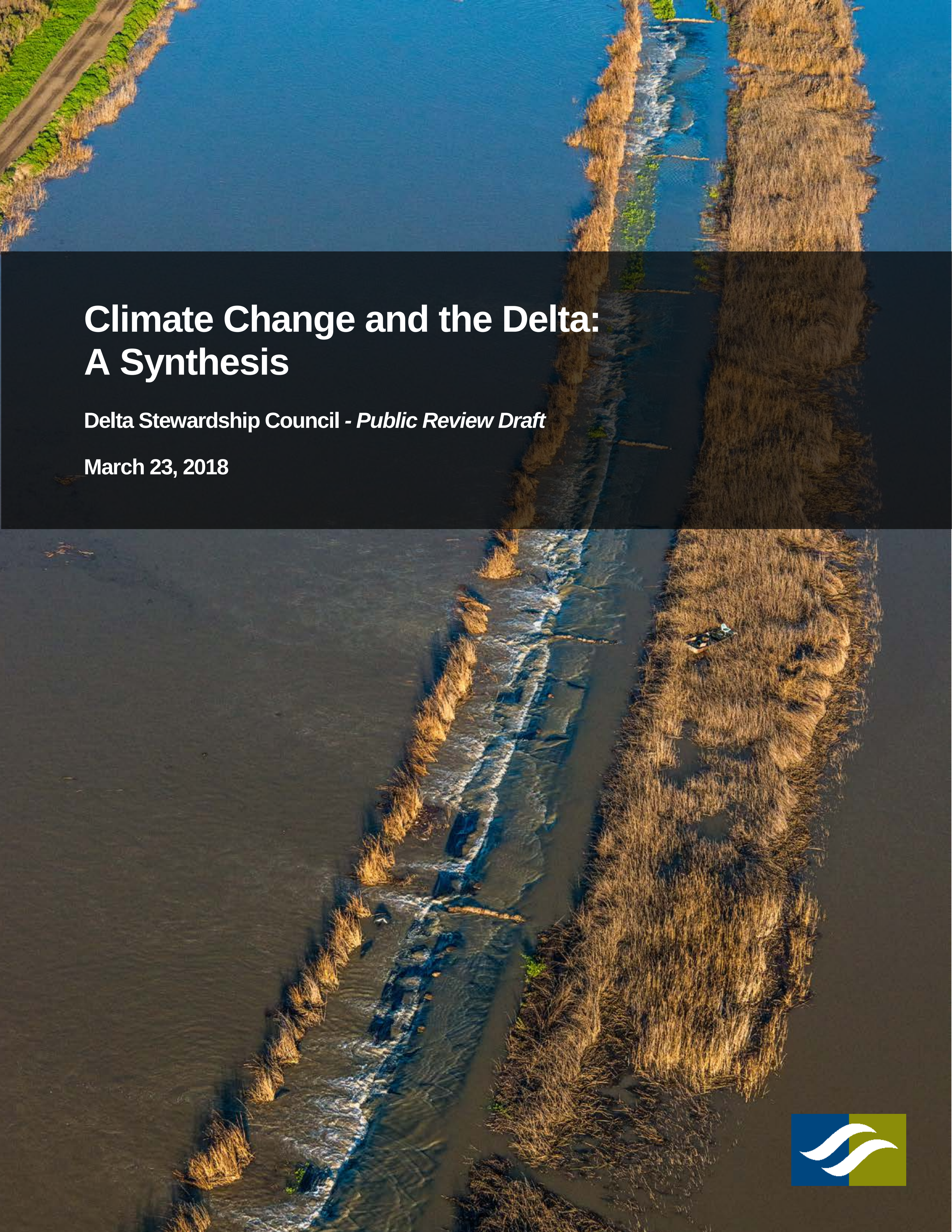

Climate Change and the Delta: A Synthesis

Delta Stewardship Council *- Public Review Draft*

March 23, 2018

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1. Introduction

The Delta Reform Act of 2009 (Water Code Section 85066) requires that the Delta Stewardship Council adopt a Delta Plan (the Plan) to achieve the coequal goals of providing a more reliable water supply for California and protecting, restoring, and enhancing the Delta ecosystem (Water Code Section 85000). In the time since the Plan was adopted in 2013, a significant shift in State planning for Delta ecosystem protection, restoration, and enhancement has occurred, prompting review of the Delta Plan to examine whether its strategies are still suited to achieve the ecological goals of the Delta Reform Act. As such, the Delta Stewardship Council (Council) is developing an amendment of the Plan's Chapter 4, *Protect, Restore, and Enhance the Delta Ecosystem*.

Council staff are reviewing the best-available science to inform amendment of Chapter 4 of the Delta Plan. To support this effort, Council staff have developed three science synthesis papers. This paper focuses on the effects of climate change in the Delta and is accompanied by two other papers focused on the Delta ecosystem (terrestrial and aquatic resources) and restoration. Climate change is of interest for the Chapter 4 amendment given recent rapid advancements in research on climate change and its effects on the Delta ecosystem that have occurred since the Delta Plan was adopted in 2013 (Dettinger et al. 2016).

Climate change has the potential to significantly affect the Delta ecosystem by raising air and water temperatures, changing the timing and volume of flows into and through the Delta, increasing tidal inundation with sea-level rise (SLR), and increasing salinity intrusion into the Delta. Climate change is recognized as a global stressor in Chapter 4 of the 2013 Delta Plan, but the effects of climate change on Delta ecosystems are discussed only briefly and with limited consideration of management strategies that address the issue. Chapter 4 of the Delta Plan identifies five key stressors to the Delta ecosystem and core strategies for addressing each. Climate change has interrelated effects on all five core strategy areas: Delta flows, habitat, water quality, non-native species, and hatcheries and harvest management.

The Delta Reform Act specifies consideration of "the future impact of climate change and sea-level rise" (Water Code Section 85066), and identifies a restoration timeline horizon of 2100 (Water Code Section 85302). More generally, Executive Order B-30-15, signed by Governor Brown in April 2015, requires that State agencies incorporate climate change into planning and investment decisions, and that they prioritize natural infrastructure and actions for climate preparedness.

This synthesis paper is organized into nine sections, plus references cited. The next section (Section 2) provides background on climate change as a global stressor to the Delta ecosystem and summarizes the anticipated primary physical effects on the Delta and Suisun Marsh. The subsequent five sections (Sections 3 through 7) further detail the effects of climate change in each of the Plan's five core strategy areas: delta flows; habitat; ecosystem water quality; non-native species; and hatcheries and harvest management. The core strategies make up the organizational structure of the existing

Chapter 4 narrative and accompanying policies, recommendations, and performance measures, so that structure is used here. Section 8 provides a discussion of overall conclusions that apply across all core strategy areas. The last section outlines a set of high-level considerations for amending Chapter 4.

For convenience, as in the Delta Plan, "the Delta" is used to refer to the statutory Delta and Suisun Marsh collectively.

2. Climate change: A global stressor in the Delta

The consensus of a large body of scientific work clearly indicates that the earth's climate is changing and will continue to change at an increasingly rapid pace (Wuebbles et al. 2017, Royal Society 2017, Griggs et al. 2017). These changes will affect the Sacramento-San Joaquin Delta (Delta) and Suisun Marsh ecosystem and subsequently, the Delta Reform Act's mandate to protect, restore, and enhance these areas while achieving the coequal goals. This section summarizes the processes that contribute to warming and the anticipated changes to air and water temperature, precipitation and runoff, hydrologic extremes, and SLR. The summary draws from a literature review of climate change projections, ecosystem science and restoration, fish ecology, and climate change adaptations related to the Delta and Suisun Marsh, and to other geographies where information specific to the Delta are unavailable.

This paper considers a planning horizon of 2100, consistent with the Delta Reform Act, while recognizing that the 2050 planning horizon is used for the Delta Plan and proposed amendments.

2.1 Global climate change processes and emissions scenarios

Human-induced greenhouse gas (GHG) emissions, particularly those from burning fossil fuels, have been accumulating in the atmosphere, where they trap heat – a process referred to the "greenhouse" effect. Multiple sources of data indicate that the increase in GHGs is already altering the climate, increasing the temperature of the Earth's atmosphere and oceans. For example, atmospheric temperatures have risen about 1.8 degrees Fahrenheit (°F) over the last 115 years, 1901–2016, such that the present day is now the warmest in the history of modern civilization (Wuebbles et al. 2017). Ocean surface temperatures have also warmed in that period—roughly 0.7°F over the last 136 years, 1880-2017 (National Oceanic and Atmospheric Administration 2017). Human contributions are extremely likely to have caused more than half of this warming and may have caused more than 93% of this warming (Knutson et al. 2017).

These increasing global temperatures cause thermal expansion of the oceans and melting of land-based glaciers like the Greenland and the West Antarctic Ice Sheets (Griggs et al. 2017). As a result, the oceans' average water levels have risen about 8 inches (roughly 20 centimeters [cm]) over the last century, with accelerated rates since 1990 (Griggs et al. 2017). Other observed changes include increased ocean water temperature, melting glaciers, diminished snow cover, shrinking sea ice, ocean acidification, and increasing atmospheric water vapor (Wuebbles et al. 2017).

The influence of GHGs already emitted and anticipated future emissions will continue to cause global warming and climate change (Fahey et al. 2017). Although it is extremely likely that atmospheric and ocean temperatures will continue to warm, predictions of the exact rate of change remain uncertain. One source of uncertainty is the future emission pathway of GHGs. To capture the possible range of climate change, emissions scenarios, known as Representative Concentration Pathways (RCPs), have been developed (IPCC 2014). Three commonly-used RCPs, each representing a possible future emissions scenario, are:

- RCP 8.5 assumes no significant global efforts to reduce emissions. It is a severe scenario with trapped solar radiation (radiative forcing) reaching at least 8.5 Watts per square meter (W/m^2) by 2100 and rising beyond that.
- RCP 4.5 is an intermediate scenario, in which radiative forcing is stabilized at approximately 4.5 W/m^2 by 2100.
- RCP 2.6 is a scenario in which radiative forcing peaks at approximately 3 W/m^2 before 2100 and then declines due to global policy and emissions decisions. This scenario assumes severely reduced emissions that closely align with the goals from the United Nations Framework Convention on Climate Change (Griggs et al. 2017).

These emissions scenarios are thought to encompass a likely upper bound (RCP 8.5) and lower bound (RCP 2.6) for future emissions, which are used to estimate or model future changes to SLR and climate stressors, including temperature and precipitation changes.

2.2 Climate change stressors in the Delta and Suisun Marsh

In the Delta and Suisun Marsh, global warming creates four primary stressors with the potential to affect the ecosystem of the Delta and the Delta's watershed: increasing air temperature, changing precipitation and runoff patterns, increased frequency of extreme events, and rising sea levels. The following sections describe how climate change is projected to affect each of the stressors, as background for later sections that describe how these stressors are likely to impact the Delta's ecosystem and to inform the core strategies to protect, restore, and enhance the Delta and Suisun Marsh. These anticipated changes are summarized in Table 1 below.

This paper considers timeframes in the shorter-term (2030, 2050) and longer-term (2100). Changes will occur in the Delta, both gradually, such as with SLR, and also more rapidly from extreme events like floods and droughts, which are likely to become more common (Dettinger et al. 2016, Diffenbaugh et al. 2015). By many accounts, we are already seeing the effects of climate change in earlier runoff, higher sea levels and the leading edge of more extreme events (Fritze et al. 2011; Kunkel et al. 2013; Pierce et al. 2013; Dettinger 2016; Dettinger et al. 2016).

Table 1. Summary of Climate Change Stressors and their Impacts on Core Strategies to Protect, Restore, and Enhance the Delta and Suisun Marsh

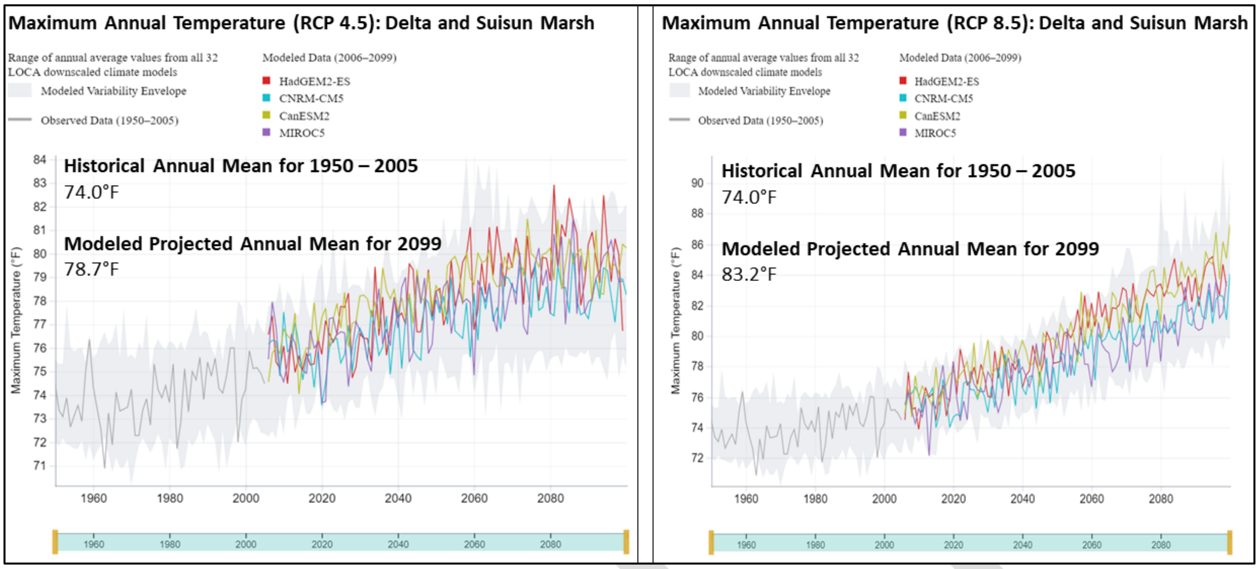
Stressor	Impacts to Core Strategies
Temperature	• Delta flows: Decreased snowpack; Increased evapotranspiration contributes to decreased river inflows, especially in summer • Wildlife and Fish Habitat: Increased frequency of extreme heat; cool refugia become more important. Increased summer stress on cold water-adapted species such as delta smelt. Change in phenology. • Ecosystem Water Quality: Increased water temperature affects native fish, which vary by species in ability to adapt. Potential mismatch between the timing of spawning and prey availability for fish whose spawning is triggered by temperature (e.g. delta smelt). • Non-native species: Habitats more hospitable for non-native species adapted to warmer climates • Hatcheries: Increased warmer temperatures correlate to increased smolt growth, decreased amount of cold water available for hatchery operations
Precipitation and Hydrologic Patterns	• Delta flows: Runoff earlier in the wet season. Decreased dry season flow from reduced snowpack. • Wildlife and Fish Habitat: Affected inundation patterns. Decrease in periods of sustained floodplain inundation that are important for native fish such as delta smelt. • Ecosystem Water Quality: Increased average annual and summer salinity due to reduction in snowpack (and snowmelt runoff). Changes in timing and areas of habitat for species reliant on specific salinities and temperature thresholds due to earlier snowmelt and more precipitation falling as rain. • Non-native species: None identified. • Hatcheries: Changed timing and less cold water available from snowmelt for hatcheries.
Frequency of Extreme Events	• Delta flows: Increased frequency of floods (including atmospheric rivers) and droughts. • Wildlife and Fish Habitat: Shift in timing, location, and extent of floodplain habitat. More extreme flows, but decrease in periods of sustained floodplain inundation that are important for native fish such as Delta smelt. More difficult to use reservoir management to improve conditions such as stream temperatures, cold-water pools, and salinity concentrations. • Ecosystem Water Quality: Increased sedimentation from extreme flood events and decreased water quality during drought. • Non-native species: None identified. • Hatcheries: None identified.
Sea level rise	• Delta flows: Increased tidal water levels. • Wildlife and Fish Habitat: Reduced marsh habitat, reduced growth rate of submerged vegetation, increased erosion, salt penetration higher up the Delta; changes in organismal distributions, decreases in freshwater Delta habitat for key species such as delta smelt and increase in saline Delta habitat. • Ecosystem Water Quality: Higher sea level will increase salinity intrusion into the Delta. • Non-native species: None Identified. • Hatcheries: May affect hatchery operations and where fish are moved by truck.

