula amurensis*) further reducing available resources, and environmental stressors such as drought (Sommer et al. 2007; McNally et al. 2010; Nobriga et al. 2016). This issue collectivity became known as the Pelagic Organism Decline (POD) (Sommer et al. 2007)

4.4 Environmental Water Quality

The daily, seasonal, and inter-annual variability in flows and water quality constituents drive temporal and spatial variability for species distributions and food web conditions throughout the Delta (Schoellhamer et al. 2016). Although inundation patterns are a primary driver of aquatic ecosystem form, the interaction of stream flow, tidal influence, and water quality also directly affect physical, chemical, and ecological processes throughout the Delta (Cloern et al. 2016; Schoellhamer et al. 2016). This section focuses on the effects of water quality on aquatic ecosystems. The Climate Change Paper reviews the effects of climate change and the expected shifts in water quality constituents important to ecosystem function.

Nutrients, salinity, temperature, turbidity, and dissolved oxygen all serve as regulators of food web function and species habitat quality throughout the Delta. Alterations to these gradients have had influences on the species composition within the aquatic food web (Peterson and Vayssieres 2010; Hasenbein et al. 2013; Hennessy and Enderlein 2013; Borgnis and Boyer 2015). For example, some species have wide salinity tolerances, whereas others do not. In nutrient-limited conditions, primary production (e.g., phytoplankton production) can be constrained by the lack of necessary compounds (Glibert et al. 2014a; Brown et al. 2016a). These factors are described in more detail below.

Nutrient (e.g., nitrogen and phosphorus) concentrations influence ecological conditions as fundamental components of primary production. Nutrients are drivers of phytoplankton and microalgae community composition and growth. Typically increases in nutrients result in increased productivity; however, high concentrations of nutrient compounds can be toxic to organisms and can result in excessive blooms of macroalgae that eventually decompose and lead to conditions of low dissolved oxygen (Cloern 2001). In the Delta, high nutrient concentrations, along with warm temperature and low salinity, provides favorable conditions for toxic Microcystis blooms (Paerl 1988; Sellner et al. 1988; Rocha et al. 2002; Robson and Hamilton 2003; Lehman et al. 2015; Lehman et al. 2017).

The chief sources of anthropogenic nutrients to the Delta are agricultural drains and wastewater treatment plants (Hager and Schemel 1992). There are higher concentrations of nitrogen and phosphorus in the San Joaquin River than the Sacramento River due to lower flow and greater agricultural land use; however, the Sacramento River has higher total nutrient (i.e., ammonium) loading, largely because of major wastewater treatment plants (Monsen et al. 2007; Lehman et al. 2015). The largest of these, the Sacramento Regional Sanitation District Wastewater Treatment Plant on the Sacramento River near Clarksburg (opposite, east bank), provides a very large point source of nutrients. There has been debate regarding the effects of these increased nutrients on aquatic ecosystems downstream of this plant. It is important to note that this plant is being upgraded to improve treatment processes, so any such effects are likely to change (see: www.regionalsan.com/echowater-project for more information) (Dahm et al. 2016).

Salinity gradients are determined by the interaction of riverine flows, landward tidal movement of saline water, and geography. Salinity strongly influences species composition across the food web (Peterson and Vayssieres 2010; Hasenbein et al. 2013; Hennessy and Enderlein 2013; Borgnis and Boyer 2015).

Some species have wide salinity tolerances, whereas others do not. Salinity tolerances may interact with species competition and predator-prey relationships to drive community composition. For example, the invasive clam Potamocorbula amurensis is most abundant in brackish water areas, and grazing by this species has been associated with changes in both total phytoplankton biomass and community composition across the low salinity zone (Kimmerer and Thompson 2014; Lucas et al. 2016; Baumsteiger et al. 2017; Kayfetz and Kimmerer 2017).

All species have certain temperature requirements and thresholds; as a result, changes in temperatures can affect species distribution and abundance, with cascading effects on the food web. Seasonal changes in water temperature, driven by increased atmospheric temperature can result in higher temperatures during summer months. However, the seasonal temperature swings vary by location, with smaller temperature changes and cooler water overall in the westward Suisun Bay and Grizzly Bay area because of marine water influences, when compared to the more-eastward Delta (Kimmerer 2004). Higher temperatures increase metabolic rates, which may increase phytoplankton production (Durand 2008, 2015) but also may favor harmful algal blooms (Lehman et al. 2013). These events have become more pervasive in the Bay-Delta and may become an increasing problem as climate change affects upstream aquatic ecosystems where there are greater ranges in air temperature (Dettinger et al. 2016; Otten et al. 2017).

High turbidity in the Delta results from both suspended sediment and organic particles (algae and detritus) in the water column. The Delta generally has high suspended sediment concentrations when compared to other estuaries (Schoellhamer 2011), and turbidity is a major limiting factor on phytoplankton production in the Bay-Delta, where production is generally light-limited rather than nutrient-limited (Jassby 2005). Resuspension of sediment in shallow areas with long fetch that allows wind waves and suspension of sediments may increase turbidity, particularly at certain points in the spring-neap tidal cycle (May et al. 2003). While community composition, nutrients, contaminants, and temperature also contribute to regulating phytoplankton productivity, light availability may explain as much as 80 percent of observed patterns in net primary productivity for the Bay-Delta (Cole and Cloern 1984). Because of the ubiquity of high turbidity in the Delta, the algal species that were historically dominant (diatoms) may be adapted to low light conditions, experiencing photo-inhibition in high light (Glibert et al. 2014b).

In addition to effects on primary productivity, high turbidity may be beneficial for Delta Smelt and Chinook Salmon, two fish species of concern. Delta Smelt abundance is positively correlated with high-turbidity habitat conditions, and long-term, general reductions in turbidity may be restricting Smelt habitat availability in the Delta (Nobriga et al. 2008). Turbidity has been hypothesized to reduce predation risk for all Delta Smelt life stages because it provides a visual defense from sight-feeding predatory species (Ferrari et al. 2014). Turbidity also may increase feeding success by decreasing stress, though it reduces feeding efficiency at very high turbidity levels (Hasenbein et al. 2013; Baxter et al. 2015). Turbidity has also been shown to reduce perceived predation risk in Chinook Salmon (Gregory 1993).

Dissolved oxygen (DO) in the water has the potential to be a major limiting factor for fish and other organisms in a wetland. The Delta rarely experiences extreme low DO conditions owing to high vertical mixing rates and low productivity, though temporary periods of low DO have occurred in Suisun Marsh (Brooks et al. 2011), and the Stockton Deep-water Ship Channel (National Marine Fisheries Service 2009; Schoellhamer et al. 2016). Drivers of low DO at these locations include long residence times, high temperatures, and high biological oxygen demand caused by accumulation of organic matter. Food limitation (hypothesized to be a major factor in recent pelagic organism declines) can exacerbate the effects of hypoxia because energy reserves are not available to compensate for increased stress (Baxter et al. 2010; Brooks et al. 2011; Komoroske et al. 2015).

A wide array of toxins has been implicated in declining ecosystem conditions (Fong et al. 2016). Agriculture practices (e.g., drain water) and urbanization (e.g., stormwater runoff, wastewater effluent) result in the discharge of many contaminants into the Delta and its tributaries (Fong et al. 2016). In 2010, the Delta was listed on the Environmental Protection Agency 2010 List of Impaired Water Bodies (SWRCB 2010). The 2010 list of contaminants includes metals (copper, cadmium, mercury, and zinc), pesticides (chlordane, chlorpyrifos, DDE, DDT, diazinon, dieldrin, organophosphate insecticides, and toxaphene), and chlorinated compounds (dioxins, furans, and polychlorinated biphenyls [PCBs]). The Delta is also listed for sediment toxicity and unknown toxicity.[1] Since the 2010 list was adopted, additional contaminants of concern have been identified including additional pesticides, flame retardants, nutrients, naturally occurring toxins, micro-plastics (e.g., from synthetic clothing), and pharmaceuticals and personal care products (PPCPs). Essential elements (e.g., selenium) and nutrients, when outside the beneficial ranges, may negatively affect organism or community health. A legacy of contaminants in the Delta, such as persistent organic chemicals and mercury, can accumulate through the food web, leading to health risks for humans and wildlife (Fong et al. 2016). Several investigations have conceptualized but not quantified the role of contaminants in Delta fish declines (Brooks et al. 2012; Scholz et al. 2012). For example, new analysis presented in Fong et al. (2016) indicates that pyrethroid insecticide use in the Delta is strongly correlated with fish abundances. Additional quantification of correlative relationships is needed to include contaminant effects in ecosystem evaluations in order to better understand underlying mechanistic relationships (Fong et al. 2016).

Water quality is a key factor affecting primary productivity. Key water quality constituents that should be considered as part of an ecosystem restoration strategy include turbidity, salinity, nutrient loading and concentration, and dissolved oxygen. Turbidity is typically limiting for overall productivity. Salinity is spatially and temporally variable, and is a key determinant of species distributions within the Delta. Nutrients, while often limiting in other systems, are not typically limiting within the Delta, although they may affect some species (including Harmful Algal Blooms and Microcystis). Addressing these issues will require a comprehensive approach that considers the often-complex interactions between these and other biophysical factors.

[1] An unknown toxicity listing results from toxicity being detected in lab or field studies, but not yet being linked to a specific chemical.

5. Stressors on the Delta Ecosystem

Anthropogenic (human) actions on the Delta landscape have altered the geomorphic and ecological conditions of the region (Bay Institute 1998; Healy et al. 2008, 2016). Effects on the geomorphic setting have created constraints on the location and type of restoration actions that can be taken to re-establish ecological function. The loss of natural land cover has limited the capacity of the landscape to meet the life history requirements of fish and wildlife populations. Additionally, impaired water quality and the introduction of non-native species have further altered ecosystem structure and food web dynamics. Direct management of fish populations with hatcheries have further stressed native salmon populations.

Multiple peer reviewed works and technical reports have identified a set of primary stressors that are acting upon the Delta ecosystem (i.e., Mount et al. 2012; Gray et al. 2013; Luoma et al. 2015; Healy et al. 2016). Table 2 provides a summary of these stressors and a high-level description of the effects on ecosystem conditions within the Delta. This summary builds on the five stressors addressed in the Delta Plan (2013) by considering issues of hydrologic connectivity, vegetation, and fish migration obstacles as more refined aspects of habitat. An additional crosscutting stressor, climate change, is considered here and discussed in more detail in the Climate Change Paper. Improving ecosystem health within the Delta will require addressing each of these stressors given their cumulative effects (Gray et al. 2013; Luoma et al. 2015; Healy et al. 2016).

Several important considerations constrain the re-establishment of connected lands that support food web processes and native fish and wildlife species populations. Floodplain and tidal plain disconnection, the loss of riparian and wetland vegetation, and fish migration barriers have significantly limited the space on the landscape which can serve as species habitat (see Table 2; Figure 5; DWR 2014; SFEI-ASC 2016). Similarly, the loss and disconnection of floodplain and tidal plan ecosystems has reduced overall primary production (Cloern et al. 2016; Robinson et al. 2016). Actions that address flow dynamics, water quality, invasive species, and fish management alone will not resolve these reductions in the extent and distribution of the Delta ecosystem (Lund et al. 2010; NRC 2012; PPIC 2018). A crucial conservation target is the re-establishment of space on the landscape which has connectivity (e.g., hydrologic, migratory, vegetation extent; both in-Delta and upstream/downstream) and supports natural vegetation communities (SFEI-ASC 2016; Dybala et al. 2017b).

