Delta Stewardship Council
A CALIFORNIA STATE AGENCY

DELTA ADAPTS: CREATING A CLIMATE RESILIENT FUTURE

TECHNICAL MEMORANDUM

ECOSYSTEM

MAY 2021

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ACRONYMS AND OTHER ABBREVIATIONS

CCVA	Climate Change Vulnerability Assessment
cm	Centimeters
Delta	San Francisco-San Joaquin Delta, including the Suisun Marsh
DEM	Digital Elevation Model
DSM2	Delta Simulation Model II
EH	Extreme Heat
ft	Feet
GIS	Geographic Information System
in	Inches
LOCA	Localized Climate Analogues
MHHW	Mean Higher High Water
MHW	Mean High Water
MLLW	Mean Lower Low Water
MLW	Mean Low Water
MSL	Mean Sea Level
RCP	Regional Climate Projection
SLR	Sea Level Rise
USGS	U.S. Geological Survey
VegCAMP	Vegetation Classification and Mapping Program

CHAPTER 1. BACKGROUND

1.1 Delta in the Context of the West Coast

Ecosystems created by the interface of river systems and the ocean are some of the most productive landscapes in the world (Lotze et al. 2006). Humans have substantially altered estuaries and their associated river systems, resulting in significantly impacted form, function, and ecological resilience (Lotze et al. 2006, Gleason et al. 2011). In the face of a rapidly changing climate, estuaries are critical regional resources in addressing issues of adaptation, resilience, and climate change mitigation.

The west coast of the United States encompasses over 140 estuaries where freshwater river outflows meet salty, tidal ocean water (Gleason et al. 2011). The Sacramento–San Joaquin Delta and Suisun Marsh ('Delta') comprise the upper portion of the San Francisco Bay–Delta Estuary (Bay–Delta), which is the largest estuary on the west coasts of North and South America. In statute, the State of California recognizes the estuary as "a critically important natural resource for California and the Nation", and "the most valuable estuary and wetland ecosystem on the west coast of North and South America" (California Water Code Section 85002).

1.1.1 A Classic Estuary

Gleason et al. (2011) characterize the Bay–Delta as a "classic estuary", influenced by three important sources of energy input: significant river flow, tidal forcing, and wave dynamics. Of 146 estuaries evaluated in the Pacific Northwest and California, only 14 percent are classic estuaries. Most west coast estuaries are comprised of lagoons, river mouths, and tidal bays; each more singularly dominated by wave energy, river energy, or tidal energy, respectively (Ibid). Classic estuaries have hydrological and geomorphic characteristics that drive food web productivity and marsh formation processes, all of which contribute to the habitats of rich fish and wildlife assemblages. These hydrological aspects include tidal dynamics and freshwater input, which drive the time water remains in the system (residence time), turbidity, and sediment trapping efficiency. The ecosystems of classic estuaries are therefore sensitive to and impacted by alterations in downstream geometry and tidal action, dams or diversions that reduce or alter streamflow, and shifts in sediment input from upstream sources (Ibid).

1.1.2 A Large Estuary

Most western coastal estuary catchments are relatively small, with only the Fraser River, Columbia River, and Umpqua River draining large watersheds. The Bay–Delta conveys more than two times the mean annual freshwater inflow of these larger estuaries due to ocean dynamics and the orographic effect of the Sierra Nevada and Cascade mountain ranges that capture large amounts of precipitation (Emmett et al. 2000). The estuary receives freshwater flows from California's largest river systems and 40 percent of its land area. The Mediterranean climate drives large inter- and intra-annual variations in streamflow, sediment, and nutrient inputs. The upper estuary is composed of an inland delta of distributary river channels constrained by coastal mountains (Atwater and Belknap 1980). The lower estuary is connected to the ocean through a series of bays and associated coastal plains.

1.1.3 An Estuary with High Biodiversity

The California floristic province is well known for its high biodiversity and endemism. At the heart of this province, the Bay–Delta and its watershed supports relatively high biodiversity among the west coast estuaries, with more than 750 species of plants and wildlife (Gleason et al. 2011, Healey et al. 2016). The estuary serves as a migration corridor for all anadromous fish species in the Central Valley, including salmon, as adults return to their natal rivers to spawn and juveniles out-migrate downstream to the ocean. Despite extensive anthropogenic alterations, the Bay–Delta is as a biodiversity hotspot of global importance (Wat. Code Section 85022, Myers et al. 2000, Healey et al. 2008). Within this large and hemispherically important estuary lies a unique upper estuary - the Sacramento-San Joaquin River Delta, and Suisun Marsh (Delta). This technical memo explores the characteristics and climate vulnerabilities of the upper estuary (Figure 1).

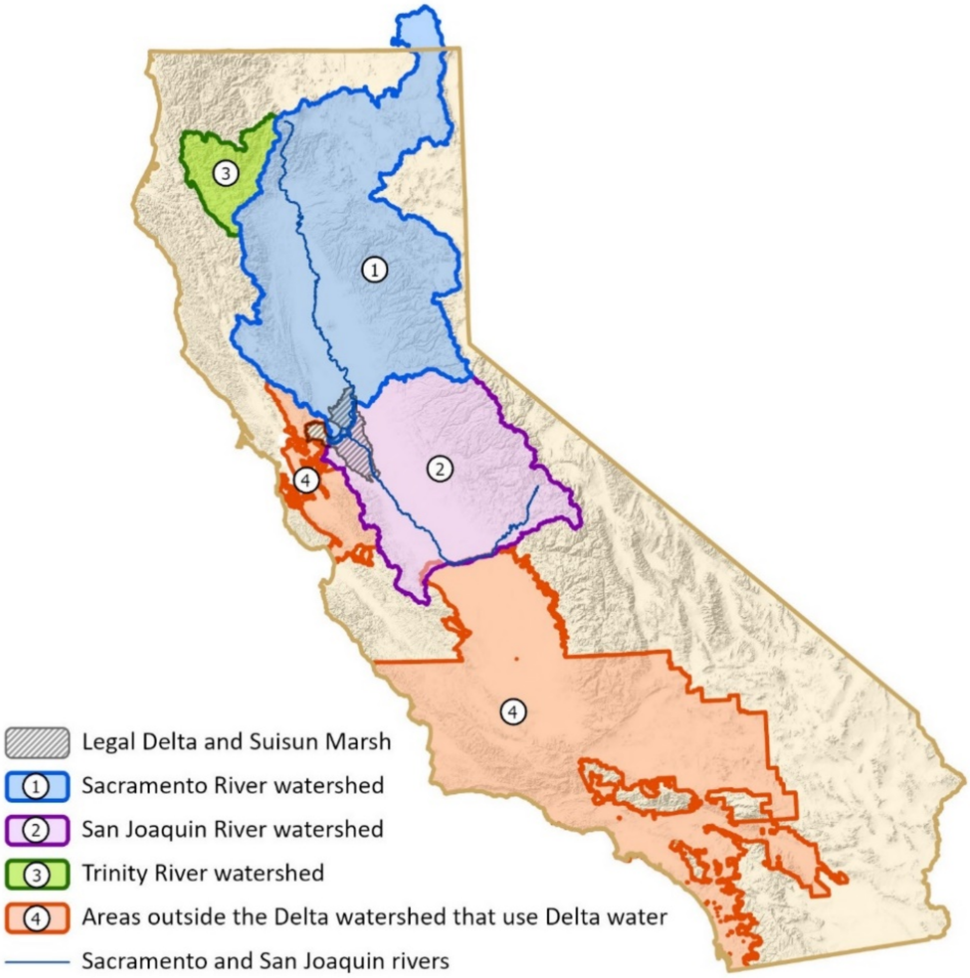


Figure 1. Map of the Delta watershed and areas of California that use Delta water

1.2 Landform Perspective

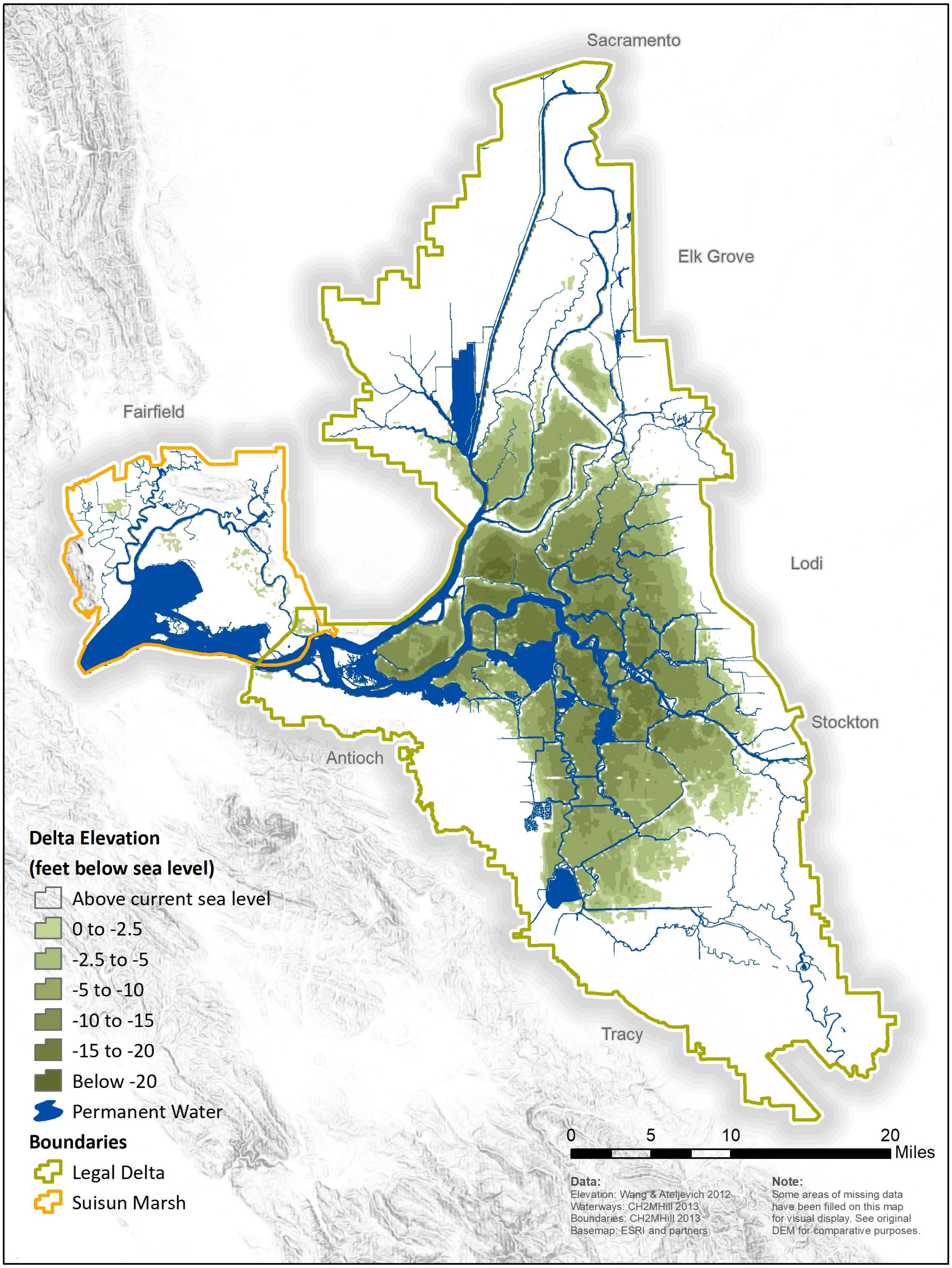
The inland Delta formed sometime between 10,000 and 6,000 years ago when the rising sea level inundated a broad valley (Atwater et al. 1979, Atwater and Belknap 1980). The landscape maintained its elevation over the past 10,000 years, despite sea level changes and tectonic subsidence, through a balance of upstream sediment input, and organic deposits (i.e., plant detritus), and erosion (Atwater et al. 1979, Atwater and Belknap 1980, Mount and Twiss 2005). These geomorphic dynamics supported a historical Delta landscape consisting of marsh plains, channel network systems, flood basins, and natural levees that supported freshwater emergent and riparian vegetation, ponds, and salt pannes (Shlemon and Begg 1975, Atwater and Belknap 1980, SFEI–ASC 2012).

1.1.1 Loss of Accretion Mechanisms

The Delta landscape has lost the ability to maintain elevation relative to changes in sea levels and tectonic subsidence. River impoundment has blocked sediment input from the drainage basins and upper watersheds. Bank and bed stabilization downstream of dams interrupted the transfer zone sediment dynamics of Central Valley river systems. Within the deltaic zone, wetland reclamation, levee construction, channelization, and dredging have interrupted the geomorphic processes that deliver sediment to the marsh plains within the Delta. In addition to geomorphic impacts, the loss of extent and distribution of vast wetlands has eliminated the processes that allowed the accumulation of organic matter (Mount and Twiss 2005). Levee construction and dredging led to a substantial reconfiguration of bays, sloughs, and channels, disconnecting rivers from floodplain terraces and tidal and seasonal wetlands, resulting in the substantial loss of native vegetation communities and limiting the interaction of water and sediment over the majority of the Delta landscape (SFEI–ASC et al. 2014). 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 (SFEI–ASC 2012, Herbold et al. 2014, SFEI-ASC 2016).

1.1.2 Subsidence

As wetland ecosystems were drained for agriculture and other uses, the Delta's peat soils were subjected to oxidation, compaction, and wind erosion, causing widespread loss of land surface elevation known as subsidence. Due to subsidence, 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. Estimates of ongoing regional subsidence rates range from <0.3 to >1.8 cm/year (Deverel and Rojstaczer 1996, Deverel and Leighton 2010, Deverel et al. 2016, Sharma et al. 2016; Figure 2). Levee failure in this context poses dire consequences including effects on tidal and flow forcing, decrease in 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).



Data:
Elevation: Wang & Ateljevich 2012
Waterways: CH2MHill 2013
Boundaries: CH2MHill 2013
Basemap: ESRI and partners

Note:
Some areas of missing data have been filled on this map for visual display. See original DEM for comparative purposes.

Figure 2. Subsidence in the Delta

Source: Adapted from Wang and Altjecvich 2012

1.3 Watershed Connections

The Delta lies at the confluence of California's two largest river systems and other major tributaries on the east and west sides of the Delta. The Sacramento River flows south across 400 miles, and the San Joaquin River flows north over 200 miles. Historically, these watersheds connected landscapes across a gradient of geographies, climates, and vegetation communities to the lower estuary and ocean. The Central Valley was composed of extensive floodplains and basins supporting riparian, wetland, and oak-grassland ecosystems. The river systems connected the Delta to wetter, cooler climates in the north, and hotter, drier climates in the south. Energy flows, sediment, and organic material from the upper watersheds were transported to the ocean through the Delta. Chinook salmon (*Oncorhynchus tshawytscha*) and steelhead (*Oncorhynchus mykiss*), which spend most of their life cycle in the ocean, had access to the mountain headwaters of the Delta watershed (Bay Institute 1998).

1.1.1 Loss of Lateral Connectivity

As within the Delta, reclamation and levee construction have interrupted and significantly reduced associated biotic and abiotic floodplain processes including frequent and extensive inundation, sediment nutrient transfer, vegetation recruitment and succession, and primary productivity. Less than 5 percent of the historical riparian vegetation remains on the landscape within the Central Valley (Katibah 1984, Bay Institute 1998).

1.1.2 Loss of Longitudinal Connectivity and Access to High Elevations

Dams and diversions have altered river system hydrology and interrupted sediment dynamics and fish migration. Anadromous fish have lost access to more than 80 percent of spawning habitat, including access to high elevation habitats. Spawning now occurs below dams at low elevations or through hatchery operations. Reservoir releases are timed to manage cold-water habitats for spawning and rearing on the floor of the Central Valley to benefit anadromous fish.

1.1.3 Flow and Water Quality Alterations

Discharge of contaminants from agricultural and urban sources have altered water quality (Preece et al. 2017). These changes have led to declines in habitat conditions, and food web function (Poff et al. 2010, Moyle et al. 2011).

In estuaries, water quality is also characterized by salinity. California's Mediterranean climate causes large intra- and inter-annual variations in precipitation and streamflow in the Delta watershed. Historically, this intersected with tidal forcing which led to a dynamic estuarine salinity gradient (Moyle et al. 2010, Ingebritsen et al. 2000). The construction and operation of water supply and flood control infrastructure, such as dams and diversions, have altered water quality (Fleenor et al. 2010, NRC 2012, Swanson et al. 2015, SWRCB 2017). Reservoirs capture streamflow during the wet season, and releases are used in combination with operable gates and changes in channel configuration to maintain freshwater conditions within the Delta.

In the winter and spring, freshwater often extends into San Pablo Bay, while in the summer and fall brackish water can intrude into the western Delta. The location of the brackish-freshwater salinity gradient within the estuary, driven by freshwater inflows, corresponds with presence, abundance, and vital rates of several aquatic organisms including mysids and shrimp, larval fish, piscivorous fish, and food web dynamics (Jassby et al. 1995). An index that represents the salinity gradient, called “X2”, has been developed. It is the kilometer distance from the Golden Gate Bridge in which benthic water salinity is 2 parts per thousand (Ibid). The loss of wetlands and land-water connections in the Delta has limited the opportunities for the position of X2 to intersect with extant tidal marsh. For species such as the Delta Smelt, biological response is highest when X2 position overlaps with the remnant wetlands at the confluence of the Sacramento and San Joaquin Rivers (Nobriga et al. 2008). Given the loss of wetlands both upstream and downstream of the confluence of the Sacramento and San Joaquin Rivers, careful flow management is required to have X2 intersect with existing wetlands.

1.4 Biodiversity in the Delta and Suisun Marsh

The loss of wetland and riparian ecosystems, impacts to biotic and abiotic processes, and loss of habitat connectivity have impacted species vital rates (i.e. poor survival, reproduction, recruitment), led to species range contractions and loss of sub-populations, and resulted in small populations sizes that are vulnerable to stochastic events. Populations impacted in this way exhibit a poor ability to respond to natural and anthropogenic stressors due to reduced genetic diversity and an inhibited evolutionary capacity to adapt to changing environmental conditions (Willi et al. 2006). Impacts to ecosystem conditions within the Delta and Suisun Marsh, and degraded conditions upstream within the watersheds have significantly reduced the resilience of fish and wildlife species that live in these landscapes.

1.1.1 Anadromous Fish Populations

The Delta provides migratory corridors and critical rearing habitat for endemic populations of anadromous fish species and support endemic estuarine fish species. Four runs of adult Chinook salmon (i.e., fall, late fall, winter, and spring run), steelhead (*Oncorhynchus mykiss irideus*), green sturgeon (*Acipenser medirostris*), and white sturgeon (*A. transmontanus*) move through the Delta during most months of the year. Chinook salmon and steelhead juveniles depend on the Delta for transient rearing habitat while they migrate to the ocean; these juveniles can remain in the system for several months feeding in marshes, tidal flats, and sloughs. Numerous other species are year-round Delta residents, such as the native Delta smelt, longfin smelt, Sacramento splittail (*Pogonichthys macrolepidotus*), the introduced threadfin shad (*Dorosoma petenense*), and non-native striped bass (*Morone saxatilis*). The Delta also supports the world’s southernmost spawning runs of Chinook salmon and green sturgeon, and one of the southernmost spawning populations of steelhead (Moyle 2002). Populations at the edge of a species’ distribution are often better adapted to extreme climatic conditions compared to populations in the core of the distribution. Therefore, with climate change, these edge populations can play an important role in enabling species persistence (Rehm et al 2015), giving the Delta Chinook salmon, steelhead, and green sturgeon runs special importance.

Alterations to flows, loss of connection between land and water, and loss of natural land cover have had significant effects on the native fish, as well as on the phytoplankton and zooplankton that form the base of the aquatic food web. Non-native invasive species occur in all trophic levels within the Delta, including phytoplankton, invertebrates, and fishes (Nobriga and Feyrer 2007, Hestir 2010, Lucas and Thompson 2012, Mahardja et al. 2017).

Modification of the Delta ecosystem over the last century has resulted in localized and system-wide conditions that favor non-native predatory fish (Moyle et al. 2012, DWR 2015, DWR 2016, Perry et al. 2013, 2015, Buchanan et al. 2013, Conrad et al. 2016). It has also resulted in a substantial loss of rearing and foraging habitat and a reduction in salmonid food resources. Collectively, these changes have created conditions that favor non-native predators and reduce native species populations (Conrad et al. 2016, Grossman 2016). Upstream in the Delta's watershed, dams and high water temperatures that result from water management are the primary stressors limiting population recovery.

The impact of both the State Water Project and the federal Central Valley Project on winter and spring run chinook salmon, steelhead, and green sturgeon was recognized by the National Marine Fisheries Service in a 2009 Biological Opinion (NMFS 2009), issued under consultation as required by Section 7 of the Federal Endangered Species Act. The 2009 Biological Opinion concluded that water project operation under status quo conditions would likely put the persistence of these species in jeopardy and adversely affect their critical habitat. The Opinion found that the projects have contributed to the loss of juvenile rearing habitat in the Delta and the Sacramento River by elevating water temperatures that lead to lethal and sub-lethal effects on egg incubation and juvenile rearing, and that pumping and other diversions in the Delta and its watershed impede fish migration patterns. The document found that four of the five climate change scenarios considered were likely to lead to negative outcomes for the focal species and their habitats. The Opinion put forth a series of Reasonable and Prudent Alternatives to be enacted alongside continued water project operation (NMFS 2009). However, populations of focal species have continued to decline, and in 2016, the US Bureau of Reclamation (USBR) and California Department of Water Resources (DWR) reinitiated the consultation process.

New Biological Opinions from the U.S. Fish and Wildlife Service and the National Marine Fisheries Service were released in October 2019. Key elements include real-time monitoring to adaptively manage Delta pumping operations, keeping a larger cold-water pool in Lake Shasta, and improving temperature management to benefit winter-run Chinook salmon. When the actions prescribed in the new Biological Opinions are taken, the hope is that the pumping and fish impact will be at or below the levels that resulted from following the 2009 Biological Opinions.

In parallel, the State Water Resources Control Board (SWRCB) is currently considering Voluntary Agreements with public water agencies that may provide additional flows, habitat restoration funding, or other ecosystem benefits.

1.1.2 Migratory Birds

Suisun Marsh and the Yolo Bypass are designated as Important Bird Areas of global importance and the Delta is designated an Important Bird Area of state importance (Cooper 2004). Important Bird Areas contain large concentrations of birds, assemblages of range-restricted or biome-restricted bird species, or bird species of global conservation concern.

Endemic resident species use the remnant wetlands within the Delta, including three subspecies of the Song Sparrow (*Melospiza melodia* ssp.), and the Saltmarsh Common Yellowthroat (*Geothlypis trichas sinuosa*). Bird species endemic to the California Floristic province are also associated with the remnant wetland and riparian vegetation communities including species such as the California Black Rail (*Laterallus jamaicensis coturniculus*), Tricolored Blackbird (*Agelaius tricolor*), and Least Bell's Vireo (*Vireo bellii pusillus*). Other western birds of conservation concern, including the Swainson's Hawk, Western Yellow-billed Cuckoo, and Willow Flycatcher (*Empidonax traillii*), have strong associations with marshes, floodplains, and riparian corridors (Nur and Gardali 1997). Various recovery and conservation planning documents for the Delta have identified 44 special-status bird species (DSC 2018a).

The Sacramento–San Joaquin Delta and its watershed lie along a major migration route for birds that extends from Alaska and Canada to South America (Gilmer et al. 1982). It supports hundreds of bird species, including ducks, geese, shorebirds, and raptors migrating along the flyway or spending the winter in the area. The seasonal wetlands and agricultural areas in the Sacramento Valley constitute one of the most prominent wintering sites for waterfowl in the world, supporting more than 1.5 million ducks and 750,000 geese (Water Education Foundation YEAR). Water for the federal wildlife refuges, state wildlife management areas, privately managed wetlands, and agricultural landscapes that support the migrating and overwintering birds is delivered from both the Delta watershed and the Delta itself (NorCal Water n.d.).

In the Delta, corn and rice agriculture support large numbers of bird species overwintering in the Delta and numerous private duck clubs are managed for waterfowl. Regularly flooded agricultural lands in the Delta also support tens of thousands of shorebirds and hundreds of thousands of waterfowl as well as Swainson's Hawk (*Buteo swainsoni*), Tundra Swan (*Cygnus columbianus*), and Sandhill Crane (*Grus canadensis*). In the winter, the Yolo Bypass supports tens of thousands of ducks, geese, and many species of shorebirds, some of which can number in the thousands. Because of the mix of freshwater and tidal marsh in Suisun Marsh, nearly every wetland bird species in the region occurs here, often in exceptional numbers. More than 100,000 waterfowl spend the winter, with dabbling ducks especially well represented. California Black Rails, Short-eared Owls (*Asio flammeus*), and American White Pelicans (*Pelecanus erythrorhynchos*) are also common.

The Central Valley Joint Venture Implementation Plan coordinates partnership-based conservation efforts for shorebirds, waterbirds, and riparian songbirds (Dybala et al. 2020). Central Valley Joint Venture 2006). Several programs (e.g., Refuge Water Supply Program, Waterbird Habitat Enhancement Program) ensure continued management of the Sacramento Valley for migratory birds.

1.5 Restoration in the Delta

Despite the impaired condition of the estuary and its river systems, it continues to support a diverse array of fish and wildlife. To date, there has been some implementation of habitat restoration to bolster anadromous fishes, riparian species, and tidal marsh species (Council 2018). However, species are continuing to decline, and actions to support the needs of fish and wildlife are urgent. Restoration of the Delta under present conditions is complex and further complicated by climate change and sea level rise (SLR). As described below, the Delta's ecosystems will experience increases in air and water temperatures, changes in the magnitude and timing of precipitation and runoff, and rising sea levels, which will affect salinity, sedimentation, and accretion. Worldwide, species distribution and phenology are already shifting in response to climate-induced changes (Bókony et al. 2019).

1.1.1 Ecological Resilience

A vital adaptation strategy to reduce the vulnerability of the Delta's natural systems to the effects of climate change is to address the loss of ecological resilience described above by increasing the extent of natural ecosystems, including marshes, floodplains, and riparian areas, which are important for both habitat provision and primary production that fuels the food web. Significant opportunities exist to 1) restore geomorphic and ecological processes through reconnection of tidal marsh plain and floodplain, 2) re-establish native vegetation communities, 3) improve water quality, and 4) halt and reverse continued loss of land elevation. To succeed, these actions need to work in step with active management of non-native invasive species.

Ecosystem restoration, which improves the existing conditions through re-establishment of complex and connected ecosystems and recovery of endangered species, is a stated goal of the Delta Reform Act. It directs the Delta Plan to include the following sub-goals and strategies for restoration (Wat. 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.

1.1.2 EcoRestore

The EcoRestore program, coordinated by the California Natural Resources Agency to offset the impacts of the water supply and flood control infrastructure operations and maintenance, aims to protect, enhance and restore at least 30,000 acres in the Delta region by 2020, including over 17,500 acres of floodplain, 3,500 acres of managed wetlands, 9,000 acres of tidal wetland, and an additional 1,000 acres of assorted ecosystem types. While these actions will not reverse the history of habitat loss, they are likely to improve the functioning of the Delta ecosystem, which will increase the system's resilience to climate change. For example, accelerating the pace of restoration efforts to harness the biophysical interactions that allow for tidal wetlands is noted as one of the most effective means of promoting wetland resilience to sea level rise. As of September 2019, a small portion of EcoRestore projects have been completed (total project area: 3,745 acres) and/or are currently under construction (total project area: 6,894 acres).

1.1.3 Delta Conservation Framework

Another initiative for guiding conservation planning for the Delta is the Delta Conservation Framework. It provides a common long-term, landscape-level vision for how to create a mosaic of working agricultural and habitat lands in a manner which results in improved ecosystem functions. The Delta Conservation Framework developed seven different conservation opportunity regions which divide the Delta and Suisun Marsh into smaller regions with distinct characteristics; each conservation opportunity region has a common vision for restoration, a description of opportunities for conservation, and potential solutions for known challenges. The intent of the Delta Conservation Framework is not to provide a prescriptive target for what actions should take place, but rather to guide collaborative stakeholder groups in developing more specific and refined conservation strategies and approaches tailored to the unique characteristics of the local regions.

CHAPTER 2. CLIMATE CHANGE EFFECTS IN THE DELTA AND ITS WATERSHED

As discussed above, extensive land conversion during the 19th and 20th centuries in and upstream of the Delta and the construction of dams and other water management infrastructure altered the amount and timing of water flowing through the Delta (Fox et al. 2015, Andrews et al. 2017). These alterations influence the ways in which climate change affects the Delta. Watershed inflows meet ocean tides in the Delta, and the spatial and temporal dynamics between salt and freshwater are determined by climate-driven precipitation trends and SLR. As the climate continues to change, precipitation variability, higher sea levels, and higher overall temperatures are very likely to alter the riverine inflow and the frequency of extreme events, channel and floodplain geometry, the location of the salinity zone, and water temperatures (Houlton et al. 2018). These impacts will interact with existing stressors such as subsidence and wetland disconnection. By many accounts, we are already seeing the effects of climate change in earlier runoff, higher sea levels, and more extreme weather events, like multi-year droughts and winter-spring atmospheric rivers (Fritze et al. 2011, Kunkel et al. 2013, Pierce et al. 2018, Dettinger 2016, Dettinger et al. 2016).

2.1 Conceptual Understanding of the Effects of Climate Change on Processes, Habitats, Species, and Stressors

Conceptual models summarize understandings of cause-effect relationships and are helpful for articulating scientific uncertainties within those relationships. They are critically important for linking goals, objectives, and potential consequences to project actions, management monitoring, data collection, and research. For the Delta, a suite of conceptual models has been developed to illustrate how key aspects of the system (processes, habitat, species, and stressors) are affected by environmental conditions or human activities. Parameters that will be affected by climate change (e.g., water temperature, flows, and X2; reviewed in detail below) are included in many of the models, though without a discussion on the effect of climate change on these parameters. Of the 43 models examined, only four models explicitly incorporate sea level rise, temperature change, and/or inflow pattern changes due to climate change (Hartman 2017: Tidal Wetlands Evolution; Fremier et al. 2008: Riparian Vegetation; Opperman 2018: Floodplains; Siegel et al. 2010: Suisun Marsh Physical Processes). Another three models briefly discuss possible effects of climate change in the text (Williams et al. 2010: Chinook Salmon and Steelhead; Kratville 2008: Splittail; IEP MAST 2015).

2.2 Changes in Water Inflow

California generally receives most of its rainfall during relatively few high-rainfall events, and climate change is expected to amplify this trend. Precipitation during the wettest 5 percent of wet days is predicted to increase, and precipitation outside that window to decrease (Dettinger 2016). Therefore, across the Delta's watershed, both floods (Ibid) and droughts (Diffenbaugh et al. 2015, Dettinger et al. 2016) are likely to increase in frequency and magnitude with climate change. Precipitation and runoff are also expected to occur during a narrower period at the peak of the wet season, leading to shorter, wetter wet seasons and longer, drier dry seasons.

In addition, the fraction of precipitation that falls as rain instead of snow is predicted to increase. Observations from the last decade show a downward trend in the northern Sierra's snowpack that may be caused by anomalous increases in sea surface temperatures, foreshadowing the shift from snow to rain (Hatchett et al. 2017). Whereas snow accumulates as snowpack and runs off gradually as snowmelt later in the year, rainfall runs off more quickly (Dettinger et al. 2016). Schwartz et al. (2017) modeled snowmelt runoff timing for the end of the 21st century and found that for all climate models and scenarios (including business-as-usual and mitigation scenarios), the snowmelt-driven surface runoff will be much earlier in the year than it was during the time period between 1991-2000. The decrease in snowfall will deplete the natural reservoir that snowpack provides for surface runoff and groundwater recharge, affecting local and regional water supplies. Simulations by Berg and Hall (2017) suggest that snowpack was reduced by 25 percent on average during the 2011-2015 drought. Future snowpack could be reduced during droughts by up to 60-85 percent due to climate change, with springtime snowpack water content expected to decline by at least 50 percent by 2100.

Changes in runoff timing and volume will modify Delta flows and affect ecosystems. The amount of water flowing through the Delta and interactions between the four drivers (river inflow, tidal fluctuations, channel and floodplain geometry, and water operations), cause fluctuations in water level, which determine the parts of the Delta that can become inundated and how frequently, when, and for how long this inundation occurs. These inundation patterns shape tidal and fluvial wetland habitat (SFEI-ASC 2016). Changes in these patterns are likely to induce both directional change towards warmer, drier conditions, and increase system variability, which will directly influence water quality and water temperature in the Delta. For example, modeled projections for the Eight-River Index, an index of unimpaired runoff for eight rivers in the Sacramento and San Joaquin river watershed, show both increases in the projected mean and maximum flows as well as a shift to earlier maximum flows in the year (Cal-Adapt 2017). Additionally, both droughts and floods are expected to become more frequent, producing greater volatility in conditions from year to year (Swain et al. 2018).

2.1.1 Impacts of Changing Water Inflows on Salmon Habitat

Changes in these dynamics are likely to change the distribution and timing of available habitat for salmon. For example, timing and volumes of reservoir releases control much of salmon survival downstream (Zeug et al 2014). Consecutive years of drought and exceptionally high air, stream, and sea surface temperatures have had widespread negative effects on the freshwater, estuary, and marine phases of Chinook and Coho Salmon and Steelhead from 2012– 2016 (Williams et al. 2016). Under present conditions, salmonids are faced with conditions far different than what they have evolved for. Watershed simplification due to dams, land use change, levees, water management, reduced freshwater reaching the San Francisco Bay (which impacts salmonid migration), and other stressors already impair the survival of salmonid populations. These impacts are likely to intensify under climate change (Herbold et al. 2018).