2.2.1 Air Temperature

In the next century, the Delta and Suisun Marsh are very likely to experience higher air temperatures 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), see Figure 1. 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 altitude 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 (Lebassi et al. 2009), 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), see Figure 2. In this way, the Delta and Suisun Marsh may serve as a refuge for species that would otherwise be subject to more temperature stress.

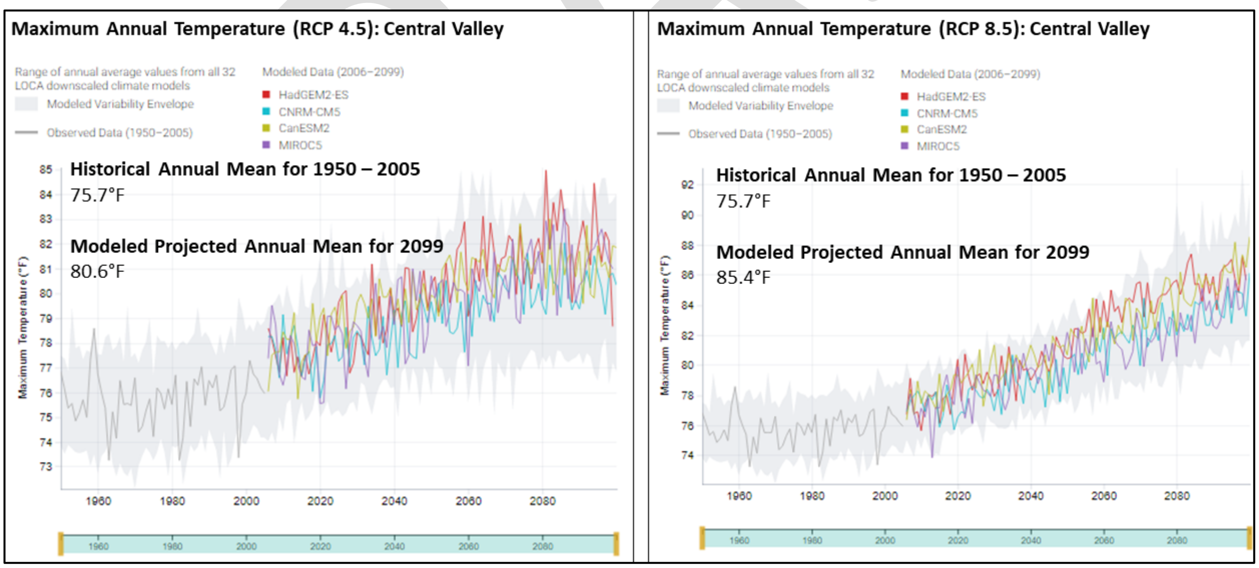
Figure 1. Maximum Annual Mean Temperature for Delta and Suisun Marsh



__Note:__ On each graphic, the gray line (1950-2005) is observed data. The colored lines (2006-2100) are projections from 10 LOCA downscaled climate models selected for California. The light gray band in the background shows the least and highest annual average values from all 32 LOCA downscaled climate models. Source: CalAdapt. http://cal-adapt.org/.

Figure 2. Maximum Annual Mean Temperature in the Central Valley

Source: Cal-Adapt, 2017



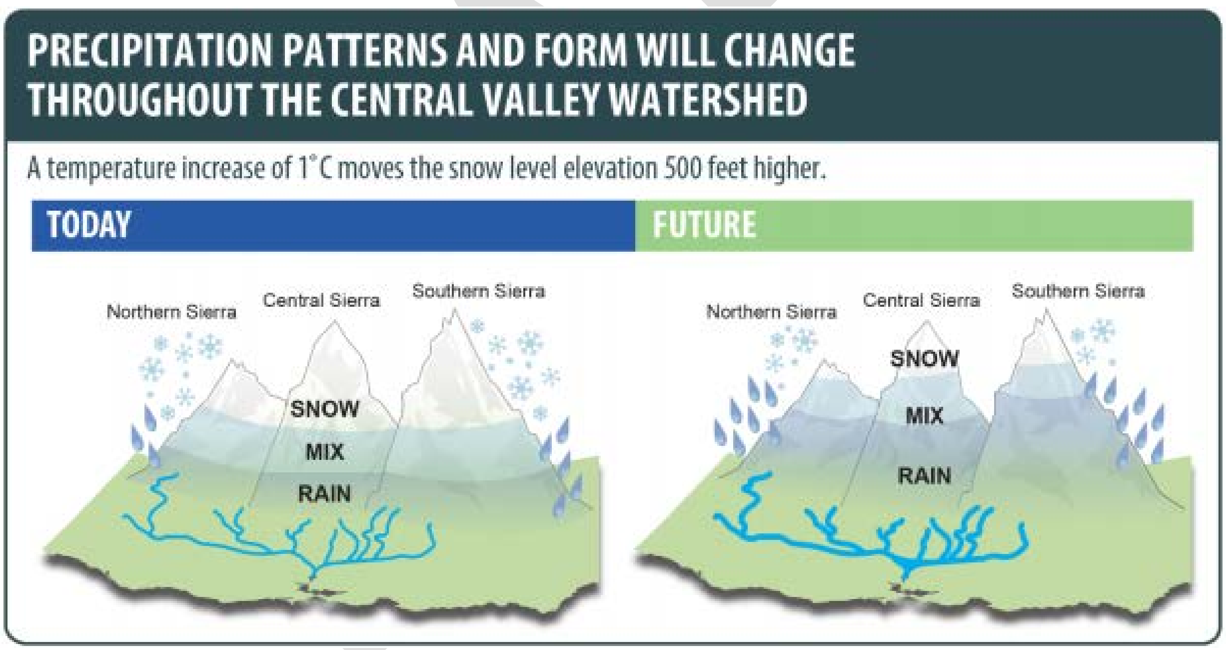
__Note:__ On each graphic, the gray line (1950-2005) is observed data. The colored lines (2006-2100) are projections from 10 LOCA downscaled climate models selected for California. The light gray band in the background shows the least and highest annual average values from all 32 LOCA downscaled climate models. Source: CalAdapt. http://cal-adapt.org/.

2.2.2 Precipitation and Runoff

A warmer atmosphere will modify precipitation and runoff patterns, which will alter both the timing and volume of flow as described below, and affect extreme hydrologic events like floods and droughts. Figure 3 illustrates how warmer storm systems brought by a warmer atmosphere will increase the fraction of precipitation across the Delta's watersheds that falls as rain instead of snow. Observations from the last decade, which exhibit a downward trend in the northern Sierra's snow fraction that may be caused by anomalous increases in sea surface temperatures, foreshadow the shift from snow to rain that is likely with climate change's warming (Hatchett et al. 2017). Rainfall runs off more quickly than snow (Dettinger et al. 2016), which normally accumulates as snowpack and runs off gradually as snowmelt later in the year. Schwarz 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.

Figure 3. Projected Future Climate Change Impacts on Central Valley Precipitation Patterns

Source: DWR 2017a

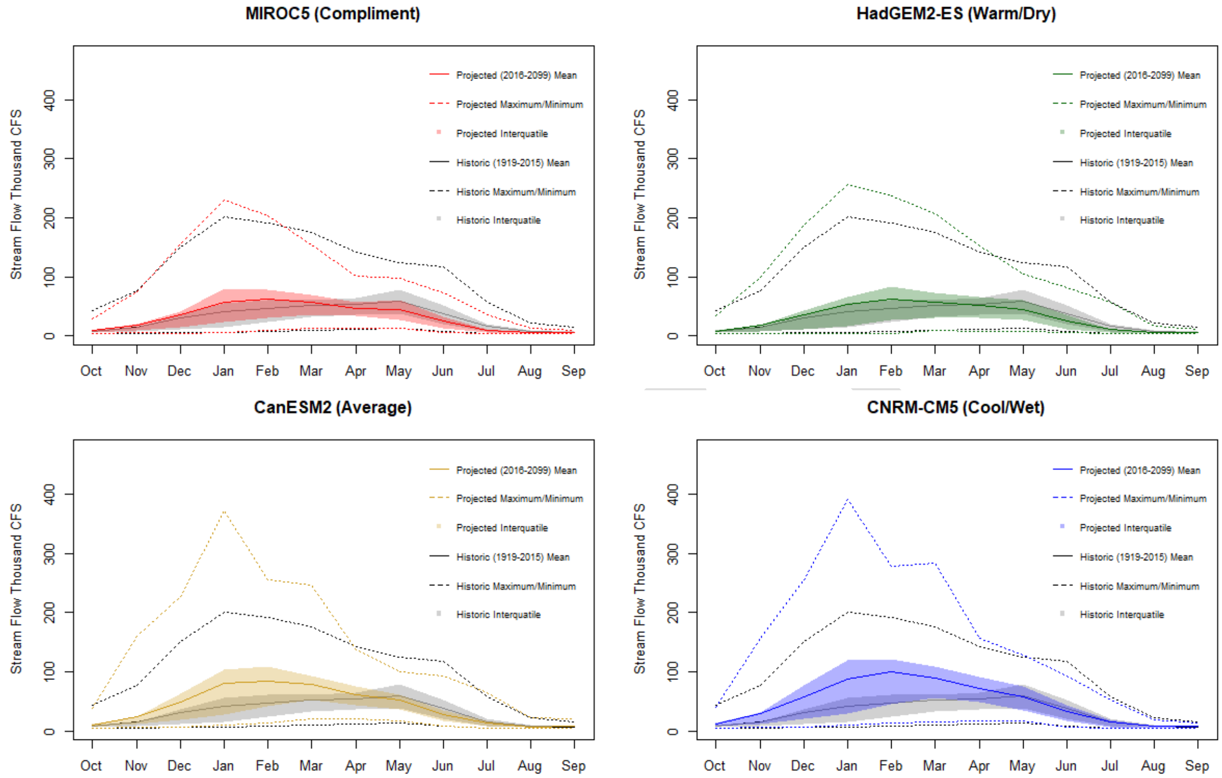


Runoff supplies the reservoirs and rivers in the Delta's watershed, which flow into the Delta and Suisun Marsh via the Sacramento River from the north, the San Joaquin River from the south, and several other smaller rivers from the east. Changes to runoff timing, volume, and temperatures are likely to modify Delta flows and have effects on water operations. For example, Figure 4 shows modeled projections for the eight-river index, an index of unimpaired runoff for eight rivers in the Sacramento and San Joaquin river watershed, which show both increases in the projected mean and maximum flows as well as a shift to earlier in the year (Cal-Adapt 2017).

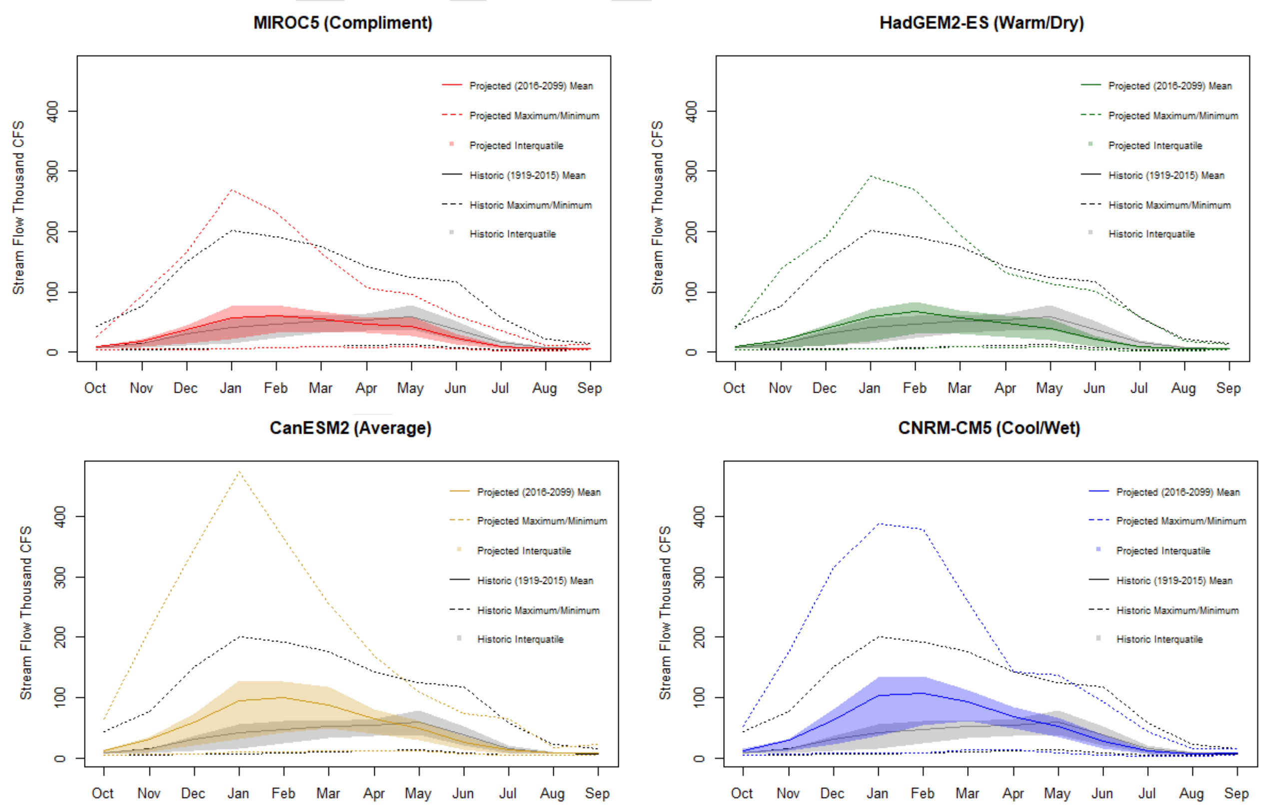
Figure 4. Sacramento-San Joaquin Eight River Index Flows

Source: Cal-Adapt 2017

a. Emission Scenario RCP 4.5 for Four Models



b. Emission Scenario RCP 8.5 for Four Models



Although precipitation and runoff within the Delta's watershed play the predominant role in Delta hydrology, analyses also anticipate a higher annual mean precipitation within the boundaries of the Delta and Suisun Marsh. For the RCP 8.5 emission scenario, and averaging several climate models at 2100, these increases include Solano County (increasing 6.0 inches to a total of 25.4 inches), Contra Costa County (increasing 4.7 inches to 23.1 inches), Yolo County (increasing 5.7 inches to 25.1 inches), Sacramento County (increasing 3.8 inches to 22.2 inches), and San Joaquin County (increasing 3.0 to a total of 16.8 inches) (Cal-Adapt 2017).