In addition to addressing habitat loss and connectivity, best management practices on agricultural lands that lessen the impacts to native species, or provide analogue habitat resources represent an important component of landscape-scale conservation, especially given the dominance of agriculture on the Central Valley and Delta landscape (Dybala et al. 2017a; Strum et al. 2017). Specific approaches for supporting biodiversity on agricultural lands are summarized in Table 3. The Restoration Paper provides a more in-depth discussion of the opportunities and science needs associated with these practices.

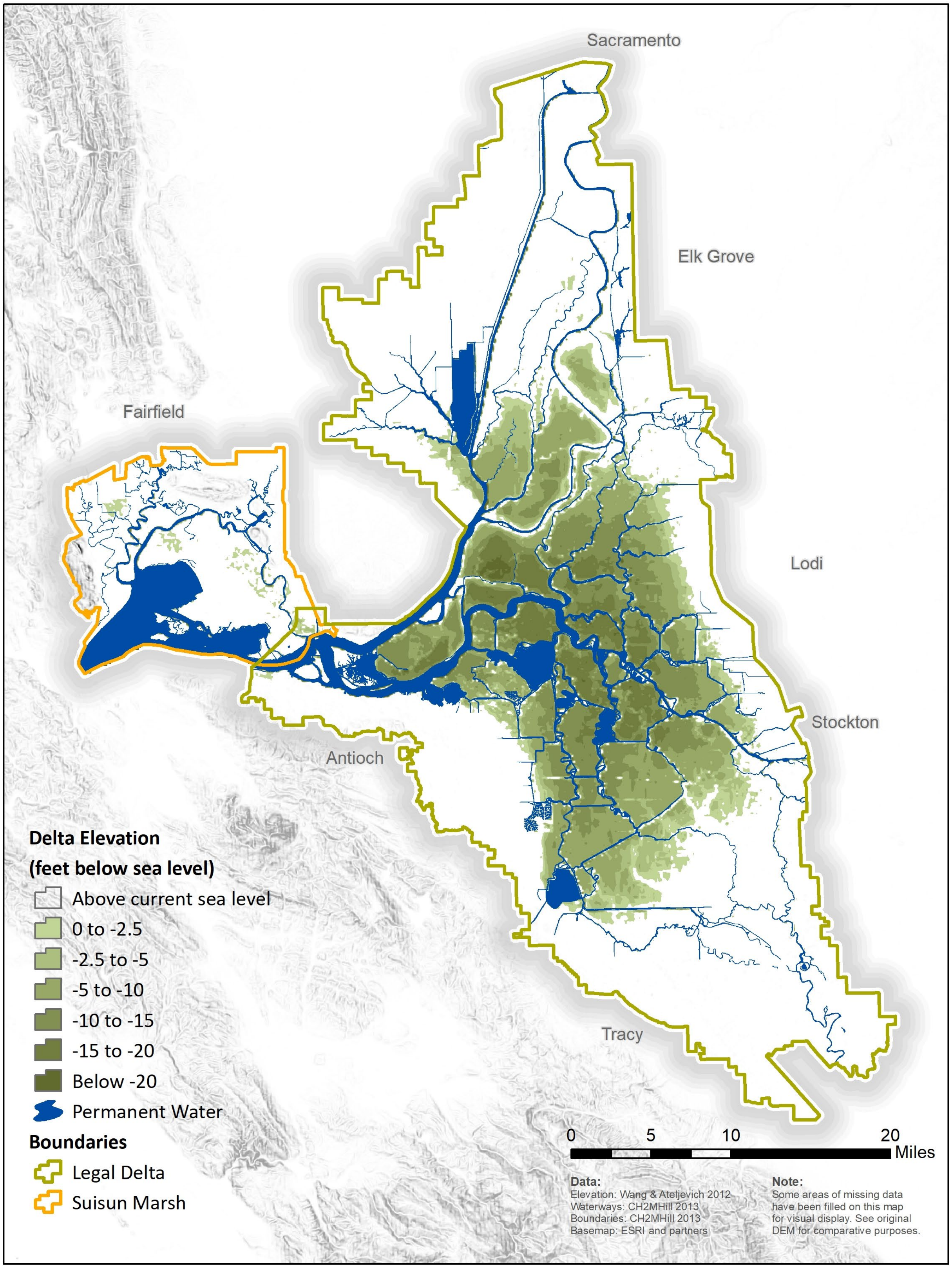
Table 2. Summary of Primary Stressors of the Delta Ecosystem

Stressor Category	Affected Ecosystem Condition
Climate Change	Sea-level rise, shifts in temperature and precipitation, and changes in hydrograph will affect salinity and inundation patters for the Delta ecosystem and reduce flexibility in ecosystem management of the existing ecosystem. See Climate Change Paper
Flow Alteration	Dam construction, operation, and diversions have altered the magnitude, timing, and direction of flows (i.e., inflow, in-Delta flow, out flow) within the Delta (Fleenor et al. 2010; SWRCB 2017; NRC 2012). These alterations have effects on geomorphic processes, water quality, and food web function, all which reduce ecological health (Poff 2010; Moyle et al. 2011; Yarnell et al. 2015; Zimmerman et al. 2017; Hutton et al. 2017a, 2017b)
Floodplain and Tidal Plain Disconnection	Hydrologic connectivity and geomorphic function have been impaired through channel simplification, levee construction, and bank stabilization. Wetland and floodplain complexity, vegetation dynamics, and food web function have been lost on disconnected lands. Exposure of peat soils has led to the subsidence of Delta lands, resulting in constraints for where existing and future tidal marsh restoration could take place (Deverel et al. 2016).
Loss of Riparian and Wetland Vegetation	Approximately 95% of the native ecosystems and vegetation communities were lost in the late 1800s and early 1900s (Thompson 1957; Bay Institute 1998; ASC-SFEI 2014). Physical habitat extent, distribution, and resilience (i.e., connectivity, complexity, redundancy, biologically relevant ecosystem scale) has been lost or greatly simplified for many aquatic and terrestrial species (ASC-SFEI 2014, 2016).
Water Quality Impairment	Flow alterations, and nutrient and contaminant inputs from agriculture and wastewater treatment facilities affect food web function (i.e., primary production), facilitate non-native aquatic plant growth, and create toxic conditions for native species (Luoma et al. 2015). Aquatic species are directly impacted and water quality is implicated as a major driver of the Pelagic Organism Decline (Luoma et al. 2008; Baxter et al. 2010).
Non-native Invasive Species	The Delta is one of the most heavily invaded ecosystems in the world (Luoma et al. 2015; Healy et al. 2016). Non-native species alter ecosystem structure and function, including food web processes, water quality, and physical habitats of terrestrial and aquatic species. Non-native species directly and indirectly affect native species populations through predation and competition for limited resources (Perry et al. 2013, 2015; Buchanan et al. 2012, 2013).
Fish Management	Genetic integrity of Central Valley salmonids is threatened by artificial propagation programs (Moyle 2002; Myers et al. 2004; Araki et al. 2007). Hatchery fish compete and interbreed with wild fish, displacing or lowering fitness of native stocks (Williams 2006; Perry et al. 2016).
Fish Migration Barriers	Barriers to fish migration cause mortality or limit rearing opportunities (DWR 2014).

Table 3. Select Approaches for Supporting Biodiversity on Agricultural Lands

Best Management Practice	Scientific Studies
Creating seasonal or permanent wetlands within fields	Sullivan et al. 2014; Meadows 2014
Flooding fields to mimic floodplain processes	Katz et al. 2013; Conrad et al. 2016; Katz et al. 2017; Corline et al. 2017
Planting hedgerows and buffer strips	Hinsley and Bellamy 2000; Heath et al. 2017
Planting oaks to simulate oak savannahs in the agricultural landscape	Grossinger and Whipple 2009; Whipple et al. 2010; Jedlicka et al. 2014
Adjusting timing of field work	Strum et al. 2017; Dybala et al. 2017b
Reducing pesticide and herbicide application	Wiederholt et al. 2017; Shackleford et al. 2015
Implementation of water conservation methods	SFEI-ASC 2016

In evaluating the tradeoffs between existing agricultural land uses and restoration, it is important to acknowledge that subsidence has limited opportunities for reconnection of tidal plains, as many of the islands in the central Delta are 10 to nearly 25 feet below sea level, see Figure 10 (Wang and Ateljevich 2012). In addition, urbanization has and will further constrain opportunities for reconnection of tidal and flood plains (Wilson and Sleeter 2017). Sub-regional assessment of land elevation and urban land use trajectories should inform selection of conservation actions at a site scale (i.e., selection of wildlife friendly agriculture vs. restoration of natural communities). For example, subsidence reversal efforts that seek to restore suitable intertidal habitat elevations should occur on areas that will keep pace with sea-level rise and ideally occur by 2100 (DRA 2009). While Deverel et al. (2014) did not include potential levee failures or improvements; they identified areas in the periphery of the Delta that could be restored to tidal elevations within 50 to 100 years. Importantly, Deverel et al. (2017) found that the economic outcomes associated with a conversion to a mosaic of wetlands and crops including rice appears to be financially viable, and offer landowners a critical incentive to participate. Given the limits on hydrologic reconnection, subsidence reversal requires prioritization where the physical landscape supports its implementation and limited financial resources, such as carbon credit revenues, can be utilized. In areas where subsidence is less severe, elevations can be built through managed wetlands targeted at carbon sequestration and subsidence reversal, direct placement of sediment, and or related tactics like warping, a method where sediment accretion is increased by intermittently flooding areas just long enough for sediment to precipitate out of the water column (Doody 2007; SFEI-ASC 2016). Pilot subsidence reversal wetlands are currently under study at two sites in the Delta, where maximum land-surface elevation gains of 7–9 cm per year have been achieved (Miller et al. 2008; SFEI-ASC 2016). Given observed rates of accretion at subsidence reversal wetlands, the practice be less effective given the long periods (e.g., 50 to 100 years) required at deeply subsided regions of the Delta (Deverel et al. 2014). Effective implementation of this practice is time sensitive (i.e., it requires near-term action) and requires strategic siting and accompanying levee investments.



Source: Wang and Altjevich 2012

Figure 10. Map of Subsidence in Delta

6. Examples of Restoration Actions that Target Resilience

Resilient ecosystems are to recover from disturbance without significant loss of structure or function, which is thought to be an important consideration in light of a rapidly changing climate (see discussion in Restoration Paper). Increasing ecosystem resilience within the Delta at a landscape level is a key conservation target and requires considerations of connectivity, complexity, redundancy, and scale (see discussion in Restoration Paper). Implementation of restoration actions that reconnect tidal plains and re-establish native vegetation communities within the Delta has been limited to date (Delta Independent Science Board [ISB] 2013; Melcer and Anderson 2017; see the Restoration Paper). Projects that target these outcomes provide opportunity for species to migrate in response to changes in sea level (i.e., “marsh migration”), salinity, and other factors. Motile species such as fish would also have increased access to a range of habitats and refugia across the Delta as well as upstream and downstream of the Delta itself. Table 4 provides several examples, at various spatial scales, of the types of restoration and management actions needed to address the loss of resilient natural systems within the Delta.