2.1.2 Water Management

An ongoing conflict related to Delta flows revolves around water allocated for endangered species versus water allocated to State and Federal Water Project operations. Water diversions throughout the watershed and Delta remove a notable proportion of total Delta inflows, which increases salinity in the Delta. Freshwater is released to maintain a hydraulic salinity barrier that keeps intakes at the water project pumps fresh. This freshwater is described as “system water” (Gartrell et al. 2017). To regulate ecosystem conditions in the Delta, the SWRCB Water Quality Control Plans determine flow and salinity requirements. Motivated by the Federal Endangered Species Act, federal fish and wildlife agencies restrict water exports to protect endangered species (Ibid). Gartrell et al. (2017) call water released for this purpose “ecosystem water”. However, system water will also have beneficial impacts on ecosystem functions (an estimated 83 percent of system water), and thus it is critical to highlight that not all uncaptured Delta outflows constitute ecosystem water (Gartrell et al. 2017, Reis et al. 2019).

Gross export of water for ecosystem purposes has increased since the implementation of the SWRCB’s 1995 Water Quality Control Plan (Gartrell et al. 2017). However, recent work highlights that relative to total annual runoff from the Delta watershed, the proportion of total flow reaching the San Francisco Bay during the ecologically important winter through spring months has steadily declined since 1930 (including during the period from 1995 to 2016; Reis et al. 2019). This trend has persisted despite SWRCB water quality protections adopted in the mid-1990s and regulations protecting endangered species adopted in 2009. Between 2011 and 2018, a period that included historic drought conditions, 24.7 percent of Delta outflow was attributable to maintaining the hydraulic salinity barrier necessary for water operations, 5.3 percent of outflows was attributable to endangered species requirements (with 1.5 percent attributable to Delta Smelt requirements specifically), and 5.4 percent of outflows was attributable to general protection of fish and wildlife (Reis et al. 2019). As sea level rises, system water requirements to maintain the hydraulic salinity barrier are highly likely to increase (Gartrell et al. 2017). Detailed accounting of when and why ecosystem-related flow requirements are implemented will be essential for effectively managing the Delta’s ecosystems under climate change.

2.3 Sea Level Rise

The Delta Reform Act specifies consideration of "the future impact of climate change and sea level rise" (Wat. Code Section 85066) and identifies a restoration timeline horizon of 2100 (Wat. Code Section 85302). The latest review of SLR projections for California finds that the rate of ice loss from the Greenland and Antarctic ice sheets is increasing (Griggs et al. 2017). By 2100, there is a 67 percent chance that water levels at the Golden Gate of San Francisco Bay, the mouth of the Delta, will increase by 1 foot to 3.4 feet (0.3 to 1 m). Extreme, but much less likely, rates of ice-sheet loss could result in sea level rise (SLR) at that location of up to 10 feet (Griggs et al. 2017). While the projection outcomes are not novel (NRC 2012, Dettinger et al. 2016), this study's calculations of the likelihood of projected SLR improve adaptation planning. The State of California Sea Level Rise Guidance 2018 Update (OPC 2018) uses SLR values based on results from the Griggs et al. study (2017;Table 1).

Table 1. Projected Sea Level Rise (in feet) for San Francisco

		Median *50% probability SLR meets or exceeds*	Likely Range *66% probability SLR is between*	1-in-20 chance *5% probability SLR meets or exceeds*	1-in-200 chance *0.5% probability SLR meets or exceeds*	H++ Scenario *Extreme scenario not associated with a probability*
Emission Scenario	Year	N/A	Low-risk aversion	N/A	Medium-high risk aversion	Extreme risk aversion
RCP 8.5	2030	0.4	0.3–0.5	0.6	0.8	1.0
RCP 8.5	2050	0.9	0.6–1.1	1.4	1.9	2.7
RCP 4.5	2070	1.3	0.8–1.7	2.1	3.2	5.2
RCP 8.5	2070	1.4	1.0–1.9	2.3	3.5	5.2
RCP 4.5	2100	1.8	1.2–2.7	3.5	5.8	10.2
RCP 8.5	2100	2.5	1.7–3.4	4.4	6.9	10.2

Notes: Probabilistic projections are based on the Kopp et al. 2014 method and shown in feet. Probabilistic projections are with respect to a baseline of the year 2000, or more specifically the average relative sea level over 1991–2009. Projections are shown for the San Francisco tide station. California State guidance recommends using SLR projections for RCP 8.5 through 2050 due to the current emissions trajectory (OPC 2018). The H++ projection is a single scenario and does not have an associated likelihood of occurrence as do the probabilistic projections.

The OPC Guidance uses a tiered risk framework to help project planners prioritize SLR scenarios, probabilities of occurrence, and time horizons to calculate risk (OPC 2018). The tiers are based on public safety and economic damage, not ecosystem benefit. OPC recommends that 0.5 feet of SLR at 2030, the high bound of the "likely" range, should be used for projects that pose low consequences of flooding. The 1-in-200 chance values, 0.8 feet of SLR at 2030, should be used for projects with moderate risk. The H++ values, 1 foot of SLR at 2030 or 10 feet at 2100, may be most appropriate when planning for a high-risk situation, e.g., where consequences of flood damage or loss are severe. The H++ scenario is included because the probabilistic projections may underestimate the likelihood of extreme SLR resulting from loss of the West Antarctic ice sheet, particularly under high emissions scenarios. The probability of this scenario is unknown.

MacWilliams et al. (2016) studied what SLR in the Delta might mean for critical salinity thresholds (such as X2) and sediment patterns in the Delta, but did not estimate the hydraulic and water level changes due to SLR across the region. Another study (Radke et al. 2017) investigated extreme events and mapped potential inundation from a 100-year storm event modeled with SLR. These findings can be insightful regarding implications for land use and habitat; however, the projections do not include levee failures, tidal-stage interactions, or the expected magnitudes of peak inflow events, and they likely underestimate inundation levels.

2.1.1 System Responses to Sea Level Rise

The current physical configuration of the Delta makes landward migration of key habitat and species difficult as the climate changes. Where space is available, intertidal marshes will migrate to adjacent higher areas. Currently, most wetlands cannot move landward due to infrastructure such as levees and roadways (Orr and Sheehan 2012, Dettinger et al. 2016). Opportunities are severely limited except within the Yolo Bypass and the Cosumnes River Preserve, where wetland and fluvial upland transition zones allow for migration. Where tidal marsh abuts levees and developed areas or has no adjacent upland (e.g., remnant in-channel islands), marsh that does not accrete as rapidly as the sea level rises will be squeezed into progressively narrower bands then lost over time (Tsao et al. 2015). Restoration to allow landward migration of wetlands into upland transition zone will increase resiliency of the landscape (Goals Project 2015).

In addition to the gradual changes associated with SLR, increases in extreme climatic events will make the tidal-terrestrial transition zone a refuge for species from high waters due to extreme storm surges, waves, and flow events (Tsao et al. 2015). The tidal-terrestrial transition zone is where tidal and terrestrial processes interact to result in "mosaics of habitat types, assemblages of plant and animal species, and sets of ecosystem services that are distinct from those of the adjoining estuarine or terrestrial ecosystems" (SFEI-ASC 2016). These higher-elevation habitats around the margins of the Delta are potential future tidal marsh areas. Like tidal marshes, transition zones shift upslope as sea sea level rises and require connections to sufficient accommodation space. As sea level rises and higher salinity intrudes further into Delta both gradually and from extreme events, vegetation and sedimentation patterns will shift. Salt stress will tend to shift existing fresh and brackish marsh vegetation to more salt-tolerant communities, with a corresponding shift to lower biomass productivity (Callaway et al. 2012).

2.1.2 Levee Overtopping and Failure

Levees (Figure 3) that protect natural and human communities are vulnerable to flooding from high water events. SLR and extreme climatic events will increase vulnerability to flooding from levee overtopping and failure (Delta Plan 2013b, Deverel et al. 2016). Increased threat of inundation will introduce challenges for people and some species that live in the Delta (Tsao et al. 2015). Risk of inundation of currently leveed habitat varies across species (Gray et al. 2014, CDFW 2007, Tsao et al. 2015, LandIQ 2017). For example, the endangered salt marsh harvest mouse (*Reithrodontomys raviventris*) inhabits the leveed habitats of Suisun Marsh, all of which are projected to become inundated in an extreme flooding event. For the endangered Tricolored Blackbird, significant leveed areas of nesting and foraging habitat are expected to be inundated.

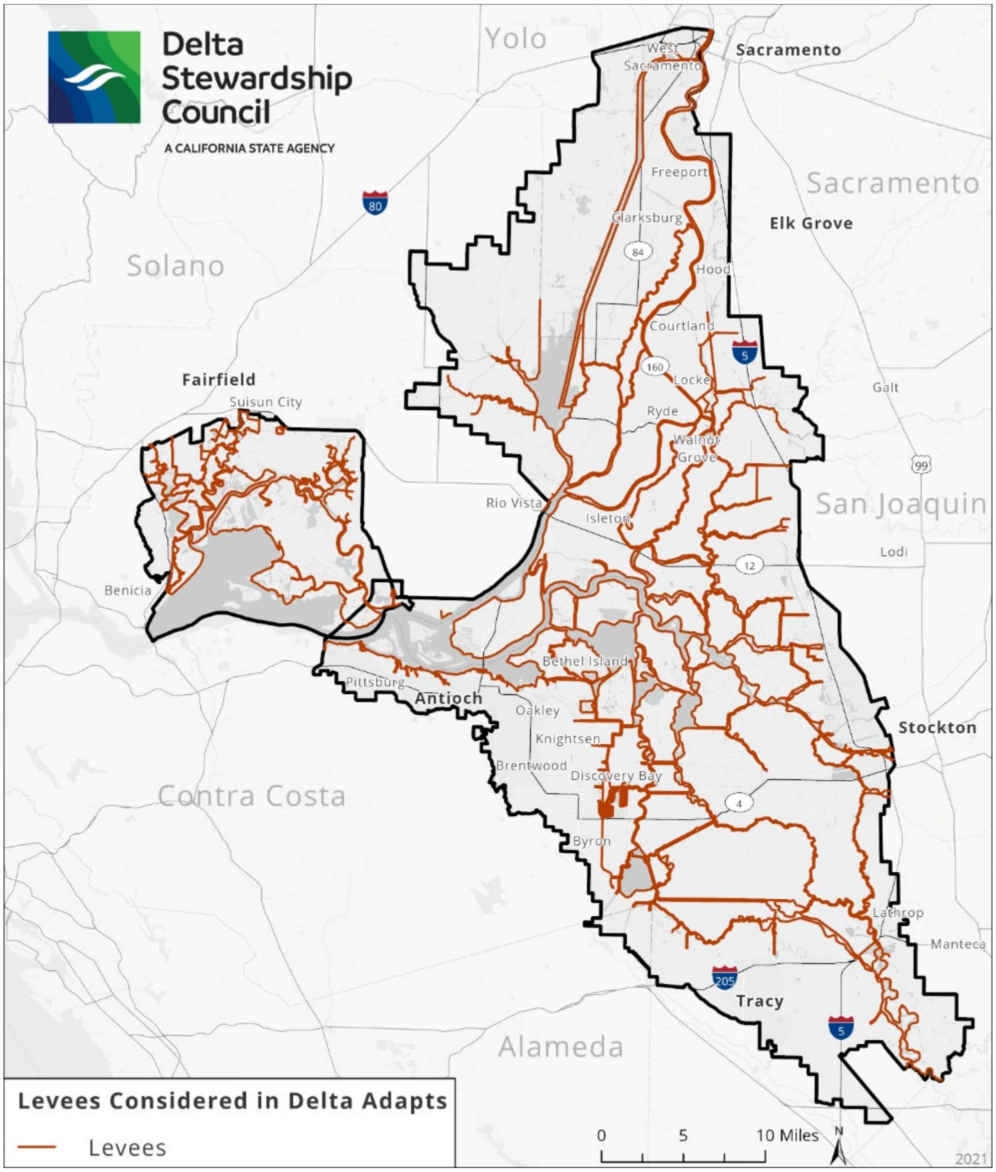


Figure 3. Levees in the Delta and Suisun Marsh Considered in Delta Adapts

SLR may make repairing and rehabilitating levee failures cost prohibitive, and future levee failures that are not repaired will result in more open water areas. Since many of the levees surround deeply subsided Delta “islands,” where the land surface is well below tide levels, levee failure in these locations will produce open water areas up to 26 feet deep (Deverel et al. 2016). The habitat value of open water areas varies greatly by species, location, and specific habitat characteristics created (Cloern et al. 2011, Durand 2014, Dettinger et al. 2016, Durand 2017).

For example, Liberty Island, an unintentionally flooded area at the south end of the Yolo Bypass, provides habitat for the endangered Delta smelt because waters are turbid, accessible to the smelt, and have not been colonized by Brazilian waterweed (*Egeria densa*) or Asian clam (*Corbicula*) to date (Lehman et al. 2010, 2015; Dettinger et al. 2016). On the other hand, Mildred Island, an unintentionally flooded deeply subsided island in the south-central Delta, provides relatively high pelagic primary productivity. However, dense *Corbicula* around the perimeter of the site deplete chlorophyll-a from the water column, greatly diminishing export of primary productivity and attendant benefits to adjacent habitats (Lucas et al. 2002, Lopez et al. 2006). Extensive *Egeria densa* around the perimeter of Mildred Island supports primarily invasive fish species (Grimaldo et al. 2012) including effective non-native predatory fish species, limiting accessibility to native fish species. Flooded islands with warmer water temperatures may provide prime conditions for harmful algal blooms (Cloern et al. 2011, Fong et al. 2016).

New permanently flooded islands would affect estuarine hydrodynamics and processes. The effects include reducing tidal flows, shifting salinity regimes, changing circulation patterns, and modifying sediment transport and deposition. The associated ecological effects would depend on the specifics of the levee failure. Higher elevation islands, if breached, may support vegetation development, but that ability declines as water depth increases (Miller and Fujii 2010). Geomorphic change would accompany any significant hydrodynamic changes. With higher tidal flows from SLR and additional open water areas, existing tidal channels would experience higher flow velocities and tend to scour deeper and wider (Williams et al. 2002).

2.1.3 Sediment Supply

The upper river reaches are the primary source of sediment in the Delta. Sediments, together with in-situ biomass production, are important to allow wetlands to increase their elevation over time and thus persist when sea levels are rising (Schile et al. 2014). Sediments also make the waters turbid which provides some species (e.g. Delta smelt) cover from predators (Brown et al. 2013). During wet season flows, the Sacramento River is the primary source of sediment delivered to the Delta (Ganju and Schoellhamer 2006), which stores roughly two thirds of arriving sediment (Achete et al. 2015). Hydraulic mining activities in the Sierra Nevada in the 19th century caused increased amounts of sediments to be transported into the Delta and the San Francisco Bay. However, as the effects of hydraulic mining faded, sediment supply declined by approximately 50 percent between 1849 and 2011 (Moftakhari et al. 2015).

Modeling has demonstrated that direct human activity (such as major alterations to water project system intakes), climate change, and abrupt disasters can shift Delta sediment dynamics (Achete et al. 2017). High flows and floods can greatly alter sediment dynamics in the Delta.

Sediment supply may increase with climate change compared to current conditions due to more extreme flooding events, such as those that occur with atmospheric rivers, and as more precipitation falls as rain as opposed to snow (Stern et al. 2016, 2020; Schoellhamer et al. 2016). Sediment loads are highly dependent on the modeled scenario (Stern et al. 2016). Wildfires in the watershed may also increase sediment supply (Sankey et al. 2017).

2.1.4 Salinity Intrusion

Located at the head of the San Francisco Bay estuary, the western part of the Delta and Suisun Marsh are in the transition zone from fresh riverine water to saline ocean water. Because of the Delta's bathymetry and hydrology, as well as human management of these characteristics, freshwater typically extends across most of the Delta, to the Delta's west side near Pittsburg. During the wet season when runoff is high, freshwater extends even further west into Suisun Marsh and beyond. During the dry seasons and during drought, reservoir releases have been used to limit the eastward intrusion of saline water into the Delta.

Sea level rise and changes in freshwater flow are expected to cause eastward intrusion of saline water into the Delta. The low salinity zone may shift eastward into the Delta (MacWilliams et al. 2016). The location of the transition from fresh to saline water is important ecologically because it affects the viability of some saline-sensitive species. For example, a more westward position of X2 (the indicator that describes the position of the transition zone from fresh to saline water) correlates with a higher system-wide abundance of Delta smelt (Bever et al. 2016). Because migrating outside of the low salinity zone can cost significant energy (Komoroske et al. 2016), sustaining populations of Delta smelt is highly likely to become increasingly difficult due to both increased salinity and warmer water temperatures (Cloern et al. 2011, Brown et al. 2013). A reduction in fresh water rearing habitat due to increased salinity (DWR 2016) may reduce survival in juvenile and adult stages (Komoroske et al. 2014).

Salinity intrusion can also influence species composition across the food web (Peterson and Vayssieres 2010, Hasenbein et al. 2013, Hennessy and Enderlein 2013, Borgnis and Boyer 2015). While the complex interactions between salinity and aquatic habitat are not fully understood, it is likely that increased salinity will decrease the quality and availability of Delta habitat for native species. 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). Dettinger et al. (2016) suggest that some species may respond to changing salinity by moving to a suitable habitat. Species movement happens naturally already; estuaries are defined by varying salinity gradients, and estuary organisms are adapted to salinity fields that vary based on tidal, seasonal, annual, and longer timescales. To the extent that large aquatic ecosystems are well-connected up and down the estuary, from fresh to brackish to saline, organisms and ecosystems will have the opportunity to migrate to areas of lower salinity as these change over time.

Salinity intrusion can also affect terrestrial, emergent, submerged, and floating vegetation, with shifts in salinity regimes causing a change in ecosystem type (Callaway et al. 2007, Dettinger et al. 2016). In tidal wetlands, sites transition from freshwater/brackish tidal marshes with generally higher species diversity and primary productivity, to tidal salt marshes with generally lower species diversity and primary productivity. Vertebrate species adapted to freshwater/brackish tidal marshes may not be able to persist in tidal salt marshes, and species adapted to tidal salt marsh may not be able to effectively disperse and establish in heavily fragmented Delta wetlands. Further, a shift from freshwater/brackish to salt marsh may also influence the ability of wetlands to keep pace with SLR (see below for detailed description).

2.1.5 Wetland Accretion

Wetland accretion can determine persistence or loss of marsh habitat and should be included in modeling habitat transitions in response to climate change. To survive in place, tidal marshes must build soil elevation at a rate equal to or faster than SLR. Marsh elevation gain occurs as mineral sediments deposit on the marsh surface and as plant roots build up organic matter. Positive biophysical feedbacks tend to stabilize wetlands with SLR (Callaway et al. 2007, Kirwan and Megonigal 2013). Mineral sediments settle from the water column onto the marsh surface during periods of tidal (or fluvial) inundation, so deposition rates are greatest in low elevation marshes, which are inundated the longest. Above-ground plant shoots slow water velocities and contribute to settlement of mineral sediments. Similar feedbacks between frequency of flooding and plant biomass production occur in the root zone (Megonigal et al. 2016).

It is uncertain whether tidal marsh accretion in the Delta will be able to outpace SLR or for how long, the outcome of which has implications for restoration. Observations of marsh deterioration and loss in locations such as the Mississippi River Delta indicate that there are limits to the feedbacks that tend to sustain tidal marshes (Kirwan and Megonigal 2013). Recent research suggests that marshes persist in place with increasing rates of SLR by stabilizing lower in the intertidal zone (i.e., lower in elevation), which allows them to accrete sediment at a faster rate, until the point at which inundation becomes so great that vegetation dies off, ending the stabilizing biophysical feedbacks. The threshold SLR rate that marshes can sustain is highly site specific and dependent on available suspended sediment, as well as rates of plant productivity (Schile et al. 2014, Swanson et al. 2014, Morris et al. 2016).

Several researchers have modeled tidal marsh sustainability with SLR for San Francisco Bay, including the brackish marshes of Suisun and freshwater marshes of the Delta (Orr et al. 2003, Stralberg et al. 2011, Orr and Sheehan 2012, Schile et al. 2014, Swanson et al. 2015). The models evaluate marsh accretion rates based on initial ground elevations, suspended sediment supply, and organic accumulation for different SLR scenarios. Schile et al. (2014) and Swanson et al. (2015) additionally included changes in plant productivity with inundation. Model results from Schile et al. (2014) suggest that Suisun marshes can persist with 100 years of SLR up to 0.4 to 0.7 in/year (1.0 to 1.8 cm/year) for a range of sediment concentrations, but shift to lower in the intertidal zone. In the highest SLR and lowest sediment supply scenarios (5.9 feet [1.8 m] of SLR over 100 years and ~25 percent of existing sediment supply), marsh conversion to mudflat occurred. Model results from Swanson et al. (2015) suggest that 84 percent of the sensitivity scenarios resulted in freshwater Delta marshes persisting with 2.9 ft (88 cm) of SLR by 2100 (0.9 cm/year), while only 32 percent and 11 percent of the scenarios resulted in surviving marshes with SLR of 4.4 ft and 5.9 ft (133 cm and 179 cm) of SLR by 2100. However, Swanson et al.

assume that organic accretion does not occur at low intertidal elevations and thus appear to underestimate total accretion and marsh sustainability at lower elevations.

Cores of relatively undisturbed natural marshes in the Delta provide long-term records of historic accretion rates. In Suisun Marsh, observed accretion rates from radiometric dating of marsh cores range from ~0.08-0.16 in/year (~0.2-0.4 cm/year) (Callaway et al. 2012). In the Delta, observed accretion rates from deep cores range from 0.012 to 0.19 in/year (0.03 to 0.49 cm/year; Drexler et al. 2009). These data indicate the potential for Suisun and Delta marshes to accrete faster than current rates of SLR. This observed accretion occurred during a period of moderate SLR (0.04 to 0.08 in/year; 0.1-0.2 cm/year) and does not represent the potential maximum with higher SLR (Drexler et al. 2009). Future rates of accretion in the Delta are uncertain, but decreases in sediment supply could decrease accretion rates (Swanson et al. 2015) and increases could increase accretion rates (Stern et al. 2020). Thus, both increasing and decreasing sediment scenarios are considered in the modeling described in section 3.6.3.1.

Radiometric dating of marsh cores collected low in the intertidal zone by Reed (D. Reed, personal communication) found accretion rates of 0.35 in/year (0.9 cm/year) at Sherman Lake (31-year average) and 0.7 in/year (1.8 cm/year) at Lower Mandeville Tip (18-year average), with very little inorganic contribution. Similar to the previous studies, these rates are reflective of past lower rates of SLR and do not necessarily represent the potential maximum with higher SLR, though they may be close. They suggest the potential for much higher accretion rates of Delta freshwater vegetation at greater inundation depths. Additional research is needed to characterize how rates of accretion vary with intertidal elevation in freshwater marshes of the Delta, specifically how developing restoration sites may proceed under different scenarios.

Recent research documents the effects of additional climate-related factors on marsh elevations. Elevated atmospheric CO_2 levels can have a net positive effect on wetland stability through enhanced root production in certain plants (Kirwan and Megonigal 2013). Warming air temperature can increase both plant productivity and decomposition, that may have a small net positive effect on wetland stability (Megonigal et al. 2016). However, if increased salinity shifts community composition to communities with lower primary productivity (Callaway et al. 2012), beneficial aspects of warming and increased levels of CO_2 in the air may not be realized.

2.4 Subsidence

As historic tidal wetlands in the Delta were converted to agriculture and other uses, formerly flooded soils were drained and diked (SFEI-ASC 2016). As these largely organic soils dry and are exposed to oxygen, they are oxidized, causing a decrease in land-surface elevation known as subsidence. This process makes it challenging to restore tidal ecosystems, particularly in islands in the central Delta where subsidence has reduced the land surface elevation to 10 to 25 feet below current mean sea level. Further, subsidence can reduce levee stability and increase the risk of levee failure during flooding, resulting in saltwater intrusion into aquifers and farmlands (Mount and Twiss 2005). Flooding of deeply subsided islands in the event of levee breaks or overtopping would create expansive deep-water areas. Terrestrial ecosystems and agricultural areas previously located on the islands would be lost.

Restoration of wetted conditions stops subsidence and can slowly reverse it, eventually reducing the risk of levee failure. Sub-regional assessments of land elevation and urban land-use trajectories should inform selection of conservation actions at a site based on subsidence levels (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 less subsided islands that will keep pace with SLR and ideally occur by 2100 (Delta Reform Act 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 may be financially viable and can 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 financial resources, such as carbon credit revenues, can be utilized. In areas where subsidence is less severe, elevations can be increased through managed wetlands targeted for carbon sequestration and subsidence reversal, direct placement of sediment, and related tactics like warping, a method in which 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 these sites, the practice may be less effective for tidal reconnection given the long periods (e.g., 50 to 100 years) required for deeply subsided regions (Deverel et al. 2014). However, subsidence reversal projects may still provide habitat and considerable benefits for reducing the risk of levee failure. Effective implementation of this practice is time sensitive (i.e., it requires near-term action) and requires strategic siting and accompanying levee investments.

2.5 Temperature Changes

There is great uncertainty in predicting future climates. Scenarios that describe different, possible climate futures vary in the greenhouse gas concentration trajectory they assume. These trajectories are called Representative Concentration Pathways (RCP). In the RCP 4.5 scenario, emissions peak around 2040 and then decline; in the RCP 8.5 scenario, emissions continue to rise throughout the 21st century. Under all scenarios, the Delta is very likely to experience higher air temperatures in the next century than those at present. In these areas, the mean annual maximum temperature by 2100 could increase between 4.7°F (RCP 4.5) and 9.2°F (RCP 8.5) (Cal-Adapt 2017). The mean annual temperature in the Sierra Nevada east of Sacramento, which includes the snowy portions of the Delta’s watershed, is projected to warm above late 20th century levels by 1.8°F by 2025; between 3.6°F and 4.5°F by 2055; and between 6.3°F and 7.2°F by 2085 (Dettinger et al. 2016).

Dettinger et al. (2016) note that local temperature differences across the Delta’s watershed will occur. For example, lands at lower elevations are expected to warm more slowly than those at higher elevations (Wang et al. 2014), and warming will be greater in areas farther from the coast

(Lebassi et al. 2009). All sub-regions of Suisun Marsh and the Delta are projected to warm by 2100 (5.0 to 5.3°F for RCP 4.5 and 7.7 to 8.5°F for RCP 8.5; mean annual temperatures), with existing sub-regional temperature differences projected to persist and slightly amplify. Suisun Marsh is and will remain cooler than the Delta generally and the north Delta cooler than the South Delta (current annual mean temperatures: Suisun Marsh 72.9°F, Yolo Bypass 74.2°F, and Stockton 74.5°F; Cal-Adapt 2017). Greater warming inland may enhance cooling Delta breezes (Ibid), and thereby partially offset temperature increases within the Delta and Suisun Marsh. For the Central Valley, the mean annual maximum temperature by 2100 is projected to be warmer than the Delta and Suisun Marsh by about 2.0°F (Cal- Adapt 2017).

Tidal marshes and riparian areas have higher water content compared to upland areas, so they absorb relatively more heat and can buffer terrestrial organisms against extreme temperatures (Naiman et al. 2000). Riparian areas overhanging waterways provide shade (Sridhar et al. 2004, Cassie 2006) and groundwater recharge, which cool water temperatures (Kaandorp et al. 2019).

Sierra Nevada cold-water habitat is projected to shift to higher elevations. Basins will vary in the magnitude of changes. The high elevations of the southern Sierra Nevada are anticipated to change the least. Fish may respond to water temperature changes by shifting closer to the stream headwaters. In some streams, natural barriers such as waterfalls, intense flows, and physical heterogeneity closer to the headwaters may impede fish movements (Null et al. 2013a).

In addition, dams prevent migratory movements between ocean and mountain streams. However, the reservoirs created by these dams store cold water. Carefully controlling the release of this cold water as a management tool may mitigate warming stream temperatures for short distances downstream of a reservoir (Null et al. 2013b). Season, stream length, reservoir size, outlet structure, and reservoir elevation all affect water temperature effects of these releases.

In these ways, the Delta and its watersheds may serve as climate refugia. Morelli et al. (2016) define climate change refugia as “areas relatively buffered from contemporary climate change over time that enable the persistence of valued physical, ecological, and sociocultural resources.” Additional research is needed to understand the climate refuge potential of the Delta and its use in climate adaptation.

2.6 Other Potential Impacts

Due to the high complexity of the Delta System, there are several dynamics that may impact the Delta’s ecosystem. Stochastic events like wildfire have the potential to alter hydrology and limit sunlight, which could impact ecosystem dynamics. The Sustainable Groundwater Management Act of 2014 and other developing water policy decisions will change water management dynamics throughout the state as they are implemented, which will impact the Delta. Both urban development and changing agricultural land use due to economics will also influence the extent and configuration of the Delta’s ecosystems.

2.7 Resilience

Climate change is adding additional stress to the Delta ecosystem on top of habitat loss through land use changes, modified hydrology, and invasive species. For the system to retain even its limited functionality, increasing the system's resilience is critical.

Resilience is defined as the ability to absorb change and persist after a perturbation (Holling 1973). This concept applies to all aspects of an ecosystem including physical processes, biological processes, communities, and populations. The re-establishment of ecological resilience is important for sustaining a healthy environment with societal benefits (Holling 2001, Walker et al. 2004, Folke 2006, Virapongse et al. 2016).

Ecological resilience within the landscape has been diminished with the historical loss of wetland and riparian ecosystems and their function (Bay Institute 1998, SFEI–ASC 2012, Wiens et al. 2016). Roughly 94 percent of the Delta's tidal habitats have been converted to other uses, and most of its floodplains have been disconnected from the system. This has led to a considerable reduction in primary productivity. From the mid-20th century to today, water operations and the invasive clam *Corbicula fluminea* have further reduced primary productivity, leading to the rapid decline of pelagic fish species in the Delta (Brooks et al. 2012)., The Delta faces a double challenge on the path towards climate resilience—first, the recovery from over 150 years of degradation, and second, the added stress that climate change places on the system.

Promoting ecosystem resilience requires thinking beyond single-species habitat models. Species-specific models are helpful in narrowing down decision-making for specific regulatory functions, but there has been debate about their ability to generate overarching ecological models that benefit other species or increase ecological resilience (Lambeck 1997, Lindenmayer et al. 2002, Standish et al. 2014). Instead, the presence of multiple species that contribute to the same ecological function (e.g., multiple grazers, or multiple predator species) are thought to promote resilience (Elmqvist et al. 2003). A diversity of responses to environmental change among species contributing to the same ecosystem function ("response diversity") is considered critical to resilience (Ibid). Response diversity is particularly important for ecosystem renewal and reorganization following change and provides adaptive capacity.

Current activities aimed at restoration and reduction of stressors are largely driven by mitigation requirements for the operation of the State and Federal Water Projects and maintenance of the flood management system of the Sacramento and San Joaquin river systems (e.g., Reasonable and Prudent Alternatives [RPAs] identified in both Long-Term Operations of the Central Valley Project and State Water Project; Fish Restoration Program Agreement). These mitigation activities are a vital component of an ecosystem restoration portfolio. However, they are designed to offset specific current-day infrastructure impacts either in-kind, or designed to avoid jeopardy or critical habitat modification for endangered species. Thus, mitigation alone is unlikely to significantly address legacy impacts and improve conditions beyond the current baseline (Palmer and Filoso 2009). Restoring ecosystems to address the issue of climate resilience will require actions above and beyond offsetting the impacts of the water supply and flood control infrastructure operations and maintenance.

Targeting ecological resilience requires consideration of landscape-scale ecosystem properties, including connectivity, complexity, redundancy, and scale (SFEI-ASC 2016). “A Delta Renewed” (SFEI-ASC 2016) includes guiding principles for creating and maintaining resilient landscapes. “The principles draw from several recent efforts to develop science-based approaches to achieving long-term ecological health and resilience for the Bay–Delta system” (p. 17). The guiding principles include:

- Appreciate that people are part of the Delta.
- Consider landscape context to apply the right strategies in the right places.
- Restore critical physical and biological processes.
- Restore appropriate landscape connectivity.
- Restore landscapes with a focus on complexity and diversity.
- Create redundancy of key landscape elements, populations, and habitat types.
- Restore at large scales, with a long-term time horizon in mind.

Reducing stressors such as lack of habitat and connectivity, invasive species, and poor water quality through restoration that promotes resilience and considers current and future effects of climate is the key to creating a sustainable Delta. Assessing the vulnerability of the different ecological assets to climate change will help plan and prioritize restoration action to achieve lasting benefits in the face of climate change.

CHAPTER 3. METHODS

This section presents the methodology for assessing the vulnerability of ecosystem assets (habitat types) to primary and secondary climate drivers and hazards (Table 2). The primary climate drivers air temperature and local precipitation were assessed quantitatively with a qualitative application; SLR was assessed quantitatively. Secondary climate drivers, which include wind and water temperature, were assessed qualitatively. Climate hazards such as extreme heat, extreme precipitation events and drought were assessed qualitatively.