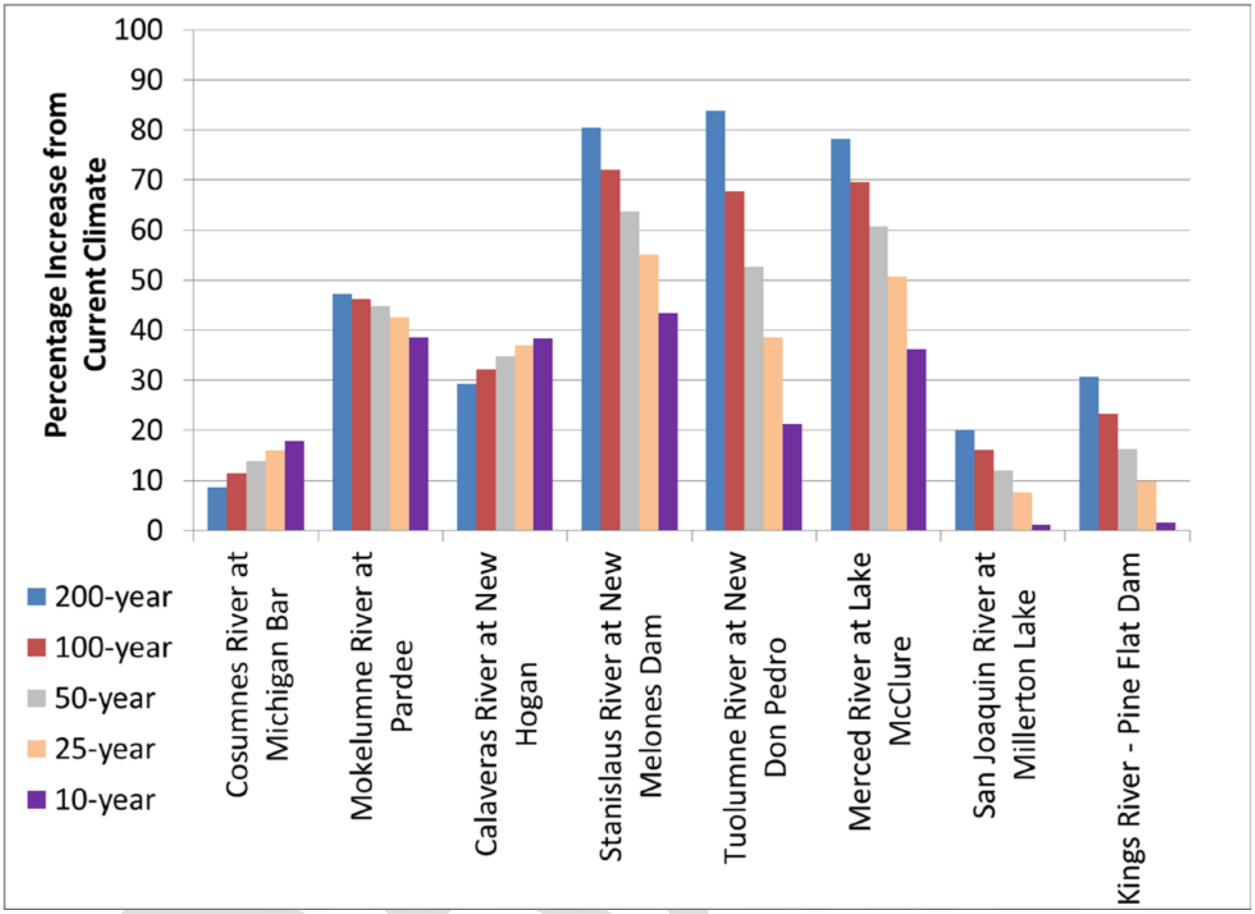
2.2.3 Hydrologic extremes: floods and drought

Both floods (Dettinger et al. 2016) and drought (Diffenbaugh 2015; Dettinger et al. 2016) are likely to increase in frequency and magnitude with climate change. Changes to extremes are likely, both because of altered event magnitude and new combinations of events that re-enforce one another (Dettinger et al. 2016). 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. California generally receives most of its rainfall during a small number of high-rainfall events, and climate change is expected to amplify this trend, with precipitation during the wettest 5% of wet days generally increasing and precipitation outside that window decreasing (Dettinger 2016).

Currently, atmospheric rivers (ARs) are potent mechanisms for generating the largest moisture influxes to the Delta and its watershed (Dettinger 2016). ARs are long, narrow streams of water vapor in the lower atmosphere, connecting moisture sources in the tropics to California. They bring the Sierra Nevada mountain range over 40% of its average precipitation, contributing prominently to flooding on the Sacramento and San Joaquin Rivers (Guan et al., 2010; Dettinger et al., 2011). In fact, over 80% of major floods and levee breaches in the Delta since 1950 were caused by ARs (Florsheim and Dettinger 2015). Data from the last 70 years indicate increasing AR intensity has contributed to increased moisture arriving in California, which is attributed to warming climate, particularly warmer sea surface temperatures (Gershunov et al. 2017). The majority of global climate models (GCMs) project an increase in the number and intensity of ARs in the 21st century if GHG emissions continue to increase (Dettinger et al. 2011; Warner et al. 2015; Gao et al. 2016; Polade et al. 2017). The increased intensity is due, in part, to the higher moisture content that warmer air can carry. In addition, the warmer air means a larger fraction of AR precipitation falling as rain instead of snow. Because changes in air temperature, snowpack, and storm intensity all favor more flooding, flood increases in the 2-year to 50-year return-interval range are likely, regardless of whether overall conditions are wetter or drier (Das et al. 2013). Flood management studies (DWR 2017b) found that flood volumes are expected to increase in both the Sacramento and San Joaquin River systems, with a larger increase in flood volumes expected on the San Joaquin River (60%-80%) when compared to the increase expected on the Sacramento River (10%-20%). This difference is because flood volumes in the San Joaquin River system are currently more driven by snowmelt from higher elevation watersheds, whereas flood volumes in the Sacramento River system are already driven by rainfall from that basin's relatively-low elevations as compared to the San Joaquin River basin. This means that changes from snow to rain are expected to cause greater increases in runoff and flood volumes in the San Joaquin system (Figure 5, following page).

Figure 5. Changes in Flood Magnitudes with Different Return Periods under the Median Climate Scenario

Source: DWR 2017b



Riverine flooding will compound with SLR, particularly for lower return period flooding and in the western Delta and Suisun Marsh, where oceanic water levels are a larger contributor to peak water levels. Wind and resultant waves can worsen flooding, particularly if levee failures create larger expanses of open water susceptible to wave fetch (van Gent 2003, Van der Meer 2002).

In addition to increased flooding, climate change is also expected to increase the frequency of drought (Diffenbaugh 2015; Dettinger et al. 2016). Warmer temperatures will exacerbate snowpack loss (Dettinger et al. 2016; Berg and Hall 2017), depleting the natural reservoir that snowpack provides for surface runoff and groundwater recharge, effecting local and regional water supplies. Simulations by Berg and Hall (2017) suggest that snowpack was reduced by 25% on average during the 2011-2015 drought; that future snowpack could be reduced during drought by up to 60-85% due to climate change. In fact, springtime snowpack is expected to decline significantly as climate warms, quite likely by at least half of present-day water contents by 2100. As a result, by 2100, arrival of snowmelt inflows to the Delta will be advanced by a month or more (Pierce and Cayan 2013; Dettinger 2016; Dettinger et al. 2016). Reduced snowpack and increase drought conditions are likely to decrease overall runoff that flows into reservoirs, and subsequently, the Delta. The implications for reservoir operations, such as increased likelihood of reaching reservoir dead pool conditions, and other effects on the Delta's ecosystem are discussed below. The potential for increased flooding means that reservoirs may need to release more water to maintain flood storage capacity, but this depleted storage may not be replenished by rainfall and snowmelt, exacerbating the potential for lower water availability in future years.

2.2.4 Sea-level Rise

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% chance that water levels at the Golden Gate on 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 SLR at that location of up to 10 feet (Griggs et al. 2017). Although the projections in this more recent research are similar to those of prior studies (NRC 2012; Dettinger et al. 2016), Griggs et al. (2017) improved upon the previous work with the addition of information about the likelihood of projected SLR.

For consideration in adaptation planning, the State of California Sea-Level Rise Guidance 2018 Update (Guidance; CNRA and OPC 2018) uses the SLR values shown in Table 2, based on results from the Griggs et al. study (2017). The document provides suggestions on using SLR scenarios to plan for the future, and specifically recommends how entities might choose from a range of SLR scenarios for future planning. The current guidance, and framing of low, moderate, and higher risks, is based upon public safety and economic damage, not ecosystem benefit.

State Guidance recommends that the upper end of the "Likely Range", for example 0.5 feet of SLR at 2030, may be appropriate to use for management projects that pose low risk or low consequences of flooding. The 1-in-200 chance values, 0.8 feet of SLR at 2030, could be used for projects of medium/moderate risk. Finally, when planning for adaptation in a high-risk situation, for example where consequences of flood damage or loss are too severe – like with the loss of a major highway, power plant, or wastewater facility – then the H++ values, 1 foot of SLR at 2030 or 10 feet at 2100, may be most appropriate. The H++ scenario was developed and included in Guidance because the probabilistic projections may underestimate the likelihood of extreme sea-level rise (resulting from loss of the West Antarctic ice sheet), particularly under high emissions scenarios. The probability of this scenario is currently unknown.

An example of using the data in Table 2 to identify when a specific level of SLR should be anticipated, based on one's level of risk tolerance, is illustrated in Figure 6. If you take an extreme risk aversion approach, for example, you should be prepared for 4.6 feet of SLR to occur by 2065. Level of risk aversion affects when one would assume 4.6 ft of SLR occurs and, working back from that date, when to begin planning and implementation of adaptation measures. Dates for the four risk aversion frameworks provided by the California Ocean Protection Council Sea Level Guidance Update (OPR 2017).

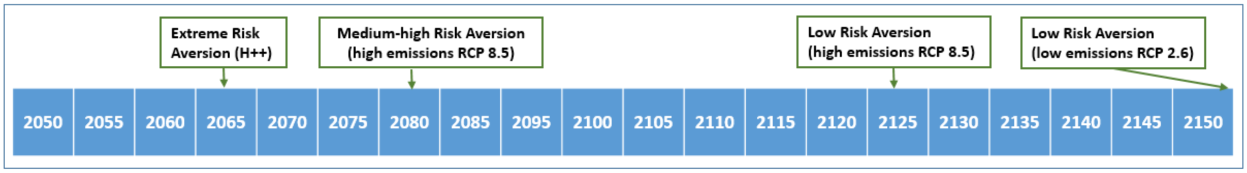
Table 2. Projected Sea level Rise (in feet) for San Francisco

		Probabilistic Projections (in feet) (based on Kopp et al. 2014)					H++ scenario (Sweet et al. 2017) *Single scenario
		Median *50% probability sea-level rise meets or exceeds…*	Likely range *67% probability sea-level rise is between…*		1-in-20 chance *5% probability sea-level rise meets or exceeds…*	1-in-200 chance *0.5% probability sea-level rise meets or exceeds…*	
				Low-risk Aversion		Medium - High risk Aversion	Extreme-risk Aversion
High emissions	2030	0.4	0.3 -	0.5	0.6	0.8	1.0
	2040	0.6	0.5 -	0.8	1.0	1.3	1.8
	2050	0.9	0.6 -	1.1	1.4	1.9	2.7
Low emissions	2060	1.0	0.6	1.3	1.6	2.4	
High emissions	2060	1.1	0.8	1.5	1.8	2.6	3.9
Low emissions	2070	1.1	0.8 -	1.5	1.9	3.1	
High emissions	2070	1.4	1.0 -	1.9	2.4	3.5	5.2
Low emissions	2080	1.3	0.9	1.8	2.3	3.9	
High emissions	2080	1.7	1.2	2.4	3.0	4.5	6.6
Low emissions	2090	1.4	1.0 -	2.1	2.8	4.7	
High emissions	2090	2.1	1.4 -	2.9	3.6	5.6	8.3
Low emissions	2100	1.6	1.0	2.4	3.2	5.7	
High emissions	2100	2.5	1.6	3.4	4.4	6.9	10.2
Low emissions	2110	1.7	1.2 -	2.5	3.4	6.3	
High emissions	2110	2.6	1.9 -	3.5	4.5	7.3	11.9
Low emissions	2120	1.9	1.2	2.8	3.9	7.4	
High emissions	2120	3	2.2	4.1	5.2	8.6	14.2
Low emissions	2130	2.1	1.3 -	3.1	4.4	8.5	
High emissions	2130	3.3	2.4 -	4.6	6.0	10.0	16.6
Low emissions	2140	2.2	1.3	3.4	4.9	9.7	
High emissions	2140	3.7	2.6	5.2	6.8	11.4	19.1
Low emissions	2150	2.4	1.3 -	3.8	5.5	11.0	
High emissions	2150	4.1	2.8 -	5.8	7.7	13.0	21.9

Source: CNRA and OPC 2018.

Note: Probabilistic projections for the height of SLR along with the H++ scenario are depicted in blue on the right-hand side of Table 2, as presented in CNRA and OPC 2018 with data from Griggs et al. *2017. The H++ projection is a single scenario and does not have an associated likelihood of occurrence as do the probabilistic projections. Probabilistic projections are with respect to a baseline of the year 2000, or more specifically the average relative sea level over 1991 - 2009. High emissions represents RCP 8.5; low emissions represents RCP 2.6. Recommended projections for use in low, medium-high and extreme risk aversion decisions are outlined in red boxes.*

Figure 6. When should you be ready for 4.6 feet of sea-level rise, based on your risk tolerance?