Table 4. Selected Examples of Restoration Projects that Address Loss of Natural Ecosystems and Connectivity Within the Delta

Project or Action	Ecological Target	Status
Cosumnes River Preserve (CRP)[a]	Floodplain and tidal plain reconnection; riparian and wetland vegetation restoration; managed marsh creation; agricultural practices and crops which support wildlife; nature-based recreation	Preserve established in 1987; currently under management; future expansion planned
North Delta Flood Control and Ecosystem Restoration Project[b]	Floodplain and tidal plain reconnection; riparian and wetland vegetation restoration; nature-based recreation	Planning; implementation in fall 2018
Dutch Slough Tidal Restoration Project[c]	Subtidal and tidal plain reconnection; riparian and wetland vegetation restoration; managed marsh creation	Planning; implementation in summer 2018.
Yolo Bypass Salmonid Habitat Restoration and Fish Passage Project[d]	Flood plain reconnection; fish passage improvement	Planning; implementation in 2020
Aquatic Invasive Plant Control Program[e]	Reduction of non-native invasive aquatic plants	Implementation in 2018

Sources:
a. CRP 2008
b. California Natural Resources Agency 2018a
c. California Natural Resources Agency 2018b
d. California Natural Resources Agency 2018c
e. California Division of Boating and Waterways 2018.

Establishing migratory corridors for fish, birds, and other animals along selected Delta river channels is one of the Delta Plan’s sub-goals for restoring a healthy ecosystem (Water Code Section 85302(e)). In order to achieve this sub-goal, the restoration of physical and ecological processes within and along large, open-water channels will be required. Restoring processes will require frequent disturbance from floods and channel migration to support recruitment and succession processes (Greco and Larsen 2014). Approaches for restoring these processes include: levee setbacks, reservoir releases that mimic naturalistic hydrographs, sediment augmentation, bank set-backs and channel-to-floodplain reconnection (Moyle et al. 2012; SFEI-ASC 2016). The Delta also has substantial remnant fluvial topographic features, such as natural levees along the rivers and depressions at the former sites of flood basin lakes that should be incorporated into plans for recovering fluvial processes and habitats (SFEI-ASC 2016; Moyle et al. 2012).

The Cosumnes River Preserve (CRP) provides an example of a sub-regional-scale restoration and management complex where actions to re-establish hydrologic connections and natural vegetation communities are being combined with agricultural practices that support fish and wildlife (CRP 2008). Restoration projects within the CRP are establishing sub-regional connectivity along waterways. Studies of both aquatic and terrestrial ecosystems demonstrate that significant benefits result from the reconnection of floodplains and re-establishment of riparian and wetland vegetation (Swenson et al. 2003; Jeffres et al. 2008; Viers et al. 2012; Ivey et al. 2014).

Within the footprint of the CRP, the North Delta Flood Control and Restoration Project is targeting reconnection of flood and tidal plains. Landscape position at both project landscape units (i.e., McCormack Williamson Tract and Grizzly Slough) provide significant opportunities for intertidal ecosystem re-establishment. They provide connectivity with previously restored wetland and riparian land cover. An unintentional levee breach at the McCormack Williamson Tract in 2017 provided early indications demonstrated significant food web benefits (e.g., primary production, secondary production via first level consumers) of floodplain restoration at this scale (Corline et al. 2017; Nakoto et al. 2017). The Aquatic Invasive Plant Management Program targets non-native invasive submerged and floating aquatic weeds. Aquatic weed management across sub-regions of the Delta is an important component of restoration of hydrologic connectivity and native vegetation re-establishment. Implementation within experimental components will allow for evaluation of the efficacy of these actions.

The Restoration Paper provides discussion the importance of scale and patch size. It includes an appendix (Restoration Paper, Appendix A) summarizing the current conservation needs of species according to existing conservation and recovery plans. These resources provide an understanding of the scale of tidal plain, flood plain and natural vegetation community re-establishment that may be required through projects described in Table 4 to meeting the life history needs of endangered species.

7. Implications for Protection, Restoration and Enhancement of the Delta Ecosystem

The initial sections of this paper summarize the geomorphic and ecological setting within the Delta. Subsequent sections identify primary stressors acting on the Delta, and review a series of restoration projects aimed at addressing major limiters on food web function and species habitats. Those sections review the best available science within focused subject areas covered in this paper. The subject areas addressed in this paper were identified because of their potential influence on achieving the coequal goals and relevance in amending Chapter 4 of the Delta Plan. This section summarizes and discusses the implications of the preceding science synthesis relative to the protection, restoration, and management of the Delta ecosystem. These implications provide the basis for the considerations included in Section 8, *Considerations for Amending Chapter 4 of the Delta Plan*.

1. The Delta is unique and of global ecological importance as an estuary.

   Estuarine systems with healthy ecosystems are the most productive landscapes in the world. The Delta's riparian wetland systems historically supported a significant amount of biodiversity, including endemic plant, wildlife, and fish species.

2. Restoration potential varies sub-regionally within the Delta.

   The Delta landscape consists of three geomorphically distinct sub-regions that vary in landscape form, watershed input, and tidal dynamics. These characteristics determine the ecosystem types that can be effectively restored. This includes differences in the feasibility of flood plain and tidal reconnection due to land elevation, variability in the vegetation community composition and structure, and issues of water quality, and non-native species.

3. Lands with suitable elevations should be prioritized for hydrologic reconnection and restoration of natural vegetation communities.

   Loss of floodplain elevations due to subsidence and urbanization constrain the extent and location of marsh plain restoration that is currently feasible, and expected sea-level rise will continue to reduce those opportunities. Early restoration will re-establish geomorphic processes that lead to accretion, shifts in marsh distribution, and sea-level rise accommodation, as further described in the (Climate Change Paper).

4. Reconciling land elevation with water surface elevation in select areas is critical to reducing the risk of levee failures leading to undesirable ecosystem conditions, and in protecting opportunities for restoration in the Delta. (Also see Climate Change Paper).

   Sediment dynamics and organic matter accretion are fundamental physical processes that have been interrupted by flow alteration, disconnection of flood and marsh plains, and bank stabilization with revetment. The loss or impairment of these processes has offset the dynamic equilibrium which allowed the Delta landscape to respond to tectonic subsidence, sea-level rise, and has also initiated oxidation and erosion of peat soils. This has resulted in land elevations that have subsided below sea level, and correspond with deep sub-tidal conditions. On lands where subsidence is mild to moderate, subsidence reversal may reconcile elevations, but near-term actions coupled with strategic levee maintenance are required. It may not be feasible to reconcile elevations within deeply subsided islands within the interior Delta within short timeframes (<150 years).

5. Recovery of native species populations within the Delta will require targeting re-establishment of vegetation communities that represent the historical species composition, structure, and function.

   The pre-1850 Delta landscape primarily consisted of tidal and seasonal emergent wetlands, riparian forests of composed of cottonwood and willows, and to a lesser extent, vernal pools, alkali seasonal wetlands, dune complexes, and oak and grassland savannahs. The species associations within each of these community types are described in VegCAMP (DFW 2007, 2016). These vegetation communities have been fragmented and lost to land cover conversion. To track progress in this regard, it is important to have routine updates of the Department of Fish and Wildlife's VegCAMP land cover and land use dataset; continuous, adequate funding is crucial to understand trends in vegetation communities over time.

6. Re-establishing food web function and increasing species habitat requires restoring multiple aspects of connectivity and native vegetation community distribution.

   Loss and alteration of hydrologic connectivity and wetland and riparian vegetation communities has significantly limited the ecological space on the landscape where food web processes and physical habitats of species exist. Altered flow (i.e., inflow from the watershed, within-Delta flows, and outflows) and fish migration obstacles have reduced connectivity between upper watersheds and the bay and ocean, affecting the flow of energy and movement of organisms. Flood plain and tidal plain disconnection has altered and reduced the space available for food web processes (e.g., primary productivity), and the movement of energy and organisms between systems. The dominant primary producer groups of the pre-1850 Delta (i.e., wetland vascular plants) have been reduced by 95 percent, within only remnants of the historical extent of vegetation remaining. Management and enhancement of existing channels and remnant vegetation communities alone will not address the habitat requirements of native species within the Delta.

7. Water quality impairs the food web function and species habitat conditions within an already limited footprint.

Alterations of the flow dynamics and the salinity gradient have reduced effects on primary productivity, species movements and competition, and species habitat structure and function. Water quality improvements (e.g., reduction in agricultural and urban nutrient inputs) will be required to improve primary production processes. Higher trophic level effects such as predation on rearing salmonids require reducing non-native fish habitat suitability, while restoring resilience in native species populations through increased habitat extent and improved conditions.

8. Impaired water quality has compounding effects on other ecosystem stressors such as non-native species and harmful algal blooms.

   Nutrients support non-native species including submerged and floating aquatic plants and harmful algal blooms (e.g. *Microcystis*) creating structural differences in aquatic habitats, reducing light, and introducing toxins into waterways.

9. Improving the health of the Delta ecosystem will require actions that address multiple primary stressors (see Table 2).

   Issues of flow dynamics, water quality, non-native invasive species, predation of native fish and other issues degrade ecological conditions and stress the existing Delta ecosystem. Actions to address these stressors, coupled with re-establishment of ecological space to support food web function and species habitats will be required to support a healthy Delta ecosystem.

10. Adoption of best management practices on agricultural lands that reduce impacts to native species or create analogue habitat resources could help mitigate ecosystem stressors.

    Agriculture makes up a significant component of the Delta and Central Valley landscape. While re-establishment of natural land cover is a priority conservation target, best management practices implemented on agricultural lands where restoration is not possible can reduce stressors and provide resources and analogue habitats for some species. Additional research is needed, see Restoration Synthesis Paper.

8. Considerations for the Delta Plan Amendment

The Delta Plan includes 14 regulatory policies, a suite of recommendations, and performance measures. Amendment of Chapter 4- Protect, Restore, and Enhance the Delta Ecosystem could include changes or additions to the narrative text, new or refined recommendations and/or policies, new or refined performance measures, or a combination of all three. While recommendations are not regulatory policies, they can help inform activities and emphasize priorities. Performance measures help evaluate the response to management actions and the factors that may influence achievement of the coequal goals, and include metrics, baseline conditions, and targets for desired future conditions.

The implications of the preceding science synthesis relative to the protection, restoration, and management of the Delta ecosystem yield a sufficient basis from which to consider changes to Chapter 4 of the Delta Plan. These implications were discussed in Section 8, *Implications for the Protection, Restoration, and Management of the Delta Ecosystem*. Periodic updates or amendments to the Delta Plan are intended to support successful achievement of the coequal goals by addressing factors such as new or changed conditions in the Delta and its watershed, best available science, changes to pertinent state policies or institutions, or others. The following discussion presents initial high-level considerations for amending Chapter 4 of the Delta Plan in light of the scientific information and implications presented herein.