Table 2. Primary and Secondary Climate Stressors and Climate Hazards Evaluated

Climate Drivers	Primary: Local Precipitation	Primary: Air Temperature	Primary: SLR	Secondary: Wind	Secondary: Water Temperature
Climate Stressors	Change over time in amount and timing of rainfall	Change over time in air temperature, seasonal changes, max. air temperature as proxy	Increase in sea level	Change in wind patterns over time, proximity to the Central Valley and the coast	Change over time in water temperature, corresponds to air temperature – dependent on atmospheric forcing, riverine flows, and tidal dispersion
Climate Hazards	Extreme precipitation events/ drought	Extreme heat events	Flooding/ levee overtopping	No wind hazards assessed	No water temperature hazards assessed

Understanding impacts of climate stressors over a longer time period exemplifies how these changes can lead to eventual ecosystem decoupling, whereas evaluating climate hazards (extreme events) demonstrates how these events may lead to catastrophic failures within the Delta over the short- and long terms.

Climate vulnerability to the aforementioned stressors and hazards can be defined as (1) the *exposure* of a given species, habitat, resource, or region to climate changes, (2) the *sensitivity* or response to such changes, and (3) the *adaptive capacity* or inherent safeguards or coping mechanisms to deal with such changes (Glick et al. 2011).

AECOM and the Delta Stewardship Council conducted a climate vulnerability assessment to address the exposure, sensitivity, and adaptive capacity of dominant ecosystem types (adapted from the San Francisco Estuary Institute–Aquatic Science Center (SFEI–ASC 2014,Table 3) to climate change variables within the Delta and Suisun Marsh project area (Figure 4, Figure 5).

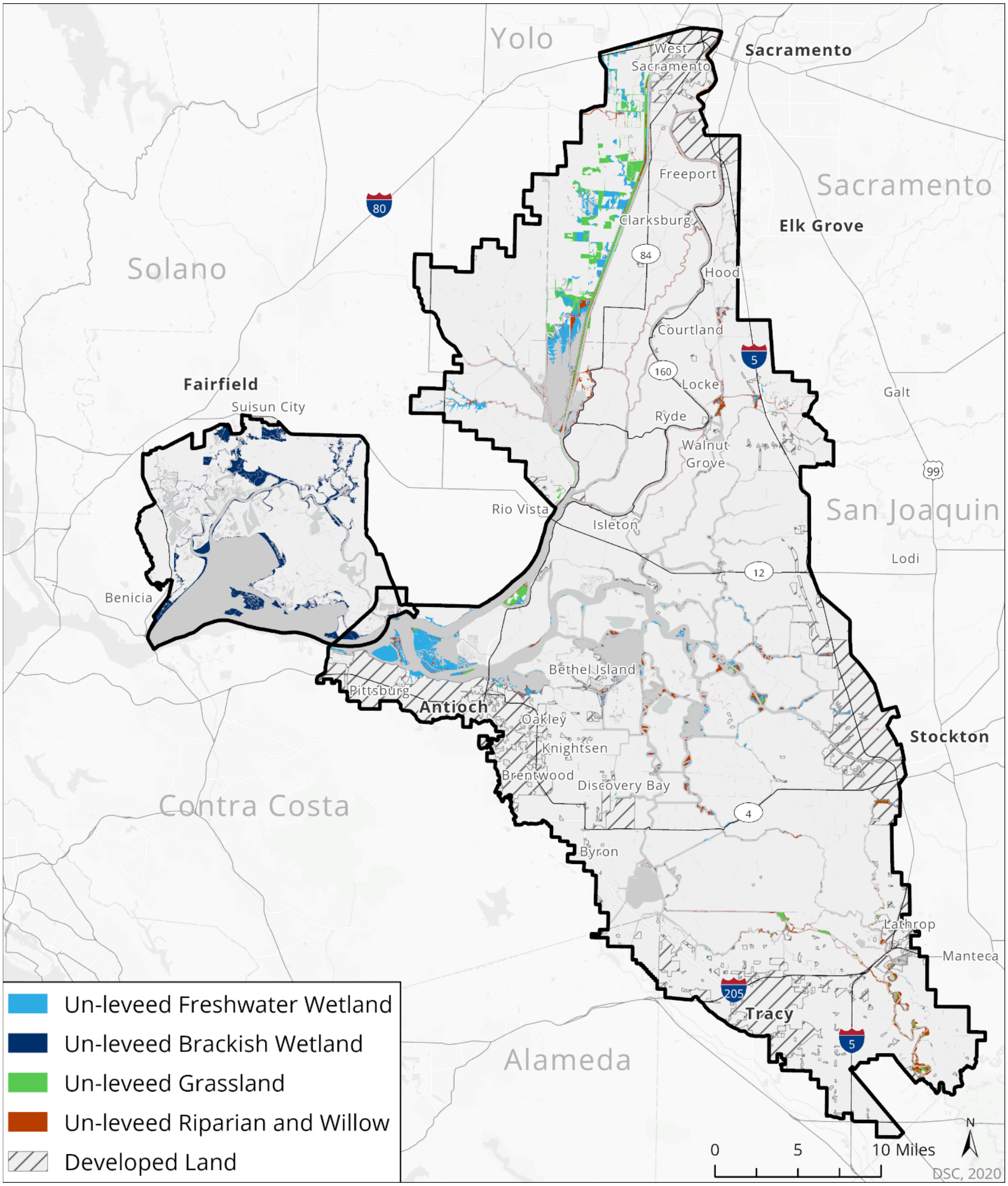


Figure 4. Existing Un-Leveed Ecosystems in the Legal Delta and Suisun Marsh

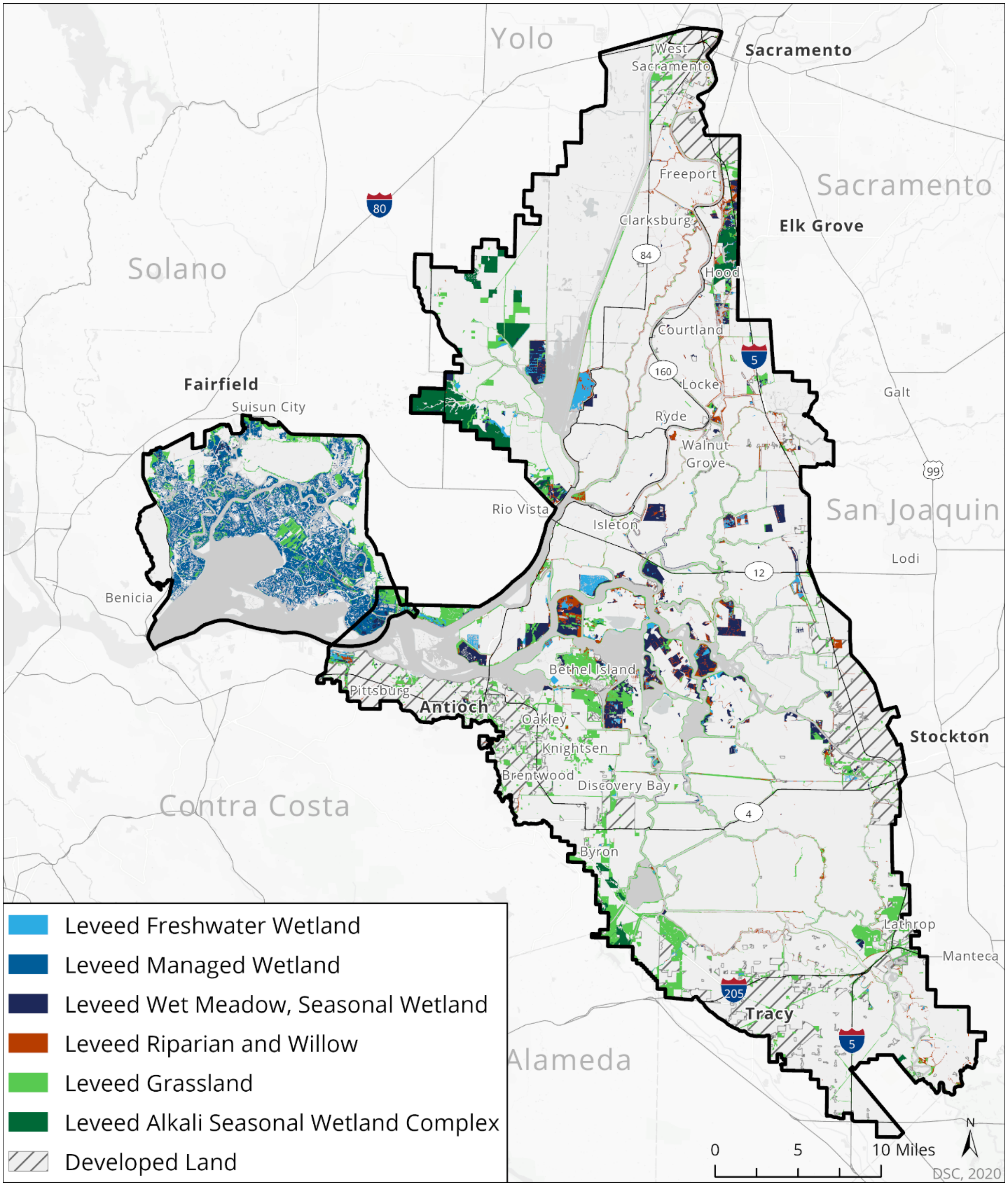


Figure 5. Existing Leveed Ecosystems in the Legal Delta and Suisun Marsh

For the purposes of this assessment, vulnerability is described as depicted in Dawson et al. 2011:

Vulnerability = Exposure + Sensitivity – Adaptive Capacity

Vulnerability "is the extent to which a species or population is threatened with decline, reduced fitness, genetic loss, or extinction owing to climate change."

Exposure "refers to the extent of climate change likely to be experienced by a species or locale.

Exposure depends on the rate and magnitude of climate change (temperature, precipitation, SLR, flood frequency, and other hazards) in habitats and regions occupied by the species."

Sensitivity "is the degree to which the survival, persistence, fitness, performance, or regeneration of a species or population is dependent on the prevailing climate, particularly on climate variables that are likely to undergo change in the near future. More sensitive species are likely to show greater reductions in survival or fecundity with smaller changes to climate variables. Sensitivity depends on a variety of factors, including ecophysiology, life history, and microhabitat preferences. These can be assessed by empirical, observational, and modeling studies."

Adaptive capacity "refers to the capacity of a species or constituent populations to cope with climate change by persisting in situ, by shifting to more suitable local microhabitats, or by migrating to more suitable regions. Adaptive capacity depends on a variety of intrinsic factors, including phenotypic plasticity, genetic diversity, evolutionary rates, life history traits, and dispersal and colonization ability. Like sensitivity, these can be assessed by empirical, observational, and modeling studies."

For the purpose of this assessment, adaptive capacity is further defined as a two-part component—the first being the inherent and natural adaptive capacity of the species or habitat without human intervention (Dawson et al. 2011), and the second being the policy adaptive capacity, which refers to existing resource management of the natural system by humans.

Climate Drivers

For the primary climate drivers air temperature and local precipitation, we applied downscaled global climate models (GCMs) to project climate change impacts for the greater Delta. We then qualitatively applied those findings to estimate the vulnerability of ecosystems assets. For SLR, asset exposure was quantitatively evaluated using geographic information, digital elevation models, and flood hazard models to depict inundation under the various modeling scenarios.

Sensitivity was determined by analyzing geographic exposure and reviewing expert knowledge. Methodology for each primary climate driver differs slightly and is described below.

Vulnerability was assessed differently for each secondary stressor/hazard. Changes in wind that are projected for the Delta region was assessed using peer-reviewed literature to qualitatively assign vulnerability to ecosystem assets, whereas drought and water temperature are related to changes in local precipitation patterns and air temperature, and thus were discussed in the vulnerability rankings for each ecosystem asset in section 4.6.

3.1 Ecosystem Assets

The Vegetation Classification and Mapping Program (VegCAMP) for the Delta, Suisun Marsh, and the Vegetation and Land Use Classification and Map Update of the Sacramento-San Joaquin River report (Kreb et al. 2019) were used to delineate the different ecosystems considered in the study. The vegetation communities in VegCAMP were assigned to the ecosystems identified in the report 'A Delta Transformed' (SFEI–ASC 2014; Table 3). The ecosystem types 'Willow Thicket', 'Willow Riparian Scrub or Shrub', and 'Valley Foothill Riparian' were combined into a single type (Riparian/Willow Ecosystems).

In the vulnerability analysis, ecosystem types were included that are not protected by levees ("un-leveed"; Figure 4):

- Freshwater Emergent Wetland,
- Brackish Emergent Wetland,
- Riparian/Willow Ecosystems, and
- Grasslands.

Four ecosystem types were included that are protected by levees ("leveed"; Figure 5):

- Non-tidal Freshwater Wetland,
- Managed Wetland, and
- Wet Meadow or Seasonal Wetland,
- Alkali Seasonal Wetland Complex,
- Agricultural areas that provide wildlife resources.

The effects of climate change on two additional, ecologically important ecosystem assets that are not identified by the VegCAMP data set are discussed in section 4.4: (1) Floodplains can contain different ecosystems but as a unit will be affected by climate change, and (2) cold-water pools in reservoirs lining the Central Valley are used to manage in-stream temperatures for salmon, sturgeon, and other fish species.

3.1.1 Asset Categories: Ecosystem Types

The Delta is a dynamic inland deltaic system at the confluence of the Sacramento and San Joaquin Rivers. This region is situated on the North America's Pacific coast in a Mediterranean climate that consists of hot, dry summers and cool, wet winters. It is located within the California Floristic Province—a biodiversity hotspot characterized by rare and endemic species. Since the mid 1800's there have been anthropogenic modifications that altered the once thriving ecosystem to one that remains productive, yet is highly managed, has undergone significant land conversion, and has witnessed species declines and the influx of nonnative species.

Table 3. Asset Categories: Ecosystem Types[1]

Habitat Type	Description
Water[X]	*Tidal mainstem channel*: Rivers, major creeks, or major sloughs forming Delta islands where water has ebb and flow in the channel at times of low river flow. These delineate the islands of the Delta. *Fluvial mainstem channel*: Rivers or major creeks with no influence of tides. Tidal low order channel: Dendritic tidal channels (i.e., dead-end channels terminating within wetlands) where tides ebb and flow within the channel at times of low river flow. *Fluvial low order channel*: Distributaries, overflow channels, side channels, swales. No influence of tides. These occupy non-tidal floodplain environments or upland alluvial fans. *Freshwater pond or lake*: Permanently flooded depressions, largely devoid of emergent Palustrine vegetation. These occupy the lowest elevation positions within wetlands. *Freshwater intermittent pond or lake*: Seasonally or temporarily flooded depressions, largely devoid of emergent Palustrine vegetation. These are most frequently found in vernal pool complexes at the Delta margins and in the non-tidal floodplain environments.
Emergent Wetlands[*^]	*Tidal freshwater emergent wetland*: Perennially wet, high water table, dominated by emergent vegetation. Woody vegetation (e.g., willows) may be a significant component for some areas, particularly the western-central Delta. Wetted or inundated by spring tides at low river stages (approximating high tide levels). *Non-tidal freshwater emergent wetland*: Temporarily to permanently flooded, permanently saturated, freshwater non-tidal wetlands dominated by emergent vegetation. In the Delta, occupy upstream floodplain positions above tidal influence. *Tidal brackish emergent wetland*: Intertidal emergent wetland at the confluence of fresh and saltwater dominated by grasses, forbs, and shrubs and tolerant to moderate salinities.
Willow Thicket [*^]	Perennially wet, dominated by woody vegetation (e.g., willows). Emergent vegetation may be a significant component. Generally located at the “sinks” of major creeks or rivers as they exit alluvial fans into the valley floor.
Willow Riparian Scrub or Shrub [*^]	Riparian vegetation dominated by woody scrub or shrubs with few to no tall trees. This habitat type generally occupies long, relatively narrow corridors of lower natural levees along rivers and streams.

Habitat Type	Description
Valley Foothill Riparian *^	Mature riparian forest usually associated with a dense understory and mixed canopy, including sycamore, oaks, willows, and other trees. Historically occupied the supratidal natural levees of larger rivers that were occasionally flooded.
Wet Meadow or Seasonal Wetland^	Temporarily or seasonally flooded, herbaceous communities characterized by poorly drained, clay-rich soils. These often comprise the upland edge of perennial wetlands.
Vernal Pool Complex^X	Areas of seasonally flooded depressions characterized by a relatively impermeable subsurface soil layer and distinctive vernal pool flora. These often comprise the upland edge of perennial wetlands.
Alkali Seasonal Wetland Complex^	Temporarily or seasonally flooded, herbaceous or scrub communities characterized by poorly drained, clay-rich soils with a high residual salt content. These often comprise the upland edge of perennial wetlands.
Stabilized Interior Dune Vegetation^X	Vegetation dominated by shrub species with some locations also supporting live oaks on the more stabilized dunes with more well- developed soil profiles.
Grassland*^	Low herbaceous communities occupying well-drained soils and composed of native forbs and annual and perennial grasses and usually devoid of trees. Few to no vernal pools present.
Wildlife-associated Agriculture^	Cultivated lands that were identified in the literature to be associated with wildlife species and include the following crop types: Alfalfa and Alfalfa Mixtures; Corn, Sorghum and Sudan; Idle; Miscellaneous Field Crops; Miscellaneous Grain and Hay; Miscellaneous Grasses; Miscellaneous Truck Crops; Mixed Pasture; Potatoes and Sweet Potatoes; Rice; Safflower; Sunflowers; Tomatoes; Wheat; Wild Rice
Managed Wetland^	Areas that are intentionally flooded and managed during specific seasonal periods, often for recreational uses such as duck clubs.
Urban/Barren^X	Developed, built-up land often classified as urban, barren, or developed. Includes rock riprap bordering channels.

[1] Adapted from SFEI–ASC 2014, pp. 18–19

* Effects of gradual SLR for areas for un-leveed ecosystems were analyzed

^ Effects of episodic SLR for leveed ecosystems were analyzed

[X] Not analyzed as part of this effort

3.2 Assessing Vulnerability

Ecosystem vulnerability to climate change is a function of exposure, sensitivity, and adaptive capacity to the effects of climate change. The following section explains how these three aspects were assessed for the climate drivers air temperature, local precipitation, and SLR.

3.1.1 Exposure

The exposure analysis evaluates an asset's susceptibility to climate variables. All ecosystems were assessed for susceptibility to each climate variable independently. The exposure analysis identifies the ecosystem asset (e.g., Tidal Freshwater Emergent Wetland) with exposure to projected changes in climate variables – air temperature, local precipitation, and SLR.

3.2.1.1 Air Temperature and Local Precipitation

For air temperature and precipitation, the climate variables that relate directly to atmospheric conditions, exposure is subject to level of detail and uncertainty in the downscaled models. Therefore, these climate stressors were assessed at a project-wide level using downscaled data specific to the project area. More fine-scale analyses to show local variations in air temperature and precipitation changes are presented in Section 3.4 and Section 3.5 for the project area.

3.2.1.2 Sea Level Rise

To understand the exposure of ecosystem assets to SLR scenarios, digital elevation data, average daily water levels, and peak water levels at multiple locations were generated. Spatially explicit modeling was conducted to explore where ecosystems will be exposed to SLR. Using a geographic information system (GIS) layer of hydrologically connected areas, the ecosystems in Table 3 were analyzed separately in un-leveed (hydrologically connected to tidal or riverine flow) and leveed (hydrologically disconnected from tidal or riverine flow) categories (Figure 6).

Exposure was rated on the percent of acres of an ecosystem type at risk from flooding. The rating of un-leveed ecosystems was based on a deterministic scenario where the sea level is projected to increase by 3.5 ft by end-of-century. The rating of leveed ecosystems was based on a probabilistic scenario, where a medium probability of flooding (1-2 percent Equivalent Annual Probability of Exceedance, which equals a 50-100-year return period) is projected by end-of-century. Assets with 1 to 33 percent at risk have an exposure score of 1 (low); 33 to 66 percent have a score of 2 (moderate); and 66 to 100 percent have a score of 3 (high).

For tidal freshwater and brackish wetlands, the Wetland Accretion Rate Model of Ecosystem Resilience (WARMER) was used to determine exposure (Buffington et al. in review, Buffington and Thorne 2021, Swanson et al. 2015). This quantitative framework is detailed in Section 3.1.2, and allowed for comparing various scenarios to determine exposure. Because this model takes accretion into account, it includes some measure of sensitivity; thus, for tidal freshwater and brackish wetlands, the same score was given for exposure and sensitivity.

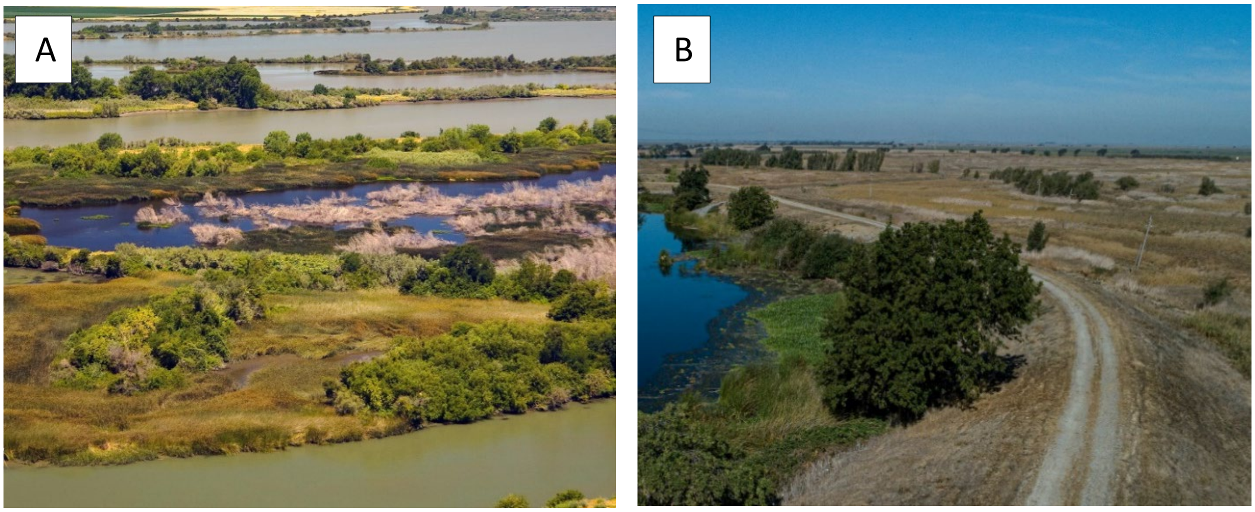


Figure 6. Un-leveed Ecosystems are Connected to Water (Panel A); Leveed Ecosystems are Disconnected from Water (Panel B)

3.1.2 Sensitivity

For this assessment, sensitivity factors were selected based on primary ecosystem functions of the ecosystem types outlined in Section 3.1.1. Sensitivity was qualitatively assessed for each asset based on the natural history of each ecosystem type, associated fish and wildlife species, and foundational physical processes according to the expert knowledge of scientists familiar with Delta ecology and peer-reviewed literature (see Chapter 4 Results and Discussion, and Table 15).

To determine ecosystem sensitivity, each was assessed under three subcomponents:

- Dominant Vegetative Communities: These are the dominant plant species that are known to occur in each ecosystem type.
- Fish and Wildlife Species: These are the associated animal species known to occur in and be dependent on a specific ecosystem type.
- Physical Processes: These are the physical processes that support primary habitat functioning such as soil moisture content, evapotranspiration, sedimentation/accretion, water quality, tidal exchange, and related factors.

Each ecosystem subcomponent was scored on a scale of 1-3 for sensitivity to air temperature, local precipitation, and SLR. The scores were summed into a total sensitivity score for that ecosystem type. Total scores were categorized using the impact scale described in Table 4. Ecosystem types that scored a moderate or high score were assessed for their exposure and adaptive capacity. Natural adaptive capacity is included in this assessment because an ecosystem’s natural adaptive capacity is tied to its sensitivity to a particular climate stressor. Secondary climate stressors (wind and water temperature) were not included in the matrix.

For SLR, sensitivity of un-leveed ecosystems was qualitatively assessed based on expert knowledge of the effects of flooding on the ecosystems.

Table 4. Asset Sensitivity to Climate Variables and Secondary Impacts to Ecosystem Function

Asset Sensitivity	None - *No impact to asset function*	Low - *Asset still functional*	Medium - *Asset function compromised*	High - *Asset no longer functional*
Ecosystems	Negligible or no change	Short-term, minor but reversible interruption	Significant but not permanent loss	Widespread and permanent loss

3.1.3 Adaptive Capacity

For ecosystems, adaptive capacity can be divided into natural adaptive capacity – the inherent ability or resiliency of a habitat to respond to climate changes, and institutional adaptive capacity – which includes policies and management measures already in place to protect that habitat. The sensitivity analysis considered each ecosystem asset's inherent ability to adjust to changes in temperature, local precipitation and SLR to maintain its ecosystem function.

Institutional adaptive capacity was assessed qualitatively based on a set of considerations unique to each asset category and was assessed based on the natural history of each habitat type, using the expert knowledge of Delta scientists. For the preexisting policies and natural resource management components of adaptive capacity, professional opinions of Delta Stewardship Council staff and the project Technical Advisory Committee were included.

3.1.4 Vulnerability

The vulnerability of ecosystem types to air temperature and local precipitation is calculated based on the scoring used in the sensitivity analysis. This approach takes exposure and inherent adaptative capacity into consideration. Scores are based on a 1-3 scale for each subcomponent (vegetative communities, fish and wildlife, and physical properties), resulting in overall vulnerability scores ranging from 3-9.

Ecosystems with low vulnerability to air temperature or local precipitation received scores of 3 (since these two stressors are not binary and all ecosystem types will be exposed to some degree of warming or variation in precipitation, thus no scores of 0 were possible), moderate vulnerability received scores of 4-6, and high vulnerability received scores of 7-9.

To arrive at SLR vulnerability scores, low, moderate, and high exposure, sensitivity, and adaptive capacity ratings were translated into scores of 1, 2, and 3, respectively.

The vulnerability score was then calculated using this formula:

Vulnerability = Exposure + Sensitivity – Adaptive Capacity

This could result in vulnerability scores ranging from -1 to 5.

Low vulnerability was assigned to scores of -1 to 1, moderate vulnerability was assigned to a score of 2-3, and high vulnerability was assigned to scores of 4-5.

3.3 Finer Scale Vulnerability

In addition to analyzing the vulnerability to each climate variable independently, and with respect to annual changes throughout the century, a finer level of detail was applied to the primary climate stressors to assess spatial and temporal variability. SLR was assessed according to spatial variability within the Delta, whereas air temperature and local precipitation were assessed in terms of temporal variability (seasonality) throughout the year. Temperature and local precipitation were not assessed for spatial variability due to the negligible differences obtained during preliminary analyses.

3.1.1 Spatial Variability – Delta Regions

Within the Delta, considerable spatial differences exist between its regions. For SLR analyses, the Delta was delineated into five regions by grouping conservation units (Blue Ribbon Task force 2008). The five regions of the project area (Figure 7) are outlined below.

1. Yolo-Cache: Cache Slough, Yolo Bypass
2. North Delta Region: Netherlands, East Side (North), Sutter Island, Prospect Island, Mokelumne/Cosumnes Corridor.
3. Central Delta Region: Deep Delta, Deepest Delta, East Side (South), Dutch Slough, Southwest Delta, Stockton, Southwest Delta Cities, Western Delta Islands
4. South Delta Region: South Delta
5. Suisun Marsh Region: Suisun Marsh

3.1.2 Temporal Variability – Seasonality

Given the Delta's Mediterranean climate, temporal variability was considered to understand the sensitivity of habitats to climate change by season. Seasonality plays a key role in determining key ecosystem processes such as reproduction, growth, and survival of organisms (phenology). Seasonal data were used to analyze shifts in temperature and precipitation regimes, and to compare projected changes between seasons.

Seasonal data for temperature and precipitation were divided into the seasons as follows:

1. Winter: December, January, February
2. Spring: March, April, May
3. Summer: June, July, August
4. Fall: September, October, November

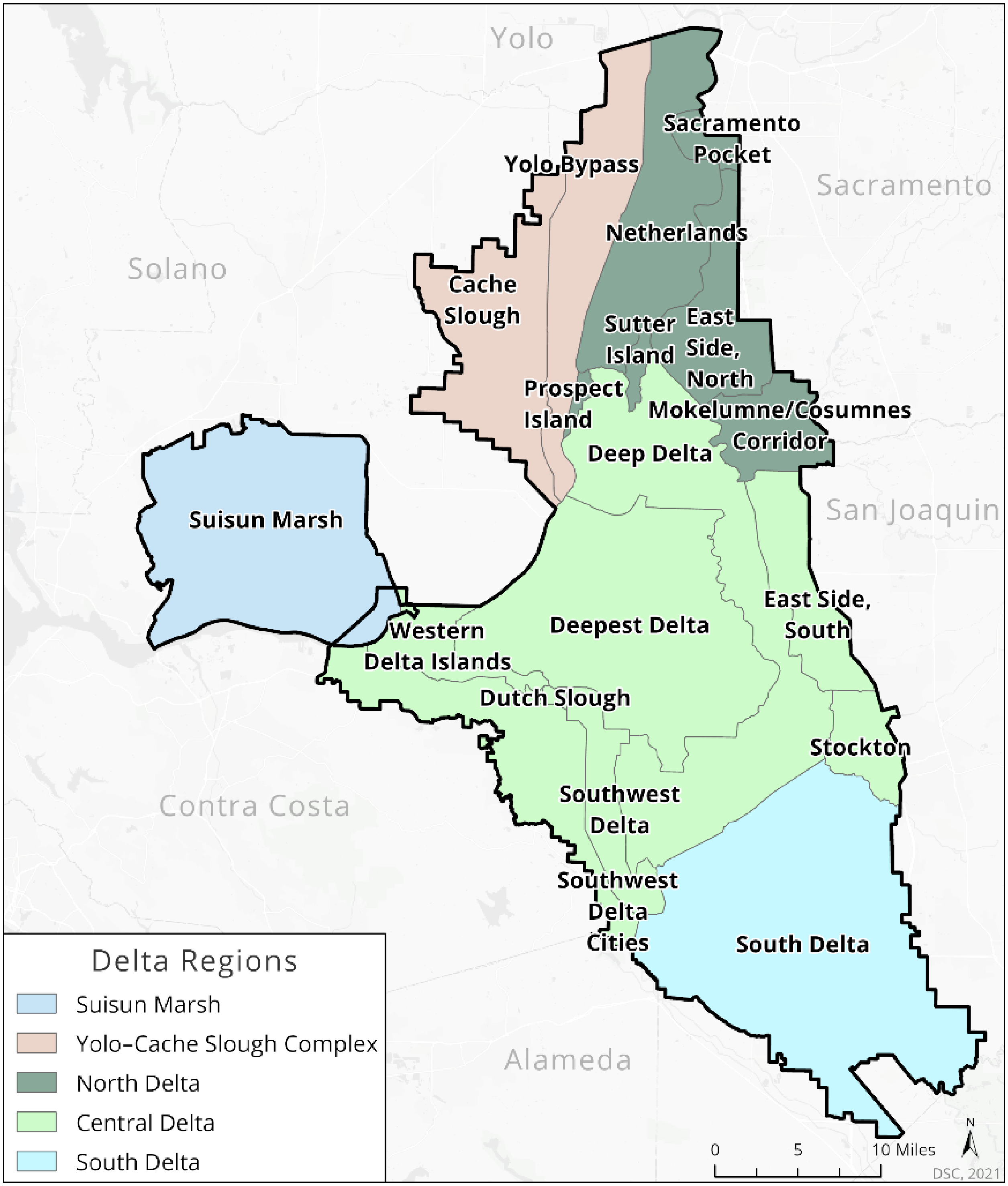


Figure 7. The Delta Project Area is Separated into Five Regions – Yolo-Cache Slough Complex, North Delta, Central Delta, South Delta, and Suisun Marsh

Note: The subregions are the original conservation units used to develop the regions.

3.4 Air Temperature

3.1.1 Data Sources

Historical and projected air temperature and precipitation data for the Delta were obtained from Cal-Adapt[1]. The data were derived from CMIP5 global climate models (GCMs) downscaled using the Localized Constructed Analogues (LOCA), a statistical method which is highly resolved in both space (1/16° grid, ca. 3.7 miles × 3.7 miles) and time (daily resolution) (Cal-Adapt 2017, Pierce et al. 2018).

For this assessment, 10 out of 32 GCMs[2] identified by California's Climate Action Team Research Working Group were averaged to obtain one output per variable of interest for the analysis of projected temperature and precipitation changes in the Delta (Cal-Adapt 2017). Models were averaged together to acquire an output more likely than any one individual model, however, individual model values yield a more accurate depiction of the range of possible temperature and precipitation outcomes for the future. Out of the 10 models, the maximum and minimum values were used to present the range of temperature and precipitation possibilities surrounding the average output. All averaged values were then used to differentiate changes from historical conditions. Modeled historical values (based upon observed values) were subtracted from the modeled temperature and precipitation projections to demonstrate absolute changes for the remainder of the century from a historical baseline.

The data were divided into 30-year periods and include:

1. Modelled historical: 1961 – 1990,
2. Mid-Century: 2035 – 2064, and
3. Late-Century: 2070 – 2099

Projection scenarios, or representative concentration pathways (RCPs) were also denoted. RCPs encapsulate different climate futures depending on greenhouse gas and aerosol emission scenarios in the years to come. Two RCP scenarios were applied (1) RCP 4.5: where emissions peak around 2040, then decline, and (2) RCP 8.5: the "business as usual scenario" where emissions continue to rise strongly through 2050 and plateau around 2100 (Cal-Adapt 2017).