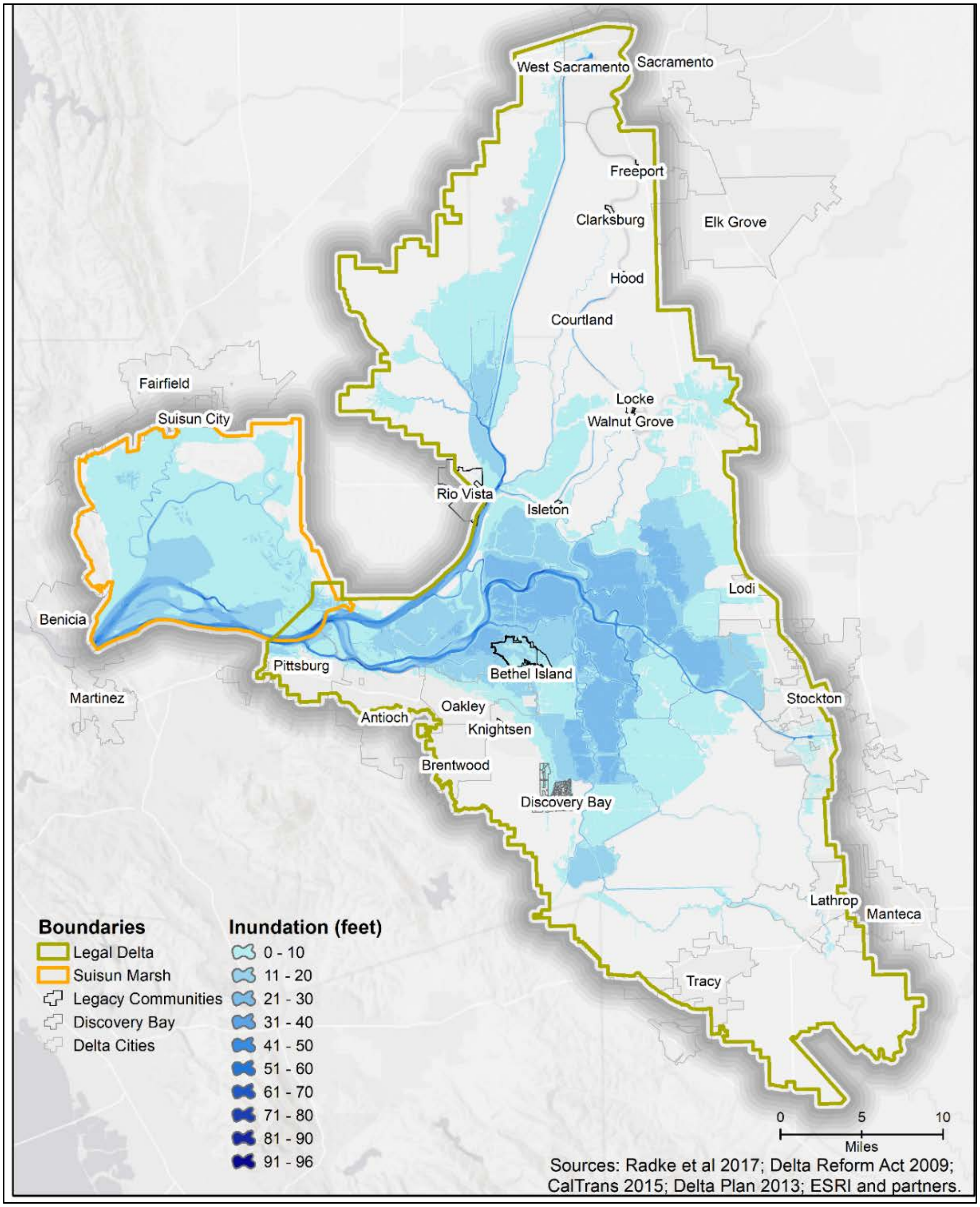
Generally, water-surface elevations in western-Delta waterways proximal to the Carquinez Strait are expected to mirror SLR at the Golden Gate relatively closely (U.S. Bureau of Reclamation et al. 2013a and b). However, less water-surface elevation change is anticipated in waterways farther east; for example, if sea level changes by 4.6 feet (1.4 m) at the Golden Gate, water-surface elevations are expected to change much less than that (on the order of 2.95 feet [0.9 m]) in the Central Delta region (Sathaye et al. 2011). Though significant hydraulic modeling has been performed in the Delta, there are no hydraulically-robust projections for the spatially-varying rise in tidal elevations across the Delta. MacWilliams et al. (2016) acknowledges that SLR will cause increased water levels in the Delta, and the work goes into some detail as to what that will mean for critical salinity thresholds and sediment patterns in the Delta, but the paper does not provide estimates of the hydraulic and water level changes due to SLR across the region. One study (Radke et al. 2017) investigated extreme events and mapped potential inundation from a 100-year storm event modeled with SLR (Figure 7). These findings can be insightful for the implications on land use and habitat (discussed in section 4); 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.

2.2.5 Uncertainties About Climate Change Projections and Use of Adaptive Management

Dettinger et al. (2016) discuss three types of uncertainty in climate change projections and the time frame on which they affect projections. First, natural variability, such as El Nino and the Pacific Decadal Oscillation, may affect projections over the next two decades. By 2050, the second type, uncertainties in how climate systems will respond to GHG increases, becomes the dominant source of uncertainty. This type of uncertainty is reflected in the differences between global climate models (GCMs) and can be characterized by aggregating results across multiple models. By the end of the century and into next century, the third type of uncertainty, which stems from which emissions scenario occurs, dominates. This third type of uncertainty can be characterized by considering projections across the range of likely scenarios, from RCP 2.6 to RCP 8.5.

Figure 7. Inundation in the Delta and Suisun Marsh for 4.6 feet of SLR and a 100-year Storm Event

Source: Radke et al. *2017.*



***Note:** the overtopping analysis assumes no levee improvements. The areas shown as most deeply inundated in the legend (91-96 feet) are within the existing channel in the Carquinez Strait, and are not from levee overtopping; leveed areas in the Delta and Suisun Marsh are inundated up to a maximum of 21-30 feet.*

The projected changes discussed in the preceding sections focus on responses that are likely to occur, either because of direct linkages (e.g. increased air temperature due to increased GHGs) or because of consistency across GCMs. When projections were less certain even in the direction of change, they were omitted from the earlier sections. For example, there is directional uncertainty in the projected changes in total annual precipitation; among GCMs about half project increasing annual precipitation for the Delta's catchment, while the other half project decreasing precipitation. Thus, this parameter was not mentioned. However, because more than half of the models project precipitation increases in winter months and declines in the spring and fall seasons, this parameter (seasonal variation) was mentioned. Studies based on historical observations that support future projections were also cited.

Cloern et al. (2011) similarly note that some relative uncertainty can be interpreted from the difference among GCMs in their sensitivity to GHG emissions and a range of possible emissions trajectories. These suggest that there is more certainty in the projected trend of air temperature, water temperature, SLR, snowmelt decline, salinity increase, and suspended sediment concentrations, as they are relatively insensitive to the difference in GCM scenarios. In contrast, projections for precipitation and unimpaired runoff are very sensitive to the amount of GHGs and are more uncertain.

Adaptive management (AM) is widely embraced in formal management plans as a means of addressing uncertainty associated with climate change. However, authentic implementation of adaptive management is infrequent and usually fails where decision stakes are high. A usual cause is unwillingness or inability of managers to implement decisions that change existing resource management policies solely on the basis of new science or where there are deep uncertainties – both attributes common to climate change science (DSC 2016). However, as a policy framework, AM is uniquely able to deal with uncertainties over long periods of time for ecosystem management, if science is made to be part of the process. LoSchiavo et al. (2013) identified five key principles for success: (1) legislative and regulatory authorities are critical for funding and implementation; (2) integration of adaptive management activities into agency framework ensures roles and responsibilities are clearly understood; (3) applied science framework is critical to establish a pre-restoration ecosystem reference condition; (4) clear identification of uncertainties that pose risks to meeting restoration goals (such as decision matrices); and (5) independent external peer review of an adaptive management program provides important feedback. Continual external review, such as what the National Academy of Sciences (NAS) is providing for the Florida Everglades, is critical for balance along the way. Kwakkel et al. (2015) highlights the importance of "dynamic adaptive policy pathways" whereby planners envision the future, commit to short-term actions, and establish a framework to guide future actions. The value of this approach is that it ensures short-term actions do not preclude long-term options.

3. Delta flows

Flows of fresh and saline water are key processes for the functions of the Delta ecosystem. River inflow, tidal fluctuations, channel and floodplain geometry, and water operations (e.g., upstream reservoir releases) and exports (i.e., diversions) are the primary drivers of flow within the Delta. The amount of water flowing through the Delta, and interaction between the four drivers noted above, causes fluctuations in water level, which determine what parts of the Delta are inundated, as well as how frequently, when, and for how long this inundation occurs. These inundation patterns are primary determinants of tidal and fluvial wetland habitat (Robinson et al. 2016). In addition, Delta flows directly influence water quality and water temperature in the Delta.

During the 19th and 20th centuries, extensive land conversion 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). Over the past century and a half, land use change, levees, the construction of large-scale water management infrastructure and water exports, and in-Delta diversions and consumptive use have greatly changed flow dynamics into and through the Delta. These changes have resulted in a land use conversion from wetland-dominant to agriculture-dominant, with the remaining wetlands supporting dramatically altered aquatic habitat (SFEI-ASC 2014). More natural functional flow patterns in the Delta are linked to ecosystem health and have an influence on water supply reliability (Reed et al. 2014, Public Policy Institute of California (PPIC) 2012). Inter-annual fluctuations in Delta flows due to variability of precipitation and water management operations, for example, already impact Delta habitats (Kimmerer 2002), and the effects of climate change are likely to further alter associated ecosystem processes and functions.

The effects of climate change are likely to alter hydrology in the Delta’s watershed, the resulting riverine inflow, and also to increase tidal water levels and affect operational flows—the flows managed to meet water quality criteria and exports—for the State Water Project, Central Valley Project, and to meet Bay-Delta water quality criteria. Future Delta inflows may differ in volume and seasonal timing due to the precipitation and snowmelt runoff changes previously described. Tidal dynamics in the Delta will also change because of SLR. Each of these modifications will in turn affect the ecological processes and habitat composition in the Delta.

While operations are not directly tied to climate change effects, as they are human-managed, operations will likely need to be modified to accommodate other factors affected by climate change, such as tradeoffs in reservoir level, flood management, and water supply, and cold-pool flow releases to manage water temperature, and other demands. As an example, each one-foot rise in sea-level relative to a 1981–2000 baseline could potentially require increased outflow of 475,000 acre-feet per year to meet current salinity standards (Fleenor et al. 2008).

In addition to determining inundation; fluvial, tidal, and operational flows also transport numerous passive constituents and active aquatic inhabitants through the Delta. Passive constituents include nutrients, seeds, salinity, suspended sediment and turbidity, several planktonic organisms, and contaminants. Active inhabitants include organisms with limited locomotive ability, such as fish and mammals. The water-quality-related implications of flows are considered in a following section.

Delta flows can be grouped into three categories, based on their region of influence (both in terms of physical location and habitat types), as well as their dominant physical processes. These factors also determine the flows' potential climate change impacts. From upstream to downstream, the three flow categories are:

- **River inflows and floodplain flows** – These flows originate as either rain or snow within the Delta's watershed, can be modulated by reservoir operations and diversions, and enter the Delta via the rivers along the Delta's upstream boundaries. They supply the Delta's freshwater, seasonally inundate connected floodplains, and occasionally cause wide-spread Delta flooding.

- **In-Delta net channel flows** – Except when riverine flows are high, these flows are primarily forced by tidal patterns, which yield tidally-averaged net flows. Besides variation due to rivers and tides; channel and floodplain geometry, Delta barriers, diversions, and export pumps also alter these flows, with increasing intensity closer to these operations structures.

- **Net Delta outflows** – Net Delta outflow to San Francisco Bay is comprised of the remaining flow, after averaging tides and subtracting diversions from the Delta from the sum of all riverine inflows. These flows represent the net transport through the Delta and strongly affect the location of the salinity gradient between the Delta's fresh water and saline ocean water. The salinity gradient fluctuates across the western Delta and Suisun Bay.

These three flow categories are related. The continuity of flows means that one category provides input flows to the downstream categories: for example, riverine flows are a key factor for in-Delta net flows and net Delta outflow. In addition, as one category intensifies, it will subsume other categories in relative importance over the Delta landscape: for example, during wet season flooding, riverine flows can come to dominate the Delta, overwhelming tides that characterize in-Delta channel flows and nearly serving as a direct conduit to net Delta outflows.

3.1 Ecosystem impacts

Because of prior land use conversion and existing water supply management, the wetland ecosystems which occupied the historic Delta and Suisun Marsh have been greatly diminished in extent and are already stressed. Many aspects of climate change will further stress the ecosystem. While current scientific understanding is limited in its capacity to quantify long-term ecosystem changes, the overall trend, that climate change will exacerbate ecosystem stressors, is robust. Therefore, to mitigate ecological impacts will require management to build up the fragile resilience of the Delta ecosystems. The anticipated ecosystem impacts due to flow changes are summarized below.

3.1.1 Riverine flows and floodplains

Freshwater inflow from rivers into and through the Delta greatly influences the ecological health of the Delta, as well as water quality and species abundance that influence water exports, and therefore water supply reliability (Feyrer et al. 2011, MacWilliams et al. 2015, SWRCB 2010). The quantity, timing, and patterns of these flows drive many ecological processes, and are integral for the ecological health of the

Delta and greater San Francisco Bay Estuary (Davis et al. 2015; Kimmerer 2002; Luoma et al. 2015; NRC 2012; SWRCB 2010; Yarnell et al. 2015). In general, native species can accommodate and even benefit from the greater flow variability associated with natural flows. With climate change, connectivity between channels and floodplains and between habitats along the length of a channel will allow movement of plants and animals to areas where flows are most conducive to survival, important as these flows change over time. Seasonally inundated floodplains such as the Yolo Bypass (Sommer et al. 2014), even highly managed ones (Katz et al. 2017), provide key habitat for native fish spawning and rearing, particularly during late winter and early spring, when the colder temperature favors natives over non-natives (Moyle et al. 2013). Since climate change is likely to increase flooding for 2-year and higher return period events (Das et al. 2013), the timing, location, and extent of floodplain habitats may shift. Restoration of floodplain habitat should anticipate these shifts by including appropriate topographic variation. One potential detriment of increased inundation is the potential for increased mercury methylation (Fong et al. 2016).

Flooding intensification due to riverine discharge and SLR will challenge the Delta and Suisun Marsh's existing levees. Raising levees or repairing them in response to overtopping and breaching will likely not be feasible at all locations (Ellis et al. 2017), prompting planned or unplanned tidal or fluvial connectivity. The type and quality of restored habitat depends on location and ground surface elevation, as discussed in more detail below in the section on habitat.