1. The findings of this synthesis paper do not foundationally change the core strategies of Chapter 4 of the Delta Plan. In combination with the findings of the Climate Change and Restoration papers, they do heighten the importance of re-establishment of resilient ecosystems that provide benefits to both humans and native species. Discussions within Chapter 4 should explicitly consider the geomorphic aspects of the sub-regions of the Delta, and the opportunities to re-establish physical processes and natural land cover in the context of landscape form, watershed input, and tidal dynamics.

2. The Delta is subject to subsidence and impacts from projected sea-level rise. Updates to the Chapter 4 narrative could discuss the implications of these processes and approaches to reconcile land elevations for risk reduction and ecosystem restoration opportunities. Plan policies and recommendations could consider incorporation of content that integrates these practices into policies and recommendations (Policy ER P3, ER P4, Recommendation ER R2). Plan performance measures could consider metrics and a baseline for assessing the condition of the Delta landscape with respect to a rising sea level.

3. Loss of floodplain elevations due to subsidence constrains the extent of marsh plain that is currently feasible, and expected sea-level rise will continue to reduce opportunities for re-establishment of hydrologic connectivity. Plan could update policies and recommendations related to hydrologic connectivity and re-establishment of natural vegetation communities at sites where potential exists (see Consideration #2). Plan narrative could provide greater specificity in the characteristics of plant communities, for example plant species associations. Plan policies and recommendations could be updated to reflect the areas on the landscape with physical suitability. Plan performance measures could consider metrics and a base that would assess these ecosystem conditions, including vegetation community composition. Plan update could highlight the information need of continued mapping of land cover and land use within the Delta.

4. Advances in the scientific understanding of primary production, food web linkages, and state of those aspects of the Delta ecosystem have highlighted the importance of the loss of hydrologic connectivity, wetland and riparian vegetation communities, and water quality. Updates to Chapter 4 narrative could discuss the prioritization of improvements to address these fundamental limitations on primary production which foundation of the food web. Plan performance

measures could consider metrics and a baseline to assess the condition of primary producer groups, and connectivity across ecosystems. Key information gaps related to these important topics should be identified.

5. Water quality is a significant stressor that requires comprehensive and in-depth treatment given the complexities of multiple constituents and their effects on habitat conditions, food web function, species health and condition. Acknowledgement of the need to address these topics could inform an update to Chapter 6 of the Delta Plan.

9. References

Araki, H., B.A. Berejikian, M.J. Ford, and M.S. Blouin. 2008. Fitness of hatchery-reared salmonids in the wild. *Evolutionary Applications* 1: 342-355.

Atwater, B.F., S.G. Conard, J.N. Dowden, C.W. Hedel, R.L. Macdonald, and W. Savage. 1979. History, Landforms, and Vegetation of the Estuary's Tidal Marshes. In T.J. Conomos, editor. *San Francisco Bay: The Urbanized Estuary*. San Francisco, CA. p. 493.

Atwater, B.F. and D.F. Belknap. 1980. Tidal-wetland deposits of the Sacramento - San Joaquin Delta, California, in Field, M.E., A.H. Bouma, I.P. Colburn, R.G. Douglas, and J.C. Ingle, eds., *Quaternary Depositional Environments of the Pacific Coast*: Society of Economic Paleontologists and Mineralogists, Pacific Coast Paleogeography Symposium 4, p. 89-103.

Bates, M.E., and J.R. Lund. 2013. Delta subsidence reversal, levee failure, and aquatic habitat—a cautionary tale. *San Francisco Estuary and Watershed Science* 11(1).

Baumsteiger, J., R.E. Schroeter, T. O'Rear. 2017. Long-term Surveys Show Invasive Overbite Clams (*Potamocorbula amurensis*) are Spatially Limited in Suisun Marsh, California. *San Francisco Estuary and Watershed Science* 15(2). https://escholarship.org/uc/item/6fd377s4.

Baxter, R., R. Breuer, L. Brown, L. Conrad, F. Feyrer, S. Fong, K. Gehrts, K., et al. 2010. 2010 Pelagic organism decline work plan and synthesis of results. Interagency Ecological Program for the San Francisco Estuary. www.water.ca.gov/iep/docs/FinalPOD2010Workplan12610.pdf.

Baxter, R., L. Brown, G. Castillo, L. Conrad. 2015. *An updated conceptual model of Delta Smelt biology: Our evolving understanding of an estuarine fish.* Interagency Ecological Program, California Department of Water Resources. http://pubs.er.usgs.gov/publication/70141018.

The Bay Institute (Bay Institute). 1998. *From the Sierra to the Sea: The Ecological History of the San Francisco Bay-Delta Watershed.* https://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/docs/cmnt091412/sldmwa/tbi_1998.pdf.

Bolger, B.L., Park, Y.J., Unger, A.J., and Sudicky, E.A. 2011. Simulating the pre-development hydrologic conditions in the San Joaquin Valley, California. *Journal of Hydrology* 411(3-4): 322-330.

Borgnis, E. and K.E. Boyer. 2016. Salinity Tolerance and Competition Drive Distributions of Native and Invasive Submerged Aquatic Vegetation in the Upper San Francisco Estuary. *Estuaries and Coasts* 39: 707. https://doi.org/10.1007/s12237-015-0033-5.

Boyer, K. and M. Sutula. 2015. *Factors Controlling Submersed and Floating Macrophytes in the Sacramento-San Joaquin Delta*. Southern California Coastal Water Research Project. Technical Report No. 870. Costa Mesa, CA.

Brooks, M.L., Fleishman, E., Brown, L.R., Lehman, P.W., Werner, I., Scholz, N., et al. 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. *Estuaries and Coasts* 35(2): 603-621.

Brooks, M.L., E. Fleishman, L. Brown, P. Lehman, I. Werner, N.L. Scholz, C. Mitchelmore, et al. 2011. Life histories, salinity zones, and sublethal contributions of contaminants to pelagic fish declines illustrated with a case study of San Francisco Estuary, California, USA. *Estuaries and Coasts* 35(2):603-621.

Brown L.R., W. Kimmerer, J.L. Conrad, S. Lesmeister, and A. Mueller–Solger. 2016. Food webs of the Delta, Suisun Bay, and Suisun Marsh: an update on current understanding and possibilities for management. *San Francisco Estuary and Watershed Science* 14(3). https://escholarship.org/uc/item/4mk5326r.

Bryant, M.E. and J.D. Arnold. 2007. Diets of age-0 striped bass in the San Francisco Estuary, 1973-2002. *California Fish and Game* 93(1):1-22.

Buchanan, R.A., J. Skalski, P. Brandes, and A. Fuller. 2013. Route use and survival of juvenile Chinook salmon through the San Joaquin River Delta. *North American Journal of Fish Management* 33(1): 216-229.

California Department of Conservation (DOC). 2017. Farmland Mapping and Monitoring Program (FMMP). ftp://ftp.consrv.ca.gov/pub/dlrp/fmmp/. Accessed October 2017.

California Department of Fish and Wildlife (CDFW). 2016. 2012 Vegetation Map Update for Suisun Marsh, Solano County, California. A Report to the California Department of Water Resources. https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentID=123411&inline.

California Department of Water Resources (DWR). 2014*. Central Valley Flood System Fish Migration Improvement Opportunities.* Technical Report. https://www.water.ca.gov/LegacyFiles/fishpassage/docs/FMIO.pdf. Accessed March 11, 2018.

California Department of Water Resources (DWR). 2015. *2014 Georgiana Slough Floating Fish Guidance Structure Performance Evaluation Project Report*. Bay-Delta Office, Sacramento, CA.

California Division of Boating and Waterways. 2018. Aquatic Invasive Plant Control Program (AIPCP). http://www.dbw.ca.gov/?page_id=28764.

California Natural Resources Agency. 2018a. *McCormack-Williamson Tract Restoration Project, Sacramento County, CA*. http://resources.ca.gov/docs/ecorestore/projects/McCormack_Williamson_Tract_Project.pdf.

California Natural Resources Agency. 2018b. *Dutch Slough Tidal Marsh Restoration Project, Oakley, CA*. http://resources.ca.gov/docs/ecorestore/projects/Dutch_Slough_Tidal_Marsh_Restoration.pdf.

California Natural Resources Agency. 2018c. *Yolo Bypass Salmonid Habitat Restoration and Fish Passage Project, Yolo Bypass*. http://resources.ca.gov/docs/ecorestore/projects/Yolo_Bypass_Salmonid_Habitat_Restoration_and_Fish_Passage_Project.pdf.

Carlton, J.T., J.K. Thompson, L.E. Schemel, F.H. Nichols. 1990. Remarkable invasion of San Francisco Bay (California, USA), by the Asian clam *Potamocorbula amurensis*. I. Introduction and dispersal. *Marine Ecology Progress Series* 66(1-2):81–94.

Cloern, J.E. 2001. Our evolving conceptual model of the coastal eutrophication problem. *Marine Ecology Progress Series* 210:223-253.

Cloern, J.E. 2007. Habitat Connectivity and Ecosystem Productivity: Implications from a Simple Model. *The American Naturalist* 169: E21-E33.

Cloern, J.E., S.Q. Foster, and A.E. Kleckner. 2014. Phytoplankton primary production in the world's estuarine-coastal ecosystems. *Biogiosciences* 11: 2477-2501. www.biogeosciences.net/11/2477/2014/.

Cloern, J.E., A. Robinson, A. Richey, L. Grenier, R. Grossinger, K.E. Boyer, J. Burau, et al. 2016. Primary production in the Delta: then and now. *San Francisco Estuary and Watershed Science* 14(3). http://escholarship.org/uc/item/8fq0n5gx.

Cohen, C.N. and J.T. Carlton. 1998. Accelerating Invasion Rate in a Highly Invaded Estuary. *Science* 279(5350): 555-558. DOI: 10.1126/science.279.5350.555.

Cole, B.E., and J.E. Cloern. 1984. Significance of biomass and light availability to phytoplankton productivity in San Francisco Bay. *Marine Ecology Progress Series* 17(1):15-24.

Conrad, L.J., A.J. Bibian, K.L. Weinersmith, D. De Carion, M.J. Young, P. Crain, E.L. Hestir, et al. 2016. Novel Species Interactions in a Highly Modified Estuary: Association of Largemouth Bass with Brazilian Waterweed *Egeria densa*. *Transactions of the American Fisheries Society* 145(2): 249-263. https://doi.org/10.1080/00028487.2015.1114521.

Corline, N.J., T. Sommer, C. Jeffres, and J. Katz. 2017. Zooplankton ecology and trophic resources for rearing native fish on an agricultural floodplain in the Yolo Bypass California, USA. *Wetlands Ecology and Management* 25: 533-545. http://doi.org/10.1007/s11273-017-9534-2.

Cosumnes River Preserve (CRP). 2008. *Cosumnes River Preserve Management Plan*. Prepared by Kleinshmidt Associates. http://cosumnes.org/documents/managementplan.pdf.