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[1] Cal-Adapt was developed to provide an interactive geospatial tool for localized climate projections in California. The tool allows users to explore projected changes in temperature, extreme heat, precipitation, snowpack, wildfire, and sea level rise across the state, based on a variety of climate models and future emission scenarios. Cal-Adapt 2.0 includes high-resolution, local climate projections, using LOCA downscaling methods and emission scenarios that align with the Intergovernmental Panel on Climate Change's Fifth Assessment Report.

[2] List of 10 GCMs designated by California's Climate Action Team for performance in California and four of which were designated as priority models*: HadGEM2-ES * (Warm/Drier); CNRM-CM5 * (Cooler/Wetter); CanESM2 * (Average); MIROC5 * (Complement); ACCESS1-0; CCSM4; CESM1-BGC; CMCC-CMS; GFDL-CM3; and HadGEM2-CC.

3.1.2 Average Annual Temperature

Average annual temperature in the Delta was evaluated to understand how thermal changes (namely thermal stress) may gradually impact the vulnerability of ecosystem assets over time. Maximum average annual air temperatures were obtained from Cal-Adapt more accurately portray the range of model outputs. Results were compared to modeled historical data to understand maximum temperature changes under each scenario (RCP 4.5 and 8.5) .

3.1.3 Seasonal Temperature

Seasonal temperature was addressed in the same manner as Section 3.1.2 to understand how projected changes (by scenario and time period) may impact the sensitivity of vegetative communities, fish and wildlife species, and physical processes, all of which depend on certain thermal ranges throughout the year in order to function properly and persist into the future.

3.1.4 Literature Review

According to the literature, average daily, and thus annual temperatures, will increase over the century – the severity of these increases are directly correlated to the global emission scenario. Some literature suggests that the *difference* between daily minimum and maximum temperatures in coastal California may decrease with minima temperatures increasing at faster rates than maxima. Extreme heat days and events will become more extreme when compared to historical baseline data – these extreme events will also occur with more frequency and for longer durations in the coming century (Dettinger et al. 2016, Council 2018a, Lebassi et al. 2009).

Air temperature in the Delta was assessed as follows:

1. Average annual air temperature (stressor): average maximum daily temperatures as a proxy for average annual temperature changes within the Delta throughout the century.
2. Annual averages (stressor comparison): average maximum daily temperatures as a proxy for average annual temperature changes in the Delta project area compared to those in California’s Central Valley.
3. Seasonal averages (stressor): average maximum daily temperatures as a proxy for seasonal changes per year to better understand impacts on a finer scale to both organisms and ecosystem wide.
4. Extreme heat (climate hazard).

3.5 Local Precipitation

3.1.1 Data Sources

Data for precipitation projections were obtained and analyzed using the same methods as air temperature described in detail within Section 3.1.1.

3.1.2 Average Annual Precipitation

Average annual precipitation was assessed to understand how local rainfall changes (climate stressor) may gradually affect the vulnerability of an ecosystem asset over time. Average annual precipitation data were adopted from Cal-Adapt to more accurately portray the range of model outputs and were calculated for the entire Delta region.

3.1.3 Seasonal Precipitation

Seasonal precipitation data were obtained to better understand potential changes in phenology – the timing of recurring natural events (e.g., flowering, or bird migrations) in relation to seasonal climatic changes, and/or shifts within ecosystem assets due to shifts in precipitation regime. The data were calculated in the same manner as described in Section 3.1.1.

3.1.4 Extreme Hydrological Events: Precipitation and Drought

For extreme hydrological events, climate vulnerability to ecosystems includes a high-level discussion based on literature review, with no detailed data analysis.

3.1.5 Literature Review

Unlike projections for temperature, projections for precipitation are less certain (He et al. 2018). Delta projections show high inter-annual variability with seasonal shifts (Houlton et al. 2018). Models project precipitation increases in winter and declines in spring and fall. By mid-century, many models show a reduction in the number of rainy days but an increase in the intensity of storms (e.g., increase in atmospheric river events). With increasing temperatures, dry years will become drier and wet years wetter, and droughts and floods will increase in magnitude and frequency (Dettinger et al. 2016, Council 2018a).

Precipitation was assessed as follows:

1. Average annual local precipitation changes (stressor): Delta regional annual precipitation showing change from historical baseline and projected changes in average annual precipitation.
2. Seasonal averages (stressor): Projected average seasonal precipitation changes to better understand potential phenological impacts to ecosystem types due to altered precipitation regimes.
3. Extreme precipitation and drought (hazard).

3.6 Sea Level Rise

3.1.1 Scenarios

For the exposure analysis of leveed ecosystems, probabilistic flood maps developed for the Flood Hazard Analysis were used to determine areas exposed to flooding. Scenarios include low, medium, high, and very high probability of flooding in 2030, 2050, and 2085 respectively (see Flood Hazard Technical Memo for full details).

Tidal wetland SLR modeling requires specific timeframes. Therefore, for the exposure analysis of un-leveed ecosystems, the deterministic SLR scenarios selected for the flood hazard analysis were used and each scenario was associated with a specific year. In addition, a more extreme scenario (6 feet SLR by 2100) was explored to assess the exposure of un-leveed ecosystem assets to more severe climate change (Table 5).

Table 5. Summary of Deterministic SLR Scenarios Adapted for Ecosystem Asset Analysis

Mapping Scenario	Planning Horizon	SLR	Watershed Hydrology	Storm Event
M-2	2050	12”	Mid-century (2035-2064) RCP 8.5	100-year water level
M-3	2050	24”	Mid-century (2035-2064) RCP 8.5	100-year water level
M-4	2050+ (2085 for tidal wetlands modeling	42”	End-of-century (2070-2099) RCP 8.5	100-year water level
M-5 (Un-leveed areas)	2100	72”	End-of-century (2070-2099) RCP 8.5	100-year water level

3.1.2 Sea Level Rise Exposure Analysis Methods

SLR is expected to have a gradual effect on un-leveed ecosystems and an acute effect on leveed ecosystems because of levee overtopping during episodic high-water events (Figure 8).

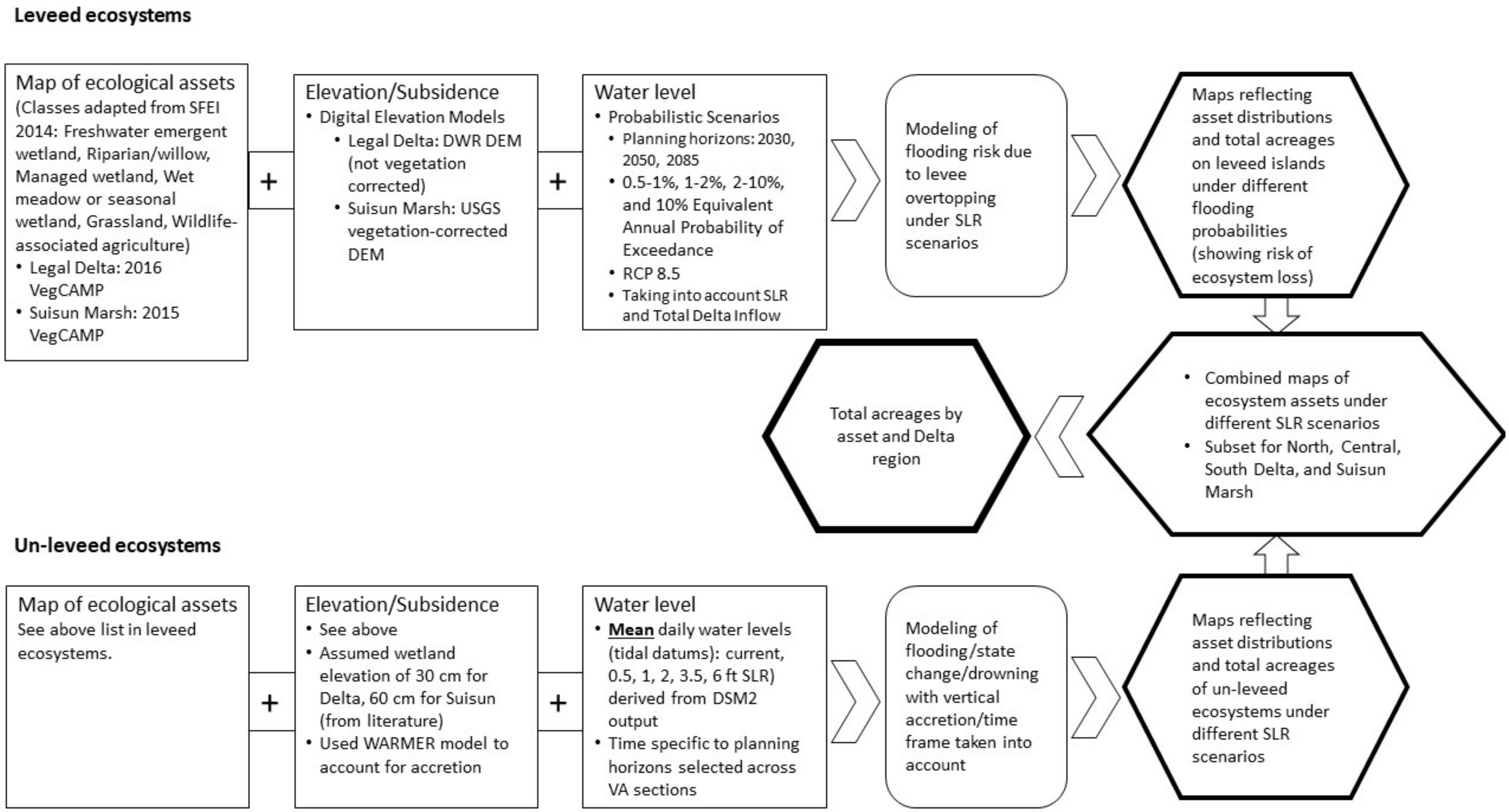


Figure 8. Exposure Modeling Workflow

3.6.2.1 Un-leveed Ecosystems

Tidal Datums

Using the Delta Simulation Model II (DSM2, see Flood Hazard Technical Memo for full details), tidal datums were generated at 430 nodes located throughout the Delta with 1, 2, 3, 4, 5, and 6 feet of SLR (deterministic scenarios). The 3.5-foot scenario was generated using the mean of the corresponding whole numbers. DSM2 nodes were associated with the nearest corresponding ecosystem patches for un-leveed ecosystems, as described below.

Un-leveed Tidal Wetlands

Tidal wetlands have intrinsic feedback processes, driven by mineral sediment accretion and organic matter production that can maintain wetland surface elevations under moderate rates of SLR (Swanson et al. 2015, Schile et al. 2014). To assess the potential impact of SLR on wetland persistence, mechanistic models are used to predict wetland surface elevations under different SLR scenarios over time. Recent efforts have expanded field-based observations of accretion rates and organic matter production by tidal wetland plant species in wetlands on Prospect Island in the North Delta, Browns Island in the Central Delta, and Rush Ranch in Suisun Marsh (Buffington and Thorne 2021). To determine the potential for tidal wetland persistence in the Delta and Suisun Marsh under the different SLR scenarios (see above), a team from the USGS used these data to parameterize the WARMER marsh accretion model (Buffington et al. in review, Buffington and Thorne 2021). This model incorporates mineral sediment accretion (based on soil core data), organic matter accretion (based on marsh plant productivity curves characteristic of different salinity regimes), and feedbacks between sea level and plant productivity to model marsh surface over time. Full documentation of the WARMER model parameterizations used for this project are available in Buffington and Thorne 2021. The model update builds on the previous WARMER model by incorporating organic productivity data for a range of regionally specific plant species related to salinity level, propagating parameter uncertainty into projections of marsh elevation with accelerating SLR, and including rates of mineral sediment accretion derived from soil cores.

Tidal freshwater and brackish wetland vegetation is dense, causing LIDAR-derived DEMs to reflect wetland surface elevations inaccurately unless they have been corrected (Buffington et al. 2019, Schile et al. 2015). A corrected DEM exists for Suisun Marsh, but not for the entire Delta. Because tidal wetlands occupy the elevation range between mean lower low water and mean high water, Swanson et al. (2015), who modeled marsh surface elevations under changing sea levels, used 20 centimeters (cm), 30 cm, and 40 cm above mean sea level (MSL) as current wetland elevations. Using the median scenario in Swanson et al. (2015), in the landscape-scale analysis presented here 30 cm above MSL was used as the starting elevation of mid/high marshes in the Delta. 20 cm and 40 cm starting elevations were also analyzed but did not change outcomes. All wetland surfaces below MSL were classified as low marsh. Similarly to the starting elevation sensitivity analysis, a different cut-off point for low marshes was tested (-10cm below MSL for the Delta and MSL for Suisun Marsh), but did not result in different results.

The starting elevation value for Suisun Marsh (60 cm) was derived from the mean of the tidal marsh elevations of 10x10m grid cells of tidal marsh identified using the vegetation-corrected DEM (Buffington et al. 2019). For each of the Delta regions, the means of the tidal datum values were calculated (mean lower low water [MLLW], mean low water [MLW], MSL, mean high water [MHW], mean higher high water [MHHW]) predicted under the selected SLR scenarios (Table 5) by the DSM2 model, and then the WARMER model was run for the selected SLR scenarios to produce annual marsh surface elevations. Marsh surface elevations were classified into mid/high marsh (above MSL), low marsh (below MSL) and drowned (below MLLW). Transitions from mid/high marsh to low marsh indicate a decrease in ecosystem quality and function, while drowned marshes no longer provide the benefits of tidal marsh ecosystems. Both transitions to low marsh and marsh drowning were considered as a part of wetland SLR exposure.

The WARMER model output was applied to the tidal marshes in the Delta regions. Rush Ranch parameters were used for Suisun Marsh, Browns Island parameters for the Central and South Delta, and Prospect Island parameters for the North Delta and Yolo-Cache Slough Complex. To extract tidal marsh polygons, wetlands were clipped from VegCAMP to Delta waterways in each of the Delta regions. The layers for the Yolo-Cache region include freshwater wetlands that are inundated when the Yolo Bypass floods. While these patches are not currently tidal, they are connected to the system’s hydrology in a way that leveed ecosystems are not and are likely to become tidal as sea level rises, thus they were included in the un-leveed exposure analysis.

There is high uncertainty about the future of sediment availability in the Delta, with evidence that sediment may increase (Stern et al. 2020) or decrease (Cloern et al. 2011). Therefore, a range of scenarios and their potential impacts on marsh resilience was explored. Across the Delta regions, three sediment scenarios (declining, constant, and increasing) were used to determine the sensitivity of marsh persistence to sediment availability. The constant scenario was modeled as 60 percent of the historical sediment supply, the declining scenario was modeled as a 1.6 percent annual reduction from the constant scenario, and the increasing scenario included 125 percent of the historical baseline.

Compared to the analysis approaches used for other ecosystem assets, using the WARMER model to consider changes in marsh surface elevation incorporates inherent adaptive capacity into the exposure analysis. Therefore, the 6-foot SLR scenario was used as a more extreme late-century scenario to calculate the exposure scores for these assets.

The modeling approach taken here, while helpful for landscape-scale planning, does not account for site-level variability in elevation and other conditions. The larger marshes studied in the Delta have been largely classified as high marsh (Schile et al. 2014, Swanson et al. 2015, Sloey et al. 2015, 2016). Adding a low marsh starting point expands on the high marsh starting points from Swanson et al. 2015, but these results should still be considered with caution at the site level.

For additional caveats and considerations regarding this approach, please see Section 4.2.

Un-leveed Grasslands and Riparian/Willow Ecosystems

For each 2.5x2.5 m grid cell of un-leveed grassland and riparian/willow ecosystem, the elevation was determined using the 2019 DWR Delta Digital Elevation Model (DEM) and the U.S. Geological Survey (USGS) Suisun Marsh vegetation-corrected DEM (Buffington et al. 2019).

To determine local rates of SLR, grassland and riparian/willow ecosystem grid cells were associated with the nearest DSM2 nodes. Based on general physiological tolerances of ecosystem assets, grassland persistence was determined by retaining grid cells with an elevation greater than the MSL at the nearest DSM2 node under each SLR scenario. Riparian/willow ecosystem persistence was determined by retaining grid cells with an elevation greater than the MLLW, to reflect the ability of riparian forest to be inundated (Stella et al. 2011). Under each SLR scenario, the size and number of grassland and riparian/willow ecosystem patches and the total area at risk of flooding of these two ecosystems were calculated.

3.6.2.2 Leveed Ecosystems

For leveed ecosystems, probabilistic flood maps were used to determine areas exposed to flooding under different scenarios (see Figure 9 and Tables 43-45 in the Flood Hazard TM). For each ecosystem asset, VegCAMP layers were clipped to flood risk layers to determine the total acreage at risk of flooding under the different scenarios. Because most islands in the Delta are at or significantly below sea level, all ecosystems on islands predicted to flood are assumed at risk, regardless of their actual elevation. Operationally, more subsided islands are likely to be more difficult to recover in the event of flooding, so ecosystems at lower elevations may be at higher risk of being permanently lost, but that analysis is beyond the scope of this effort.

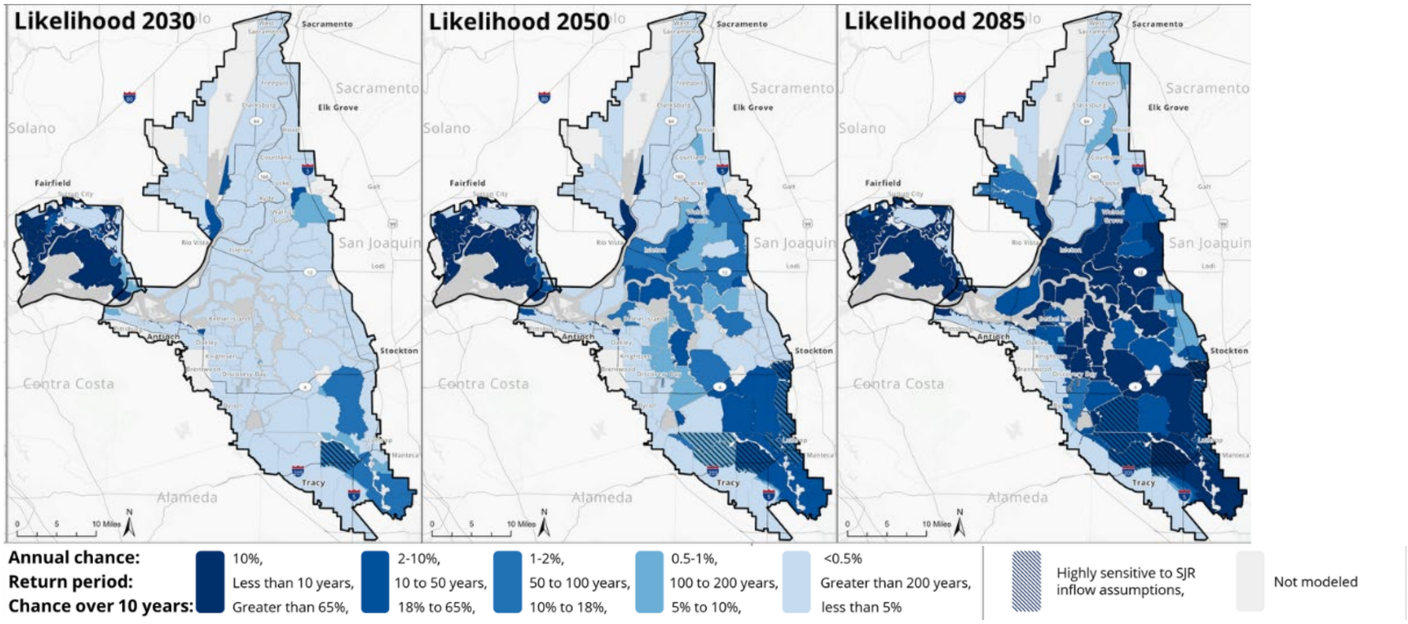


Figure 9. Probabilistic Flood Hazard Maps Used for the Leveed Ecosystem Exposure Analysis

3.6.2.3 Tidal Wetland Upland Transition Zone Accommodation Space

To explore the potential for un-leveed ecosystems to migrate into upland transition zone in response to SLR, projected sea level and current land elevations were mapped using data developed for the Chapter 4 of the Delta Plan (Council 2020). These data were subset into elevation classes reflecting current elevations and the potential of a given area to support future tidal wetland habitats at its current elevation. Levels of SLR were subset into elevation classes for low SLR (+0 to 2.5 feet MHHW), mid-high SLR (+2.5 to 7 feet), and extreme SLR (+7 to 10 feet). These layers were mapped with tidal wetland layers to qualitatively assess where upland transition zone SLR accommodation space exists adjacent to existing tidal wetlands and the location of potential areas of upland transition (Goals Project 2015).

CHAPTER 4. RESULTS AND DISCUSSION

4.1 Exposure

4.1.1 Air Temperature

4.1.1.1 Average Annual Temperature: Climate Stressor

Modelled historical average annual maximum air temperature in the Delta was approximately 73.8°F during the period 1961 to 1990. Maximum daily air temperature changes from the historical baseline are in Figure 10. These maps demonstrate that maximum air temperatures are likely to increase throughout regardless of the period and emission scenario. The late-century, RCP 8.5 emission scenario shows the most dramatic increases.

Although maximum air temperatures are forecasted to rise, localized variations in these increases may be explained by topographic differences, proximity to the coast, cooler oceanic water input, onshore winds, and coastal fog (Lebassi et al. 2009, Dettinger et al. 2016, Council 2018a). The Suisun Marsh is projected to remain cooler than the remainder of the Delta, consistent with present conditions (Figure 10). The North Delta is expected to be cooler than the South Delta. Table 6 illustrates predicted warming for the time horizons and emission scenarios used in this report. These data suggest that in the Delta average annual maximum temperatures could warm as little as 3.2°F (mid-century, RCP 4.5) and as much as 9.6°F (late-century, RCP 8.5).

Within the broader Central Valley, the average annual maximum daily temperature by 2100 is forecasted to remain warmer than in the Delta by approximately 2.0°F, though local variations in both regions will likely persist (Cal-Adapt 2017). These temperature differences suggest that the Delta could be a location of suitable habitat by species forced out of the Central Valley to seek thermal refuge where they could find similar landforms and ecosystems to support their growth and survival (Schmitz et al. 2015). According to the literature and assessments of temperature changes throughout California, it is likely that the Delta could serve as a climate refuge with respect to surrounding areas due to cooling Delta breezes, availability of water, coastal fog, and other physical processes that may act to offset increasing temperatures (Lebassi et al. 2009).

4.1.1.2 Seasonal Temperature: Climate Stressor

To gain a better understanding of inter-annual maximum air temperature variability, daily maximum air temperatures were averaged across seasons. The data suggest that summer and fall maximum air temperatures will increase at a greater rate than in winter and spring. The range of temperature increases projected across all seasons span as low as 2.4°F under RCP 4.5, mid-century winter projections to 12.0°F under RCP 8.5, late-century summer projections based off minimum and maximum outputs from the 10 models used for this analysis (Figure 11).

On average, across all 10 GCMs and both RCPs, air temperatures are expected to increase as follows and are presented as minimum and maximum output ranges from the 10 models (Figure 11): winter (3.1 to 6.8°F), spring (3.6 to 7.2°F), summer (4.8 to 9.2°F), and fall (4.4 to 9.4°F).

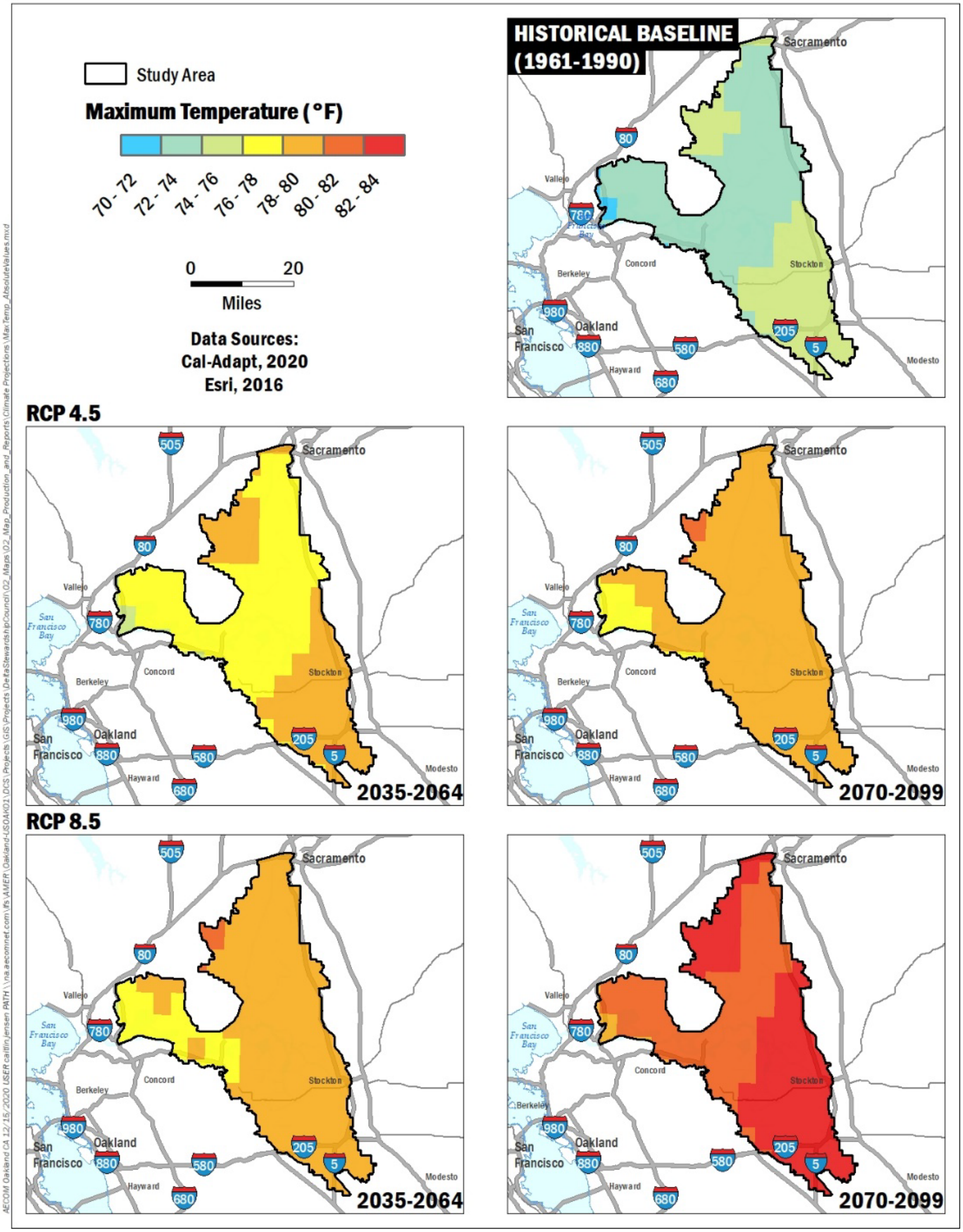
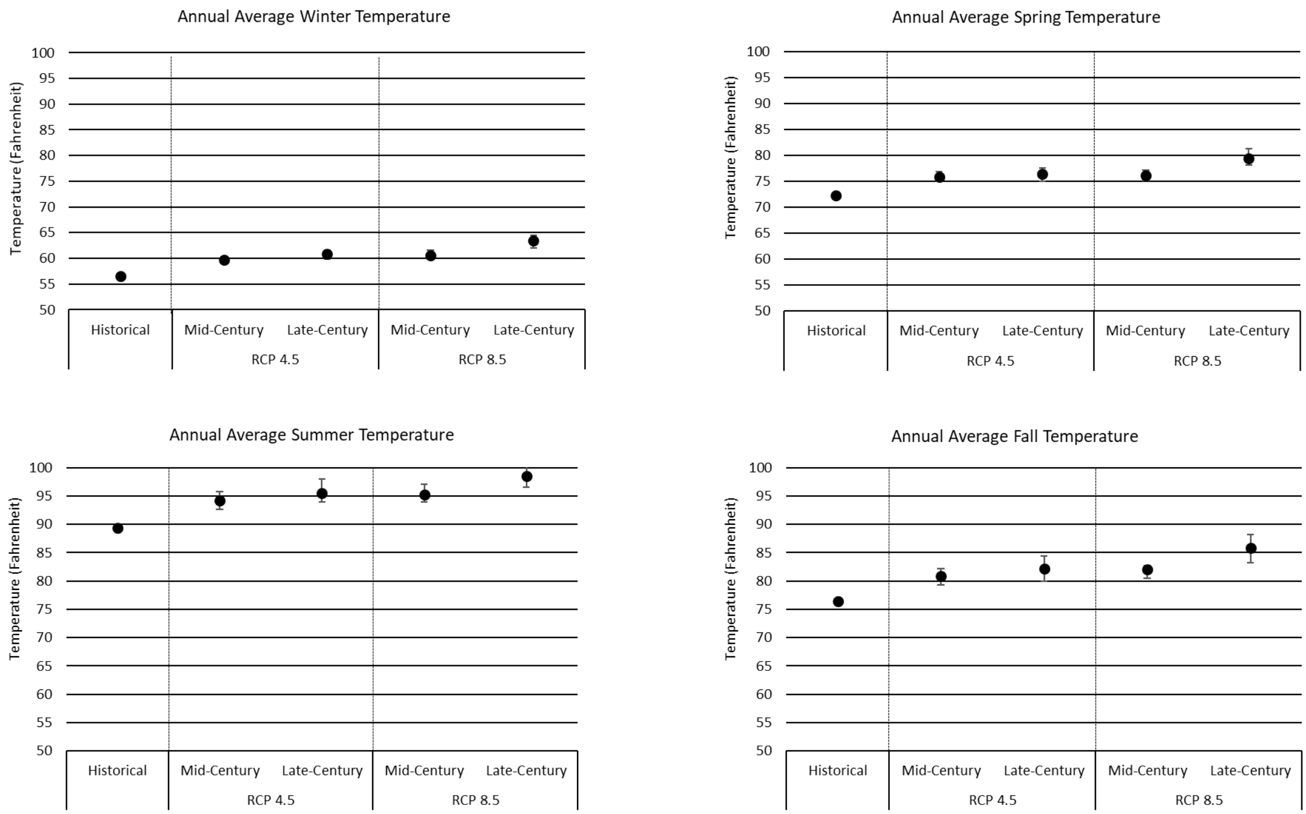


Figure 10. Spatial Variability of Projected Changes in Absolute Average Daily Maximum Temperature in the Delta

Table 6. Projected Changes in Average Annual Maximum Air Temperatures

Emission Scenario	Time Horizon	Average Annual Maximum Temperature (°F) and Range (Min, Max)
Historical	Modelled Historical (1961–1990)	73.8°F (70.7 – 77.4°F)
RCP 4.5	Mid-Century (2035–2064)	+3.9°F (+3.2°F – +4.8°F)
RCP 8.5	Mid-Century (2035–2064)	+4.9°F (+4.0°F – +5.8°F)
RCP 4.5	Late-Century (2070–2099)	+5.1°F (+3.6°F – +6.3°F)
RCP 8.5	Late-Century (2070–2099)	+8.1°F (+6.5°F – +9.6°F)

These are changes from the historical baseline. Annual average values were calculated for each 30-year time period for 10 of the 32 LOCA downscaled GCMs under RCP 4.5 and RCP 8.5 emission scenarios using data obtained from Cal-Adapt.



Notes: Average values were calculated for each 30-year time period for 10 of the 32 Localized Constructed Analogs (LOCA) downscaled global climate models (GCMs) under RCP 4.5 and RCP 8.5 emission scenarios using data obtained from Cal-Adapt.

Figure 11. Projected Average Seasonal Air Temperatures Under RCP Scenarios 4.5 and 8.5

Extreme Heat: Climate Hazard

Increasing average annual temperatures also impact extreme heat conditions. Extreme heat days are defined as temperatures that exceed the 98th percentile of observed historical temperatures for a particular location (Cal-Adapt 2017). For much of the Delta, the 98th percentile for air temperature corresponds to days with temperatures over 100 degrees. Historical extreme heat conditions in the Delta average about 4 or 5 days per year and are projected to increase throughout the century (mid-century range of 17 to 24 days per year; late-century range of 22 to 41 days per year).

4.1.2 Local Precipitation

4.1.2.1 Average Annual Local Precipitation: Climate Stressor

Based on the GCMs selected for this analysis, average annual precipitation is projected to increase across the Delta with localized differences occurring due to topography and proximity to the coast (Figure 12). Average annual precipitation trends indicate that the north Delta and Suisun Marsh will receive more rainfall compared to the central and south Delta regions. These changes are most pronounced with the late-century, RCP 4.5 and RCP 8.5 emission scenarios with highest increases in rainfall projected for late-century, RCP 8.5. Central and south Delta regions are projected to experience little to no change in precipitation.

Projected average annual precipitation shows little variation between the climate emission scenarios (Figure 13). Historical average annual precipitation in the Delta was approximately 15.0 inches, whereas average annual projected precipitation ranges from 15.6 inches at the mid-century, RCP 4.5 emission scenario to 16.5 inches at the late-century, RCP 8.5 emission scenario. The emissions scenario did not appear to impact average annual precipitation, and the models used did not agree on a consistent trend during the next century (precipitation decreases and increases from annual average across the 10 models ranged from -2.3 – +4.7 inches in the mid-century, RCP 4.5 emission scenario to -2.7 – +4.5 inches in the late-century, RCP 8.5 emission scenario (Table 7). Projected precipitation trends are often the least certain aspects of climate models, as the downscaled models are not able to resolve many of the fine-scale and complex interactions that occur locally. Additionally, the Delta region presently experiences high interannual precipitation variability making it difficult to detect a strong signal in future precipitation projections when considering average annual local precipitation levels. Averaging across the 10 GCMs to obtain the average outputs smooths out the noise of individual models which show very diverse outcomes for precipitation into the future.