The projected increase in drought will negatively alter the limited extent of existing Delta floodplain ecosystems and potential restored floodplains by depriving them of riverine inundation in a system where floodplains are already disconnected by levees. Droughts exacerbate other stressors in these already-stressed floodplain systems and favor non-native fish, which do not depend on floodplains for spawning. Furthermore, droughts are also likely to challenge the already-difficult management of riverine fish habitats upstream of the Delta, particularly with regard to reduced cold-water pools that can be used for temperature regulation. Managing for both upstream and Delta habitats will probably require tradeoffs between these two habitats. These extreme conditions, although occurring infrequently, may serve as tipping points for population viability.

3.1.2 In-Delta net channel flows

During the wet season, in-Delta flows are typically dominated by the riverine flows described above. When these riverine flows subside, either due to the arrival of the dry season or drought, tides play a more dominant role for in-Delta flows and water levels. SLR will shift the tides upwards, altering the ground-surface elevation ranges for intertidal habitats (discussed in Section 4).

Restoration will also affect the relative balance of channel versus floodplain geometry, and hence alter tidal propagation and mixing characteristics. While individual restoration projects have negligible effects on tides outside their immediate project area, restoration at the scale of the Delta, i.e. multiple thousands of acres, has the potential to alter tidal propagation and increase mixing (MacWilliams et al. 2016). These changes could make it more difficult to achieve more natural flow patterns by altering hydrodynamics and possibly requiring additional fresh “operational” water to move water through the Delta to meet water quality criteria or for export.

Currently, in-Delta flow conditions can periodically limit water exports, in an effort to limit net flows towards the pumps and resulting fish entrainment. Climate change will likely alter the operational demands and regulation, as discussed in more detail below.

3.1.3 Net Delta outflows

As a mechanism for controlling the location of the Delta’s salinity gradient, management of net Delta outflows are a prominent factor for setting the location and extent of transitional saline/fresh estuarine habitat. As described above, climate change, in the form of both shorter wet season and SLR, will tend to shift the salinity gradient landward into the Delta. Reservoir releases can counter this salinity intrusion under many future conditions; however, achieving this via additional reservoir releases could reduce export supply by 10% by mid-century and by 25% for end of century (Fleenor 2008; DWR 2009). If reservoir releases are not increased and the salinity gradient trends further inland, the gradient may not be as favorably located in the Suisun Marsh region, but it may also provide a return to greater salinity fluctuations in the western Delta, closer to historic conditions, that may favor native species in that part of the Delta. Specifics about the salinity and its role with regard to habitat are discussed below in the section on water quality.

3.2 Possible operational responses to climate change

Changes in precipitation, runoff, and SLR are likely to affect water resources and reservoir operations in a number of ways, diminishing operational flexibility and exports over time. Reduced snowpack will alter the timing of runoff entering the reservoirs and increase the temperature of water which will affect many competing demands including ecological flows and exports. The effects of climate change are likely to limit the degree to which reservoir management can be used to improve conditions such as stream temperatures, cold-water pools, and salinity concentrations. Meanwhile, pressure for exports is not likely to abate; U.S. Bureau of Reclamation (2015) projects larger agricultural water demand in the Central Valley.

Increasing flood magnitude and frequency may stress reservoirs more frequently during wet years, requiring more frequent and larger reservoir releases. Balancing flood safety with water supply needs may become more difficult as a result of climate change. Operating rules require that dams release water when reservoirs reach the flood-storage pool capacity. By delaying runoff into reservoirs, snowpack helps separate flood and storage operating rules, thereby increasing the stored water available for water supply demands. However, with the expected earlier rainfall and less snow accumulation, releases for flood safety may reduce replenishment of reservoir storage. On the other end of hydrologic extremes, more frequent droughts are likely to increase the frequency of challenges to meeting various operating criteria for ecological, water quality, and export needs. Any changes in operating rules to address these issues should also consider their potential impacts on habitat. Increased drought, increasing water temperature, and reduced overall inflow decrease the reservoir volumes which reduces this ability to manage for cold-water pools and associated releases for downstream habitat.

SLR is expected to cause salinity intrusion into the Delta, which may be exacerbated by reduced snowpack and inflows into the Delta and Suisun Marsh. This would require more frequent reservoir releases to forestall salinity intrusion, however, the flood management challenges and increasing drought potential will further limit water stored by reservoirs.

During extreme drought conditions, which may become more prevalent with climate change, management for water quality purposes may include additional temporary barriers, such as the False River barrier installed in response to 2015 drought (DWR 2017c). While such barriers may offer water quality benefits, they also change in-Delta flows and affect fish migration pathways.

4. Habitat

Historic habitat loss and fragmentation resulting from human land use is one of the largest legacy stressors to the Delta and Suisun Marsh ecosystem (DSC 2013). The anticipated impacts of climate change are likely to exacerbate these losses, making restoration even more important to the long term protection of the ecosystem. Notably, climate change will affect tidal marsh in the Delta, as well as leveed and managed habitat areas, open water habitat, and seasonal floodplain (Ordonez et al. 2014).

Expanding habitats for native species is identified in Chapter 4 of the Delta Plan as an essential part of restoring the Delta's ecosystem. To be successful, habitat restoration will need to consider the context of how climate change will manifest alterations across the landscape. This section describes these effects on Delta and Suisun Marsh habitats. More discussion on restoration and science is provided in the Restoration synthesis paper.

4.1 SLR and changes to tidal marsh

It is widely recognized that the locations, types and extents of Delta and Suisun tidal marshes will shift with SLR (Kirwin and Megonigal 2013; Goals Project Update 2015; Dettinger et al. 2016; Robinson et al. 2016; CDFW 2017a). As sea level rises, tidal marshes can respond in two ways: 1) by accreting soil matter, allowing the elevation of the marsh to rise with SLR; and 2) by moving spatially on the landscape, migrating into the adjacent upland margin. Whether tidal marshes survive with higher rates of SLR will depend primarily on sediment availability, vegetation response to increased inundation, and opportunities for landward migration. Tidal marsh provides critical habitat for native and special-status species such as the salt marsh harvest mouse, Ridgway's rail, and California black rail.

4.1.1 Basic processes and biophysical feedbacks that sustain wetlands

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 (Kirwin and Megonigal 2013; Callaway 2007). 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.

Landscape factors are also important for marsh sustainability. Where marsh elevation keeps pace with SLR, the extent of marsh and location on the landscape depend on the relative balance of new marsh creation (via migration) at the upland edge and marsh loss through lateral erosion at the sea-ward marsh edge. Broad connections between tidal marsh and gradually sloping adjacent uplands allow the marsh to expand upslope as sea level rises.

4.1.2 Threshold rates of SLR

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 (Kirwin 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 (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/yr (1.0 to 1.8 cm/yr) 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% of existing sediment supply), marsh conversion to mudflat occurred. Model results from Swanson et al. (2015) suggest that 84% of the sensitivity scenarios resulted in freshwater Delta marshes persisting with 2.9 ft (88 cm) of SLR by 2100 (0.9 cm/yr), while only 32% and 11% 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 (see discussion of empirical data below).

Cores of relatively undisturbed natural marshes in Suisun Marsh and 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/yr (~0.2-0.4 cm/yr) (Callaway et al. 2012). In the Delta, observed accretion rates from deep cores range from 0.012 to 0.19 in/yr (0.03 to 0.49 cm/yr; 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/yr; 0.1-0.2 cm/yr) and does not represent the potential maximum with higher SLR (Drexler et al. 2009). Projected future decreases in sediment supply (see discussion in “Ecosystem water quality” section below) could decrease accretion rates and are considered in the scenarios modeled.

Radiometric dating of marsh cores collected low in the intertidal zone by Reed (D. Reed, personal communication) found accretion rates of 0.35 in/yr (0.9 cm/yr) at Sherman Lake (31-year average) and 0.7 in/yr (1.8 cm/yr) 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 data are needed to characterize how rates of accretion vary with intertidal elevation in freshwater marshes of the Delta.

Recent research documents the effects of additional climate-related factors on marsh elevations. Elevated CO_2 can have a net positive effect on wetland stability through enhanced root production in certain wetland plants (Kirwan and Megonigal 2013). Temperature warming can increase both plant productivity and decomposition, with recent research suggesting a small net positive effect on wetland stability (Megonigal et al. 2016). Other factors such as warming effects on plant community composition remain poorly understood and difficult to predict.

4.1.3 Landward migration of marshes and tidal-terrestrial transitional habitat

The current physical configuration of the Delta and Suisun Marsh will make landward migration of key habitat and species difficult as the climate changes. Where space is available, intertidal marshes will expand at the edges of the Delta and Suisun Marsh, migrating over adjacent higher areas. In the current landscape, however, many remaining wetlands cannot move landward due to the presence of extensive levees, roadways, and other infrastructure (Orr and Sheehan 2012; Dettinger et al. 2016). The Yolo Bypass and parts of the Cosumnes River Preserve offer land where marsh may migrate with SLR, but overall opportunities are severely limited. Where tidal marsh comes up against levees and developed edges of the Delta or has no adjacent upland (as is the case for remnant in-channel islands), marsh that does not accrete as rapidly as SLR will be squeezed into progressively narrower bands, then lost over time (Tsao et al. 2015). Restoration to allow landward migration of marshes with SLR will increase sustainability.

In addition to the gradual changes associated with SLR, increases in extreme climatic events will affect terrestrial species and birds that use the marsh, making the tidal-terrestrial transition zone important as refuge 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” (Robinson et al. 2016). These higher-elevation habitats around the margins of the Delta and Suisun Marsh are potential future tidal marsh areas. Like tidal marshes, transition zones shift upslope as sea level rises and require sufficient accommodation space.

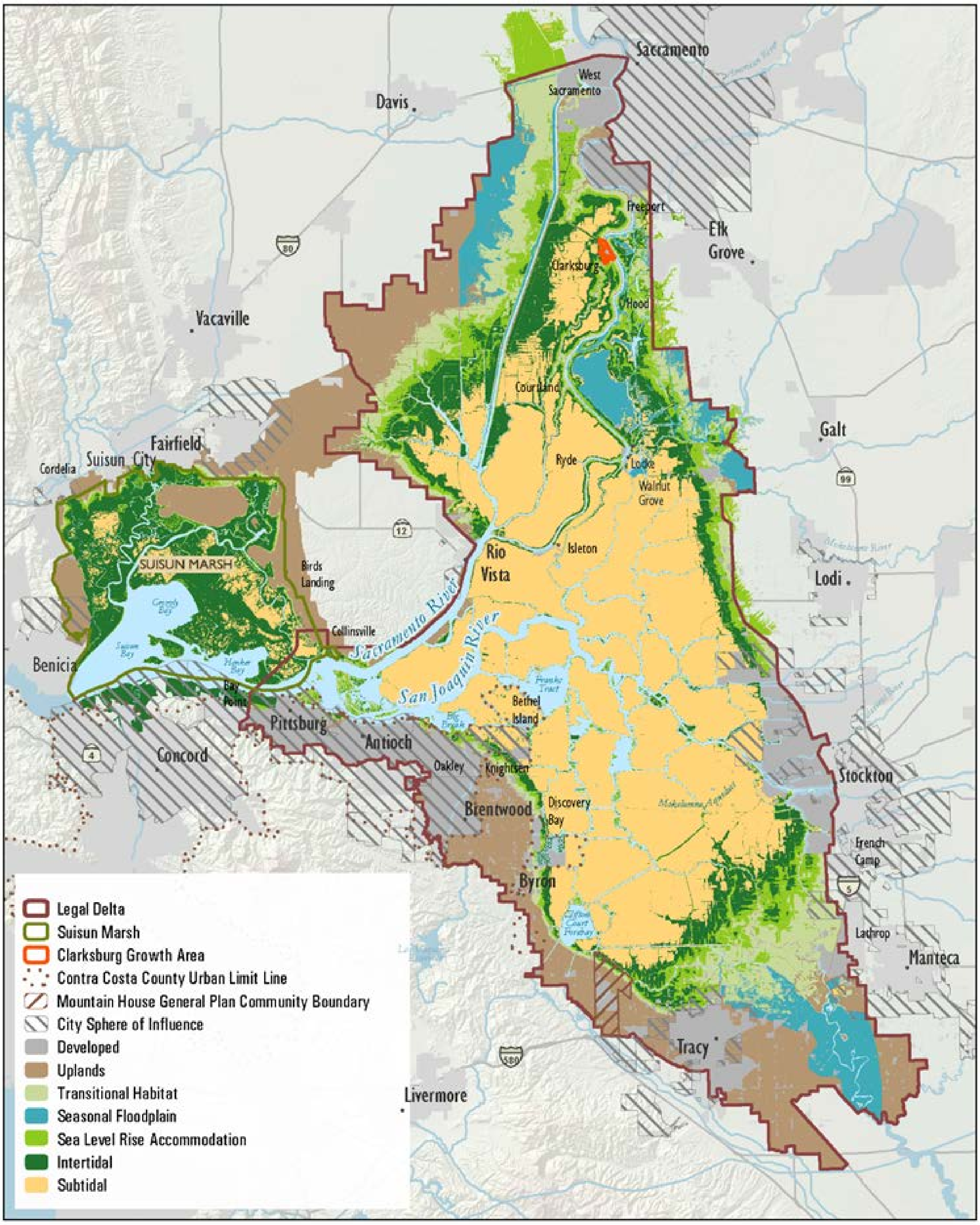
4.1.4 Salinity shifts, extreme events and other climate-related effects on tidal marsh

As sea level rises and higher salinity intrudes further into Suisun Marsh and the 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). Effects of salinity shifts on sedimentation are more difficult to predict, as sediment supply varies geographically, and the availability of suspended sediment in the water column is affected by complex processes and interactions. Where suspended sediment is available in the water column, settlement rates will be augmented by increased salinity (Krone 1987).

4.1.5 Sea-level rise effects on habitats by elevation

Figure 4-6 from the Delta Plan (Figure 8) shows potential habitat types in the absence of levees based on elevation in the Delta and Suisun Marsh – subtidal, intertidal, SLR accommodation, transitional habitat, and uplands. Sea-level rise will affect this habitat distribution and the figure shows a 3-foot vertical band as an allowance for SLR. An update to this figure to reflect updated SLR estimates and planning guidance (CNRA and OPC 2018) is underway. A future map, and indeed future habitat suitability based on elevation, may show a wider band for SLR accommodation to reflect higher rates of rise (e.g., to 10 feet). The areas labeled as transitional habitat and uplands would move upslope. These higher-elevation habitats around the margins of the Delta and Suisun Marsh are of increased importance as potential future tidal marsh areas. Seasonal floodplains, too, will be affected by higher flows with more extreme precipitation events (discussed below). In addition to revisions of this figure prompted by updated consideration of climate change, there are substantive updates that may be considered based on use of updated data sources – for example, updated tidal datums and land elevation data (Fregoso et al. 2017). Due to the presence of vegetation and standing water, LiDAR-derived land elevations in certain areas, such as the diked wetland areas of Suisun Marsh, may be overestimated (Orr and Sheehan 2012), requiring adjustments to accurately map potential subtidal and intertidal marsh habitat. Additional updates could be made for the developed areas and urban limits based on the most recent plans and land uses.