Dahm, C.N., A.E. Parker, A.E. Adelson, M.A. Christman, and B.A. Bergamaschi. 2016. Nutrient Dynamics of the Delta: Effects on Primary Producers. *San Francisco Estuary and Watershed Science* 14(4). http://escholarship.org/uc/item/1789c0mz.

Darnell, R.M. 1967. Organic detritus in relation to the estuarine ecosystem. Pages 376-382 in G. H. Lauff, editor. *Estuaries: Nutrients and Biological Production*. Publication No. 83 American Association for the Advancement of Science, Washington, DC.

Das, T., M.D. Dettinger, D.R. Cayan, and H.G. Hidalgo. 2011. Potential Increase in Floods in California's Sierra Nevada under Future Climate Projections. *Climatic Change* 109: 71-94.

Day Jr., J.W., A. Yáñez-Arancibia, W.M. Kemp, and B.C. Crump. 2013. Introduction to Estuarine Ecology. In: Editor(s): Day, J.W., B.C. Crump, W.M. Kemp, and A. Yáñez-Arancibia. Estuarine Ecology, Second Edition. Wiley Online Library. https://doi.org/10.1002/9781118412787.ch1.

DeHaven, Richard D. 1989. *Distribution, extent, replaceability and relative values to fish and wildlife of shaded riverine aquatic cover of the Lower Sacramento River, California; Part I: 1987-88 Study Results and Recommendations*. U.S. Fish and Wildlife Service. Division of Ecological Services, Sacramento, CA.

Delta Independent Science Board (ISB). 2013. Habitat Restoration in the Sacramento-San Joaquin Delta and Suisun Marsh: A Review of Science Programs.

Delta Stewardship Council (DSC). 2013. *The Delta Plan, Ensuring a reliable water supply for California, a healthy Delta ecosystem, and a place of enduring value*. Sacramento, CA.

Dettinger, M.D., and D.R. Cayan. 1995. Large-Scale Atmospheric Forcing of Recent Trends Toward Early Snowmelt Runoff in California. *Journal of Climate* 8:606-623.

Dettinger, M.D., D.R. Cayan, M.K. Meyer, and A.E. Jeton. 2004. Simulated Hydrologic Responses to Climate Variations and Change in the Merced, Carson, and American River Basins, Sierra Nevada, California, 1900–2099. *Climatic Change* 62:283-317.

Dettinger, M.D. 2011. Climate change, atmospheric rivers, and floods in California–a multimodel analysis of storm frequency and magnitude changes. *JAWRA Journal of the American Water Resources Association* 47(3): 514-523.

Dettinger M., J. Anderson, M. Anderson, L.R. Brown, D. Cayan, D., and E. Maurer. 2016. Climate change and the Delta. *San Francisco Estuary and Watershed Science* 14(3): 1-26. http://escholarship.org/uc/item/2r71j15r.

Deverel, S.J., D.A. Leighton, C. Lucero, and T. Ingrum. 2017. Simulation of Subsidence Mitigation Effects on Island Drain Flow, Seepage, and Organic Carbon Loads on Subsided Islands Sacramento–San Joaquin Delta. *San Francisco Estuary and Watershed Science* 15(4).

Deverel, S.J., T. Ingrum, and D. Leighton. 2016. Present-day oxidative subsidence of organic soils and mitigation in the Sacramento-San Joaquin Delta, California, USA. *Hydrogeology* 24(3): 569-586.

Deverel, S.J, T. Ingrum, C. Lucero, and J.Z. Drexler. 2014. Impounded Marshes on Subsided Islands: Simulated Vertical Accretion, Processes, and Effects, Sacramento-San Joaquin Delta, CA USA. *San Francisco Estuary and Watershed Science* 12(2).

Deverel, S.J. and D.A. Leighton. 2010. Historic, recent, and future subsidence, Sacramento–San Joaquin Delta, California, USA. *San Francisco Estuary and Watershed Science* 8(2).

Deverel, S.J. and S.A. Rojstaczer. 1996. Subsidence of agricultural lands in the Sacramento–San Joaquin. *Water Resources Research* 32(8): 2359–2367.

Doody, J.P. 2007. *Saltmarsh Conservation, Management and Restoration*. Springer Science & Business Media.

Durand, J. 2008. *DRERIP Delta Aquatic Foodweb Conceptual Model. Sacramento (CA): Delta Regional Ecosystem Restoration Implementation Plan.* http://www.dfg.ca.gov/ERP/drerip_conceptual_models.asp.

Durand, J. 2015. A Conceptual Model of the Aquatic Food Web of the Upper San Francisco Estuary. *San Francisco Estuary and Watershed Science* 13(3). http://escholarship.org/uc/item/0gw2884c.

Durand, J.R. 2017. Evaluating the Aquatic Habitat Potential of Flooded Polders in the Sacramento – San Joaquin Delta. *San Francisco Estuary and Watershed Science* 15(4): https://doi.org/10.15447/sfews.2017v15iss4art4.

Dybala, K.E., N.E. Seavy, M.D. Dettling, M. Gilbert, R. Melcer, Jr., and T. Gardali. 2014. Does Restored Riparian Habitat Create Ecological Traps for Riparian Birds Through Increased Brown-Headed Cowbird Nest Parasitism? *Ecological Restoration* 32(3): 239-248.

Dybala, K.E., N. Clipperton, T. Gardali, G.H. Golet, R. Kelsey, S. Lorenzato, R. Melcer, Jr., et al. 2017a. Population and Habitat Objectives for Avian Conservation in California's Central Valley Riparian Ecosystems. *San Francisco Estuary and Watershed Science* 15(1) https://dx.doi.org/10.15447/sfews.2017v15iss1art5.

Dybala, K.E., N. Clipperton, T. Gardali, G.H. Golet, R. Kelsey, S. Lorenzato, R. Melcer, Jr., et al. 2017b. A General Framework for Setting Quantitative Population Objectives for Wildlife Conservation. *San Francisco Estuary and Watershed Science* 15(1) https://doi.org/10.15447/sfews.2017v15iss1art8.

Feyrer, F., B. Herbold, S.A. Matern, and P.B. Moyle. 2003. Dietary shifts in a stressed fish assemblage: Consequences of a bivalve invasion in the San Francisco Estuary. *Environmental Biology of Fishes* 67(3): 277-288.

Fleenor, W., W. Bennett, P. Moyle, J. Lund, and D. Solutions. 2010. On developing prescriptions for freshwater flows to sustain desirable fishes in the Sacramento-San Joaquin Delta. Submitted to the State Water Resources Control Board Regarding Flow Criteria for the Delta Necessary to Protect Public Trust Resources. https://watershed.ucdavis.edu/pdf/Moyle_Fish_Flows_for_ the_Delta_15feb2010.pdf.

Fong, S., S. Louie, I. Werner, J. Davis, and R.E. Connon. 2016. Contaminant effects on California Bay–Delta species and human health. *San Francisco Estuary and Watershed Science* 14(4). http://dx.doi.org/10.15447/sfews.2016v14iss4art5.

Fox, P., P.H. Hutton, D.J Howes, A.J. Draper, and L. Sears. 2015. Reconstructing the Natural Hydrology of the San Francisco Bay–Delta Watershed. *Hydrology and Earth System Sciences* 19(10): 4257–4274. https://doi.org/10.5194/hess-19-4257-2015.

Geographic Information Center (GIC). 2003. *The Central Valley Historic Mapping Project*. California State University, Chico, Department of Geography and Planning and Geographic Information Center. Chico, CA.

Gilmer, D.S., M.R. Miller, R.D. Bauer, J.R. LeDonne. 1982. *California's Central Valley Wintering Waterfowl: Concerns and Challenges.* US Fish and Wildlife Publications 41. https://digitalcommons.unl.edu/usfwspubs/41.

Glibert, P.M., R. Dugdale, F.P. Wilkerson, A.E. Parker, J. Alexander, E. Antell, S. Blaser, A. Johnson, J. Lee, T. Lee, S. Murasko, S. Strong. 2014a. Major–but rare–spring blooms in 2014 in San Francisco Bay Delta, California, a result of the long-term drought, increased residence time, and altered nutrient loads and forms. *Journal of Experimental Marine Biology and Ecology* 460:8-18.

Glibert, P.M., F.P. Wilkerson, R.C. Dugdale, A.E. Parker, J. Alexander, S. Blaser, and S. Murasko. 2014b. 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 in Marine Science* 1:17.

Gray, A., C.A. Simenstad, D.L. Bottom, and T.J. Cornwell. 2002. Contrasting functional performance of juvenile salmon habitat in recovering wetlands of the Salmon River estuary, Oregon, U.S.A. *Restoration Ecology* 10(3):514-526.

Gray, B. 2013. Integrated management of delta stressors institutional and legal options. http://www.ppic.org/content/pubs/report/R_612JMR.pdf.

Greco, S.E., Fremier, A.K., Larsen, E.W. and Plant, R.E. 2007. A tool for tracking floodplain age land surface patterns on a large meandering river with applications for ecological planning and restoration design. *Landscape and Urban Planning* 81: 354-373.

Greco, S.E. and Larsen, E.W. 2014. Ecological design of multifunctional open channels for flood control and conservation planning. *Landscape and Urban Planning* 131: 14-26. http://10.1016/j.landurbplan.2014.07.002.

Greene, V.E., Sullivan, L.J., Thompson, J.K., and Kimmerer, W.J. 2011. Grazing impact of the invasive clam *Corbula amurensis* on the microplankton assemblage of the northern San Francisco Estuary. *Marine Ecology Progress Series* 431: 183-193.

Gregory, R.S. 1993. Effect of turbidity on the predator avoidance behaviour of juvenile Chinook Salmon (*Oncorhynchus tshawytscha*). *Canadian Journal of Fisheries and Aquatic Sciences* 50(2):241-246.

Grewell, B., J. Callaway, J., and W. Ferren. 2007. Estuarine Wetlands. In Barbour M., Keeler-Wolf T., and A. Schoenherr. (Eds.), Terrestrial Vegetation of California, 3rd Edition (pp. 124-154). University of California Press. http://www.jstor.org/stable/10.1525/j.ctt1pnqfd.9.

Grimaldo, L.F., A.R. Stewart, and W. Kimmerer. 2009. Dietary Segregation of Pelagic and Littoral Fish Assemblages in a Highly Modified Tidal Freshwater Estuary. *Marine and Coastal Fisheries* 1(1): 200-217. http://www.bioone.org/doi/pdf/10.1577/C08-013.1.

Grossinger, R.M. 1998. Historical and Modern Baylands 1998 (EcoAtlas Version 1.50b4). San Francisco Estuary Institute. http://www.sfei.org/content/ecoatlas-version-150b4-1998#sthash.5lkLAmtB.dpbs.

Grossinger, R.M., and A. Whipple. 2009. *Re-Oaking the Valleys: Bringing Native Trees Back into California's Suburban Landscapes*. State of the Estuary Conference, Oakland, CA.

Grossman, G., T. Essington, B. Johnson, J. Miller, N. Monsen, T. Pearsons. 2013. *Effects of fish predation on salmonids in the Sacramento River–San Joaquin Delta and associated ecosystems*. Panel final report. 71 p. Sacramento (CA): California Department Fish Wildlife, Delta Stewardship Council, and National Marine Fisheries Service. http://www.dfg.ca.gov/erp/predation.asp.