Despite these variable model outcomes within the Delta, there is agreement across models that overall precipitation in the Delta is likely to increase. By mid-century many models show a reduction in the number of days when it will rain but the intensity of storms will increase due to an increase in the frequency of large storm and atmospheric river events.

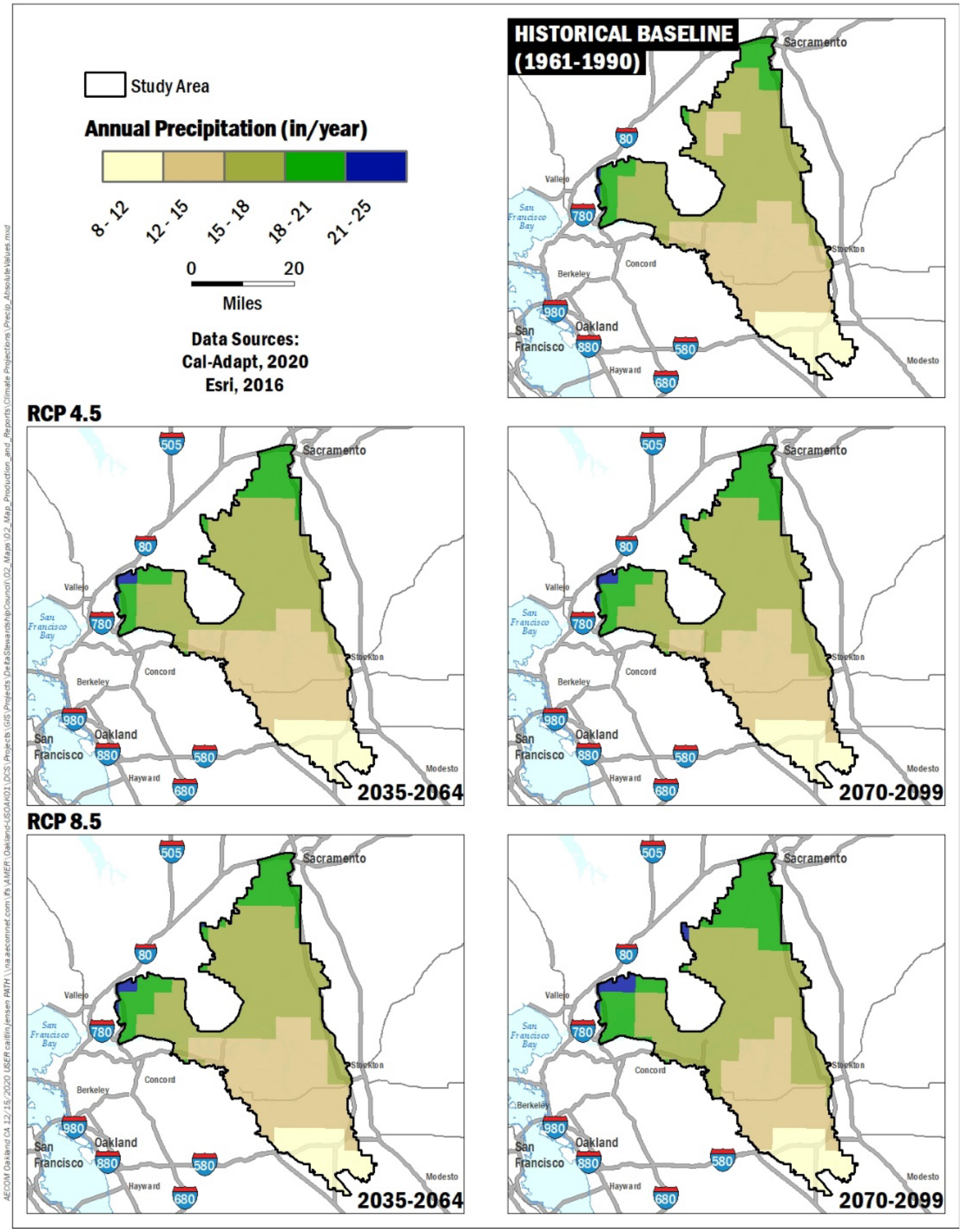


Figure 12. Spatial Variability of Projected Changes in Annual Average Precipitation in the Delta

Table 7. Projected Changes in Average Annual Precipitation

Emission Scenario	Time Horizon	Average Annual Precipitation Changes (in) and Range (Min, Max)
Historical	Modelled Historical (1961–1990)	15.0 inches (4.2 – 31.0 inches)
RCP 4.5	Mid-Century (2035–2064)	15.6 inches
RCP 4.5	Mid-Century Range (2035, 2064)	-2.3 – +4.7 inches
RCP 8.5	Mid-Century (2035–2064)	15.8 inches
RCP 8.5	Mid-Century Range (2035, 2064)	-2.6 – +3.8 inches
RCP 4.5	Late-Century (2070–2099)	15.8 inches
RCP 4.5	Late-Century Range (2070, 2099)	-2.8 – +3.5 inches
RCP 8.5	Late-Century (2070–2099)	16.5 inches
RCP 8.5	Late-Century Range (2070, 2099)	-2.7 – +4.5 inches

Notes: Average values were calculated for each 30-year time period for 10 of the 32 LOCA downscaled GCMs under RCP 4.5 and RCP 8.5 scenarios using data obtained from Cal-Adapt.

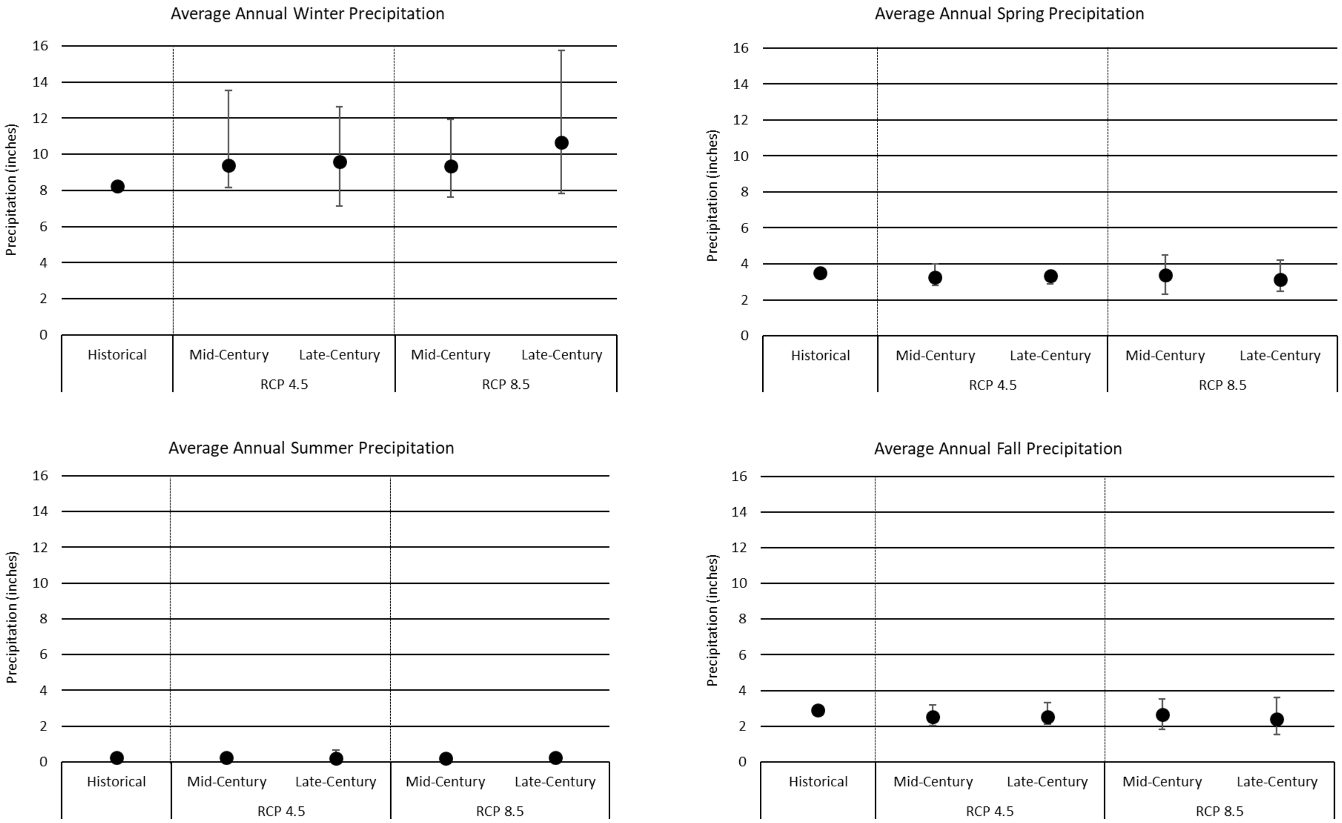
4.1.2.2 *Seasonal Precipitation: Climate Stressor*

To account for California's Mediterranean rainfall patters of wet winters and dry summers, seasonal precipitation data were analyzed to better understand interannual precipitation changes and their potential phenological impacts of ecosystems. Winter rainfall is expected to increase under all scenarios, with the highest increases seen under the late-century, RCP 8.5 projection (average increase of 2.4 inches, range -0.4 to 7.5 inches) (Figure 13).

Spring and fall precipitation are projected to decrease under all scenarios with minimal variability across average projected changes (spring decrease range -0.2 to -0.4 inches; fall decrease range -0.2 to -0.5 inches). Summer precipitation remains largely unaffected with average rainfall at 0-inches (range -0.1 to 0.4 inches) across all emission scenarios and time horizons.

4.1.2.3 *Climate Hazard: Extreme Precipitation and Drought*

Climate change is expected to increase the frequency and magnitude of floods due to extreme precipitation events and droughts (Diffenbaugh et al. 2015, Dettinger et al. 2016). Extreme precipitation and drought events, and predicted changes throughout century, were interpreted and reported based upon a literature review. These changes to the hydrologic extremes are driven by altered event magnitudes and novel combinations of events that reinforce one another (Dettinger et al. 2016). For example, by mid-century many models show a reduction in the number of days when it will rain but the intensity of storms will increase (e.g., increase in atmospheric river events) and with increasing temperatures, dry years are expected to become drier and wet years wetter (Dettinger et al. 2016, Council 2018a). There is also a potential for a hydrological cycle intensification known as 'climate whiplash'. This precipitation volatility occurs when there is a fast transition from extremely dry to extremely wet conditions and these whiplash events are expected to increase by 25 100 percent by 2100 (Swain et al. 2018).



Notes: Average values were calculated for each 30-year time period for 10 of the 32 LOCA downscaled GCMs under RCP 4.5 and RCP 8.5 scenarios using data obtained from Cal-Adapt.

Figure 13. Projected Average Seasonal Precipitation Under RCP Scenarios 4.5 and 8.5

4.1.3 Sea Level Rise

4.1.3.1 Un-leveed Ecosystems

Tidal Freshwater Wetland

For mid-century (2050) scenarios with modeled constant sediment scenario for un-leveed freshwater tidal wetlands starting at approximately 1 foot (~30cm) above MSL, 100 percent of ecosystems are at risk to transitioning to low marsh under 2 feet of SLR by 2050. Under 1 foot SLR by 2050, all of these ecosystems will lose some elevation relative to MSL, but are not at risk of transitioning to low marsh (Table 8 and Table 9).

For late-century (2085 and 2100 with constant sediment scenario) for un-leveed freshwater tidal wetlands starting at 1 foot (~30cm) above MSL, 100 percent are at risk to transitioning to low marsh under 3.5 feet SLR by 2050 and 100 percent of ecosystems are at risk of drowning and transitioning to open water under the 6 feet SLR by 2100. Under 2 feet SLR by 2085, these ecosystems will lose elevation relative to MSL but are not at risk of transitioning to low marsh.

For the constant sediment scenario, alternative starting elevations were also tested. Starting elevations of 1.31 feet (40cm) and 0.67 feet (20cm) were also tested and produced the same results as the 1 foot (30cm) scenario. To test the sensitivity of low marsh ecosystems, a starting elevation of -0.33 feet (-10cm) was evaluated. Under this scenario, all tidal freshwater wetlands drowned under 3.5 feet of SLR by 2085.

In addition to the constant sediment scenario used for the results above (60 percent of historical), scenarios for increasing sediment (125 percent of historical availability), and decreasing sediment (60 percent of historical with 1.6 percent decrease each year) were also tested. While these scenarios produced different outcomes, their results did not change the exposure results, resulting in the same overall levels of risk in the system.

Table 8. Predicted State Changes of Un-Leveed Wetlands with SLR

Year	Scenario	Delta Freshwater + 1 ft MSL Starting Elevation	Suisun Brackish + 2 ft MSL Starting Elevation	Low Marsh Start -0.33 ft and 0 ft MSL Starting Elevation
2050 (low)	1 foot	High/Mid Marsh	High/Mid Marsh	Low Marsh
2050 (high)	2 feet	Low Marsh	High/Mid Marsh	Low Marsh
2085 (low)	2 feet	High/Mid Marsh	High/Mid Marsh	Low Marsh
2085 (high)	3.5 feet	Low Marsh	Low Marsh	Drowned
2100	6 feet	Drowned	Drowned	Drowned

Notes: Under 3.5 ft SLR by 2085, 2 percent of Delta freshwater wetlands and 7 percent of Suisun Brackish wetlands are at risk of drowning. When assuming a low marsh as the starting elevation, the predicted state changes are the same for freshwater and brackish tidal wetlands.

Table 9. Un-leveed Tidal Wetland Acres and Percentage at Risk with SLR

Ecosystem Asset	Region	Current Acres	1 ft by 2050 Transition Risk **(acres, %)** Drowning Risk *(acres, %)*	2 ft by 2050 Transition Risk **(acres, %)** Drowning Risk *(acres, %)*	2 ft by 2085 Transition Risk **(acres, %)** Drowning Risk *(acres, %)*	3.5 ft by 2085 Transition Risk **(acres, %)** Drowning Risk *(acres, %)*	6 ft by 2085 Transition Risk **(acres, %)** Drowning Risk *(acres, %)*
Tidal Freshwater Wetland	Yolo-Cache	4,941	0 (0%) *0 (0%)*	4,941 (100%) *0 (0%)*	0 *(0%)* *0 (0%)*	4,941 *(100%)* 0 *(0%)*	0 (0%) *4,941 (100%)*
	North Delta	675	0 (0%) *0 (0%)*	675 (100%) *0 (0%)*	0 *(0%)* *0 (0%)*	629 (93%) *46 (7%)*	0 (0%) *675 (100%)*
	Central Delta	6,101	0 (0%) *0 (0%)*	6,101 (100%) *0 (0%)*	0 (0%) *0 (0%)*	6,060 (>99%) *41 (<1%)*	0 (0%) *6,101 (100%)*
	South Delta	232	0 (0%) *0 (0%)*	211 (91%) *21 (9%)*	0 (0%) *0 (0%)*	105 (46%) *127 (54%)*	0 (0%) *232 (100%)*
	Delta	**11,950**	**0 (0%)** ***0 (0%)***	**11,929 (>99%)** ***21 (<1%)***	**0 (0%)** ***0 (0%)***	**11,735 (98%)** ***214 (2%)***	**0 (0%)** ***11,950 (100%)***
Tidal Brackish Wetland	**Suisun**	**8,691**	**0 (0%)** ***0 (0%)***	**8,691 (100%)** ***0 (0%)***	**0 (0%)** ***0 (0%)***	**8,124 (93%)** ***567 (7%)***	**58 (1%)** ***8,633 (99%)***

Notes: *Transition risk* reports the acres at risk of falling below MSL and transitioning from high/mid marsh to low marsh. *Drowning risk* reports the acres at risk of falling below MLLW and being lost to drowning (Thorne et al. 2019, Swanson et al. 2015, Schile et al. 2014). Scenarios are based on starting elevations of 1 foot (30cm) above MSL for freshwater tidal wetlands and 2 feet (60cm) above MSL for brackish tidal wetlands and a constant sediment supply.

Tidal Brackish Wetland

Under the constant sediment scenario, un-leveed tidal brackish wetland ecosystems in Suisun Marsh (with a starting elevation of 2 ft) are expected to have high exposure to moderate rates of SLR, with 7 percent of current total acres at risk of loss for all scenarios under 3.5 and 6 feet of SLR, and all high marsh expected to transition to low marsh by 3.5 feet (Table 8). Un-leveed tidal wetlands in the Delta have low exposure to SLR through 3.5 feet by 2085.

For 2050 scenarios with constant sediment scenario for un-leveed brackish tidal wetlands starting at approximately 2 feet (~60cm) above MSL, these ecosystems will lose elevation relative to MSL, but are not at risk of transitioning to low marsh under 1 or 2 feet of SLR by 2050.

For late-century (2085 and 2100 with constant sediment scenario), un-leveed brackish tidal wetlands starting at approximately 2 feet (60cm) above MSL, 100 percent are at risk to transitioning to low marsh under 3.5 feet SLR by 2050 and 99 percent are at risk of drowning and transitioning to open water under the 6 feet SLR by 2100. Under 2 feet SLR by 2085, all will lose some elevation relative to MSL but are not at risk of transitioning to low marsh.

For the constant sediment scenario, alternative starting elevations were also tested. Starting elevations of 2.62 feet (80cm) and 1.31 feet (40cm) were also tested and produced the same results as the 2 feet above MSL (60cm) scenario. To test the sensitivity of low marsh ecosystems, a starting elevation of 0 feet above MSL (0cm) was evaluated. Under this scenario, 100 percent of tidal brackish wetlands were drowned under 3.5 feet of SLR by 2085.

In addition to the constant sediment scenario used for the results above (60 percent of historical sediment availability reflecting changes to sediment supply in the 20th century), scenarios for increasing sediment (125 percent of historical availability), and decreasing sediment (60 percent of historical with 1.6 percent decrease each year) were also tested. While these scenarios produced different outcomes for final wetland surface elevations, their results did not change the exposure results, resulting in the same overall levels of risk in the system.

Riparian and Willow Ecosystems

Un-leveed riparian and willow ecosystems in the Delta are expected to have low exposure to moderate rates of SLR, with less than 1 percent of current total acres at risk with 0.5 feet of SLR, approximately 2 percent at risk with 1 foot of SLR, 6 percent at risk with 2 feet SLR, and 18 percent at risk with 3.5 feet of SLR (Table 10,Figure 14). Under the 6-foot scenario, these ecosystems are expected to have moderate exposure, with approximately 38 percent of current total acres at risk. Regionally, South Delta riparian areas are expected to have the lowest exposure, with 16 percent at risk under 6 feet SLR, and Central Delta riparian areas are expected have the highest exposure, with 67 percent at risk.

Accretion rates for un-leveed riparian/willow ecosystems in the Delta are not known (but see Stella et al. 2011 for accretion rates in the Sacramento River north of the Delta). Thus, these results do not account for potential vertical accretion in riparian/willow ecosystems subject to SLR, and additional research is needed to determine these rates.

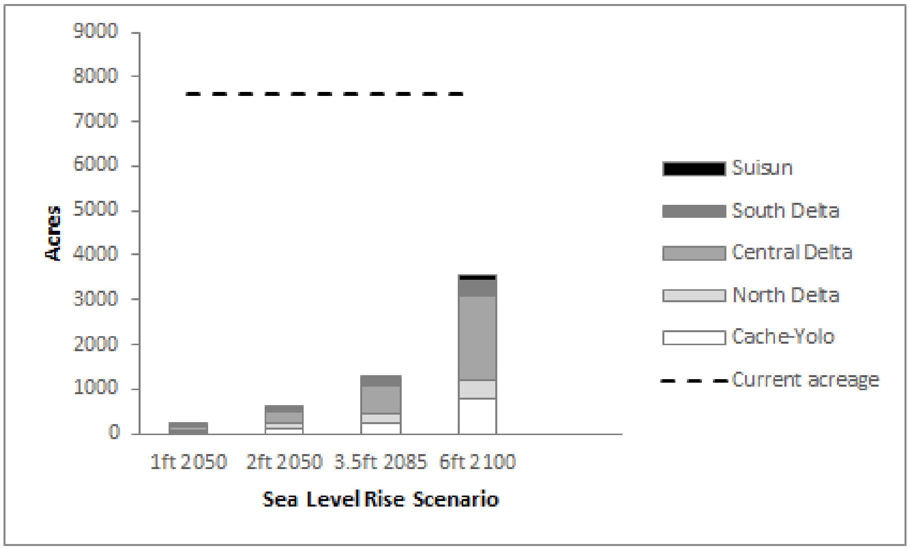


Figure 14. Un-Leveed Riparian/ Willow Acres at Risk of Permanent Flooding with SLR

Note: The dashed line indicates the current acreage of riparian and willow ecosystems.

Grassland

Un-leveed grassland ecosystems are expected to have low exposure to moderate rates of SLR, with 2 percent of current total acres at risk for all scenarios under 2 feet of SLR, 13 percent at risk with 3.5 foot of SLR, and 30 percent at risk with 6 feet SLR (Table 10 scenarios, Figure 15). Regionally, North Delta grasslands are expected to have the lowest exposure, with 9 percent at risk under 6 feet SLR, and Cache Yolo grasslands are expected to have the highest exposure, with 67 percent at risk.

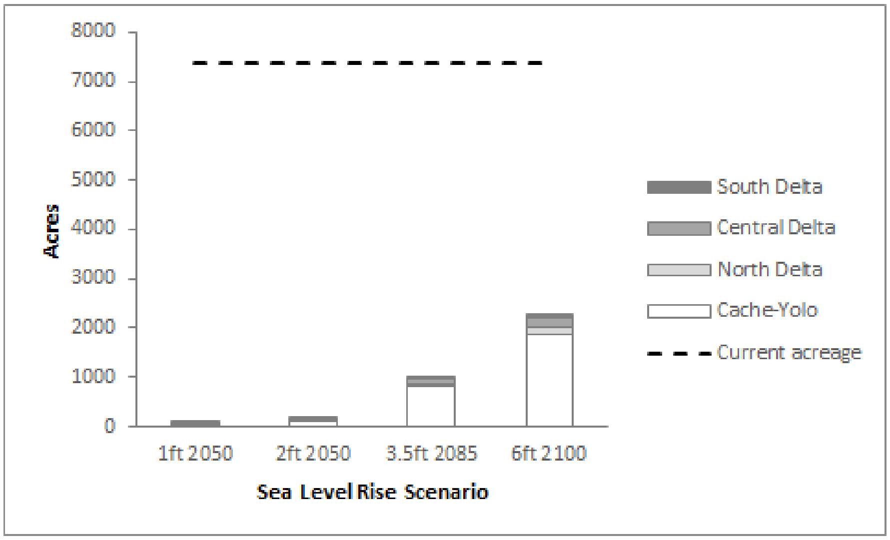


Figure 15. Un-leveed Grassland Acres at Risk of Permanent Flooding with SLR

Note: The dashed line indicates the current acreage of grassland ecosystems.

Table 10. Acres of Un-Leveed Riparian/Willow Ecosystems and Grasslands at Risk with SLR

Ecosystem Asset	Region	Current Acres	Acres at risk *(%)* 6" by 2030	Acres at risk *(%)* 12" by 2050	Acres at risk *(%)* 24" by 2050	Acres at risk *(%)* 42" by 2085	Acres at risk *(%)* 72" by 2100
Riparian/ Willow	Yolo-Cache	1,484	1 (<1%)	19 (1%)	113 (8%)	236 (16%)	797 (54%)
	North Delta	966	28 (3%)	54 (6%)	121 (13%)	213 (22%)	395 (41%)
	Central Delta	2,840	41 (1%)	81 (3%)	236 (8%)	614 (22%)	1904 (67%)
	South Delta	2,032	19 (1%)	47 (2%)	88 (4%)	192 (9%)	315 (15%)
	Suisun	301	1 (1%)	2 (1%)	10 (3%)	22 (7%)	126 (42%)
	Delta and Suisun	**7,623**	**89 (1%)**	**203 (3%)**	**568 (7%)**	**1,277 (17%)**	**3,536 (46%)**
Grassland	Yolo-Cache	4868	28 (1%)	42 (1%)	111 (2%)	828 (17%)	1879 (39%)
	North	1396	3 (<1%)	7 (1%)	17 (1%)	46 (3%)	131 (9%)
	Central	601	15 (3%)	21 (3%)	34 (6%)	80 (13%)	185 (31%)
	South	513	1 (<1%)	2 (<1%)	2 (<1%)	3 (1%)	68 (13%)
	Suisun	0	0	0	0	0	0
	Delta and Suisun	**7,377**	**47 (1%)**	**71 (1%)**	**164 (2%)**	**957 (13%)**	**2262 (31%)**

4.1.3.2 Leveed Ecosystems

For all leveed ecosystems, tables of exposure in 2030 (Table 12) and 2050 (Table 13) are not discussed but can be reviewed in those tables.

Non-tidal Freshwater Wetland

Leveed non-tidal freshwater wetland ecosystems in the Delta are expected to have high exposure to moderate rates of SLR, with 80 percent of current total acres at risk in 2085 with a medium probability of flooding (Table 13, Figure 16). Regionally, Yolo-Cache non-tidal freshwater wetlands are expected to have lowest exposure, with 53 percent at risk, and Central Delta non-tidal freshwater wetlands are expected to have the highest exposure, with 89 percent at risk.

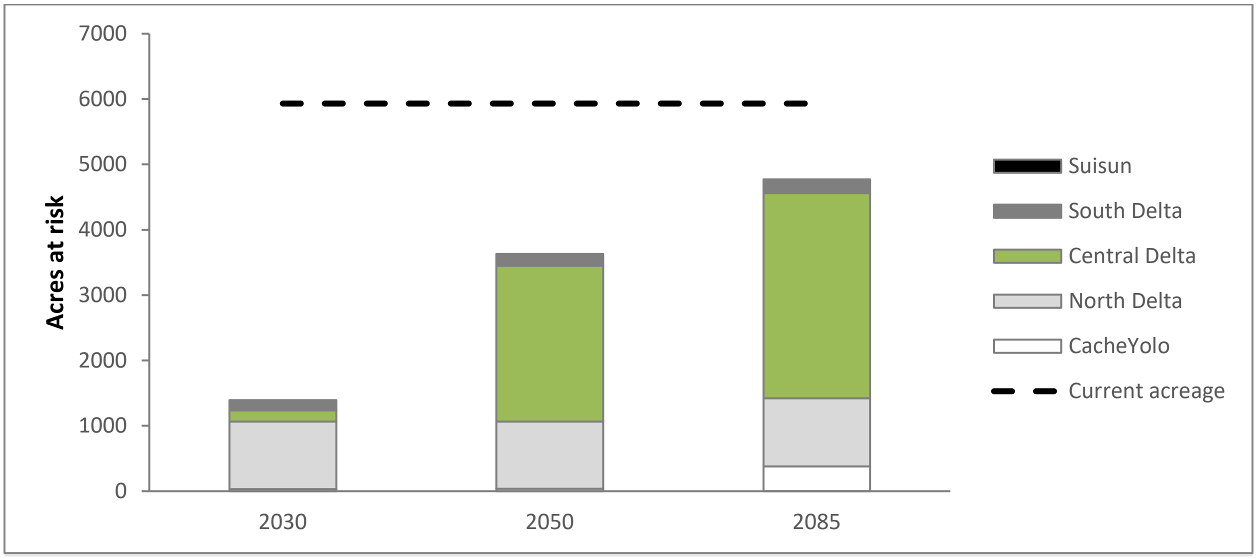


Figure 16. Leveed Freshwater Non-Tidal Wetlands Acres at Risk of Permanent Flooding with SLR

Notes: This figure includes a medium probability of flooding (1-2 percent Equivalent Annual Probability of Exceedance, which equals a 50-100-year return period). The dashed line indicates the current acreage of leveed freshwater non-tidal wetlands.

Managed Wetlands in Suisun Marsh

Managed wetlands in Suisun have high exposure to moderate rates of SLR, with 100 percent of current acres at risk in 2085 with a medium probability of flooding (Table 13, Figure 17).

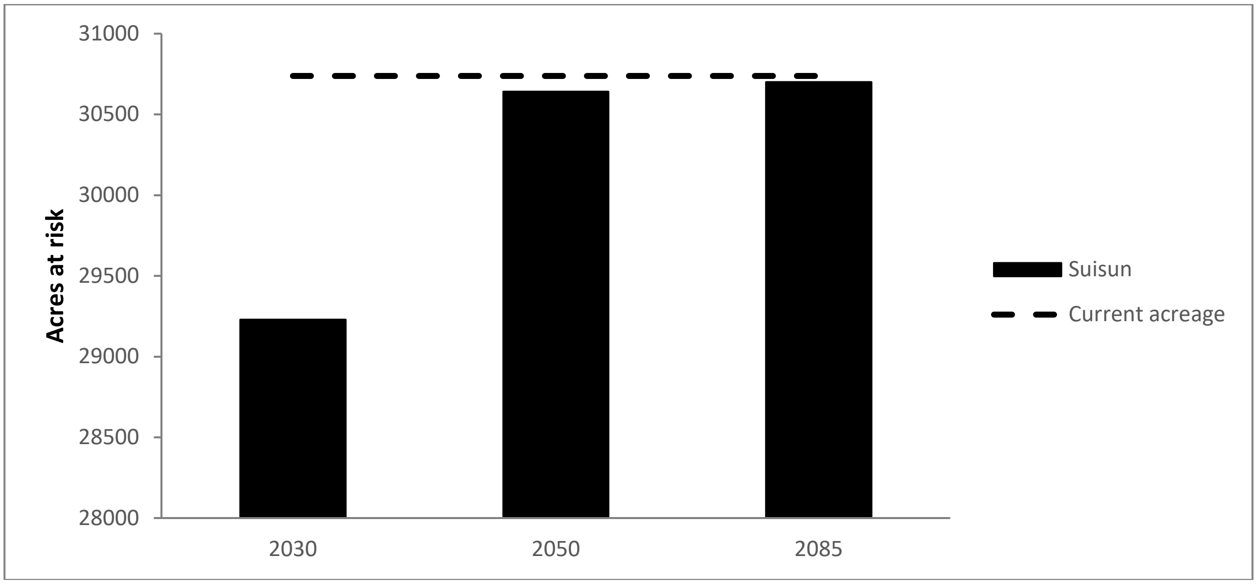


Figure 17. Managed Wetlands Acres in Suisun Marsh at Risk of Permanent Flooding with SLR

Notes: This figure includes a medium probability of flooding (1-2 percent Equivalent Annual Probability of Exceedance, which equals a 50-100-year return period). The dashed line indicates the current acreage of managed wetlands in Suisun Marsh.

Riparian and Willow Ecosystems

Leveed riparian and willow ecosystems are expected to have moderate exposure to moderate rates of SLR, with 64 percent of current total acres at risk in 2085 with a medium probability of flooding (Table 13, Figure 18). Regionally, North Delta riparian areas are expected to have the lowest exposure, with 22 percent at risk, and Suisun Marsh and South Delta riparian areas are expected to have the highest exposure, with 98 percent and 99 percent at risk, respectively.

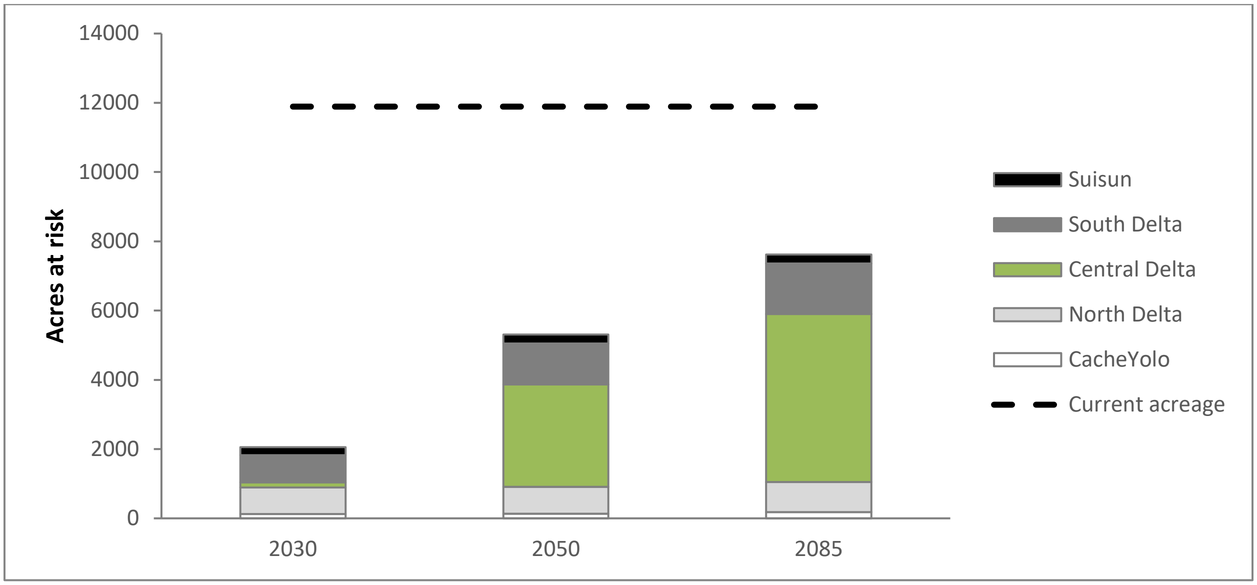


Figure 18. Leveed Riparian and Willow Acres at Risk of Permanent Flooding with SLR

Notes: This figure includes a medium probability of flooding (1-2 percent Equivalent Annual Probability of Exceedance, which equals a 50-100-year return period). The dashed line indicates the current acreage of leveed riparian and willow ecosystems.