Figure 8. Habitat Types Based on Elevation, Shown with Developed Areas in the Delta and Suisun Marsh



In the Delta and Suisun Marsh, the NOAA Center for Operational Oceanographic Products and Services (CO-OPS) manages 24 stations (12 in the Delta, 12 in Suisun Marsh) that provide information on tidal datums, such as Mean Sea Level (MSL), Mean Lower-Low Water (MLLW), Mean Higher-High Water (MHHW), at the given location (NOAA 2018). These benchmarks provide important information for wetland restoration planning as they characterize the inundation frequency, magnitude, and duration at a particular location, which in turn informs site selection with desired inundation regimes for intertidal habitat. Furthermore, these tidal datums can allow for scenario modeling of future tidal conditions including SLR, water conveyance, marsh restoration, and levee failures. However, the quality of the information is uncertain and the spatial coverage is poor as most of the stations are located in the interior of the Delta, and are unable to adequately characterize tidal heights at locations with appropriate elevations for habitat restoration. To address the quality and spatial coverage concerns with the NOAA CO-OPS tidal datums, efforts are being made to use information from the long-term tide stage gages (~40) maintained in the Delta by DWR and USGS to generate tidal elevations at a high nodal resolution throughout the Delta (DWR 2018). This work will allow for an update of Figure 4-6 as a part of the amendment of Chapter 4.

4.2 Leveed and managed habitat

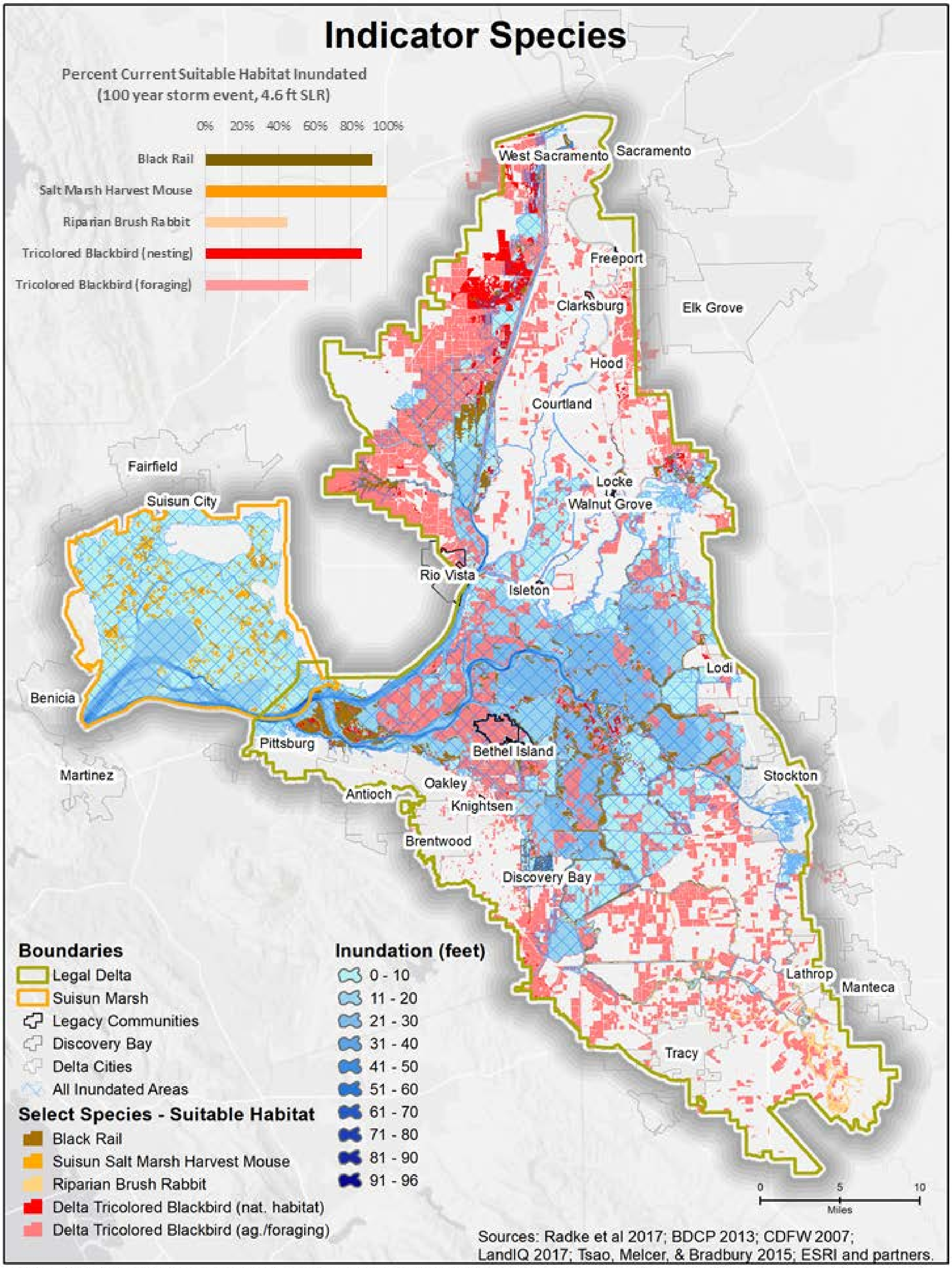
Over 1,100 miles of levees in the Delta and Suisun Marsh protect select areas of terrestrial habitats and managed wetlands that support native species. For example, managed wetlands in Suisun Marsh are an important stop on the Pacific Flyway for migratory birds. Agricultural-associated areas in the Delta offer a range of habitats from lands on Staten Island managed for sandhill cranes to mostly small, isolated pockets of habitat. The Delta's leveed and managed habitat areas are increasingly vulnerable as sea level rises and extreme floods threaten to overtop levees or permanently submerge habitat.

The levees of the Delta and Suisun Marsh are vulnerable to flooding from high water events. Future SLR and more extreme climatic events will increase the frequency of high water events, increasing vulnerability to flooding from levee overtopping (discussed here) and failure (discussed below) (Delta Plan 2013b; Deverel et al. 2016). Increased threat of inundation will introduce challenges for the people that live in the area as well as some species that use the Delta and Suisun Marsh as habitat (Tsao et al. 2015).

Inundation estimates released on Cal-Adapt (Radke et al. 2017) for 4.6 feet of SLR during a 100-year storm provide an opportunity to understand where inundation could occur and the sorts of human and species habitats that could be impacted. The Radke et al. (2017) projections shown in Figure 7 simulate levee overtopping but do not include levee failures or peak inflow events. Using the Radke et al. (2017) estimates, inundation of current leveed habitat varies across indicator species (Figure 9) (BDCP 2013; CDFW 2007; LandIQ 2017; Tsao, Melcer, and Bradbury 2015). For example, the endangered salt marsh harvest mouse inhabits the extensive leveed habitats of Suisun Marsh, all of which are inundated. For the endangered tricolored blackbird, significant leveed areas of nesting and foraging habitat are expected to be inundated.

1 **Figure 9. Inundation of Indicator Species**

2 *Source: Radke* et al.*, 2017*



3 **Disclaimer:** This map reflects BDCP models of current suitable habitat for the species depicted and does not include potential suitable habitat at higher elevations.

4.3 Open water habitats and potential levee failures

To the extent that habitats (or other lands) on leveed Delta islands are managed and drained, these habitats will continue to subside, worsening the consequences of levee failure and releasing carbon, a greenhouse gas, from the soil into the atmosphere. Operation of managed wetlands with dense emergent marsh vegetation can be used to halt and reverse ongoing subsidence, in some cases raising land elevations sufficiently to allow long-term tidal wetland restoration. Subsidence reversal provides the benefits of GHG mitigation (carbon sequestration) and select ecological benefit. Miller *et al*. (2008) measured subsidence reversal rates at two wetlands on Twitchell Island from 1997-2006. Land-surface elevations increased by an average of 1.6 in/year (4 cm/year) in both wetlands with a range of -0.2 to 3.6 in/year (-0.5 to +9.2 cm/year).

Bates and Lund (2013) analyzed the potential for subsidence-reversal techniques to raise Delta islands to mean sea level, an elevation consistent with tidal wetland restoration best practices. The analysis used a subsidence reversal rate of 1.6 in/year (4 cm/year) and, for each Delta island, took into account initial elevations and the probability of levee failure based on current levee conditions. Results of the analysis indicate that elevation gains of 3.3 to 6.6 feet (1-2 m) are probable prior to flooding. This gain is sufficient to raise the least subsided islands (8 of the 36 islands evaluated) to mean sea level. If the intent of subsidence reversal is long-term tidal wetland restoration, more specific tidal emergent vegetation elevation thresholds and future relative elevation loss are also important considerations; Bates and Lund do not include an allowance for SLR or ongoing subsidence.

Sea-level rise may make repairing and rehabilitating all future 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 deep open water areas (Deverel et al. 2016). The aquatic habitat value of open water areas varies greatly by species, by location, and by other factors related to the 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 *Egeria densa* (Brazilian waterweed) or *Corbicula* (Asian clam) to date (Lehman 2010; Lehman 2015; Dettinger et al. 2016). On the other hand, Mildred Island, an unintentionally flooded area in the south-central Delta, provides a very different type of open water habitat. The deeply-subsided interior of the island provides relatively high pelagic primary productivity. However, dense Corbicula around the perimeter of the site, at the outflows, 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).

Permanently flooded islands would affect estuarine hydrodynamics and processes – for example reducing tidal flows, shifting salinity regimes, changing circulation patterns, and modifying sediment transport and deposition – in ways that would depend on the sizes and locations of the new open water areas. The associated ecological effects would depend on the specifics of the levee failure, and could vary widely. 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). Unpublished analysis by Williams (2016) suggests that channel scour may be significant.

4.4 Seasonal Floodplain

Floodplains are ecologically important components of the Delta ecosystem. They provide habitat and trophic resources for aquatic and terrestrial animals, and are sites of high productivity that support high biodiversity (Corline, Sommer, and Katz 2017). Floodplains also recharge local groundwater, contributing to more-sustained and cooler dry-season flows. Restoration of floodplains can provide benefits to human communities by lowering flood water levels, reducing flood risk.

The majority of floodplains in California's Central Valley have been destroyed or disconnected by levees, dams, agriculture, or other human development (Jeffres 2008). However, the remaining seasonal floodplains provide ecological benefits including support for greater juvenile Chinook Salmon growth, for example, when compared to salmon growth in-river or in perennial floodplain pond habitats (Corline, Sommer, and Katz, 2017; Jeffres, 2008).

The ecological benefits of floodplains are linked to the extent, depth, duration, and temperature of flood inundation. Seasonal flooding was historically tied to large precipitation events like ARs or spring snowmelt. With climate change, floods in the Delta are likely to increase in frequency and intensity of peak flows, but decrease in duration. Sustained periods of inundation on the order of weeks and months are important for native fish. The Sacramento Splittail, for example, needs at least 30 consecutive days of inundation for successful spawning and rearing (Cloern et al. 2011). Evaluation of Yolo Bypass flood conditions by Cloern et al. (2011) indicates that desirable floodplain conditions for splittail spawning and rearing decrease in a warmer and drier climate scenario. Matella and Merenlender (2014) modeled streamflow dynamics along the San Joaquin River just upstream of the Delta under historical and future (climate change) scenarios to evaluate potential for Sacramento Splittail and Chinook Salmon rearing habitat. Their work found significant declines in the availability of required flow-related habitat conditions for Splittail spawning and rearing, and Chinook Salmon rearing; roughly 4-17% of the years between now and 2100 are likely to produce sufficient flow for those benefits. They suggest that flows will likely need to be augmented to sustain Splittail and Salmon in the future.

The effects of more prolonged drought periods on riparian vegetation are uncertain and will depend on species response to increased temperature, increased frequency of low flows and drought, and on groundwater interactions.

5. Ecosystem water quality

The Delta Plan recognizes that consistently good water quality is crucial for healthy aquatic habitats, sustenance of native plants and animals, and other beneficial uses of Delta water. Climate change will affect water quality in the Delta and Suisun Marsh primarily by increasing salinity concentrations and water temperatures, making it harder to restore a healthy Delta ecosystem, and exacerbating already-existing challenges. Dissolved oxygen will change as a result of increasing water temperature; turbidity, nutrients, and loading of contaminants may also change as a function of climate, but the information available to date is highly uncertain, making it difficult to project impacts to the ecosystem at this time. The following sections describe the ecosystem effect of salinity intrusion and water temperature increases as well as effects of sediment, turbidity, and acidification in the Delta and Suisun Marsh.

5.1 Salinity Intrusion from climate change

At the head of the San Francisco Bay estuary, the Delta and Suisun Marsh serve as a 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 season and during drought, reservoir releases are often used to limit salinity's eastward intrusion into the Delta.

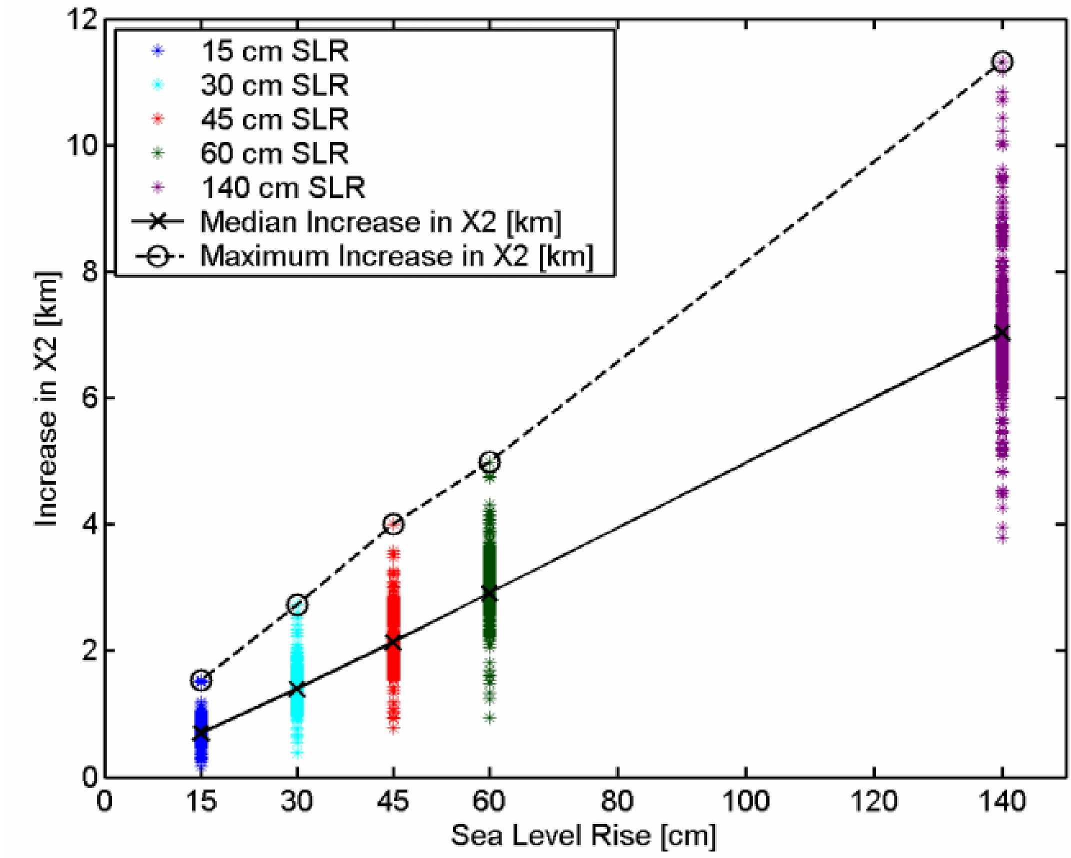
Climate change is likely to force salinity to intrude eastward into the Delta via SLR and changes in freshwater flow. From the downstream end, SLR will tend to push saline water further into the Delta. Three-dimensional modeling by Macwilliams et al. (2016) predicts that for 2002 conditions,[1] 0.5 ft. of SLR shifts salinity eastward into the Delta (as measured by the location of the 2 parts per thousand (ppt) isohaline, X2) by 0.4 miles and that 4.6 ft. of SLR shifts saline water eastward by more than 4 miles (Figure 10).