Grossman, G.D. 2016. Predation on fishes in the Sacramento–San Joaquin Delta: Current knowledge and future directions. *San Francisco Estuary and Watershed Science* 14(2). https://escholarship.org/uc/item/9rw9b5tj.

Hager, S.W. and L.E. Schemel. 1992. Sources of nitrogen and phosphorus to northern San Francisco Bay. *Estuaries and Coasts* 15(1): 40–52. DOI: 10.2307/1352708.

Hasenbein, M., L.M. Komoroske, R. Connon, J. Geist, and N.A. Fangue. 2013. Turbidity and Salinity Affect Feeding Performance and Physiological Stress in the Endangered Delta Smelt. *Integrative and Comparative Biology* 53(4):620-634.

Healey, M., M. Dettinger, and R. Norgaard, eds. 2008. The State of Bay-Delta Science, 2008. CALFED Science Program: Sacramento, CA.

Healey, M., P. Goodwin, M. Dettinger, and R. Norgaard. 2016. The state of Bay–Delta science 2016: an introduction. *San Francisco Estuary and Watershed Science* 14(2).

Heath, S.K., C.U. Soykan, K.L. Velas, R. Kelsey, S.M. Kross. 2017. A bustle in the hedgerow: Woody field margins boost on farm avian diversity and abundance in an intensive agricultural landscape. *Biological Conservation* 212: 153-161.

Hennessy, A. and T. Enderlein. 2013. Zooplankton monitoring 2011. *IEP Newsletter* 26(1):23-30.

Herbold, B., D.M. Baltz, L. Brown, R. Grossinger, W. Kimmerer, P. Lehman, C.S. Simenstad, et al. 2014. The role of tidal marsh restoration in fish management in the San Francisco Estuary. *San Francisco Estuary and Watershed Science* 12(1). http://escholarship.org/uc/item/1147j4nz.

Herzog, S.K. 1996. Wintering Swainson's Hawks in California's Sacramento-San Joaquin River Delta. *The Condor* 98:876-879.

Hestir, E.L. 2011. "*Trends in Estuarine Water Quality and Submerged Aquatic Vegetation Invasion.*" Ph.D. dissertation, University of California, Davis.

Hickson, D. and T. Keeler-Wolf. 2007. *Vegetation and Land Use Classification and Map of the Sacramento-San Joaquin River Delta.* Vegetation and Mapping Program. Department of Fish and Wildlife. https://www.wildlife.ca.gov/Data/VegCAMP/Reports-and-Maps.

Hinsley, S.A., and P.E. Bellamy. 2000. The Influence of Hedge Structure, Management and Landscape Context on the Value of Hedgerows to Birds: A Review. *Journal of Environmental Management* 60:33-49.

Howe, E.R., C.A. Simenstad, J.D. Toft, J.R. Cordell, and S.M. Bollens. 2014. Macroinvertebrate prey availability and fish diet selectivity in relation to environmental variables in natural and restoring North San Francisco Bay tidal marsh channels. *San Francisco Estuary and Watershed Science* 12(1). https://escholarship.org/uc/item/0p01q99s.

Hutton, P.H., J.S. Rath, and S.B. Roy. 2017a. Freshwater flow to the San Francisco Bay-Delta estuary over nine decades (Part 1): Trend evaluation. *Hydrological Processes* 31(14): 2500-2515.

Hutton, P.H., J.S. Rath, and S.B. Roy. 2017b. Freshwater flow to the San Francisco Bay-Delta estuary over nine decades (Part 2): Change attribution. *Hydrological Processes* 31(14): 2516-2529.

ICF International (ICF). 2013. Appendix 1.A: Evaluation of Species Considered for Coverage. Bay Delta Conservation Plan. Revised Administrative Draft. March. Sacramento, CA. Prepared for California Department of Water Resources, Sacramento, CA. http://baydeltaconservationplan.com/Libraries/Dynamic_Document_Library/BDCP_Appendix_1_A_%e2%80%93_Evaluation_of_Species_Considered_for_Coverage_3-14-13.sflb.ashx.

Ingebritsen, S., M. Ikehara, D. Galloway, and D. Jones. 2000. *Delta Subsidence in California: The Sinking Heart of the State*. 2327-6932, Geological Survey (US).

Ivey, G.L., C.P. Herziger, and D.A. Hardt. 2014. *Conservation priorities and best management practices for wintering Sandhill Cranes in the Central Valley of California.* Prepared for The Nature Conservancy of California. International Crane Foundation. Baraboo, WI.

Jassby, A., J. Cloern, and B. Cole. 2002. Annual primary production: Patterns and mechanisms of change in a nutrient-rich tidal ecosystem. *Limnology and Oceanography* 47:698-712.

Jassby, A.D. 2005. Phytoplankton regulation in an eutrophic tidal river (San Joaquin River, California). *San Francisco Estuary and Watershed Science* 3(1). https://escholarship.org/uc/item/9jb2t96d.

Jassby, A., and J. Cloern. 2000. Organic matter sources and rehabilitation of the Sacramento–San Joaquin Delta (California, USA). *Aquatic Conservation: Marine and Freshwater Ecosystems* 10(5):323352.

Jedlicka, J.A., R. Greenberg, and P.T. Raimondi. 2014. Vineyard and riparian habitat, not nest box presence, alter avian community composition. *The Wilson Journal of Ornithology* 126(1):60-68. https://doi.org/10.1676/13-058.1.

Jeffres, C.A., J.J. Opperman and P.B. Moyle. 2008. Ephemeral floodplain habitats provide best growth conditions for juvenile Chinook salmon in a California river. *Environmental Biology of Fishes* 83(4): 449–458. https://doi.org/10.1007/s10641-008-9367-1.

Katz, J., P.B. Moyle, R.M. Quiñones, J. Israel, and S. Purdy. 2013. Impending Extinction of Salmon, Steelhead, and Trout (Salmonidae) in California. *Environmental Biology of Fishes.* DOI 10.1007/s10641-012-9974-8.

Katz, J., C. Jeffres, J.L. Conrad, T.R. Sommer, J. Martinez, S. Brumbaugh, and P.B. Moyle. 2017. Floodplain farm fields provide novel rearing habitat for Chinook salmon. *PLoS ONE* 12(6): e0177409. https://doi.org/10.1371/journal.pone.0177409.

Kayfetz, K. and W.J. Kimmerer. 2017. Abiotic and biotic controls on the copepod *Pseudodiaptomus forbesi* in the upper San Francisco Estuary. *Marine Ecology Progress Series* 581:85–101.

Kimmerer, W. and L. Lougee. 2015. Bivalve grazing causes substantial mortality to an estuarine copepod population. *Journal of Experimental Marine Biology and Ecology* 473:53–63.

Kimmerer, W., E. Gartside, and J. Orsi. 1994. Predation by an introduced clam as the likely cause of substantial declines in zooplankton of San Francisco Bay. *Marine Ecology Progress Series* 113:81-93.

Kimmerer, W. 2004. Open water processes of the San Francisco Bay Estuary: from physical forcing to biological responses. *San Francisco Estuary and Watershed Science* 2(1). http://escholarship.org/uc/item/9bp499mv.

Kimmerer, W. and J.K. Thompson. 2014. Phytoplankton growth balanced by clam and zooplankton grazing and net transport into the low-salinity zone of the San Francisco Estuary. *Estuaries and Coasts* 37:1202–1218. http://dx.doi.org/10.1007/s12237-013-9753-6.

Kirby, M.E., S.P. Lund, and C.J. Poulsen. 2005. Hydrologic variability and the onset of modern El Niño–Southern Oscillation: a 19 250-year record from Lake Elsinore, southern California. *Journal of Quaternary Science* 20:239–254. ISSN 0267-8179.

Kirby, M.E., S.P. Lund, W.P. Patterson, M.A. Anderson, B.W. Bird, L. Ivanovici, et al. 2010. A Holocene record of Pacific Decadal Oscillation (PDO)-related hydrologic variability in Southern California (Lake Elsinore, CA). *Journal of Paleolimnology* 44(3): 819–839.

Komoroske, L.M., R.E. Connon, K.M. Jeffries, and N.A. Fangue. 2015. Linking transcriptional responses to organismal tolerance reveals mechanisms of thermal sensitivity in a mesothermal endangered fish. *Molecular Ecology* 24:4960-4981.

Lehman, P.W., S. Mayr, L. Mecum, and C. Enright. 2010. The freshwater tidal wetland Liberty Island, CA was both a source and sink of inorganic and organic material to the San Francisco Estuary. *Aquatic Ecology* 44(2):359-372.

Lehman, P., K. Marr, G. Boyer, S. Acuña, and S. Teh. 2013. Long-term trends and causal factors associated with *Microcystis* abundance and toxicity in San Francisco Estuary and implications for climate change impacts. *Hydrobiologia* 718:141-158.

Lehman, P.W., C. Kendall, M.A. Guerin, M.B. Young, S.R. Silva, G.L. Boyer, and S.J. Teh. 2015. Characterization of the Microcystis bloom and its nitrogen supply in San Francisco Estuary using stable isotopes. *Estuaries and Coasts* 38(1):165-178.

Lehman, P.W., T. Kurobe, S. Lesmeister, D. Baxa, and A. Tung. 2017. Impacts of the 2014 severe drought on the Microcystis bloom in San Francisco Estuary. *Harmful Algae* 63: 94–108. http://dx.doi.org/10.1016/j.hal.2017.01.011.

Light, T., T. Grosholz, P.B. and Moyle. 2005. *Delta Ecological Survey (Phase I): Nonindegenous aquatic species in the Sacramento-San Joaquin Delta, a Literature Review*.

Lucas, L.V., J.E. Cloern, J.K. Thompson, M.T. Stacey, and J.R. Koseff. 2016. Bivalve grazing can shape phytoplankton communities. *Frontiers in Marine Science* 3:14.

Lucas, L.V., J.K. Thompson. 2012. Changing restoration rules: Exotic bivalves interact with residence time and depth to control phytoplankton productivity. *Ecosphere*, Volume 3, Issue 12, pp 1-26.

Lund, J., E. Hanak, W. Fleenor, R. Howitt, J. Mount and P. Moyle. 2007. *Envisioning Futures for the Sacramento–San Joaquin Delta.* San Francisco (CA): Public Policy Institute of California. 285 p.

Lund, J., E. Hanak, W. Fleenor, W. Bennett, R. Howitt, J. Mount, and P. Moyle. 2010. *Comparing Futures for the Sacramento-San Joaquin Delta.* University of California Press, Berkeley, CA.

Luoma, S., S. Anderson, B. Bergamaschi, L. Holm, C. Ruhl, D. Schoellhamer, R. Stewart. 2008. "Water Quality." In *The State of Bay-Delta Science, 2008*, ed. M.C. Healey, M.D. Dettinger, and R.B. Norgaard (Sacramento, CA: CALFED Science Program).

Luoma, S.N., C.N. Dahm, M. Healey, and J.N. Moore. 2015. Challenges facing the Sacramento–San Joaquin Delta: complex, chaotic, or simply cantankerous?. *San Francisco Estuary and Watershed Science* 13(3).