Wet Meadow and Seasonal Wetlands

Leveed wet meadow and seasonal wetland ecosystems are expected to have high exposure to high rates of SLR with 81 percent at risk in 2085 with a medium probability of flooding (Table 13, Figure 19). Regionally, wet meadow and seasonal ecosystems are expected to have the lowest exposure in the North Delta, with 6 percent at risk, and the highest exposure in Suisun Marsh, with 100 percent at risk.

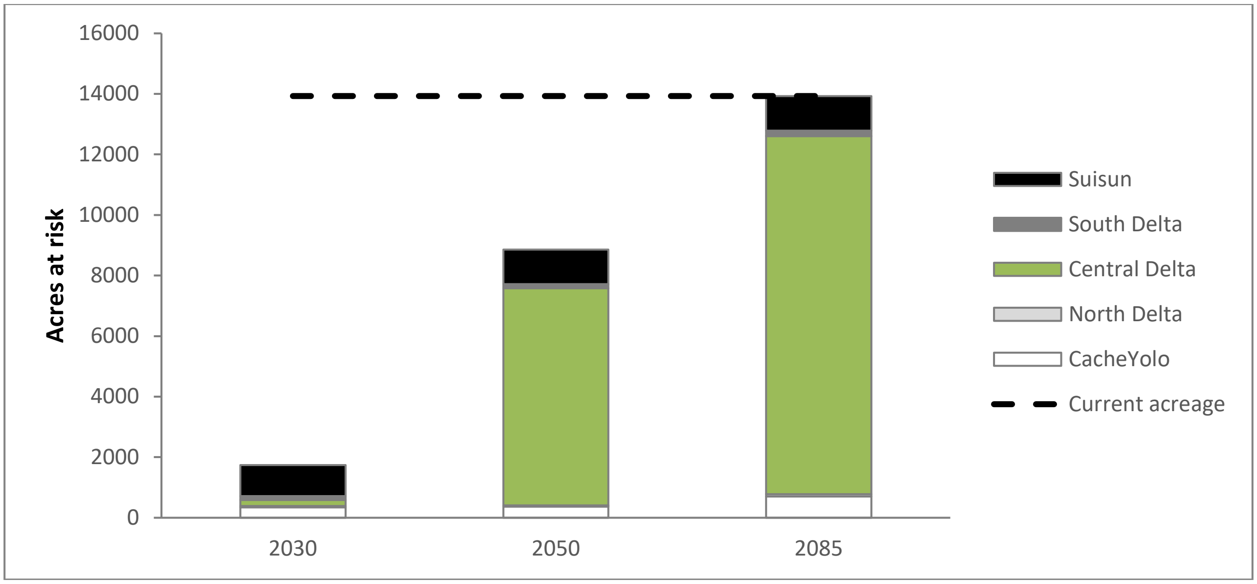


Figure 19. Leveed Wet Meadow and Seasonal Wetland Acres at Risk of Permanent Flooding with SLR

Notes: This figure includes a medium probability of flooding (1-2 percent Equivalent Annual Probability of Exceedance, which equals a 50-100-year return period). The dashed line indicates the current acreage of leveed wet meadow ecosystems.

Alkali Seasonal Wetlands

Leveed alkali seasonal wetland complexes are expected to have low exposure to moderate rates of SLR, with 38 percent at risk in 2085 with a medium probability of flooding (Table 13, Figure 20). Regionally, North Delta alkali seasonal wetlands are expected to have the lowest exposure, with no risk of loss, and South Delta alkali seasonal wetlands are expected to have the highest exposure, with 100 percent at risk; however, in the Yolo-Cache area the largest area of alkali seasonal wetlands (3,679 acres) are at risk.

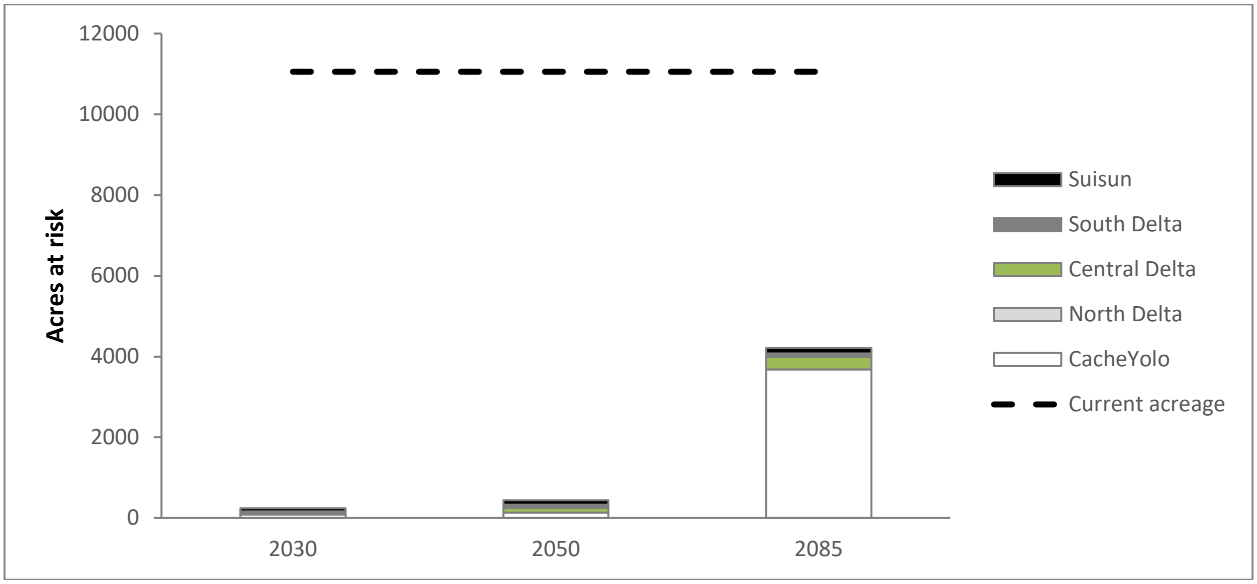


Figure 20. Leveed Alkali Seasonal Wetlands Acres at Risk of Permanent Flooding with SLR

Notes: This figure includes a medium probability of flooding (1-2 percent Equivalent Annual Probability of Exceedance, which equals a 50-100-year return period). The dashed line indicates the current acreage of leveed alkali seasonal wetlands.

Grassland

Leveed grassland ecosystems are expected to have moderate exposure to moderate rates of SLR, 63 percent at risk in 2085 with a medium probability of flooding (Table 13, Figure 21). Regionally, North Delta grasslands are expected to have the lowest exposure, with 16% at risk, and Suisun grasslands are expected to have the highest exposure, with 90 percent at risk.

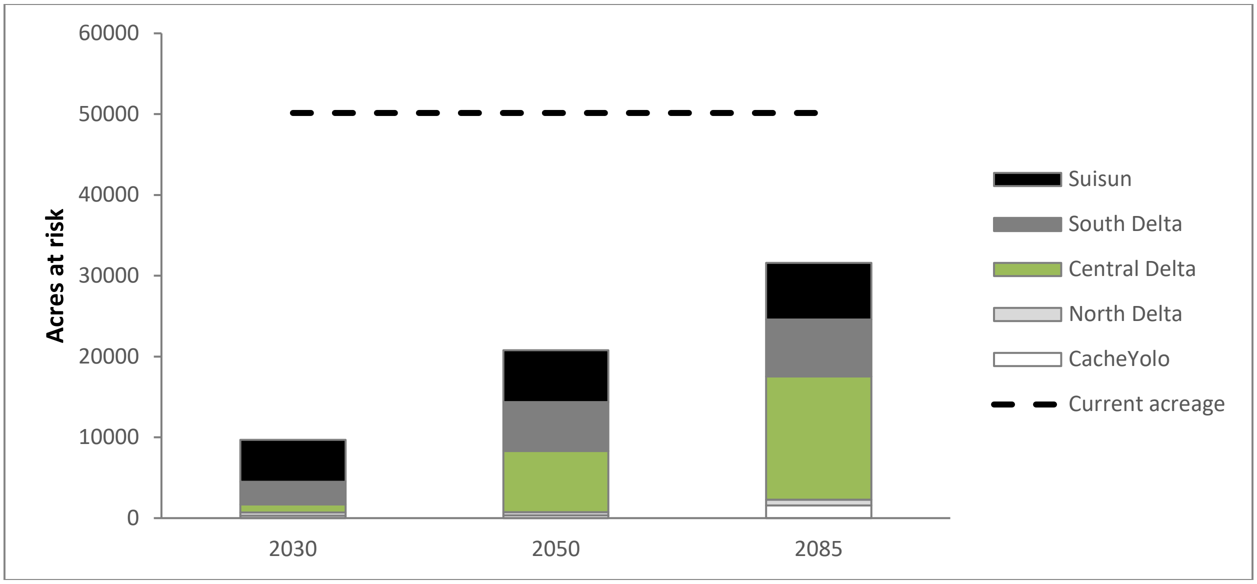


Figure 21. Leveed Grassland Acres at Risk of Permanent Flooding with SLR

Notes: This figure includes a medium probability of flooding (1-2 percent Equivalent Annual Probability of Exceedance, which equals a 50-100-year return period). The dashed line indicates the current acreage of leveed grassland.

Wildlife-associated Agriculture

Wildlife-associated agriculture has high exposure to moderate rates of SLR in 2085, with 68 percent of current total acres at risk (Table 13, Figure 22). Wildlife-associated agriculture in the North Delta is expected to have the lowest exposure, with 17 percent at risk, and agriculture in the South Delta is expected to have the highest exposure, with 85 percent at risk.

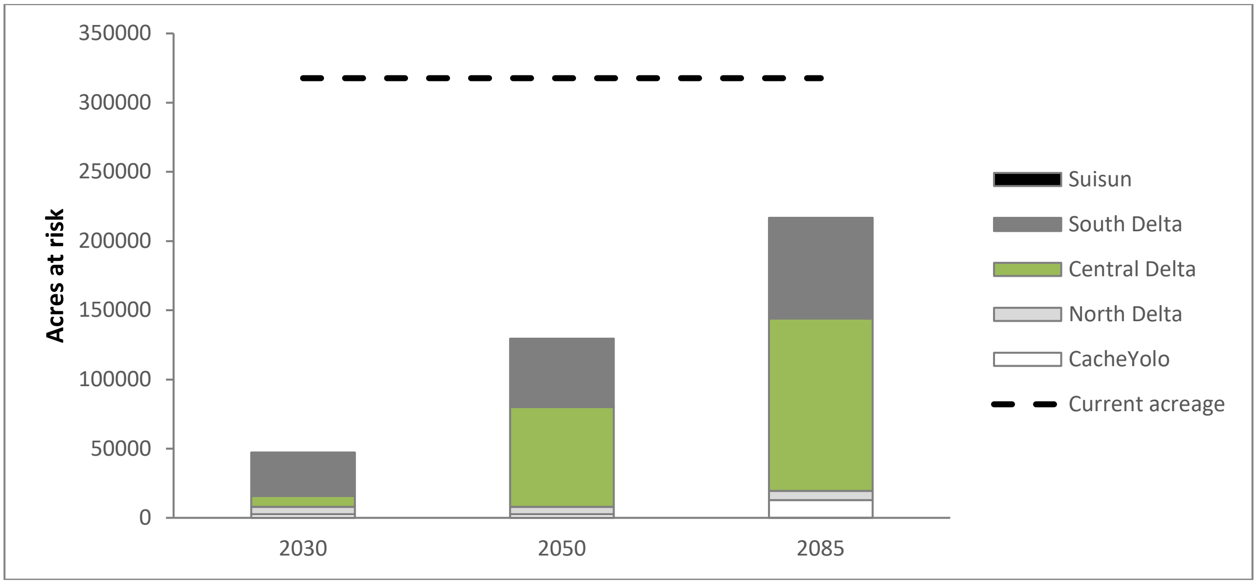


Figure 22. Wildlife-associated Agriculture Acres at Risk of Permanent Flooding with SLR

Notes: This figure includes a medium probability of flooding (1-2 percent Equivalent Annual Probability of Exceedance, which equals a 50-100-year return period). The dashed line indicates the current acreage of wildlife-associated agriculture in the Delta.

Table 11. Leveed Ecosystem Acreage at Risk of Permanent Flooding with SLR in 2030

Ecosystem Asset	Region	Current Acres	Acres (%) at low risk of flooding	Acres (%) at medium risk of flooding	Acres (%) at high risk of flooding	Acres (%) at very high risk of flooding
Nontidal Freshwater Wetlands	Yolo-Cache	725	33 (5%)	33 (5%)	33 (5%)	0
	North Delta	1430	1031 (72%)	1031 (72%)	1026 (72%)	0
	Central Delta	3511	386 (11%)	173 (5%)	137 (4%)	93 (3%)
	South Delta	265	165 (62%)	159 (60%)	0	0
	Total	5931	1614 (27%)	1396 (24%)	1196 (20%)	93 (2%)
Managed Wetland	**Total**	30738	29514 (96%)	29228 (95%)	29011 (94%)	27123 (88%)

Ecosystem Asset	**Region**	**Current Acres**	Acres (%) at **low** risk of flooding	Acres (%) at **medium** risk of flooding	Acres (%) at **high** risk of flooding	Acres (%) at **very high** risk of flooding
Riparian/ Willow Ecosystems	Yolo-Cache	314	121 (39%)	121 (39%)	121 (39%)	0
	North Delta	3894	773 (20%)	773 (20%)	379 (10%)	0
	Central Delta	5917	266 (4%)	147 (2%)	125 (2%)	105 (2%)
	South Delta	1495	896 (60%)	782 (52%)	0	0
	Suisun	269	234 (87%)	234 (87%)	232 (86%)	226 (84%)
	Total	11890	2290 (19%)	2057 (17%)	856 (7%)	331 (3%)
Wet Meadow and Seasonal Wetland	Yolo-Cache	1996	344 (17%)	344 (17%)	344 (17%)	0
	North Delta	1214	42 (3%)	42 (3%)	16 (1%)	0
	Central Delta	12580	289 (2%)	207 (2%)	198 (2%)	186 (1%)
	South Delta	184	128 (70%)	126 (69%)	0	0
	Suisun	1141	1037 (91%)	1021 (89%)	1019 (89%)	917 (80%)
	Total	17115	1841 (11%)	1741 (11%)	1577 (9%)	1103 (6%)
Alkali Seasonal Wetland	Yolo-Cache	7606	86 (1%)	86 (1%)	86 (1%)	0
	North Delta	1893	0	0	0	0
	Central Delta	1308	50 (4%)	1	1	0
	South Delta	79	79 (100%)	79 (100%)	0	0
	Suisun	168	76 (45%)	76 (45%)	76 (45%)	76 (45%)
	Total	11054	290 (3%)	242 (2%)	162 (1%)	76 (1%)
Grassland	Yolo-Cache	3625	305 (8%)	305 (8%)	305 (8%)	0
	North Delta	4540	387 (9%)	386 (9%)	135 (3%)	0
	Central Delta	24099	1496 (6%)	997 (4%)	978 (4%)	297 (1%)
	South Delta	10080	3028 (30%)	2828 (28%)	0	0
	Suisun	7800	5356 (69%)	5178 (66%)	4769 (61%)	4243 (54%)
	Total	50144	10572 (21%)	9695 (19%)	6187 (12%)	4540 (9%)
Wildlife-associated Agriculture	Yolo-Cache	36378	2533 (7%)	2533 (7%)	2533 (7%)	0
	North Delta	38986	5316 (14%)	5316 (14%)	1891 (5%)	0
	Central Delta	156901	11949 (8%)	8020 (5%)	8020 (5%)	7711 (5%)
	South Delta	85417	33920 (40%)	31422 (37%)	0	0
	Total	317682	53718 (17%)	47292 (15%)	12444 (4%)	7711 (2%)

Notes: Risk in 2030 is assessed at four levels of flood risk probability (1-2 percent Equivalent Annual Probability of Exceedance, which equals a 50-100-year return period).

Table 12. Leveed Ecosystem Acreage at Risk of Permanent Flooding with SLR in 2050

Ecosystem Asset	**Region**	**Current Acres**	Acres (%) at **low** risk of flooding	Acres (%) at **medium** risk of flooding	Acres (%) at **high** risk of flooding	Acres (%) at **very high** risk of flooding
Nontidal Freshwater Wetlands	Yolo-Cache	725	37 (5%)	36 (5%)	34 (5%)	33 (5%)
	North Delta	1430	1040 (73%)	1031 (72%)	1031 (72%)	1013 (71%)
	Central Delta	3511	2553 (73%)	2385 (68%)	1723 (49%)	173 (5%)
	South Delta	265	202 (76%)	181 (68%)	173 (65%)	0
	Total	5931	3831 (65%)	3633 (61%)	2960 (50%)	1219 (21%)
Managed Wetland	**Total**	30738	30649 (100%)	30640 (100%)	30633 (100%)	29228 (95%)
Riparian/ Willow Ecosystems	Yolo-Cache	314	138 (44%)	134 (43%)	129 (41%)	117 (37%)
	North Delta	3894	829 (21%)	773 (20%)	773 (20%)	224 (6%)
	Central Delta	5917	3537 (60%)	2959 (50%)	1939 (33%)	147 (2%)
	South Delta	1495	1282 (86%)	1184 (79%)	1069 (71%)	0
	Suisun	269	257 (96%)	257 (96%)	256 (95%)	234 (87%)
	Total	11890	6042 (51%)	5307 (45%)	4167 (35%)	722 (6%)
Wet Meadow and Seasonal Wetland	Yolo-Cache	1996	382 (19%)	371 (19%)	355 (18%)	326 (16%)
	North Delta	1214	75 (6%)	42 (3%)	42 (3%)	6 (1%)
	Central Delta	12580	9264 (74%)	7166 (57%)	3923 (31%)	207 (2%)
	South Delta	184	147 (80%)	140 (76%)	132 (71%)	0
	Suisun	1141	1139 (100%)	1139 (100%)	1139 (100%)	1021 (89%)
	Total	17115	11008 (64%)	8858 (52%)	5591 (33%)	1560 (9%)

Ecosystem Asset	Region	Current Acres	Acres (%) at **low** risk of flooding	Acres (%) at **medium** risk of flooding	Acres (%) at **high** risk of flooding	Acres (%) at **very high** risk of flooding
Alkali Seasonal Wetland	Yolo-Cache	7606	151 (2%)	130 (2%)	108 (1%)	52 (1%)
	North Delta	1893	0	0	0	0
	Central Delta	1308	271 (21%)	122 (9%)	96 (7%)	1 (0%)
	South Delta	79	79 (100%)	79 (100%)	79 (100%)	0
	Suisun	168	116 (69%)	108 (64%)	108 (64%)	76 (45%)
	Total	11054	617 (6%)	439 (4%)	392 (4%)	129 (1%)
Grassland	Yolo-Cache	3625	361 (10%)	337 (9%)	319 (9%)	291 (8%)
	North Delta	4540	474 (10%)	388 (9%)	388 (9%)	117 (3%)
	Central Delta	24099	9304 (39%)	7581 (31%)	4242 (18%)	997 (4%)
	South Delta	10080	6484 (64%)	6064 (60%)	3520 (35%)	0
	Suisun	7800	6479 (83%)	6417 (82%)	6375 (82%)	5178 (66%)
	Total	50144	23102 (46%)	20787 (41%)	14845 (30%)	6584 (13%)
Wildlife-associated Agriculture	Yolo-Cache	36378	2539 (7%)	2538 (7%)	2536 (7%)	2527 (7%)
	North Delta	38986	6464 (17%)	5316 (14%)	5316 (14%)	453 (1%)
	Central Delta	156901	94976 (61%)	72076 (46%)	42149 (27%)	8020 (5%)
	South Delta	85417	54697 (64%)	49578 (58%)	45371 (53%)	0
	Suisun	0	0	0	0	0
	Total	317682	158676 (50%)	129509 (41%)	95372 (30%)	11001 (3%)

Notes: Risk in 2050 is assessed at four levels of flood risk probability (1-2 percent Equivalent Annual Probability of Exceedance, which equals a 50-100-year return period

Table 13. Leveed Ecosystem Acreage at Risk of Permanent Flooding with SLR in 2085

Ecosystem Asset	Region	Current Acres	Acres (%) at **low** risk of flooding	Acres (%) at **medium** risk of flooding	Acres (%) at **high** risk of flooding	Acres (%) at **very high** risk of flooding
Nontidal Freshwater Wetlands	Yolo-Cache	725	450 (62%)	382 (53%)	37 (5%)	0
	North Delta	1430	1057 (74%)	1040 (73%)	1040 (73%)	0
	Central Delta	3511	3143 (90%)	3137 (89%)	3132 (89%)	93 (3%)
	South Delta	265	213 (80%)	213 (80%)	210 (79%)	0
	Total	5931	4863 (82%)	4772 (80%)	4419 (75%)	93 (2%)
Managed Wetland	**Total**	30738	30703 (100%)	30700 (100%)	30698 (100%)	27123 (88%)
Riparian/ Willow Ecosystems	Yolo-Cache	314	187 (60%)	181 (58%)	138 (44%)	0
	North Delta	3894	1225 (31%)	864 (22%)	829 (21%)	0
	Central Delta	5917	5068 (86%)	4851 (82%)	4823 (82%)	105 (2%)
	South Delta	1495	1462 (98%)	1462 (98%)	1430 (96%)	0
	Suisun	269	265 (99%)	265 (99%)	265 (99%)	226 (84%)
	Total	11890	8206 (69%)	7622 (64%)	7485 (63%)	331 (3%)
Wet Meadow and Seasonal Wetland	Yolo-Cache	1996	724 (36%)	708 (36%)	382 (19%)	0
	North Delta	1214	124 (10%)	75 (6%)	75 (6%)	0
	Central Delta	12580	11884 (94%)	11828 (94%)	11826 (94%)	186 (1%)
	South Delta	184	178 (97%)	178 (97%)	177 (96%)	0
	Suisun	1141	1140 (100%)	1140 (100%)	1140 (100%)	917 (80%)

Ecosystem Asset	Region	Current Acres	Acres (%) at **low** risk of flooding	Acres (%) at **medium** risk of flooding	Acres (%) at **high** risk of flooding	Acres (%) at **very high** risk of flooding
	Total	17115	14050 (82%)	13930 (81%)	13600 (79%)	1103 (6%)
Alkali Seasonal Wetland	Yolo-Cache	7606	3954 (52%)	3679 (48%)	151 (2%)	0
	North Delta	1893	0 *0*	0 *0*	0 *0*	0 *0*
	Central Delta	1308	328 (25%)	319 (24%)	308 (24%)	0
	South Delta	79	79 (100%)	79 (100%)	79 (100%)	0
	Suisun	168	129 (77%)	129 (77%)	125 (75%)	76 (45%)
	Total	11054	4491 (41%)	4207 (38%)	663 (6%)	76 (1%)
Grassland	Yolo-Cache	3625	1957 (54%)	1563 (43%)	361 (10%)	0
	North Delta	4540	1253 (28%)	711 (16%)	474 (10%)	0
	Central Delta	24099	15649 (65%)	15259 (63%)	15032 (62%)	297 (1%)
	South Delta	10080	7172 (71%)	7061 (70%)	6659 (66%)	0
	Suisun	7800	7098 (91%)	6996 (90%)	6957 (89%)	4243 (54%)
	Total	50144	33128 (66%)	31589 (63%)	29484 (59%)	4540 (9%)
Wildlife-associated Agriculture	Yolo-Cache	36378	13753 (38%)	12852 (35%)	2539 (7%)	0
	North Delta	38986	8817 (23%)	6638 (17%)	6464 (17%)	0
	Central Delta	156901	125650 (80%)	124431 (79%)	123182 (79%)	7711 (5%)
	South Delta	85417	73543 (86%)	72772 (85%)	61322 (72%)	0
	Suisun	0	0	0	0	0
	Total	317682	221763 (70%)	216693 (68%)	193508 (61%)	7711 (2%)

Notes: Risk in 2085 is assessed at four levels of flood risk probability (1-2 percent Equivalent Annual Probability of Exceedance, which equals a 50-100-year return period

4.2 Sensitivity

The sensitivity analysis evaluates the degree to which an ecosystem asset is sensitive to a particular climate stressor. For the following sensitivity matrix (Table 15), primary climate stressors were evaluated and include: Air Temperature, Local Precipitation, and SLR.

For all climate stressors Air Temperature and Local Precipitation, the sensitivity matrix synthesizes the results of both exposure and sensitivity. Due to the spatially explicit quantitative results available for exposure and sensitivity, these were analyzed separately for the climate stressor SLR, except for tidal freshwater and brackish wetlands, where modeling results that incorporate sensitivity were included as part of the exposure analysis.

Sensitivity to SLR of leveed ecosystems is determined by levee height, levee condition, and subsided land elevation. Ecosystem sensitivity therefore varies between Delta islands; however, it is beyond the scope of this study to assess levee condition. Dominant vegetation communities and physical processes of leveed ecosystems were evaluated as highly sensitive to SLR because most islands are subsided, and ecosystems would shift to open water habitat if islands flood (Durand 2017). The response of fish and wildlife species was evaluated in a more differentiated manner. In general, permanent flooding of terrestrial island ecosystems will increase fish habitat, but the quality and type of habitat will vary across Delta regions and risk (Ibid). Avian species will likely be able to adapt to some changes in ecosystems configuration due to their mobility (Dybala et al. 2020). Terrestrial species like salt marsh harvest mice and giant garter snakes may be less sensitive to gradual changes in SLR, but highly sensitive to episodic flooding events (e.g., Smith et al. 2020). Due to the diversity of climate change impacts on fish and wildlife species, we have attempted to highlight the relevant impacts to the extent possible, but responses are likely to be highly species specific.

Sensitivity of un-leveed ecosystems to SLR is ultimately determined by the current elevation, the ability to accrete surface elevation in place, and the ability to move upland.

Due to the use of the WARMER model to project tidal wetland surface elevations for the exposure section, some aspects of sensitivity are already incorporated into the analysis for these ecosystems, which factored into the sensitivity rankings for freshwater and brackish tidal marshes. The ability of tidal wetlands to move upland was assessed by qualitatively by examining the adjacency of existing tidal wetlands identified by VegCAMP to upland transition zone as mapped by Council 2020. This demonstrated that the opportunity for tidal wetlands to move to adjacent upland transition zones is highly limited in the Delta. This is particularly true in the Central Delta, where the accretion potential is the highest, which makes tidal freshwater ecosystems across the Delta highly sensitive to SLR. Some potential for upland transition exists in the Suisun Marsh, which was identified by Schile et al. 2014 as critical for increasing tidal marsh sustainability at Rush Ranch. However, upland transition area for tidal brackish wetland does not occur everywhere in the Suisun Marsh. In addition to the impacts of SLR or marsh surface elevations, brackish tidal wetlands in Suisun Marsh may also be impacted by changes in salinity. Increasing salinity will change species composition, lower organic productivity, and subsequently lower the ability of tidal wetlands to keep pace with SLR.

Table 14. Sensitivity Matrix of Delta Ecosystems to Primary Climate Stressors on a Scale of 1 (Low) to 3 (High)

Ecosystem Type	Ecosystem Components	Sensitivity of each ecosystem component to **SLR**	Sensitivity of overall ecosystem to **SLR**	Sensitivity of ecosystem component to **air temperature**	Sensitivity of ecosystem to **air temperature**	Sensitivity of ecosystem component to **local precipitation**	Sensitivity of ecosystem to **local precipitation**
Tidal Freshwater Emergent Wetland	Dominant Vegetation Communities	3	high	1	Low	1	low
	Fish and Wildlife Species	3		1		1	
	Physical Processes	2		1		1	
Non-tidal Freshwater Emergent Wetland (leveed)	Dominant Vegetation Communities	3	high	1	moderate	1	moderate
	Fish and Wildlife Species	2		2		2	
	Physical Processes	3		1		1	
Tidal Brackish Emergent Wetland (Un-leveed)	Dominant Vegetation Communities	3	high	1	low	1	low
	Fish and Wildlife Species	3		1		1	
	Physical Processes	2		1		1	
Managed Wetland (leveed)	Dominant Vegetation Communities	3	high	1	low	1	low

Ecosystem Type	Ecosystem Components	Sensitivity of each ecosystem component to SLR	Sensitivity of overall ecosystem to **SLR**	Sensitivity of ecosystem component to **air temperature**	Sensitivity of ecosystem to **air temperature**	Sensitivity of ecosystem component to **local precipitation**	Sensitivity of ecosystem to **local precipitation**
	Fish and Wildlife Species	2	🟥	1	🟨	1	🟨
	Physical Processes	3		1		1	
Riparian/Willow Ecosystems (un-leveed)	Dominant Vegetation Communities	1	low	2	moderate	2	moderate
	Fish and Wildlife Species	1		2		2	
	Physical Processes	1		2		2	
Riparian/Willow Ecosystems (leveed)	Dominant Vegetation Communities	3	high	2	moderate	2	moderate
	Fish and Wildlife Species	2		2		2	
	Physical Processes	3		2		2	
Wet Meadow and Seasonal Wetland (leveed)	Dominant Vegetation Communities	3	high	3	high	3	high

Ecosystem Type	Ecosystem Components	Sensitivity of each ecosystem component to SLR	Sensitivity of overall ecosystem to SLR	Sensitivity of ecosystem component to air temperature	Sensitivity of ecosystem to air temperature	Sensitivity of ecosystem component to local precipitation	Sensitivity of ecosystem to local precipitation
	Fish and Wildlife Species	3		3		3	
	Physical Processes	3		3		3	
Alkali Seasonal Wetland Complex (leveed)	Dominant Vegetation Communities	3	high	3	high	3	high
	Fish and Wildlife Species	3		3		3	
	Physical Processes	3		3		3	
Grassland (un-leveed)	Dominant Vegetation Communities	2	moderate	2	moderate	2	moderate
	Fish and Wildlife Species	1		2		2	
	Physical Processes	2		2		2	
Grassland (leveed)	Dominant Vegetation Communities	3	high	2	moderate	2	moderate
	Fish and Wildlife Species	2		2		2	

Ecosystem Type	Ecosystem Components	Sensitivity of each ecosystem component to **SLR**	Sensitivity of overall ecosystem to **SLR**	Sensitivity of ecosystem component to **air temperature**	Sensitivity of ecosystem to **air temperature**	Sensitivity of ecosystem component to **local precipitation**	Sensitivity of ecosystem to **local precipitation**
	Physical Processes	3		2		2	
Wildlife-associated Agriculture (leveed)	Dominant Vegetation Communities	3	high	1	low	1	low
	Fish and Wildlife Species	2		1		1	
	Physical Processes	3		1		1	

4.1.1 Tidal Freshwater Emergent Wetland

4.2.1.1 Air Temperature

Tidal freshwater emergent wetlands were rated low for sensitivity to increases in air temperature. Increased air temperatures will likely lead to increased local water temperatures which could adversely affect the distribution of aquatic species within this habitat (Durand 2008, 2015; Schoellhamer et al. 2016). However, as these systems are largely influenced by tidal action, the incoming cooler oceanic waters may ameliorate the stress of increased air temperatures on this ecosystem type (Dettinger and Cayan 1995, Kimmerer 2004, Lebassi et al. 2009). Since these ecosystems are often inundated, they can absorb more heat and buffer organisms against rising temperatures (Naiman et al. 2000).

4.2.1.2 Precipitation

Tidal freshwater emergent wetlands were rated low for sensitivity to changes in precipitation. These tidal systems are less dependent on local precipitation. Similarly, emergent vegetation, wildlife and aquatic species are adapted to the daily fluctuations in water availability and periods of desiccation (Kimmerer 2002). Salinity levels will change with wet or dry periods; however, plant and wildlife species are adapted to these fluctuations (Glibert et al. 2014, Brown et al. 2016). Further, water system operations to maintain the hydraulic salinity barrier (see section 2.1.2) are likely to prevent salinity intrusion, even during droughts.

4.2.1.3 Sea Level Rise

Tidal freshwater emergent wetlands were rated moderate for sensitivity to SLR.

Dominant Vegetative Communities

Organic and mineral accretion allow these ecosystems to keep pace with moderate rates of SLR (Thorne et al. 2018, Swanson et al. 2015, Schile et al. 2014, this study). Under 2 feet of SLR, 47 percent of freshwater tidal wetlands will transition from high to low marsh. Under 6 feet of SLR, 47 percent of freshwater tidal wetlands will have drowned and 53 percent will transition to low marsh. Upland transition zone SLR accommodation space for tidal freshwater wetlands is limited in the Delta, preventing existing tidal wetlands from migrating upland. Therefore, sensitivity was rated high for dominant vegetative communities of tidal freshwater emergent wetland.

Fish and Wildlife Species

Sensitivity of fish and wildlife species in tidal freshwater emergent wetlands to SLR is high. As high marsh habitats transition to low marsh primary productivity decreases, which will have implications for both aquatic and terrestrial species. Under SLR of 6 feet and above, substantial areas of fish and wildlife habitat are likely to disappear. In addition, high water storm and king tide events are likely to impact resident species in acute events beyond the chronic changes reflected in this analysis, particularly where upland transition and high tide refugia are not available (SFEI and SPUR 2019). Therefore, sensitivity was rated high for fish and wildlife species.