As an indicator of the position of the salinity gradient, X2 has been defined as the distance from the Golden Gate to the location where the tidally-averaged salinity near the channel bed is 2 ppt, about 5% of the ocean's salinity (35 ppt). A more westward position for X2 correlates with larger area and volume for key aquatic species (Kimmerer et al. 2013) and higher observed abundance of delta smelt in particular (Bever 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. From upstream of the Delta, projected changes to precipitation and reduced runoff may result in less water flowing into the Delta between March and October (DWR 2016b), which would reduce the net Delta outflows that shift X2 westward.

[1] The two water years (WY) that overlap the 2002 modeling period are WY 2002, which was a dry year, and WY 2003, which was a normal year.

Figure 10. Scatter Plot of the Simulated Daily Increases in X2 during 2002 for the SLR Cases

Source: MacWilliams et al. *2016*



5.2 Ecosystem effects of salinity intrusion

Salinity intrusion will affect species differently. Though the complex interactions between salinity and aquatic habitat are not fully understood, it is likely that the increased salinity will decrease the quality and availability of Delta habitat, though the degree of effect is species-specific. In the case of delta smelt, for example, migrating outside of the low salinity zone can cost significant energy (Komoroske et al. 2016). Cloern et al. (2011) further note that sustaining populations of delta smelt will become increasingly difficult due to both salinity and warming.

Dettinger et al. (2016) suggest that some species may respond to changing salinity by moving to a suitable estuarine habitat. This 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 time-scales. However, Dettinger et al. also notes that the salinity change will likely affect the spatial extent of species as well as their abundance. For example, delta smelt may be vulnerable to reductions in rearing habitat due to increased salinity (DWR 2016a) and salinity increases may affect survival in juvenile and adult stages (Komoroske et al. 2014). More information on this topic is presented in the Delta Ecosystem synthesis paper. To the extent that aquatic habitats 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, and other organisms (Dettinger et al. 2016). More information on this topic is presented in the Delta Ecosystem synthesis paper.

5.3 Ecosystem effects of increased water temperature

A change in flow regime, with more precipitation falling as rain and snow melting earlier in the season, will stress native species adapted to the seasonal water temperatures and colder snowmelt. Specifically, increased water temperature will stress native species reliant on cold waters in the Delta (Moyle et al. 2013). Brown et al. (2013) suggest that warmer water temperatures would reduce the amount of suitable habitat for delta smelt. Reduced cold water in reservoirs will affect Chinook Salmon, Steelhead, and Sturgeon, which rely on cold water releases downstream of reservoirs (Dettinger et al. 2016).

Fifty percent of California's native fish are critically or highly vulnerable to extinction already, and fishes requiring cold water (below 71.6°F) have been identified as particularly likely to become extinct. These temperature increases may have effects on species mortality and health. In fact, 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 2100, Sacramento River water temperatures at Rio Vista are projected to warm by 5.4 to 10.8°F; for delta smelt the number of lethal days could increase from none currently to approximately 60 days per year (Wagner et al. 2011).

Jeffries et al. (2016) highlight that it will be important to understand species-specific physiological responses to warming; however, both Delta and Longfin smelt are expected to be stressed from increases in temperature. Delta smelt have limited ability, in contrast to longfin smelt, to tolerate some level of warming (Komoroske et al. 2014), however long fin smelt are more anadromous, and may be able to move to more suitable habitat as necessary between the estuary and the open ocean (Jeffries et al. 2016).

5.3.1 Decreased flexibility in operation and management

Managing salinity and water temperature in the Delta will become increasingly complex in the future. To counter salinity intrusion and maintain present-day X2 locations for both ecosystem and water supply and quality objectives, additional reservoir releases would be needed to counter an eastward salinity shift. These releases for salinity management are expected to reduce Delta water exports by ~10% by 2050 and by ~25% by 2100 (Dettinger *et al*. 2016). In other words, a 1-foot SLR (30 cm) would require almost 500,000 acre-feet of additional Delta outflow, (generally in the form of reservoir releases) to meet salinity requirements (Fleenor and Bombardelli 2013). Climate change will likely increase these demands. Therefore, the reservoirs' capacity to maintain X2 according to current regulations will diminish.

Initially, as SLR is less severe, there is some capacity in the current operations system to maintain existing salinity rules in the Delta with increased freshwater reservoir releases, as are often used in drought years. However, as higher SLR drives salt further into the Delta, precipitation becomes more variable, and snowpack decreases, the ability to meet salinity rules with freshwater releases may not always be possible. Future shifts in human demand (e.g. municipal, industrial, agricultural, etc.) for water within California may also limit the capacity to maintain existing salinity rules through reservoir operations. Finally, larger storms may result in changes to reservoir operations to accommodate flood safety rules.

Managing water temperature from reservoirs will also be less flexible. With less precipitation falling as snow, reservoirs will not have the same amount of cold water nor at the same times as they currently do.

5.4 Sediment and turbidity in the Delta

Sediment delivered from the Central Valley watershed is deposited in the Delta landscape, where it creates and sustains habitats such as tidal marsh, floodplain, open channels, mudflats and shoals. Sediment supply is also needed to create turbidity in the water column, a key driver of desirable conditions for native fish.

5.4.1 Sediment supply and deposition patterns

Sediment flows are closely tied to freshwater inflows in the Delta from the Sacramento and San Joaquin Rivers. About 80% of sediment flows to the Delta come from the Sacramento River Basin (Stern et al. 2016). This sediment is deposited episodically, rather than steadily over time; large river floods supply most of the sediment to the Delta over only a few days per year. This sediment is then deposited in the Delta landscape, sustaining floodplain, intertidal, and subtidal aquatic habitats. Tidal currents affect the suspension and deposition of sediment on a tidal time scale, meaning that sediment is deposited and re-suspended during flood and ebb tides at the semidiurnal tidal time scale (Schoellhamer et al. 2012). Tidally-averaged sediment transport usually moves sediment from the Delta into Suisun Bay.

The Bay and Delta are sediment limited, confounding tidal wetland restoration activities that rely on sedimentation to raise marsh elevations. The total sediment load in the Delta has decreased by 50% during the last 50 years, primarily due to the diminishment of the sediment pulse that resulted from 19th-century hydraulic mining, sediment trapping behind dams, deposition of sediment in flood bypasses, and armoring of river channels (Wright and Schoellhamer, 2004). This decrease in sediment load will tend to reduce resilience to climate change for ecological processes that depend on sedimentation compared to 19th and 20th century conditions.

The effect of climate change on sediment supply is highly dependent on climate, but there is evidence to suggest that sediment supply may increase compared to current conditions. Stern et al. (2016) modeled the effects of climate change on sediment supply, using a range of wet and dry hypothetical scenarios. They found that sediment loads are highly dependent on the modeled scenario and increases in sediment loads could occur due to increases in climate extremes (like atmospheric rivers), which mobilize more sediment (Schoellhamer et al. 2016). Morgan et al. (in press, 2018) suggest that sediment supply to the estuary is not expected to decrease further and Sankey et al. (2017) indicate that increased sediment supply is possible due to wildfires in the watershed.

Kimmerer and Weaver (2013), Schoellhamer et al. (2012), and others note that sea level change will also modify sediment transport processes in estuaries through erosion, deposition, and changes in circulation patterns. Modeling by Schoellhamer et al. (2012) shows that SLR in open water will be partially countered by increases in sediment deposition if there is a net decrease in hydrodynamic energy. They also indicate that submerged aquatic vegetation creates a positive feedback loop by decreasing suspended sediments, which increases the amount of water column light, in turn increasing the growth of vegetation.

5.4.2 Sediment supply and turbidity

Turbidity is an important component of habitat for key fish species such as the delta smelt (Cloern et al. 2011). Turbidity depends on sediment supply (Ganju and Schoellhamer 2010), with a decline in sediment supply contributing to less desirable conditions. Discharge from the Sacramento River is a primary driver of turbidity in critical delta smelt habitat and thus has implications for the future survival of delta smelt and other species which share similar ecological preferences.

5.5 Estuarine Acidification

The Delta may respond to climate impacts associated with acidification, an impact usually associated with the ocean ecosystem (Kimmerer and Weaver 2013). Acidification is a climate change impact that is already affecting oceans; increased acidity can weaken the shells of marine animals. This impact is likely not exclusive to oceans and may affect estuaries as well. Observational programs of coastal waters show that they are acidifying faster than the open ocean, due to the combined effects of eutrophication (enhanced metabolism and CO_2 production) and atmospheric CO_2 uptake (Cloern et al. 2016; Cai et al. 2011). Species that have evolved to the gradients of and seasonal changes in pH, salinity, and temperature in estuaries may respond to acidification differently than ocean-dwelling species. Further study will be required to measure and identify the impacts of acidification on estuaries and their species.

6. Non-native species

Species not historically present in the Delta that have been able to establish populations are considered non-native. They include all types of flora and fauna, such as *Egeria densa*, a waterweed from Brazil and *Morone saxatilis,* Striped Bass from the East Coast of North America. California has over 50 species of non-native fish (Moyle et al. 2013). Solely the introduction of non-native species is often enough to establish a population that can become invasive, particularly if the species has no natural predators. However, the many other historical changes to the Delta, such as timing and volume of flows, salinity levels and other water quality changes, and reduction and shifting of habitat, have all made the Delta more hospitable to certain non-native species (Moyle et al. 2013).

Non-native species are a major obstacle to successful restoration of the Delta ecosystem because they affect the survival, health, and distribution of native Delta wildlife and plants. There is little chance of eradicating most established non-native species, but management can reduce the abundance of some. The resilience of native species is reduced by ongoing introductions of non-native species and management actions that enhance conditions for non-native species. More discussion on restoration and science is provided in the Delta Ecosystem and Restoration synthesis papers.

Though the effects of climate change on species are difficult to predict, non-native species are likely to fare better than native species (Dettinger et al. 2016). Native species are already struggling to adapt to existing anthropogenic changes and will likely have increased difficulty adapting to the changes brought by climate change, which will open niches for non-native species.

Aquatic species that are non-native will also likely expand their population size and extent under the new climate conditions. Since many non-native species are tolerant to a wide range of environmental conditions (Kolar and Lodge 2002; Sorte et al. 2013), the changing climate is likely to facilitate the establishment of non-native species. However, many non-native species evolved in static freshwater ecosystems, and may be negatively affected by variable salinity patterns (e.g., Kuczynski et al. 2017). Additionally, non-native species adapted to warmer climates and water temperatures that are not currently present in the Delta will be better able to colonize future, warmer Delta environments (Moyle et al. 2013). By eliminating cold temperatures that currently prevent survival of non-native species, climate change will influence the likelihood of new species becoming established in the Delta and its watershed (Rahel and Olden 2008). If the response to changes in precipitation is the building of more reservoirs, these reservoirs would serve as hotspots for non-native species (Havel et al., 2015). On the whole, 82% of native species were classified as highly vulnerable to climate change compared with only 19% of non-natives (Moyle at al. 2013).

Combating non-native species in the face of climate change will require increased efforts from agencies currently responsible for addressing non-native species. Early detection and monitoring of new non-native species will be crucial to stopping new species from spreading in the Delta because it is easiest to eradicate non-native species when they first begin to colonize a habitat (Rahel and Olden 2008). Increased coordination and sharing of resources among entities involved in invasive species management will also be vital to stopping the spread of these new species (Hellman et al. 2008).

7. Hatcheries and harvest management

In California, fish hatcheries have been used to mitigate for declines in wild stocks of Pacific salmon, trout, and other fish species for over 100 years (CDFW 2010). Hatcheries typically propagate fish from eggs and milt obtained from spawning adult salmon, then raise the eggs to smolt size in a controlled environment, safe from predators and with a constant supply of food. In the Sacramento-San Joaquin Watershed, the fish are then either released in-river or trucked to the receiving water bodies' estuary. The fish that return to the hatchery are then harvested for their eggs and milt, and the process begins again.

The California Department of Fish and Wildlife (CDFW) owns and operates 24 salmon, trout, and steelhead trout hatcheries, with 6 hatcheries providing juvenile salmon and steelhead trout to the Delta and its watershed. The Coleman National Fish Hatchery, operated the US Fish and Wildlife Service, also produces salmon and steelhead trout for release or trucking to the Delta. Together, these hatcheries produce millions of juvenile salmon every year.

The conservation benefit of hatcheries and their ecological impacts on wild salmon are a subject of considerable debate, but they are an institutionalized component of salmon management in California and account for a majority of the salmon found in the state and commercially harvested both in-river and in the ocean. While scientific research has focused on the impact of fish hatcheries on wild salmon stocks, little research has looked at hatcheries and their vulnerability to climate change.

The impacts of climate change on fish hatcheries will likely be tied to increased water temperatures and changes in timing of water availability, two effects that have been previously discussed in this paper. Hanson and Peterson (2014) modeled the effects of climate change at a salmon hatchery in Washington State and found that warmer water temperatures in summer accelerated juvenile salmon growth. However, this coincided with periods when water availability would also be lower, thus increasing the likelihood of physiological stress in the juvenile salmon. Though the majority of California hatchery fish are released into the river or trucked to the Delta between January and June, increased temperatures and the timing of water availability are still likely to have an impact on hatchery fish (Huber and Carlson 2015). Further study and information is needed, though, specific to water availability and the need for cooling water. Currently, some California hatcheries already have the ability to cool water before it reaches the salmon in the stock ponds.

Once fish leave the hatchery, they will experience climate change impacts similar to those related to wild fish; timing and availability of colder waters, changes in salinity in different parts of the Delta, and other impacts of the altered hydrological cycle will likely negatively affect and stress fish (Hanson and Ostrand 2011).