MacNally, R., J.R. Thomson, W.J. Kimmerer, F. Feyrer, K.B. Newman, A. Sih, W.A. Bennett, et al. 2010. Analysis of pelagic species decline in the upper San Francisco Estuary using multivariate autoregressive modeling (MAR). *Ecological Applications* 20: 1417-1430.

Mahardja, B., M.J. Farruggia, B. Schreier, and T. Sommer. 2017. Evidence of a Shift in the Littoral Fish Community of the Sacramento-San Joaquin Delta. *PLoS ONE*, *12*(1), e0170683. https://doi.org/10.1371/journal.pone.0170683.

Maier, G.O. and C.A. Simenstad. 2009. The role of marsh-derived macrodetritus to the food webs of juvenile Chinook salmon in a large altered estuary. *Estuaries and Coasts* 32(5):984-998.

May, C.L., J.R. Koseff, L.V. Lucas, J.E. Cloern, and D.H. Schoellhamer. 2003. Effects of spatial and temporal variability of turbidity on phytoplankton blooms. *Marine Ecological Progress Series* 254:111-128.

Meadows, R. 2014. Pop-up Wetlands Help Birds through CA Drought. *Frontiers in Ecology and the Environment* 12:540-544.

Melcer Jr., R. and K. Anderson. 2017. *Managing Expectations – An Assessment of Land Use and Ecological Restoration in the Sacramento – San Joaquin Delta.* Poster Presentation. State of the Estuary Conference, Oakland, CA.

Miller, R.L., M. Fram, R. Fujii, and G. Wheeler. 2008. Subsidence Reversal in a Re-Established Wetland in the Sacramento-San Joaquin Delta, California, USA. *San Francisco Estuary and Watershed Science* 6.

Monsen, N.E., J.E. Cloern, and J.R. Burau. 2007. Effects of flow diversions on water and habitat quality: examples from California's highly manipulated Sacramento-San Joaquin Delta. *San Francisco Estuary and Watershed Science* 5(3). http://escholarship.org/uc/item/04822861.

Mordecai, E.A., N.A. Molinari, K.A. Stahlheber, K. Gross, and C. D'Antonio. 2015. Controls over native perennial grass exclusion and persistence in California grasslands invaded by annuals. *Ecology* 96(10): 2643-2652.

Mount, J.F., and R. Twiss. 2005. Subsidence, Sea Level Rise, Seismicity in the Sacramento–San Joaquin Delta. *San Francisco Estuary and Watershed Science* 3(1).

Mount, J., W. Bennett, J. Durand, W. Fleenor, E. Hanak, J. Lund, and P. Moyle. 2012. *Aquatic Ecosystem Stressors in the Sacramento–San Joaquin Delta* (No. R_612JMR). Sacramento: Public Policy Institute of California. http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.367.1509.

Moyle, P.B. 2002. *Inland fishes of California, Revised and Expanded*. University of California Press, Berkeley, CA.

Moyle, P.B., J.R. Lund, W.A. Bennett, and W.E. Fleenor. 2010. Habitat Variability and Complexity in the Upper San Francisco Estuary. *San Francisco Estuary and Watershed Science* 8(3).

Moyle, P.B., J.V.E. Katz, and R.M. Quiñones. 2011. Rapid Decline of California’s Native Inland Fishes: A Status Assessment. *Biological Conservation* 144: 2414–23.

Moyle, P., W. Bennett, J. Durand, W. Fleenor, B. Gray, E. Hanak, and J. Mount. 2012. Where the Wild Things Aren’t: Making the Delta a Better Place for Native Species. http://www.ppic.org/content/pubs/report/R_612PMR.pdf.

Moyle, P.B., P.K. Crain, J.D. Kiernan, and K. Quiñones. 2013. *Projected Effects of Future Climates on Freshwater Fishes of California* (No. CEC-500-2012-029) (p. 60). Sacramento, California: California Energy Commission. www.energy.ca.gov/2012publications/CEC-500-2012-028/CEC-500-2012-028.pdf.

Muller-Solger A.B., A.D. Jassby, and D.C. Muller-Navarra. 2002. Nutritional quality of food resources for zooplankton (Daphnia) in a tidal freshwater system (Sacramento-San Joaquin River Delta). *Limnology and Oceanography* 47(5):1468-1476.

Myers, N., R.A. Mittermeier, C.G. Mittermeier, G.A.B. da Fonseca, and J. Kent. 2000. Biodiversity hotspots for conservation priorities. *Nature* 403(6772): 853-858.

Myers, R.A., S.A. Levin, R. Lande, F.C. James, W.W. Murdoch, and R.T. Paine. 2004. Hatcheries and endangered salmon. Science 303(5666): 1980.

Nakoto et al. 2017

National Marine Fisheries Service (NMFS). 2009. *Biological Opinion and Conference Opinion on the Long-term Operations of the Central Valley Project and the State Water Project*. National Marine Fisheries Service, Long Beach, California.

National Research Council (NRC). 2012. *Sustainable Water and Environmental Management in the California Bay-Delta*. Washington DC: National Academies Press.

Nilsson, C., and K. Berggren. 2000. Alterations of Riparian Ecosystems Caused by River Regulation: Dam operations have caused global-scale ecological changes in riparian ecosystems. How to protect river environments and human needs of rivers remains one of the most important questions of our time. *BioScience* 50(9): 783-792.

Nobriga, M.L. and F. Feyrer. 2007. Shallow-water piscivore-prey dynamics in California's Sacramento–San Joaquin Delta. *San Francisco Estuary and Watershed Science* 5(2). https://escholarship.org/uc/item/387603c0.

Nobriga, M.L., T.R. Sommer, F. Feyrer, and K. Fleming. 2008. Long-term trends in summertime habitat suitability for delta smelt (*Hypomesus transpacificus*). *San Francisco Estuary and Watershed Science* 6(1). http://escholarship.org/uc/item/5xd3q8tx.

Nobriga, M.L., and J.A. Rosenfield. 2016. Population Dynamics of an Estuarine Forage Fish: Disaggregating Forces Driving Long-Term Decline of Longfin Smelt in California's San Francisco Estuary. *Transactions of the American Fisheries Society* 145: 44–58.

Null, S.E., J.H. Viers, J.F. Mount. 2010. Hydrologic response and watershed sensitivity to climate warming in California's Sierra Nevada. *PLOS one* https://doi.org/10.1371/journal.pone.0009932.

Odum, E.P. 1971. *Fundamentals of ecology.* Saunders, Philadelphia, Pennsylvania, USA.

Orsi, J.J., and W.L. Mecum. 1996. Food limitation as the probable cause of a long-term decline in the abundance of *Neomysis mercedis* the opossum shrimp in the Sacramento-San Joaquin Estuary. Pages 375-401 in J. T. Hollibaugh, editor. *San Francisco Bay the Ecosystem*. Pacific Division of the American Association for the Advancement of Science, San Francisco, CA.

Otten, T.G., H.W. Paerl, T.W. Dreher, W.J. Kimmerer, and A.E. Parker. 2017. The Molecular Ecology of Microcystis sp. Blooms in the San Francisco Estuary Delta. *Environmental microbiology* 19(9): 3619-3637.

Paerl, H.W., 1988. Nuisance phytoplankton blooms in coastal, estuarine and inland waters. *Limnology and Oceanography* 33: 823–847.

Perry, R.W., P.L. Brandes, J.R. Burau, A.P. Klimley, B. MacFarlane, C. Michel, and J.R. Skalski. 2013. Sensitivity of survival to migration routes used by juvenile Chinook salmon to negotiate the Sacramento-San Joaquin River Delta. *Environmental Biology of Fishes* 96: 381-392.

Perry, R.W., P.L. Brandes, J.R. Burau, P.T. Sandstrom, and J.R. Skalski. 2015. Effect of tides, river flow, and gate operations on entrainment of juvenile salmon into the interior Sacramento–San Joaquin River Delta. *Transactions of the American Fisheries Society* 144(3): 445-455.

Perry, R.W., R. Buchanan, P.L. Brandes, J.R. Burau, and J.A. Israel. 2016. Anadromous Salmonids in the Delta: New Science 2006–2016. San Francisco Estuary and Watershed Science 14(2).

Peterson, H.A. and M. Vayssieres. 2010. Benthic assemblage variability in the upper San Francisco Estuary: a 27-year retrospective. *San Francisco Estuary and Watershed Science* 8(1). https://escholarship.org/uc/item/4d0616c6.

Pethick, J.S., and S. Crook. 2000. Development of a Coastal Vulnerability Index: A Geomorphological Perspective. *Environmental Conservation*, Vol. 27, 2000, pp. 359–367.

Pickart, A. and M. Barbour. 2007. Beach and Dune. In Barbour, M., Keeler-Wolf T., and A. Schoenherr. (Eds.), *Terrestrial Vegetation of California, 3rd Edition* (pp. 155-179). University of California Press. http://www.jstor.org/stable/10.1525/j.ctt1pnqfd.10.

Poff, N.L., J.D. Allan, M.B. Bain, J.R. Karr, K.L. Prestegaard, B.D. Richter, et al. 1997. The natural flow regime. *BioScience* 47(11): 769-784.

Poff, N.L., B.D. Richter, A.H. Arthington, S.E. Bunn, R.J. Naiman, E. Kendy, et al. 2010. The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards. *Freshwater Biology* 55(1): 147-170.

Public Policy Institute of California. 2018. California's Future: Water. http://www.ppic.org/wp-content/uploads/r-118ehr.pdf

Poff, N.L., B.D. Richter, A.H. Arthington, S.E. Bunn, R.J. Naiman, E. Kendy, et al. 2010. The Ecological Limits of Hydrologic Alteration (ELOHA): A New Framework for Developing Regional Environmental Flow Standards. *Freshwater Biology* 55: 147–70.

Preece, E.P., F.J. Hardy, B.C. Moore, and M. Bryan. 2017. A review of microcystin detections in Estuarine and Marine waters: Environmental implications and human health risk. *Harmful Algae* 61 (2017) 31–45.

Reed, D.J. 2002. Sea-Level Rise and Coastal Marsh Sustainability: Geological and Ecological Factors in the Mississippi Delta Plain. *Geomorphology* 48: 233–243.

Roberts, W.G., J.G. Howe, and J. Major. 1977. A survey of riparian forest flora and fauna in California. p. 3-19. In: A. Sands (ed.). *Riparian forests in California: their ecology and conservation*. Institute of Ecology Publication No. 15. 122 p. University of California, Davis.

Robinson, A., A. Richey, J. Cloern, K. Boyer, J. Burau, E. Canuel, J. DeGeorge, et al. 2016. *Primary production in the Sacramento–San Joaquin Delta—a science strategy to quantify change and identify future potential.* Richmond (CA): San Francisco Estuary Institute–Aquatic Science Center. http://www.sfei.org/sites/default/files/biblio_files/Primary Production in the Sacramento-San Joaquin Delta 3-31-2016.pdf.

Robson, B.J., and D.P. Hamilton. 2003. Summer flow event induces a cyanobacterial bloom in a seasonal Western Australia estuary. *Marine and Freshwater Research* 54: 139–151.