Future assessments of sensitivity should determine the extent of upland transition under more extreme SLR scenarios to discern the full impact on wildlife species.

Physical Processes

Tidal freshwater marshes generally persist between MLLW and MHHW (Schile et al. 2014; Swanson et al. 2015). Biophysical feedbacks between vegetation primary productivity (above and belowground) and mineral sediment allow wetlands to keep pace with moderate levels of SLR. The modeling performed for this effort indicates that the physical processes needed for tidal wetland persistence are likely to be retained through 3.5 feet of SLR by 2085. However, if island breaches change the hydrodynamics of the system, local water levels may be impacted. Further, by end-of-century SLR may lead to increases in salinity, reducing organic matter production and lowering rates of accretion, putting the persistence of these ecosystems at risk (Swanson et al. 2015). Sensitivity of physical processes to SLR was rated moderate.

Site-Level and Regional Wetland Sensitivity to SLR

The sensitivity of un-leveed ecosystems to SLR is determined by the current elevation, the ability to move upland, and the ability to accrete surface elevation in place.

Because a vegetation-corrected DEM does not exist for the Delta, a single initial elevation value reflecting the median value of high/mid marsh (30 cm in the Delta based on Swanson et al. 2015; 60 cm in Suisun Marsh based on Buffington et al. 2019) was used for each patch of tidal wetland, effectively removing site-level variation from the model results. Thus, transitions to low marsh are considered at the site level. Freshwater wetland species are able to persist in areas that are continuously inundated (Sloey et al. 2015, 2016).

4.1.2 Non-Tidal Freshwater Wetland

4.2.2.1 Air Temperature

Non-tidal freshwater wetlands were rated moderate for sensitivity to increases in air temperature.

Dominant Vegetative Communities

It is expected that warming temperatures will increase evapotranspiration rates causing stress on vegetation (Anderson et al. 2008). However, these habitats will likely be buffered by inundation because these habitats are permanently saturated due to management and high water table levels(Naiman et al. 2000). Additionally, emergent vegetation such as bulrushes, tule and cattails are adapted to seasonally dry conditions (SFEI–ASC 2012). Therefore, dominant vegetation communities were ranked as having a low sensitivity to changes in air temperature.

Fish and Wildlife

Fish and wildlife species within this habitat type were ranked as having a moderate sensitivity to changes in air temperature. Increasing air temperatures will result in warming waters and reduced inundation extent (Durand 2008, 2015). These changes could negatively impact aquatic species reliant on specified temperature thresholds for physiological processes (Wagner et al. 2011) and sustained inundation. Other wildlife may be less impacted as dominant vegetation communities will still provide adequate habitat and some level of shading (DeHaven 1989).

Physical Processes

With increasing temperatures, non-tidal wetlands will likely be more vulnerable to desiccation and water stress due to increased evapotranspiration (Mauger et al. 2015). But as these habitats are indirectly influenced by the tides that maintain high water table levels, the impacts of higher temperatures are minimized (Naiman et al. 2000). Therefore, physical processes of non-tidal freshwater wetlands were ranked as having a low sensitivity to changes in air temperature.

4.2.2.2 Precipitation

Non-tidal freshwater wetlands were rated moderate sensitivity to change in precipitation.

Dominant Vegetative Communities

Changes to seasonal precipitation patterns, especially decreases in the fall and spring, could place undue stress on vegetation communities found in non-tidal freshwater wetlands (Diffenbaugh et al. 2015, Dettinger et al. 2016). However, as these habitats are permanently saturated due to higher water table levels, effects of decreased seasonal precipitation will likely be buffered. Additionally, common plant species within this habitat are adapted to seasonal fluctuations in precipitation (SFEI–ASC 2012). Therefore, dominant vegetation communities were ranked as having a low sensitivity to changes in precipitation.

Fish and Wildlife

Reduced spring and fall precipitation coupled with increasing temperatures could increase amphibian and reptile vulnerability to impacts of climate change. Although there may be adequate ponding throughout the year, there could be a mismatch between habitat availability and species needs, inhibiting completion of life history cycles (Mauger et al. 2015, Cloern et al. 2011). As a result, fish and wildlife species were ranked as having a moderate sensitivity to shifts in precipitation patterns.

Physical Processes

With changes in precipitation, non-tidal wetlands will likely be more vulnerable to desiccation and evapotranspiration (Anderson et al. 2008, Mauger et al. 2015). But as these habitats are indirectly influenced by the tides that maintain high water table levels, the impacts of stochastic precipitation patterns are likely buffered. Therefore, physical processes of non-tidal freshwater wetlands were ranked as having a low sensitivity to changes in precipitation.

4.2.2.3 Sea Level Rise

Fish and Wildlife

The extent of freshwater emergent wetland has decreased by 98 percent in the modern Delta (without Suisun Marsh; SFEI–ASC 2014). Any further losses due to climate change would mean a significant loss of habitat of species dependent on these ecosystems. Therefore, fish and wildlife associated with non-tidal freshwater wetlands were ranked as highly sensitive to SLR.

4.1.3 Tidal Brackish Emergent

4.2.3.1 Air Temperature

Tidal brackish wetlands were rated low sensitivity to increases in air temperature. Increased air temperatures will likely lead to increased water temperatures, adversely affecting the distribution of aquatic species within this habitat (Durand 2008, 2015; Cloern et al. 2016). However, as these systems are largely influenced by tidal action, incoming cooler oceanic waters may ameliorate the stressors of increased air temperatures (Dettinger and Cayan 1995, Lebassi et al. 2009).

4.2.3.2 Precipitation

Tidal brackish emergent wetlands were rated low sensitivity to changes in precipitation. As they are tidally influenced, they have a low reliance on direct rainfall. Similarly, emergent vegetation, wildlife and aquatic species in tidal brackish marshes are adapted to daily fluctuations in water availability and periods of desiccation (Mauger et al. 2015, Cloern et al. 2016, Schoellhamer et al. 2016). Consequently, these habitats are fairly resilient to periods of drought and storm events (Diffenbaugh et al. 2015, Dettinger et al. 2016).

4.2.3.3 Sea Level Rise

Dominant Vegetative Communities

Tidal brackish marshes generally persist between MLLW and MHHW and were rated high sensitivity to SLR. Biophysical feedbacks between vegetation primary productivity (above and belowground) and mineral sediment allow wetlands to keep pace with moderate rates of SLR (Thorne et al. 2018, Swanson et al. 2015, Schile et al. 2014), but all high marsh is likely to transition to low marsh by 3.5 feet SLR.

Fish and Wildlife

While sensitivity of fish and wildlife species in tidal brackish emergent wetlands to moderate SLR is low, it is likely to increase under SLR rates of 3.5 feet and above. In addition, high water storm and king tide events are likely to impact resident species, particularly where upland transition and high tide refugia are not available (SFEI and SPUR 2019). Salt marsh harvest mice are common in tidal brackish marshes and will be sensitive to both long-term changes in sea level and acute high water events (Rosencranz et al. 2019). Tidal brackish marshes in Suisun, particularly in the Rush Ranch area, have some upland transition zones that will allow for high-tide refuge and the potential for marshes to move upland, but not all areas have this potential (Schile et al. 2014). Further, brackish marsh wildlife is highly dependent on high marsh, and thus will be highly sensitive to transitions to low marsh (Rosencranz et al. 2019). Therefore, sensitivity was rated high for fish and wildlife species.

Future assessments of sensitivity should determine the extent of upland transition under more extreme SLR scenarios to discern the full impact on wildlife species.

Physical Processes

Physical properties were ranked as moderately sensitive to SLR. The modeling performed for this effort indicates that the physical processes needed for tidal brackish wetland persistent are likely to be retained through 2 feet of SLR, and some upland transition zone SLR accommodation space is available. If climate change increases sediment availability, these ecosystems may be able to maintain their elevation (Stern et al. 2020). However, hydrodynamics and local water levels may change in unpredictable ways if islands are breached, increasing the risk of altering physical processes. Increases in salinity may shift species composition towards a lower productivity saline marsh structure that could reduce the organic accretion rate (Schile et al. 2014).

4.1.4 Managed Wetlands

4.2.4.1 Air Temperature

Managed wetlands were ranked as having a low sensitivity to increases in temperature.

These systems are heavily managed for waterfowl and hunting purposes within the Delta (SFEI–ASC 2014). As a result, managed flooding will keep vegetation buffered from increasing temperatures and will continue to provide adequate habitat for associated species.

4.2.4.2 Precipitation

Managed wetlands were ranked as having a low sensitivity to changes in precipitation. As these systems are actively managed, vegetation and wildlife can be buffered from seasonal precipitation reductions by increasing water flow within these habitats (SFEI–ASC 2014).

4.2.4.3 Sea Level Rise

Fish and Wildlife

Fish and wildlife in managed wetlands were ranked to have moderate sensitivity to SLR. Levee overtopping may change the character of the wetland, but associated fish and wildlife species may be able to adapt. However, some species may be more sensitive to the effects of SLR on managed wetlands. For example, salt marsh harvest mice require high-tide refuge from predators, which will be heavily compromised by increasing sea levels and resulting flooding in managed wetlands (Moyle et al. 2014). Waterfowl, the primary target of managed wetlands, may be negatively impacted if these areas transition to tidal open water. However, aquatic and tidal marsh species may benefit if these areas transition to tidal brackish wetland.

4.1.5 Riparian and Willow Ecosystems

4.2.5.1 Air Temperature

The riparian/willow ecosystem was rated moderately sensitive to increases in air temperature. This ecosystem asset category includes linear habitat types with a diverse degree of tidal and other aquatic influence – those along stream/ river channels to those in valley foothill riparian areas further from water accessibility. As a result, this asset category was challenging to score.

Dominant Vegetative Communities

Vegetative communities in riparian/willow ecosystems were ranked as having a moderate sensitivity to changes in air temperature. Increasing temperatures will likely lead to increased evapotranspiration rates that will decrease soil moisture content (Porporato et al. 2004, Anderson et al. 2008). Therefore, this will increase competition for freshwater sources, driving shifts in plant phenology and potentially altering species composition of riparian/willow ecosystems (Naiman et al. 2000, Hegland et al. 2009).

Fish and Wildlife

Rising air temperatures will warm surrounding waters of riparian/willow ecosystems. Higher water temperatures may exceed the thermal threshold of aquatic species associated with this habitat (Mauger et al. 2015, Cloern et al. 2011). However, riparian areas with thicker vegetation may still provide some level of shading to buffer increasing water temperatures and provide protection from predation for these aquatic species (DeHaven 1989). Fish and wildlife were ranked as having a moderate sensitivity to changes in air temperature in riparian/willow ecosystems.

Physical Processes

Physical processes were ranked as having a moderate sensitivity to changes in air temperature. With increasing temperatures, soil moisture content is likely to be reduced through evapotranspiration which may inhibit fall seedling establishment (Porporato et al. 2004). Additionally, there may be increased competition for groundwater resources if vegetation becomes stressed due to lack of water (Sridhar et al. 2004, Cassie 2006). These stressors will be higher in riparian/willow ecosystems that are disconnected from the Delta’s hydrology.

4.2.5.2 Precipitation

The Riparian/Willow complex was rated moderate for sensitivity to changes in precipitation.

Dominant Vegetative Communities

Riparian vegetation communities were ranked as having a moderate sensitivity to changes in precipitation. Projected reductions in fall precipitation could impact fall seedling establishment, leading to phenological shifts and community composition changes (Porporato et al. 2004). Established vegetation in riparian/willow ecosystems connected to local water sources will likely not be as affected by precipitation changes as they can tap into groundwater sources (Seavey et al. 2009). However, riparian/willow ecosystems with lower water content and disconnected from rivers due to levees or those located in upland habitats will be more vulnerable to reduced precipitation as well as prolonged drought events (Naiman et al. 2000). In general, riparian/willow ecosystems are adapted to fluxes in precipitation and are resilient to storm events and short-term droughts.

Fish and Wildlife

Fish and Wildlife were ranked as having a moderate sensitivity to changes in precipitation. With projected reductions in spring and fall precipitation, intact riparian/willow ecosystems will provide suitable habitat for organisms looking to relocate for more reliable water sources, whereas isolated habitats will be less suited to provide adequate habitat for wildlife (Seavey et al. 2009). Furthermore, flooding events brought on by winter storms and atmospheric river events may have deleterious effects on water quality adding to impacts of aquatic species and other wildlife (Feyrer et al. 2011, MacWilliams et al. 2016, SWRCB 2010).

Physical Processes

Riparian/willow ecosystems can withstand, and are adapted, to major flashflood events brought on by atmospheric rivers. However, increased winter storm events are likely to negatively impact water quality (Seavey et al. 2009). This could have a disproportionate and negative effect on riparian/willow ecosystems connected to the Delta's hydrology compared to those habitats that are isolated from it. Physical processes were ranked as having a moderate sensitivity to changes in precipitation.

4.2.5.3 Sea Level Rise

Un-leveed Riparian/Willow Ecosystems

Dominant Vegetative Communities

The sensitivity to SLR of the dominant vegetation communities of un-leveed riparian/willow ecosystems is determined by accretion rates and elevation range. Because riparian and willow ecosystems can withstand periodic flooding and accretion likely occurs (although it has not been studied for these ecosystems in the Delta), they were ranked as having a low sensitivity to moderate changes in SLR.

Fish and Wildlife

Because riparian and willow vegetative communities have a low sensitivity to SLR with moderate levels of SLR, fish and wildlife species depending on these vegetation communities were also ranked to have a low sensitivity to SLR.

Physical Processes

Physical processes are expected to be unchanged by moderate levels of SLR, and accretion may counteract SLR (Stella et al. 2011). Physical processes were ranked as having a low sensitivity to changes in SLR.

Leveed Riparian/Willow Ecosystems

Fish and Wildlife

The extent of riparian/willow ecosystems has decreased by 66 percent in the modern Delta (SFEI–ASC 2014). Further losses due to climate change would mean a considerable loss of habitat of species dependent on these ecosystems. In addition, terrestrial species dependent on riparian vegetation, such as the endangered riparian brush rabbit (*Sylvilagus bachmani riparius*), are likely to be highly impacted in the event of flooding (Williams et al. 2008). Therefore, fish and wildlife associated with leveed riparian/willow ecosystems were ranked as moderately sensitive to SLR.

4.1.6 Wet Meadows/Seasonal Wetlands

4.2.6.1 Air Temperature

Wet meadows and seasonal wetlands were rated high sensitivity to increases in air temperature.

Dominant Vegetative Communities

Vegetation communities were rated highly sensitive to increases in air temperature. Warming temperatures and increased evapotranspiration could cause seasonal wetlands to prematurely dry (Ordonez et al. 2014). This may result in amplified competition for limited water supply and could shift phenological responses thereby altering species composition to favor of more robust and heat tolerant, or non-native species (Hegland et al. 2009).

Fish and Wildlife

Increasing air temperatures will also drive higher water temperatures within wet meadows and seasonal wetlands. Warming water temperatures may cause these temporary bodies of water to prematurely dry, impacting species such as invertebrates and amphibians who rely heavily on water presence for critical physiological processes such as reproduction and support of larval phases (Cloern et al. 2011, Mauger et al. 2015). Warmer water temperatures may also drive phenological shifts in species life history patterns. Food availability and resources may also be impacted, negatively affecting wildlife populations. Fish and wildlife species were rated high for sensitivity to increases in air temperature.

Physical Processes

Physical processes were subsequently rated high for sensitivity to air temperature increases. Increased evaporation will lead to decreases in soil moisture and could shift wet meadows and seasonal wetlands to become alkali meadows/wetlands. The clay-rich soils may be better adapted to hold more water, however, prolonged higher temperatures coupled with drought-like conditions could result in these water bodies and soils drying out (SFEI–ASC 2014). In the Delta, many wet meadows and seasonal wetlands are in poor shape as they are already heavily impacted by agriculture and levees (Ibid). As these habitats are highly disturbed, they are increasingly susceptible to any additional disturbances and the impacts of climate change.

4.2.6.2 Precipitation

Wet meadows and seasonal wetlands were ranked as having a high vulnerability to changes in precipitation.

Dominant Vegetative Communities

The vulnerability of wetlands to climate change is directly related to their water source (Winter 2000). Wetlands that receive most of their water from sources other than direct rainfall such as tidal action or groundwater discharge are more buffered from the effects of climate change (Vaghti and Greco 2007, Grewell et al. 2007). Wet meadows and seasonal wetlands were rated highly sensitive to changes in precipitation as their water supply is directly related to rainfall. Consequently, these habitats are highly susceptible to drought. Projected decreases in spring and fall precipitation can increase competition for limited water supply and can negatively impact species composition, favoring more drought-tolerant species (Mauger et al. 2015).

Fish and Wildlife

Shifts in wildlife habitat correspond to changes in hydrologic regimes and vegetative communities. Many amphibian species are already, and will continue to be, highly vulnerable to a combination of increasing temperatures, reduced spring and fall precipitation, and drought (McMenamin et al. 2008, Jeffries et al. 2016). Wetland desiccation and declines in suitable habitat can cause shifts in amphibious and fish species physiological processes, as available water dries out and increases competition between fish and amphibian species (Petranka et al. 2007, McMenamin et al. 2008) Fish and wildlife species are therefore ranked high for sensitivity to changes in precipitation in seasonal wetlands.

Physical Processes

Physical processes were ranked high for sensitivity to changes in precipitation. Higher precipitation during the winter months may help buffer decreased precipitation projections of spring and fall seasons. However, dry seasons coupled with warmer temperatures could cause these seasonal wetlands to dry out sooner (McMenamin et al. 2008; Diffenbaugh et al. 2015; Dettinger et al. 2016).

4.2.6.3 Sea Level Rise

Fish and Wildlife

The extent of wet meadows and seasonal wetlands has decreased by 93 percent in the modern Delta (SFEI–ASC 2014). Any further losses due to climate change would mean a significant loss of habitat of species dependent on these ecosystems. Therefore, wildlife in wet meadows and seasonal wetlands were ranked as having high sensitivity to SLR.

4.1.7 Alkali Seasonal Wetland Complex

4.2.7.1 Air Temperature

Alkali seasonal wetland complex were ranked as having a high sensitivity to increases in air temperature.

Dominant Vegetative Communities

Vegetation communities were ranked high for sensitivity to increases in air temperature. Higher temperatures can drive increased evapotranspiration which not only dries out seasonal ponds earlier in the year and may result in increased salt content in the soil more so than the vegetation communities are adapted to. As groundwater declines, alkali vegetation begins to lose contact with the water table, and total plant cover declines resulting in mortality (Elmore et al. 2006). These changes, along with decreases in soil moisture have the potential to shift phenology patterns for dominant plant species and alter overall species composition in this habitat type (Hegland et al. 2009). Shifts in vegetation community could have cascading impacts on fish and wildlife communities reliant upon this habitat.

Fish and Wildlife

Increasing temperatures will increase water temperatures and evaporation rates, negatively impacting already susceptible wildlife species such as invertebrates and amphibians (Durand 2008, 2015). Seasonal ponds with warmer water temperatures that evaporate prematurely will negatively impact species whose life history patterns are intimately tied with the presence of standing water and increase inter- and intra-species competition for the limited water resources (McMenamin et al. 2008). Additionally, there may also be shifts in the availability of food resources that can negatively affect species at the landscape scale. Fish and wildlife were ranked high for sensitivity to increases in air temperature.

Physical Processes

Physical processes were also rated high for sensitivity to air temperature increases. Increased evaporation will desiccate soils (Porporato et al. 2004). Although the clay-rich soils are adapted to hold water, prolonged high temperatures coupled with drought conditions will eventually result in alkali wetlands to dry up and lead to soil with a higher salt content (SFEI–ASC 2014).

4.2.7.2 Precipitation

Alkali seasonal wetland complex were ranked as having a high sensitivity to changes in precipitation.

Dominant Vegetative Communities

Alkali wetlands rely on rainfall and to some extent groundwater sources for their water supply. With periods of decreased rainfall in the spring and fall, competition for the limited water supply will increase or lead to total declines (Elmore et al. 2006). This may be ameliorated by winter storm events, however, during drought years, groundwater supply may be severely reduced due to groundwater overdraft, causing further stress on vegetation communities (Diffenbaugh et al. 2015, Dettinger et al. 2016). Dry periods and drought years will also drive increased soil salinity and push the vegetation communities above their salt-tolerance threshold. It is likely that phenological responses will shift and alter species composition to include more drought-tolerant species. Vegetation communities were ranked high for sensitivity to changes in precipitation.

Fish and Wildlife

Shifts in wildlife habitat correspond to changes in hydrologic regimes and vegetative communities. Many aquatic species would be highly vulnerable to a combination of increasing temperatures and reduced spring and fall precipitation (McMenamin et al. 2008). Reduction in alkali ponding and water supply can shift species' physiological processes and make it difficult for them to complete life history phases (Ibid). Increased salt content of the soil can also negatively impact wildlife and their food supply (Wang et al. 2017). Fish and wildlife species are therefore ranked high for sensitivity to changes in precipitation in alkali wetlands.

Physical Processes

Physical processes were ranked high for sensitivity to changes in precipitation. Higher precipitation during the winter months may buffer decreased precipitation projections of spring and fall seasons. However, dry seasons coupled with warmer temperatures could cause these seasonal alkali wetlands to dry out sooner, and possibly remain dry throughout the year until they can be replenished (Diffenbaugh et al. 2015, Dettinger et al. 2016). This would decrease the availability of viable habitat and food resources for the species that depend upon alkali wetlands.

4.2.7.3 Sea Level Rise

Fish and Wildlife

The extent of alkali seasonal wetlands has decreased by 97 percent in the modern Delta (SFEI–ASC 2014). Any further losses due to climate change would mean a significant loss of habitat of species dependent on these ecosystems. Therefore, fish and wildlife associated with alkali seasonal wetlands were ranked as having high sensitivity to SLR.

4.1.8 Grasslands

4.2.8.1 Air Temperature

Grasslands were ranked as having a moderate sensitivity to increases in temperature.

Dominant Vegetative Communities

Dominant vegetative communities in grasslands were ranked moderate for sensitivity to temperature increases. Grasslands in the Delta are already highly altered with almost 90 percent comprised of invasive species (SFEI-ASC 2014). It is expected that warming temperatures will drive increased evapotranspiration, leading to increased competition for water resources

(Anderson et al. 2008). These conditions will favor species that are more heat and drought tolerant and will likely lead to an increase in invasive species (Sandel et al. 2012).

Fish and Wildlife

Increasing temperatures within grassland habitats will likely cause more heat-sensitive wildlife to relocate to adjacent cooler wetlands (Parmesan 2007). Consequently, fish and wildlife were ranked moderate for sensitivity to temperature increases.

Physical Processes

Physical processes were ranked moderate for sensitivity to temperature increases. Increased temperatures will lead to increased evaporation within and therefore less soil moisture (Anderson et al. 2008, Porporato et al. 2004). Increase of invasive species may also negatively impact critical carbon, water, and energy cycles within grassland habitats (Li et al. 2017).

4.2.8.2 Precipitation

Grasslands were ranked as having a moderate sensitivity to changes in precipitation.

Dominant Vegetative Communities

Dominant vegetative communities in grasslands were ranked moderate for sensitivity to changes in precipitation. Increased winter rainfall will not likely affect these habitats, but little to no spring and fall precipitation may limit grassland production and contribute to a shift in species composition exacerbating invasive species abundance (Harpole et al. 2007, Sandel et al. 2012).

Fish and Wildlife

Fish and wildlife scored moderate for sensitivity to changes in precipitation. With a reduction in spring and fall precipitation, wildlife will likely disperse and seek refuge in adjacent wetlands for water supply which will increase competition in the adjacent wetland habitats (Parmesan 2007).

Physical Processes

Physical processes were ranked moderate for sensitivity to changes in precipitation. Reduced spring and fall rainfall regimes can shift species composition of grasslands negatively impacting key physical processes that take place within this habitat such as carbon, water, and energy regimes (Li et al. 2017). Drier conditions coupled with higher temperatures may lead to lower soil moisture and make soils less resilient and adaptive to sudden flooding events during winter (Porporato et al. 2004, Diffenbaugh et al. 2015; Dettinger et al. 2016). Additionally, drought-like conditions and higher temperatures may increase wildfire risk for grassland communities, though past studies have shown that grassland communities may have more adaptive capacity to extreme conditions including drought and wildfire (Craine et al. 2013).

4.2.8.3 *Sea Level Rise*

Un-leveed Grassland

Un-leveed grassland was rated moderately sensitive to SLR.

Dominant Vegetative Communities

Un-leveed grasslands occur at slightly higher elevations than wetlands and riparian/willow ecosystems. Accretion rates of grasslands have not been studies but are likely to be lower than those of wetland and riparian/willow ecosystems. While they can withstand temporary flooding, the dominant vegetative communities will be sensitive to permanent flooding from SLR. Grassland vegetation communities were ranked as having a moderate sensitivity to moderate changes in SLR.

Fish and Wildlife

The extent of grasslands has increased by 30 percent in the modern Delta (SFEI–ASC 2014). Grasslands in the Delta are highly altered with almost 90 percent of the plant species comprising invasive species (Ibid). Therefore, the sensitivity to SLR of wildlife species depending grasslands was ranked low.

Physical Processes

In grasslands at slightly higher elevation, physical processes are expected to be unchanged by moderate levels of SLR. If the water level rises, lower laying grasslands may convert to marsh or riparian ecosystems (Fagherazzi et al. 2019). Physical processes were ranked as having a moderate sensitivity to changes in SLR.

Leveed Grassland

Fish and Wildlife

The extent of grasslands has increased by 30 percent in the modern Delta (SFEI–ASC 2014). While many of the plant species of grasslands in the Delta are non-native, there are grassland-dependent wildlife species. Given the mobility of avian species, they are likely to adapt to changes in ecosystem distribution across the landscape. Terrestrial species dependent on grassland vegetation are likely to be highly impacted in the event of flooding. The loss of over 30,000 acres of grasslands would affect population sizes, decreasing grassland-dependent species but increasing species thriving in the aquatic ecosystems that would arise where grasslands were permanently flooded. Fish and wildlife in grassland ecosystems were ranked as having low sensitivity to SLR.

4.1.9 Agricultural Lands

4.2.9.1 Air Temperature

Agricultural lands were ranked as having a low sensitivity to increases in temperature. Warming temperatures will likely increase evapotranspiration rates thereby decreasing soil moisture content putting undue stress on croplands and associated wildlife species (Schlenker et al. 2007). However, as these areas are heavily managed, increased irrigation will likely offset these stressors (Ibid). Due to the managed nature of these systems, they have the potential to be more flexible and adaptable to consequences of climate change and can continue to act as a refugia for associated and nearby wildlife such as waterfowl and birds (SFEI–ASC 2014).

4.2.9.2 Precipitation

Agricultural lands were ranked as having a low sensitivity to changes in precipitation.

Projected reduced precipitation rates for spring and fall seasons will be ameliorated by increased irrigation activities maintaining the cropland resources and its habitat value (Schlenker et al. 2007).

During drought years, however, irrigation rates will become more variable and contingent on what farmers have available and can afford. During these dry years some fields may need to be fallowed which can negatively impact croplands and associated wildlife species. Fallowed fields are prone to increased soil erosion during flashy, winter storm events. Consequently, agricultural fields are more vulnerable to the impacts of extreme drought events. Ruderal lands, frequently found near agricultural lands, are predominantly comprised of non-native species that are highly tolerant of hot and dry conditions (SFEI–ASC 2014). During drought years vegetation communities may provide an increased fuel source during wildfire season.

4.2.9.3 Sea Level Rise

As agricultural crops rapidly change location and extent across the Delta in response to market conditions, we have not performed regional analyses for this land cover type.

Fish and Wildlife

Fish and wildlife like sandhill cranes and Canada geese that use agricultural areas will be negatively impacted if islands flood permanently. Because the area of wildlife-associated agricultural lands is large in the Central Valley, the sensitivity of wildlife to SLR was ranked as moderate.

4.3 Adaptive Capacity

4.1.1 Inherent Adaptive Capacity

The inherent ability of organisms to respond to increasing air temperatures and changes in precipitation is dependent upon many factors, and individual species will respond differently to the effects of climate change. While some species are expected to adapt in place (e.g., some marsh wildlife and native fish), others will need to relocate to more suitable areas or become extirpated (SFEI–ASC 2015). Some species have much more narrow thermal envelopes or are not adapted to extreme hydrologic patterns making it more difficult to adapt to increased temperatures, prolonged exposure to extreme heat wave events, flooding, and drought events. Species with higher genetic diversity and larger geographic extents are likely to have higher adaptive capacity (CLCP 2017).

4.1.2 Institutional Adaptive Capacity

The institutional adaptive capacity of the Delta is dependent upon current and future legislation, regional management decisions, adaptive management activities, and society’s ability to curb greenhouse gas emissions. Several policies specific to the Delta address climate change. The Delta Reform Act (2009) mandates the consideration of “the future impact of climate change and SLR” in restoration planning through 2100. The Delta Plan (2013) supports the coequal goals of a reliable statewide water supply and a resilient Delta ecosystem. The ecosystem chapter is currently undergoing a proposed amendment to reflect the latest science on climate change. Executive Order B-30-15 requires California State agencies to incorporate climate change into planning and investment decisions, to prioritize natural infrastructure over built infrastructure, and requires actions toward climate preparedness for the most vulnerable populations.

In addition to existing policies, multiple interagency efforts coordinate planning for climate change and adaptive management, and to inform policy makers. Activities include developing conceptual models, synthesizing data and published studies, convening workshops, and preparing communication materials for policy makers. Another important body is the Delta Plan Interagency Implementation Committee which comprises the highest-ranking members of 18 state, federal, and regional agencies. This committee is a venue for decision makers to align on priorities, including climate change, around land, wildlife, and water resources. Regulatory authority comes from the Delta Stewardship Council which implements the Delta Reform Act, can make policy decisions, and can require that best available science and adaptive management about climate change are considered for projects planned in the legal Delta.

Suisun Marsh is also subject to regulation under the Suisun Marsh Protection Plan and Bay Plan, which cover the lower estuary. Because many land use decisions are made at local or regional levels, aligning these decisions and actions to address climate change in the entire San Francisco Estuary is necessary. Funding of climate change adaptation actions is a major component of political adaptive capacity—without effective leveraging of resources at the policy level, high-cost adaptation measures will not be feasible.

4.1.3 Sea Level Rise

4.3.3.1 Un-leveed Ecosystems

In the Delta, remnant un-leveed ecosystems occur discontinuously along waterways where geomorphic processes have allowed for their persistence. Natural adaptive capacity to SLR lies in the potential for ecosystems to shift to higher elevations. Although likely severely limited due to levees and development that cut off the landward connection of un-leveed ecosystems, adaptive capacity was estimated by the amount of available area for un-leveed ecosystems to migrate upland.

Restoration projects, particularly when involving tidal wetlands, are key opportunities where thoughtful site design can increase adaptive capacity. By accounting for climate change (for example, creating the opportunity for upland migration via ecological transition zone space), restoration projects can reduce the risks associated with climate change.

Identifying opportunities to use dredge material may be another approach to increase adaptive capacity, especially in the brackish wetlands of Suisun Marsh (Raposa et al. 2020). However, the literature indicates possible detrimental effects on freshwater wetland vegetation including

- A reduction in germination and recruitment from seed banks,
- A reduction of rhizome productivity and hypoxic effects on roots and rhizomes,
- Seedling burial and reduction in seedling productivity,
- A reduction in mature plant productivity, and
- Changes in vegetation population (Deverel and Finlay 2007).

A study conducted on Twitchell Island that applied sediment layers to wetland mesocosms supports these findings. Detrimental effects of sediment application on biomass accumulation were observed. Sediment application also caused the soil bulk density to increase in the recently deposited sediments by 26 to 48 percent.

Another consideration is timing of dredge material availability. Dredging is not permitted after November and during the wetland dormant season when application would have less effect on plant productivity. Therefore, to apply dredge material during the dormant season would require stockpiling. Application during the wetland growing season is not recommended based on the detrimental effect on wetland vegetation.

4.3.3.2 Leveed Ecosystems

For leveed ecosystems, institutional adaptive capacity is likely to be higher than for un-leveed ecosystems. The risk of levee overtopping means a risk of ecosystem loss through deep and permanent flooding. Delta Adapts modeling results show that many levees, under current conditions, would overtop even with only 1 ft SLR, causing the islands to flood. However, Delta islands are heavily managed with a range of motivations for maintenance. Many Delta islands are productive farmland, are home to communities, contain infrastructure such as highways, train tracks, electrical power transmission lines, and pipelines, and are key to maintaining the hydraulic salinity barrier that allows for the State and Federal Water Projects and other in-Delta water diversions to continue. Ongoing investments in Delta levees are highly likely, meaning that current levee conditions will be improved, thus lowering the risk of overtopping. For high-priority islands, there is also a high likelihood that breached levees would be repaired and floodwaters pumped out. Therefore, adaptive capacity of leveed ecosystems is mainly determined by institutional factors such as the motivation to maintain levees. Here we assume a high adaptive capacity for leveed ecosystems in the Delta.

The levees protecting the managed wetlands in Suisun Marsh and maintaining the hydraulic salinity barrier that allows for the State and Federal Water Projects and other in-Delta water diversions to continue are often not maintained to the same levels as the levees protecting wetlands and agricultural lands in the legal Delta. If Suisun Marsh levees are overtopped but not breached with significant damage, water control infrastructure currently used to maintain managed wetland water levels will facilitate tidal drainage. If these flooding events persist for an extended period or occur from storm events such as atmospheric rivers that damage levees, the managed wetland habitats and wildlife populations dependent upon them can be negatively impacted. As MSL and storm event frequency increases, flooding events are likely to become more common, putting strain on the levee systems in these areas. Because there currently is no state or federal funding for a majority of the levee maintenance expenses in the Suisun Marsh, the adaptive capacity of managed wetlands was ranked as moderate.

4.3.3.3 Upland Transition and Sea Level Rise Accommodation

The 2020 Draft Amendment to the Ecosystem Chapter of the Delta Plan (Chapter 4) mapped potential accommodation space for intertidal ecosystems to move into what are currently upland areas under different climate change scenarios (Figure 23). This transition zone between tidal and fluvial ecosystems provides several critical services in addition to SLR accommodation space (Goals Project 2015). The data underlying the maps were used to explore the amount of potential transition zone for SLR accommodation space across three categories of SLR ranges in each Delta region. The results show that potential accommodation space exists throughout the Delta (Figure 23 and Figure 24), but that these areas may not have adequate tidal, floodplain, or riverine connection to function as accommodation space.

Notably, the Central Delta, where wetland accretion is predicted to be the highest, is almost completely devoid of upland transition zones adjacent to existing wetlands, which are adjacent to deeply subsided islands (Figure 23). In the Cache Slough region, extensive wetlands on Liberty Island have minimal connections to upland transition zones. Lindsey Slough and adjacent areas have more potential, but fewer contemporary wetlands (Figure 24). Unlike leveed ecosystems, where levee repair may have multiple institutional aspects motivating investments in repairing levee failures, tidal systems may not have technical, logistical, or institutional capacity to create upland transition zones adjacent to existing wetlands. Thus, tidal wetland restoration projects are key locations on the landscape where adaptive capacity can be vastly increased by incorporating upland transition zones for SLR accommodation space into project implementation. Additional research could illustrate where accommodation space has adequate connectivity to function as desired.

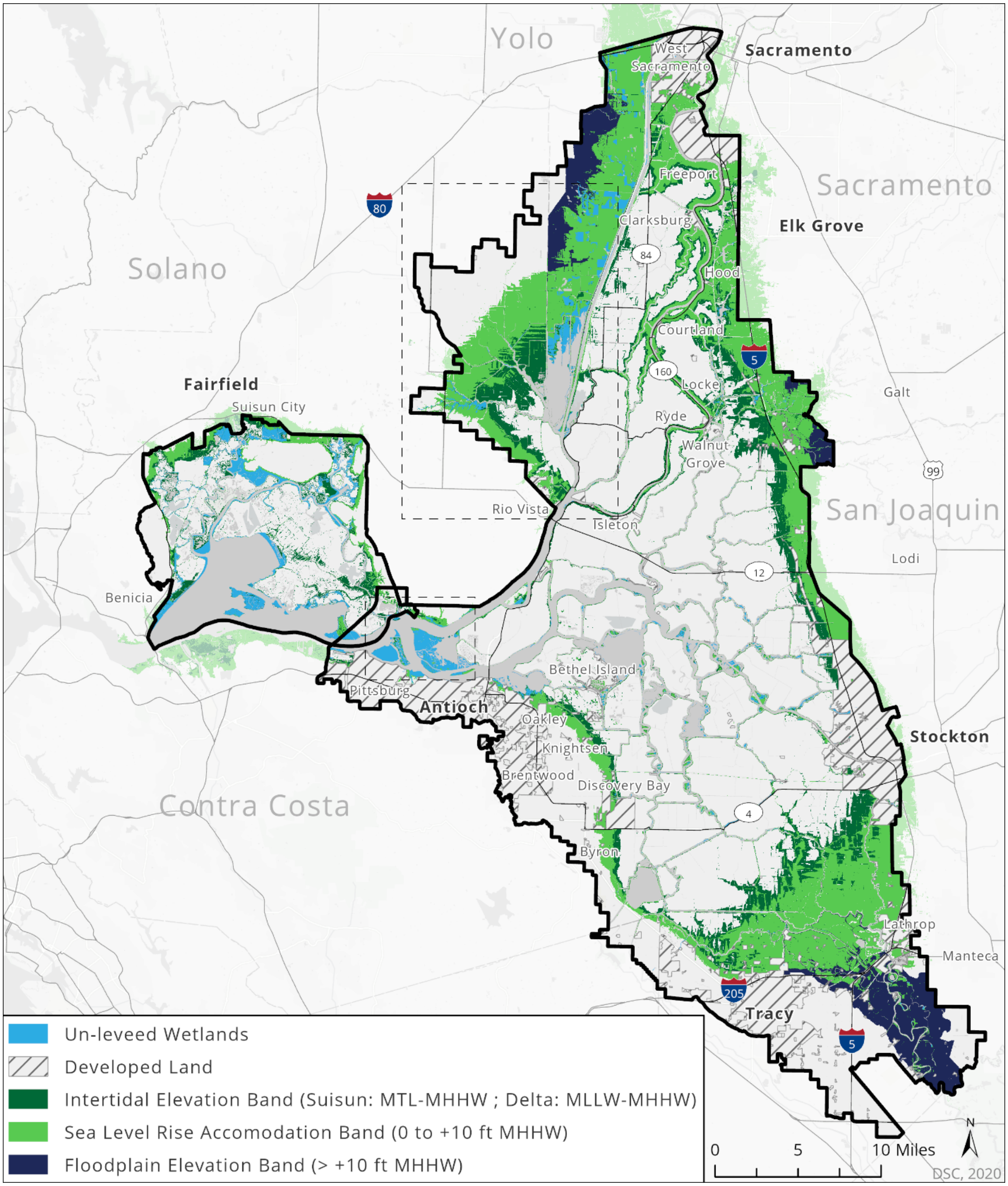


Figure 23. Potential Upland Transition Zone SLR Accommodation Space in the Delta

Note: Adapted from Council 2020. Figure 24 shows detailed maps of the inset boxes.

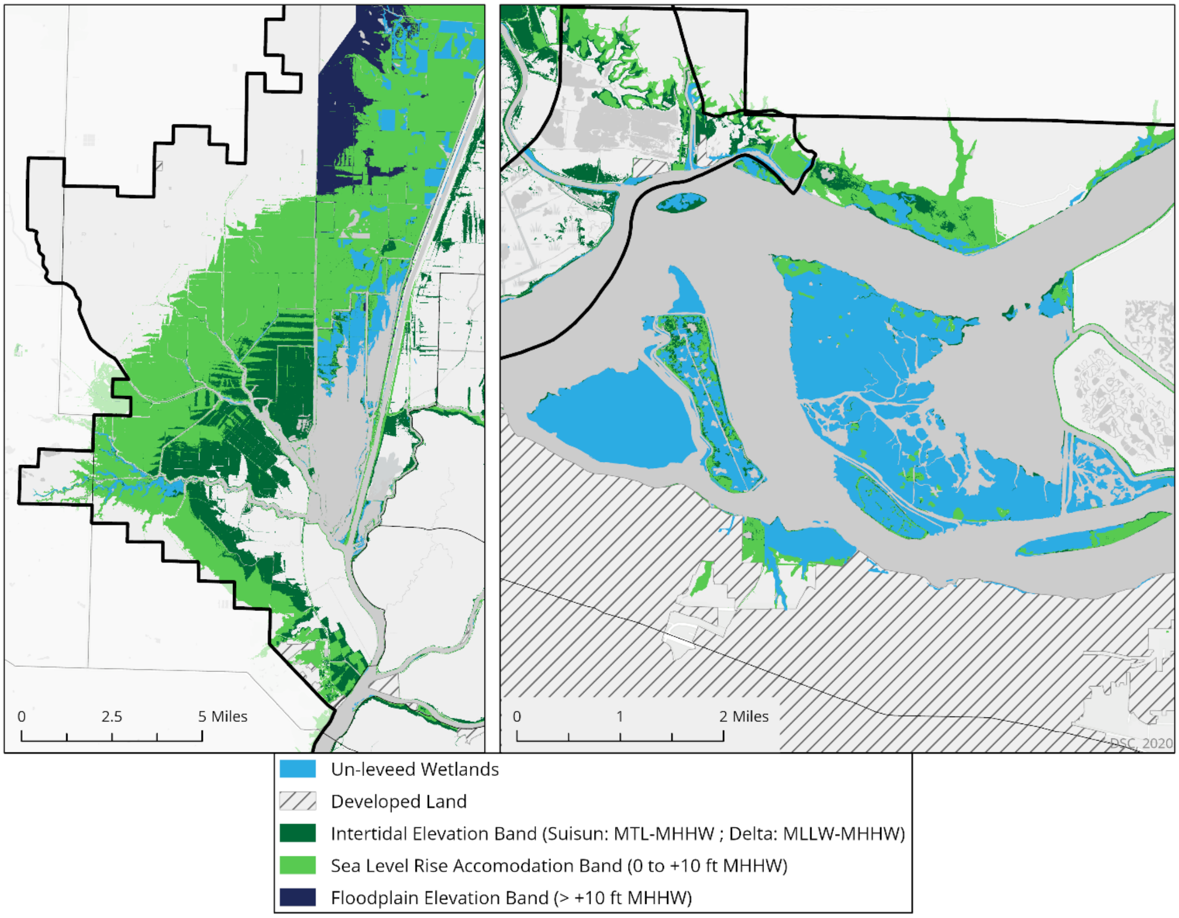


Figure 24. Insets of Potential Upland Transition Zone SLR Accommodation Space in the Delta

Note: Panel A at left shows that the Cache Slough Complex has SLR accommodation space, and Panel B shows that Central Delta tidal wetlands do not have SLR accommodation space.

4.3.3.4 Restoration and climate change

The analyses performed for this effort do not include land slated for future restoration or restoration projects currently under construction. The majority of planned restoration in the Delta is occurring under the EcoRestore program, which includes levee setbacks, fish passage improvements, subsidence reversal, and restoration of tidal wetlands, floodplains, and riparian/willow ecosystems. To date, 1,900 acres of tidal wetlands and 1,700 acres of non-tidal projects have been restored and are included in this analysis. In the fall of 2020, projects were under construction on 3,700 acres, and slated for near-term implementation on 3,900 additional acres. Restoration of over 38,500 acres are projected as part of the program (DWR 2020).

Because the Delta Plan requires projects to consider climate change in the planning process, the individual projects will largely be resilient to climate change. As all the EcoRestore projects and others are completed, they will expand the total area covered by natural ecosystems and increase the resilience of the landscape to climate change.

4.4 Other Ecological Assets

This section looks at floodplains and cold-water pool management. These assets are not possible to analyze in the same manner as the ecosystem assets mapped by VegCAMP, so qualitative analyses based on literature review are included below.

4.1.1 Floodplains

Floodplains are defined as a landscape feature that is periodically inundated by water from an adjacent river (Opperman et al. 2010). They have a high value to society, because they provide many ecosystem services, including attenuation of flood flows thereby reducing flood risk, filtration of surface water, recreation, provision of protein (fisheries) and fiber, and groundwater recharge which contributes to more sustained and cooler dry-season flows (Opperman et al. 2010). Floodplains also have a high value to biodiversity. As sites of high productivity they support high biodiversity (Corline et al. 2017), are a nursery for many fish species (Ibid), provide food in the form of plankton and insects for juvenile salmon migrating to the ocean (Jeffres 2008), and export plankton into the adjacent streams, thereby adding to the river's food web (Lehman et al. 2008).

The Yolo Bypass in the northern portion of the Delta is the primary remaining floodplain of the estuary (Frantzich et al. 2018). Despite substantial alteration, it retains different ecosystem types including multiple channel sizes, broad shoals, tidal marsh, tidal sloughs, and dead-end sloughs (SFEI–ASC 2014, Sommer et al. 2001, Goertler et al. 20178). While local tributaries flood the Yolo Bypass in most years, the Sacramento River flows into the Yolo Bypass at the Fremont and Sacramento Weirs in 60 percent of years (Frantzich et al. 2018). It is used for agriculture from spring through early autumn but managed as a floodplain in the winter (Corline et al. 2017). The inundation frequency and duration vary with patterns of precipitation. The planned Yolo Bypass Salmonid Habitat Restoration and Fish Passage Project will construct a gated notch at Fremont Weir that will allow a controlled flow from the Sacramento River into the Yolo Bypass to increase the frequency and duration of seasonal flooding.

There are also sizable floodplains along the Cosumnes River which lacks major dams and thus retains a relatively natural hydrology (Jeffres et al. 2008). This river system is rain-dominated because most of the watershed lies below the snow line. A small spring snowmelt signature however is present. In dry years, flow ceases by the end of the summer in the lower river reaches, which is exacerbated by severe declines in regional groundwater levels (SFEI-ASC 2016). Intentional levee breaches have restored former farmland to floodplain habitats (Jeffres et al. 2008). This has resulted in sediment deposition, greater topographic complexity, riparian forest establishment and succession, increased productivity, and provision of new spawning and rearing habitat for native fish (SFEI–ASC 2016).

Given the importance of Yolo Bypass flooding, understanding the influence of climate change on the frequency, magnitude, duration, and timing of flooding is critical for understanding future value of the bypass to the Bay–Delta ecosystem.

4.4.1.1 Exposure

The projected increase in drought will negatively alter the existing Delta floodplain ecosystems by depriving them of riverine inundation. At the same time, floods in the Delta are likely to increase in frequency and intensity of peak flows but decrease in duration. Understanding the influence of the gated notch and climate change on the frequency, magnitude, duration, and timing of flooding is critical for understanding future value of the bypass to the Bay–Delta ecosystem.

Work is in progress to calculate flood metrics for the Yolo Bypass including magnitude, duration, frequency, and timing of floods using model outputs from the CASCADE 2 project (Marissa Wulff, USGS, per. comm.). Model output under 20 climate change scenarios with and without the notch will be examined. Flood metrics will include the start- and end date of each flood event, the average, maximum, and minimum amount of water of each flood event, the total, average, and maximum duration of flood events, and the total number of flood events that will last over 30 days. These results will be interpreted with respect to habitat needs of native fishes and other ecosystem benefits of Yolo Bypass flooding.

4.4.1.2 Sensitivity

Floodplains are highly sensitive to the effects of climate change including extended drought periods and changing flood patterns. Floodplain forests along the Cosumnes River are sensitive to low groundwater levels that are likely to be caused by a combination of extended drought cycles and increased groundwater extraction (Dettinger et al. 2016, Skiadaresis et al. 2019). Droughts may also increase the sensitivity to non-native fish species, because native species tend to reproduce on the floodplains in isolation from non-native species (Dettinger et al. 2016). As winter floods increase and less precipitation falls as snow in Sierra Nevada, winter inundations of floodplains will become most frequent. The predicted increase in frequency of atmospheric rivers will likely exacerbate extreme inundations and damaging floods may become more frequent (Florsheim and Dettinger 2015). These events can increase the potential of juvenile salmon being washed downstream losing the benefit of raising in the floodplains (Nature Conservancy 2016).

4.4.1.3 Adaptive Capacity

Because the Yolo Bypass is a tightly managed system, its adaptive capacity is quite high. Weirs and river flows can be modified and managed to increase the frequency and duration of floodplain inundations. The planned gated notch in the Fremont Weir will be instrumental in this respect. However, to account for the effects of increased variability on floodplain inundation, other types of habitat with tidal and riverine connection that do not depend on seasonal flooding should continue to be expanded across the landscape to provide food and habitat for target species.

The adaptive capacity of the floodplains along the Cosumnes River are moderate, because floodplains are naturally adapted to variation in inundation pattern (Florsheim and Dettinger 2015), but longer drought cycles and decreasing ground water levels may affect the floodplain ecosystems beyond their adaptive capacity. Also, under climate change, infrastructure and reservoir management policies to accommodate increased winter flows (and reduced spring and summer flows) and decisions about timing, magnitude, and duration of flow releases from upstream reservoirs are likely to determine the form of those geomorphic responses can influence the adaptive capacity of the floodplains (Florsheim and Dettinger 2015). Unintentional levee breaks which in the past have often occurred because of atmospheric river storms and flooding may re-establish functioning floodplain ecosystems (Ibid).

4.1.2 Cold-water Pools

Currently, reservoirs are managed to provide cold-water releases for salmon and other species, which depend on particular temperatures to complete their life cycles. Extended droughts put this ecosystem management approach at risk (Durand et al. 2020, Zarri et al. 2019).

Management of the State and Federal Water Projects during the last drought required considerable intervention to maintain water supply reliability (Kimmerer et al. 2019, Durand 2020). As droughts become more common, dam releases will become increasingly important for maintaining the location of the 2 ppt low salinity zone (referred to as X2) needed for State and Federal Water Project operations, which will limit the ability to provide cold-water releases for fish species (Durand 2020, Stacey et al. 2015). With low reservoir levels during droughts, a conflict between ecosystem management (cold-water releases) and water supply (water releases maintain the hydraulic salinity barrier) may arise (Dettinger et al. 2016, Durand et al. 2020).

In addition, different species and seasonal runs of anadromous species like salmon have different cold-water requirements at different times of the year, which means that tradeoffs between species needs will be inevitable when system flexibility decreases (Durand 2020, NMFS 2016). Innovative management of dam releases is a potential solution that has been demonstrated at the Shasta Dam (Zarri et al. 2019). The continued use of cold-water pools for in-stream temperature management will depend on the severity and length of future droughts, statewide water management initiatives including groundwater management, and the need to control X2.

4.5 Secondary Climate Stressors

4.1.1 Wind

Due to the Delta’s proximity to the Pacific Ocean – connected via the San Francisco and Suisun Bays – the region receives more coastal winds than the San Joaquin and Sacramento Valleys. This has been observed to offset historical maximum daily temperatures and has the ability to offset increasing air temperatures that are projected for the region as a factor of climatic change (Lebassi et al. 2009).

California’s summer climate is dominated by complex large-scale atmospheric and oceanic patterns, including the coastal ocean and continental weather patterns. Small changes in these patterns can create large variations in the coastal climate, especially when considering climate change stressors, such as increasing air temperature.

The Central Valley of California is surrounded by mountain ranges—Klamath to the northwest, Cascades to the northeast, Sierra Nevada to the east, and the Coastal Range to the west. Low elevation inlets from the ocean into the Sacramento Valley allow for a channeling of cool, marine airflow, otherwise known as a westerly jet, which passes through the Golden Gate Gap—a passage from the San Francisco Bay east into the Delta. Once this cool air enters the Delta, it splits north to the Sacramento Valley and south to the San Joaquin Valley, resulting in enhanced daytime onshore winds caused by the temperature differential between cool coastal air and warm inland valley areas. The reverse process occurs in the evening, resulting from offshore land breezes that occur when the land cools quicker than the sea (Lebassi et al. 2009).

Studies indicate that projected warming of summer air temperatures in the inland valleys may produce enhanced cool-air sea breeze activity due to a large temperature gradient between the land-sea interface. This enhanced wind effect may have the ability to offset localized summer temperatures in the Delta (Ibid).

4.1.2 Water Temperature

Increasing air temperatures have direct consequences on water temperatures in the greater Delta watershed. Water temperatures at a specific location are dependent on the interplay of atmospheric forcing, riverine flows, and tidal dispersion – all of which are projected to be impacted by climate change. Warming water temperatures will vary spatially in the system and have even been projected to level off at some threshold due to evaporative cooling. These shifts will impact dissolved oxygen levels, species-specific thermal thresholds, ecological function, predator-prey dynamics, and more (Wagner et al. 2011, Council 2018a).

Warming water temperatures will similarly impact the quality of aquatic habitats and the ability of native amphibious populations to adapt to new environmental factors. Potential phenological mismatch between the timing of spawning and prey availability is likely to be triggered by the increased stress of warmer waters (Moyle et al. 2013, Council 2018a).

Fifty percent of California’s native fish are already critically or highly vulnerable to extinction, and those species that require cold water (below 71.6°F) have been identified as more likely to become extinct. By the mid-21st century, juvenile salmonids’ weights are expected to be lower in the California Central Valley as stream temperature and flow influence egg development and juvenile growth (Beer and Anderson 2013). By the end of the century, the Sacramento River water temperatures could warm as much as 5.4 to 10.8°F (Wagner et al. 2011).

Further, the effects of climate change are likely to alter the hydrologic forces in the Delta’s watershed, affecting operational flows, those managed to meet water quality criteria and exports, for the State Water Project, Central Valley Project, and to meet Bay–Delta water quality criteria. While these operations are not directly tied to climate change effects, as they are human-managed, operations will likely need to be adaptively managed and modified to accommodate factors that are affected by climate change. These include tradeoffs in reservoir level, flood management and water supply, and cold-pool flow releases to manage water temperatures, and other environmental demands (Council 2018a).

4.1.3 Water Quality

Water quality is important for ecosystem function. Broadly, water quality can include variables such as temperature (discussed above), salinity, nutrient loads, and concentration of contaminants such as heavy metals, pesticides, and herbicides. In recent years, harmful algal blooms have emerged as a concern in the Delta (Lehman et al. 2020). While algae are a component of the Delta ecosystem and important for food web function, some blue green algae or cyanobacteria (e.g., *Microcystis spp*.) have the potential to harm humans and negatively impact phytoplankton, zooplankton, and native fishes (Ibid). Harmful algal blooms are caused by a combination of lower flows, higher water temperature, and can be exacerbated by an accumulation of nutrients (Ibid). Analyses conducted for the vulnerability assessment Water Supply Technical Memorandum, and many climate projections, project more frequent periods of higher temperatures and lower streamflow. This could result in more frequent harmful algal bloom events, with negative impacts to ecosystem function.

4.6 Ecosystem Asset Vulnerability

The vulnerability of ecosystem assets is derived from the exposure, sensitivity, and adaptive capacity ratings. The vulnerability to SLR is outlined in Table 15 and the vulnerability to climate stressors is outlined in Table 16.

Table 15. Ecosystem Asset Vulnerability to SLR

Ecosystem Asset	Exposure Rating	Sensitivity Rating	Adaptive Capacity Rating*	Vulnerability Rating	Vulnerability Rating
Tidal Freshwater Wetland	High 3	High 3	Low 1	5	High
Non-tidal Freshwater Wetlands	High 3	High 3	High 3	3	Moderate
Tidal Brackish Wetland	High 3	High 3	Moderate 2	4	High
Managed Wetland	High 3	High 3	Moderate 2	4	High
Un-leveed Riparian and Willow Ecosystems	Low 1	Low 1	Low 1	1	Low
Leveed Riparian and Willow Ecosystems	Moderate 2	High 3	High 3	2	Moderate
Wet Meadow/ Seasonal Wetland	High 3	High 3	High 3	3	Moderate
Alkali Seasonal Wetland	Low 1	High 3	High 3	1	Low
Un-leveed Grassland	Low 1	Moderate 2	Low 1	2	Moderate
Leveed Grassland	Moderate 2	High 3	High 3	2	Moderate
Wildlife-associated Agriculture	High 3	High 3	High 3	3	Moderate

* For Adaptive Capacity, high ratings are positive and marked in yellow, and low ratings are negative and marked in red.

Note: Ratings are derived using the formula Vulnerability = Exposure + Sensitivity – Adaptive Capacity.

Table 16. Ecosystem Asset Vulnerability to Primary Climate Drivers

Ecosystem Asset	Un-Leveed	Air Temperature	Precipitation	SLR
Tidal freshwater emergent wetlands	Un-leveed	low	low	high
Non-tidal freshwater emergent wetland	Leveed	moderate	moderate	moderate
Tidal brackish water emergent wetland	Un-leveed	low	low	high
Managed wetlands	Leveed	low	low	high
Riparian/willow ecosystems	Un-leveed	moderate	moderate	low
Riparian/willow ecosystems	Leveed	moderate	moderate	moderate
Wet meadows/seasonal wetlands	Leveed	high	high	moderate
Alkali seasonal wetland complex	Leveed	high	high	low
Grasslands	Un-leveed	moderate	moderate	moderate
Grasslands	Leveed	moderate	moderate	moderate
Wildlife-associated agriculture	Leveed	low	low	moderate

CHAPTER 5. KEY FINDINGS

5.1 Management Implications

Key findings of this vulnerability assessment (1) highlight the ecosystem assets that scored moderate and greater and (2) identify how those ecosystem assets could be managed into the future in order to reduce vulnerability to climate drivers.

Ecosystems that scored as highly vulnerable include the following:

- Tidal Freshwater Wetland, Brackish Wetland, and Managed Wetland—high vulnerability to SLR
- Non-tidal Freshwater Wetlands, managed wetlands, and grasslands – high vulnerability to increasing air temperature
- Wet meadow/Seasonal Wetlands– high vulnerability to increasing air temperature and changes in precipitation
- Alkali Seasonal Wetlands – high vulnerability to changes in precipitation

Ecosystems that scored as moderately vulnerable include:

- Tidal Freshwater Emergent Wetlands – moderate vulnerability to increasing air temperature
- Non-Tidal Freshwater Emergent Wetlands – moderate vulnerability to changes in precipitation, and SLR
- Grasslands – moderate vulnerability to SLR
- Leveed Riparian and associated ecosystems – moderate vulnerability to increasing air temperature, changes in precipitation, and, in leveed areas, SLR
- Wet meadow – high vulnerability to air temperature, precipitation, and SLR
- Alkali Seasonal Wetland Complex – moderate vulnerability to SLR
- Grasslands – moderate vulnerability to increasing air temperature, changes in precipitation, and SLR
- Agricultural -- moderate vulnerability to increasing SLR

Tidal wetlands were ranked highly vulnerable to SLR, with risk increasing considerably under the 6-foot SLR scenarios. Across California and Oregon, near complete loss of tidal wetlands by 2110 was projected by Thorne et al. (2018). Three key issues with managing existing wetland sustainability in the context of SLR are: 1) the logistical issues with and limited efficacy of adding sediment to wetlands to increase marsh surface elevations (Deverel and Finlay 2007); 2) the decline of sediment supply in recent decades (Moftakhari et al. 2015) and uncertainty in future sediment supply from the Delta watershed (Stern et al. 2020); and 3) the limited upland transition zone available for SLR accommodation in existing tidal wetlands that increase resilience to SLR (Schile et. al 2014, Goals Project 2015, Thorne et. al 2018).

This study indicates that rapid action to restore tidal wetlands in the Delta is likely to create ecosystems that will be able to develop the biophysical feedbacks required to keep pace with moderate rates of SLR in coming decades (SFEI and SPUR 2019, Swanson et al. 2015, Schile et al. 2014). Including substantial connections to upland transition zone SLR accommodation space is critical for creating tidal wetland investments that will persist past 2100. The Delta Plan and other guiding documents require integrating climate change projections into project planning, which should consider that, unlike built infrastructure, tidal wetland restoration can take decades to develop the processes that will allow for SLR resilience. Thus, the sooner projects can be implemented, the better their chances of long-term success (SFEI and SPUR 2019).

For leveed ecosystems, SLR has different management implications. While exposure and risk are high, numerous technical opportunities exist for protecting leveed areas. Setback levees can increase levee strength while creating in-channel marshes and riparian habitat. On heavily subsided islands, transitions to managed subsidence reversal wetlands can reduce the risk of levee failure while creating extensive habitat for avian and other species.

Wet meadows, seasonal wetlands and alkali seasonal wetlands are already heavily impacted ecosystems. Extent of alkali seasonal wetlands has declined 95 percent compared with historical acreage and wet meadows/seasonal wetlands by 91 percent (Council 2018b). These sharp declines are due to a culmination of factors, including the alteration of land for agriculture and urban development. The remaining wet meadows, seasonal wetlands, and alkali wetlands are small, fragmented, and impacted by human stressors not associated with climate change (Ibid). Increased pressure from climate drivers may push these ecosystems to collapse, unless adaptive management, restoration, and conservation measures are implemented.

Managed wetlands are highly likely to flood even under base conditions, which contributes to their high vulnerability to SLR. However, they are currently managed for waterfowl, and will likely transition to tidal mudflat or wetland. This may mean that a loss of managed wetlands could lead to the creation of productive aquatic or intertidal ecosystems.

Ecosystems likely to be moderately impacted by increasing air temperature and local precipitation changes include non-tidal freshwater emergent wetlands, riparian/willow ecosystems, and grasslands. Non-tidal freshwater emergent wetlands are likely to experience increased evapotranspiration rates, leading to an increase in remnant water temperatures, which will cause stress on plant and wildlife communities and the potential for further fragmentation of this ecosystem type within the Delta.

Riparian/willow ecosystems will vary in their exposure, sensitivity, and ability to adapt to climate stressors/hazards based on the proximity to water sources and elevation. Shading provided by the trees may increase adaptive capacity of fish and wildlife species that depend on cooler water temperatures. In the present landscape, most riparian/willow ecosystem patches are very narrow and small, restoring larger riparian forests and wider riparian areas lining rivers and sloughs with minimal gaps would improve their ecological function.

Most grasslands in the Delta are currently is located on artificial levees or in subsided areas behind levees (SFEI–ASC 2016). Non-native species are common, but some levees are managed for native grass species (Tuel 2017). In the short term, these areas are important for supporting wildlife, such as lizards and snakes, grassland dependent bird species such as white-tailed kites, Swainson's Hawks, and western burrowing owls, and insects including pollinators. Because of the risk of island flooding with SLR, in the long term, grassland restoration should focus on the transition zone between aquatic and terrestrial ecosystems around the periphery of the Delta. Flooding of islands because of SLR and levee failure may result in grasslands transitioning to riparian or wetland areas which should be supported by managing for native species.

5.1.1 Targeting Resilience within the Delta

Understanding which ecosystem assets within the Delta are most vulnerable to particular climate parameters is important for future management actions, adaptation strategies, and restoration practices to lessen projected impacts. Increasing ecosystem resilience within the Delta at a landscape level is a critical conservation target that requires collaboration across sectors and considerations of connectivity, complexity, redundancy, and scale (Council 2018b).

California EcoRestore, a restoration initiative led by the California Natural Resources Agency, was established in 2015 with a mission to restore 30,000 acres of critical habitat in the Delta, Suisun Marsh, and Yolo Bypass (DWR 2020). The project employs a diversity of restoration strategies:

- Breaching levees to allow river water to flow up into the banks of the Delta with the tides, allowing fish to access more food.
- Inserting underwater passages in flood-control weirs to reopen floodplains for fish access.
- Inundating Delta islands to sequester atmospheric carbon and reverse subsidence.
- Installing setback levees to protect communities from flooding and restore ecosystems.
- Encouraging the production of zooplankton, or small bugs eaten by fish, by managing flows of river water into new areas.

Implementation of restoration actions such as these that reconnect tidal wetlands and flood plains, remove aquatic barriers, reverse subsidence, create marsh migration space, and that re-establish native plant and animal communities is important to the future of the Delta and will provide species with better opportunity to adapt to climate change.

This section summarizes the implications for the protection, restoration, and management of the Delta ecosystem (Council 2018b):

1. The Delta is unique and of global ecological importance as an estuary.
2. Restoration potential varies sub-regionally within the Delta.
3. Lands with suitable elevations should be prioritized for hydrologic reconnection and restoration of natural vegetation communities.

4. Reversing subsidence is critical to reducing the risk of levee failures leading to undesirable ecosystem conditions, and in protecting opportunities for restoration in the Delta.
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.
6. Re-establishing food web function and increasing species habitat requires restoring multiple aspects of connectivity and native vegetation community distribution.
7. Water quality impairs the food web function and species habitat conditions within an already limited footprint.
8. Impaired water quality has compounding effects on other ecosystem stressors such as non-native species and harmful algal blooms.
9. Improving the health of the Delta ecosystem will require actions that address multiple primary stressors.
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.

5.1.2 Next steps

The management implications discussed herein will be developed into a subsequent Climate Adaptation Strategy, which will outline step-wise, specific goals and objectives for the entirety of the Delta and will draw on the key findings within this chapter to create ecosystem-based adaptation strategies and specific solution to reduce vulnerability and enhance resilience under future climate scenarios.

5.1.3 Knowledge Gaps

5.1.3.1 Model limitations

- Vulnerability is assessed for individual climate parameters; however, the variables are not truly independent of one another. Accounting for cumulative or interactive effects would be much more complex to assess for the Delta Region.
- Human stressors impact the adaptability and resilience of ecosystems within the Delta, as it is already highly altered and managed.
- SLR modeling does not consider potential changes to the landscape, including future levee improvements or levee failures.

5.1.3.2 *Data Gaps*

- Precipitation projections exemplify a lot less certainty, and do not show consistent trends compared with the model predictions for air temperature and SLR.
- Much of the available climate data for air temperature and local precipitation are based off a coarse scale (typically 1/16 degree, or about 6 km grid size). This coarse resolution was necessary to provide readily available depictions of general regional areas that face the greatest climate change vulnerability; however, these data would be much more useful if developed specifically for the scale of the Delta and associated watershed areas.
- The Delta DEM is not corrected for wetland vegetation. A vegetation corrected DEM would allow for more fine scale exploration of SLR impacts on tidal wetlands.

5.1.3.3 *Future Research Opportunities*

- The true resiliency of native ecosystems is not fully known. Further research is needed to understand how ecosystems may respond to increased frequency and intensity of perturbations or disturbances.
- Ensure future restoration and conservation projects within the Delta incorporate multiple ecosystem services and co-benefits to simultaneously benefit local communities, enhance ecological function, and improve ecosystem quality.

5.1.3.4 *Further climate adaptation research to address gaps*

- Increase understanding of the effects of SLR on un-leveed riparian/willow ecosystems in the Delta by studying accretion rates.
- Additional research could illustrate where upland transition zone SLR accommodation space is functionally connected to areas that will flood with SLR, and where connectivity can be restored.
- Social science research to determine potential human-dimensions topics related to ecosystem climate adaptation.

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