Rocha, C., H. Galvão, H., and A. Barbosa. 2002. Role of transient silicon limitation in the development of cyanobacteria blooms in the Guadiana estuary, south-western Iberia. *Marine Ecology Progress Series* 228: 35–45.

Rozas, L. and W. Odum. 1988. Occupation of submerged aquatic vegetation by fishes: testing the roles of food and refuge. *Oecologia* 77(1):101-106.

San Francisco Estuary Institute-Aquatic Sciences Center (SFEI-ASC). 2014. *A Delta Transformed: Ecological functions, spatial metrics, and landscape change in the Sacramento-San Joaquin Delta*. Prepared for the California Department of Fish and Wildlife and Ecosystem Restoration Program. Publication #729. SFEI-ASC, Richmond, CA.

San Francisco Estuary Institute-Aquatic Science Center (SFEI-ASC). 2016. *A Delta Renewed: A Guide to Science-Based Ecological Restoration in the Sacramento-San Joaquin Delta*. Prepared for the California Department of Fish and Wildlife and Ecosystem Restoration Program. A Report of SFEI-ASC's Resilient Landscapes Program, Publication #799, San Francisco Estuary Institute-Aquatic Science Center, Richmond, CA.

Schelske, C.L., and E.P. Odum. 1962. Mechanisms maintaining high productivity in Georgia estuaries. *Proceedings of the Gulf and Caribbean Fisheries Institute* 14:75-80.

Schoellhamer, D.H. 2011. Sudden Clearing of Estuarine Waters upon Crossing the Threshold from Transport to Supply Regulation of Sediment Transport as an Erodible Sediment Pool is Depleted: San Francisco Bay, 1999. *Estuaries and Coasts* 34: 885–899.

Schoellhamer, D.H., S.A. Wright, J.Z0, and Drexler. 2013, Adjustment of the San Francisco estuary and watershed to reducing sediment supply in the 20th century: *Marine Geology* 345: 63-71.

Schoellhamer, D.H., S.A. Wright, S.G. Monismith, and B.A. Bergamaschi. 2016. Recent Advances in Understanding Flow Dynamics and Transport of Water-Quality Constituents in the Sacramento–San Joaquin River Delta. *San Francisco Estuary and Watershed Science* 14(4). http://escholarship.org/uc/item/3vb656d6.

Scholz, N.L., E. Fleishman, L. Brown, I. Werner, M.L. Johnson, M.L. Brooks. 2012. A perspective on modern pesticides, pelagic fish declines, and unknown ecological resilience in highly managed ecosystems. *BioScience* 62:428-434. http://dx.doi.org/10.1525/bio.2012.62.4.13.

Sellner, K.G., R.V. Lacouture, K.G. Parlish, 1988. Effect of increasing salinity on a cyanobacteria bloom in the Potomac River Estuary. *Journal of Plankton Research* 10: 49–61.

Shackelford, G.E., P.R. Steward, R.N. German, S.M. Sait and T.G. Benton. 2015. Conservation planning in agricultural landscapes: hotspots of conflict between agriculture and nature. *Diversity and Distributions* 21: 357–367.

Sharma, P., C.E. Jones, J. Dudas, G.W. Bawden, and S. Deverel. 2016. Monitoring of subsidence with UAVSAR on Sherman Island in California's Sacramento-San Joaquin Delta. *Remote Sensing of Environment* 181: 218-236.

Shlemon, R.J., and E.L. Begg. 1975. Late Quaternary evolution of the Sacramento-San Joaquin Delta, California. In: Suggate, R.P., Cressel, M.M., editors. *Quaternary studies*. Bulletin 13, The Royal Society of New Zealand. p 259-266.

Simenstad C., J. Toft, H. Higgins, J. Cordell, M. Orr, P. Williams, L. Grimaldo, and Z. Hymanson. 1999. Preliminary results from the Sacramento-San Joaquin Delta breached levee wetland study (BREACH). *Interagency Ecological Program for the Sacramento-San Joaquin Estuary Newsletter* 12(4):15-21.

Sommer, T.R., M.L. Nobriga, W.C. Harrell, W. Batham, and W.J. Kimmerer. 2001. Floodplain rearing of juvenile Chinook salmon: evidence of enhanced growth and survival. *Canadian Journal of Fisheries and Aquatic Sciences* 58:325–333. doi:10.1139/cjfas-58-2-325

Sommer, T.R., W.C. Harrell, A.M. Solger, B. Tom, and W. Kimmerer. 2004. Effects of Flow Variation on Channel and Floodplain Biota and Habitats of the Sacramento River, California, USA. *Aquatic Conservation: Marine and Freshwater Ecosystems* 14:247-261.

Sommer, T.R., C. Armor, R. Baxter, R. Breuer, L. Brown, M. Chotkowski, S. Culberson, et al. 2007. The Collapse of Pelagic Fishes in the Upper San Francisco Estuary. *Fisheries* 32: 270–77.

State Water Resources Control Board (SWRCB). 2010. *Development of Flow Criteria for the Sacramento-San Joaquin Delta Ecosystem* (p. 191). State Water Resources Control Board. http://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/deltaflow/docs/final_rpt080310.pdf.

State Water Resources Control Board (SWRCB). 2017. Scientific Basis Report in Support of New and Modified Requirements for Inflows from the Sacramento River and its Tributaries and Eastside Tributaries to the Delta, Delta Outflows, Cold Water Habitat, and Interior Delta Flows. Prepared by State Water Resources Control Board, California Environmental Protection Agency, Sacramento, CA, with assistance from ICF, Sacramento, CA. https://www.waterboards.ca.gov/water_issues/programs/peer_review/docs/scientific_basis_phase_ii/201710_bdphaseII_sciencereport.pdf.

Strum, K., K.E. Dybala, M.N. Iglecia, and W.D. Shuford. 2017. Population and Habitat Objectives for Breeding Shorebirds in California's Central Valley. *San Francisco Estuary and Watershed Science* 15(1). https://doi.org/10.15447/sfews.2017v15iss1art3.

Sullivan, B.L., J.L. Aycrigg, J.H. Barry, R.E. Bonney, N. Bruns, C.B. Cooper, T. Damoulas, et al. 2014. The eBird Enterprise: An Integrated Approach to Development and Application of Citizen Science. *Biological Conservation* 169:31-40. Sunderland, MA.

Swanson, C. 2015. *Ecological Processes – Flood Events Indicators*. Technical Appendix, State of the San Francisco Estuary 2015.

Swenson, R.O., K. Whitener, and M. Eaton. 2003. *Restoring Floods to Floodplains: Riparian and Floodplain Restoration at the Cosumnes River Preserve*. The Nature Conservancy, Cosumnes River Preserve, Galt, CA.

Thompson, J. 1957. *Settlement Geography of the Sacramento–San Joaquin Delta*. Ph.D. dissertation. Stanford, CA: Stanford University.

Vaghti, M., and S. Greco, S. 2007. Riparian Vegetation Of The Great Valley. In Barbour M., Keeler-Wolf T., and A. Schoenherr. (Eds.), *Terrestrial Vegetation of California, 3rd Edition* (pp. 425-455). University of California Press. Retrieved from http://www.jstor.org/stable/10.1525/j.ctt1pnqfd.20.

Vannote, R.L., G.W. Minshall, K.W. Cummins, J.R. Sedell, C.E. and Cushing. 1980. The river continuum concept. *Canadian Journal of Fisheries and Aquatic Sciences* 37(1): 130-137.

Viers, J.H., A.K. Fremier, R.A. Hutchinson, J.F. Quinn, J.H. Thorne, and M.G. Vaghti. 2012. Multiscale patterns of riparian plant diversity and implications for restoration. *Restoration Ecology*, 20(2), 160–169 https://doi.org/10.1111/j.1526-100X.2011.00787.x.

Wang, R. and E. Ateljevich. 2012. A Continuous Surface Elevation Map for Modeling (Chapter 6). In Methodology for Flow and Salinity Estimates in the Sacramento-San Joaquin Delta and Suisun Mars, 23rd Annual Progress Report to the State Water Resources Control Board. California Department of Water Resources, Bay-Delta Office, Delta Modeling Section. http://baydeltaoffice.water.ca.gov/modeling/deltamodeling/modelingdata/DEM.cfm.

Ward, J.V. 1989. The four-dimensional nature of lotic ecosystems. *Journal of the North American Benthological Society* 8(1): 2-8.

Whipple, A., R.M. Grossinger, and F.W. Davis. 2010. Shifting Baselines in a California Oak Savanna: Nineteenth Century Data to Inform Restoration Scenarios. *Restoration Ecology* 19(101): 88-101.

Whipple, A.A., R.M. Grossinger, and F.W. Davis. 2011. Shifting Baselines in a California Oak Savanna: Nineteenth Century Data to Inform Restoration Scenarios. *Restoration Ecology* 19:88-101.

Whipple, A.A., R. Grossinger, D. Rankin, B. Stanford, and R. Askevold. 2012. *Sacramento-San Joaquin Delta Historical Ecology Investigation: Exploring Pattern and Process. San Francisco* (p. 438). San Francisco Estuary Institute. http://www.sfei.org/sites/default/files/biblio_files/Delta_HistoricalEcologyStudy_SFEI_ASC_2012_highres.pdf.

Whitley, S.N. and S.M. Bollens. 2014. Fish assemblages across a vegetation gradient in a restoring tidal freshwater wetland: diets and potential for resource competition. *Environmental Biology of Fishes* 97(6):659-674.

Wiederholt, R., K.J. Bagstad, G.F. McCracken, J.E. Diffendorfer, J.B. Loomis, D.J. Semmens, A.L. Russell, C. Sansone, et al. 2017. Improving spatio-temporal benefit transfers for pest control by generalist predators in cotton in the southwestern US, *International Journal of Biodiversity Science, Ecosystem Services & Management*, 13:1, 27-39, DOI: 10.1080/21513732.2016.1240712.

Williams, J.G. 2006. Central Valley Salmon: A Perspective on Chinook and Steelhead in the Central Valley of California. *San Francisco Estuary and Watershed Science* 4 (3): Article 2. http://repositories.cdlib.org/jmie/sfews/vol4/iss3/art2.

Wilson, T.S., B.M. Sleeter, and D.R. Cameron. 2017. Mediterranean California's water use future under multiple scenarios of developed and agricultural land use change. PloS one 12(10): e0187181. https://doi.org/10.1371/journal.pone.0187181.

Winder, M. and A.D. Jassby. 2011. Shifts in zooplankton community structure: implications for food web processes in the upper San Francisco Estuary. *Estuaries and Coasts* 34(4):675-690.

Yarnell, S.M., G.E. Petts, J.C. Schmidt, A.A. Whipple, E.E. Beller, C.N. Dahm, et al. 2015. Functional flows in modified riverscapes: Hydrographs, habitats and opportunities. *BioScience* 65(10): 963-972.

Zimmerman, J.K., D.M. Carlisle, J.T. May, K.R. Klausmeyer, T.E. Grantham, L.R. Brown, and J.K. Howard. 2017. Patterns and magnitude of flow alteration in California, USA. *Freshwater Biology*.

This page left blank intentionally.