Climate change is predicted to drive species ranges toward the poles, thereby impacting salmon populations at southern latitudes disproportionally. However, over a longer time scale, if climate change were to continue unabated and the thermal habitat in California becomes unsuitable for wild and hatchery fish survival, salmon production would no longer be required as the target populations and associated fisheries may cease to exist.

8. Implications for the protection, restoration and management of the Delta ecosystem

The prior sections of this paper summarize the drivers of climate change and key impacts to the Delta's key species, habitats, and natural processes—including water quality considerations. Those sections examine the best available science within the focused subject areas covered in this paper. The subject areas addressed in this paper were identified because of their potential influence on achieving the coequal goals and relevance in amending Chapter 4 of the Delta Plan. This section summarizes and discusses the implications of the preceding science synthesis relative to the protection, restoration, and management of the Delta ecosystem. These implications provide the basis for the considerations included in Section 9, *Considerations for Amending Chapter 4 of the Delta Plan*.

1. Climate change effects the five core strategies

    Table 3 summarizes key findings related to the core strategies, which were discussed in detail in Sections 3 through 7.

Table 3. Summary of Climate Change Effects on Delta Plan Core Strategies

Core Strategy	Key Findings
Delta Flows	• A warmer atmosphere will mean more precipitation falls as rain instead of snow. Peak flows will be larger and occur earlier in the year. Droughts will increase in frequency and duration. • Floods in the Delta are likely to increase in frequency and intensity (with larger peak flows), but decrease in duration. Sustained periods of inundation, on the order of weeks and months, that are important for native fish (e.g., Splittail spawning and rearing, Chinook Salmon rearing) will occur less frequently. • Changes in precipitation, runoff, and SLR will affect water resources and reservoir operations in a number of ways, likely limiting the degree to which reservoir operations can be changed to improve environmental conditions, such as cold water releases and flow releases to repel salinity intrusion.
Habitat Restoration	• The locations, types and extents of Delta and Suisun tidal wetlands will shift with SLR. Tidal marshes can adapt to SLR through soil accretion (building vertically) and migration into adjacent upland areas. Recent research suggests vegetated Delta wetlands can persist in place under probable SLR scenarios by becoming lower in the tidal frame (i.e., lower in elevation). Opportunities for upland migration for marsh are limited by existing levees and infrastructure. • Critical transition areas between wetlands and uplands will shift landward with SLR. Subtidal habitats will deepen. • SLR will lead to higher salinity waters intruding deeper into the Delta. Salinity stress will tend to shift existing fresh and brackish marsh vegetation to more salt-tolerant communities. • Managed and agricultural wetlands behind levees will become more vulnerable to flooding from more extreme flood events and SLR. Subsidence reversal wetlands may be used to raise ground elevations. • SLR and more extreme flood flows may result in more levee failures. Future levee failures that are not repaired will result in more open water areas and these areas may be colonized by invasive submerged aquatic vegetation. • According to modeling of climate change scenarios, sustained periods of seasonal floodplain inundation on the order of weeks and months that are important for native fish (e.g., Splittail spawning and rearing, Chinook Salmon rearing) will occur less frequently.

Table 3. Summary of Climate Change Effects on Delta Plan Core Strategies

Core Strategy	Key Findings
Water Quality	• Climate change will increase salinity concentrations and water temperatures in the Delta and Suisun Marsh, exacerbating existing ecosystem stressors. • SLR and prolonged low flow periods will shift salinity eastward into the Delta, changing the quality and availability of Delta habitat and causing shifts in species movement. • Climate scenario modeling (Cleorn et al. 2011) shows that extreme water temperature conditions occur more frequently, conditions indicative of mortality of sensitive native species such as delta smelt and Chinook Salmon. Increased water temperatures also correspond to decreased amounts of dissolved oxygen in the water. • Turbidity, nutrients, and loading of contaminants may also change as a function of climate, but the information available to date is highly uncertain, making it difficult to project impacts to the ecosystem at this time.
Non-native Species	• Non-native species are likely to fare better than native species under climate change in the Delta, expanding their population size and extent. • New non-native species may establish populations in the Delta due to new climate conditions that will better suit them. • Moyle et al. (2013) found that 82% of native fish species and 19% of non-natives in the Delta were classified as “highly vulnerable.”
Hatcheries and Harvest Management	• Hatcheries may need to change their operations to account for increased water temperatures and changes in timing of water availability. • Once fish leave the hatchery, they will experience climate change effects similar to those related to wild fish.

2. Climate change is expected to increase ecosystem stress

The 2013 Delta Plan acknowledges climate change as a global stressor on the Delta ecosystem. Recent advances in science provide much higher projections of SLR, primarily due to improved understanding of mass loss from continental ice sheets (Griggs et al. 2017), and improve our understanding of expected stresses on the ecosystem. Climate change will have profound effects on the Delta ecosystem. The Delta’s ecosystem will experience climate change effects both from gradual changes to key stressors, and from extreme events that are likely to become more frequent. Until environmental conditions exceed organismic tolerances, gradual changes in average conditions pose smaller challenges to the Delta’s organisms when compared to extreme events that occur on top of the gradually-declining baseline (Dettinger et al. 2016). The effects of climate change are likely to limit the degree to which reservoir management can be used to improve conditions such as reducing stream temperatures and lowering salinities. Meanwhile, pressure for exports is not likely to abate; U.S. Bureau of Reclamation (2015) projects larger agricultural water demand in the Central Valley.

3. Phenology and species response will shift

Climate warming is expected to result in changes in seasonality of plant and animal life cycle events, such as plant budding, insect emergence, bird nesting, and migration. Shifts in phenology due to warming temperatures will disrupt key processes; for example, they could cause plants and pollinators to be out of sync, which could disrupt the timing of pollination and drastically affect the production of natural plants (Hegland et al. 2009). For fish, the earlier arrival of spring is correlated with a peak in larval abundance that occurs earlier in the year; Asch (2015) found that 39% of fish species surveyed over a 58-year period in Southern California had earlier peaks in larval abundance in recent years. This earlier peak may be correlated with an observed and modeled intensification of upwelling during spring and/or summer months in California's current ecosystem, as well earlier warming water temperatures. These changes may have impacts on Delta species that rely on the ocean for part of their lifecycle (i.e., anadromous fish).

Individual terrestrial and aquatic native species will respond differently to the effects of climate change. The fluctuation of wildlife population levels that occur from air temperature change will occur at different rates because individual species will respond differently to these changes. While some species are expected to adapt in place (e.g., some marsh wildlife and native fish), others will move to more suitable areas or become extirpated (Beller et al. 2015). Species with high genetic diversity and large geographic extent (e.g., salmonids and wintering shorebirds) are likely to have the highest adaptive capacity (CVLCP 2017).

4. The exact nature of ecosystem responses to climate change are difficult to predict

Dettinger et al. (2016) highlight a series of knowledge gaps with respect to climate change in the Delta. In particular, we need a better beginning-to-end understanding of processes and responses, both physical and biological. We also need models and observations that cut across scientific disciplines to anticipate unexpected and cascading consequences of climate events. In terms of basic data, an improved understanding of water levels, or tidal datums, throughout the region are critical for restoration planning.

While some changes can be expected with relative certainty, the effects of climate change interact with each other and on the ecosystem in complex ways. The complexity of climate change and ecosystem interactions means the potential for unexpected and sudden species shifts, and unintended consequences (Cloern et al. 2011; Dettinger et al. 2016). Even small changes can sometimes trigger ecosystem regime shifts. In a recent example cited by Cloern et al. (2011), a small change in mean salinity (of 1.6 psu) in Denmark's Ringkobing Fjord resulted in a sudden and unanticipated shift in biological communities across trophic levels, from phytoplankton to waterbirds. As Dettinger et al. (2016) note, "Most assuredly, there will be many surprises that require flexibility in our management systems."

5. Climate change influences planning, policy setting, and management

Climate change is clearly a driver in Delta ecosystem planning and policy setting. There are multiple initiatives, policies and regulations addressing and/or related to climate change that either directly or indirectly affect the planning, management and implementation of restoration and other projects in the Delta. Additionally, amendment to the Delta Plan's policies, recommendations, and performance measures related to ecosystem restoration take place in a regulatory context. It is therefore important to understand that context when considering potential physical and management changes to the Delta landscape. Table 4 below describes select current initiatives and related regulations.

Climate change also factors in management and even operations. For example, Dettinger et al. (2016) note that management decisions have a great influence on the response of the Delta's ecosystem to climate change. The opposite is likely true as well, as management decisions associated with reservoir operations, for example, seek to control salinity intrusion, meet water supply demands, or comply with environmental regulations on ecological flows and cold water pools. Climate change will likely exacerbate the challenges of meeting those management objectives.

Table 4. Select Climate Change-Related Initiatives and Regulations Affecting the Delta

Level	Effort/Agency	Description
Federal	The Coastal Zone Management Act (CZMA 1972)	The Coastal Zone Management Act (CZMA 1972) created a voluntary partnership between the federal government, and coastal and Great Lakes states, to address national coastal issues including protection and restoration of natural resources in "areas likely to be affected by or vulnerable to sea-level rise." The Delta Reform Act (Water Code 85300) notes that if the Delta Plan is adopted pursuant to the CZMA, the Council shall submit the Delta Plan for approval by the U.S. Department of Commerce. Once this occurs, federal efforts to understand SLR as it relates to natural resources and to regulate natural resource protection and restoration will include the Legal Delta.
Federal	U.S. Bureau of Reclamation	Reclamation operates Central Valley Project facilities in and upstream from the Delta and has guidance related to the consideration of climate change in carrying out their respective missions. This guidance is pursuant to the SECURE Water Act, Secretarial Order No. 3289, and various related federal policies and guidance for the consideration of climate change and also applies to other Federal agencies in addition to Reclamation.
Federal	NOAA and NMFS BiOp on CVP and SWP	The National Oceanic and Atmospheric Administration Office's National Marine Fisheries Service (NMFS) and the US Fish and Wildlife Service (USFWS) have each issued a Biological Opinion (BiOp) on the long-term operations of the Central Valley Project (CVP) and State Water Project (SWP). The BiOps include Reasonable and Prudent Alternatives (RPAs) designed to alleviate jeopardy to listed species and adverse modification of critical habitat for the Endangered Species Act-listed species under each agency's jurisdiction (Council 2017). Reservoir management for suitable water temperatures for listed species under a changing climate is part of the proposed RPA amendments and the re-initiation of consultation (Council 2017; NMFS 2017).

Table 4. Select Climate Change-Related Initiatives and Regulations Affecting the Delta

Level	Effort/Agency	Description
State	Executive Order B-30-15	Executive Order B-30-15 (Governor's Office of Planning and Research 2017), signed by Governor Brown in April 2015, requires State agencies to incorporate climate change into planning and investment decisions, as well as prioritize natural infrastructure and actions for climate preparedness. The Governor's Office of Planning and Research released a guidance document called "Planning and Investing for a Resilient California: A Guidebook for State Agencies" which identifies processes, principles, and resources available for State agencies to integrate climate change in planning and investment. On a closely related effort, California's Fourth Climate Change Assessment (CNRA 2017) includes a portfolio of research, much of which touches on the Delta. Research outcomes will be released in March 2018.
State	Senate Bill 246 (Wieckowski)	Senate Bill 246 (Wieckowski) created the Integrated Climate Adaptation and Resiliency Program (ICARP) to coordinate regional and local efforts with State climate adaptation strategies. The program is led by the Governor's Office of Planning and Research and consists of two key components: 1) A Technical Advisory Council brings together local government, practitioners, scientists and community leaders to help coordinate activities that better prepare California for the impacts of a changing climate, and 2) The Adaptation Clearinghouse provides a centralized source of information and resources on climate adaptation, including the best available science and research, policy guidance and decision support tools and case studies, highlighting local implementation efforts across the state.
State	CVFPP	The Central Valley Flood Protection Board (CVFPB) updated the Central Valley Flood Protection Plan (CVFPP) in 2017. The CVFPP is a strategic and long-range plan for improving flood risk management in the Central Valley, including the Delta, and guides the State's participation in managing flood risk in areas protected by the State Plan of Flood Control (CVFPP 2017). The CVFPP seeks to integrate ecosystem restoration and flood risk management through support of multi-benefit projects with the recognition that "future floods are expected to cause more damage due to sea-level rise, climate change, subsidence, and future population growth and development within floodplains." In terms of climate change adaptation, the Plan describes opportunities in both the Sacramento River and San Joaquin River Basins, noting that flood volumes could increase by 20% and 80% respectively, and that bypass expansion to accommodate larger flood flows is needed (CVFPP 2017).
State	CDFW Wildlife Action Plan	The California Department of Fish and Wildlife (CDFW) seeks to integrate climate change into the State Wildlife Action Plan (CDFW 2017b), and has assessed climate change vulnerability of fish, wildlife, and plants (CDFW 2016).
State	Delta Conservancy Climate Change Policy	The Sacramento-San Joaquin Delta Conservancy (Conservancy) recently updated their Climate Change Policy (SSJDC 2017), which adopted climate change guidelines to increase the Delta's resiliency to the effects of climate change. For projects that the Conservancy funds, preferences will be given to projects containing effective or innovative adaptation measures and strategies that would minimize the effects of climate change.

Table 4. Select Climate Change-Related Initiatives and Regulations Affecting the Delta

Level	Effort/Agency	Description
State	SLC	The California State Lands Commission (SLC 2017) seeks to facilitate SLR preparedness, and works with several interagency groups like the Coastal and Ocean Resources Working Group for the Climate Action Team.
Local	BCDC: ART	There are several local and regional efforts in which county and state agencies are engaged that identify relevant climate change policies. For example, the San Francisco Bay Conservation and Development Commission (BCDC) and the National Oceanic and Atmospheric Administration Office for Coastal Management (NOAA OCM) have brought together local, regional, State and federal agencies and organizations, as well as non-profit and private associations in a collaborative planning program, Adapting to Rising Tides (ART), to identify how current and future flooding will affect communities, infrastructure, ecosystems and the economy. The Council has provided BCDC funds to expand the ART program to Contra Costa County and Solano County.
	County Efforts	For counties in the Delta, the Solano County Climate Action Plan included a SLR Strategic Program released in 2011 (Solano 2011), which outlines adaptation steps that consider land-use planning and that the county will "collaborate on a Regional SLR Plan." The 2035 San Joaquin General Plan integrates climate change into the General Plan (San Joaquin 2016), rather than develop a separate Climate Action Plan. Specific policy includes "Interagency Coordination: The County shall coordinate with cities, regional, State, and Federal agencies and organizations to develop a comprehensive approach to planning for climate change." For Sacramento County, as part of the Climate Action Plan, a Climate Change Vulnerability Assessment (Sacramento 2017) evaluated vulnerability and identified SLR and island inundation as having severe impacts on the ecosystem, as well as negative impacts from rising temperatures and drought on vernal pools, and reduced flows on listed fish species. As of May 2017, staff are in the process of "drafting, reviewing, and revising preliminary adaptation measures" that include flooding and SLR. Yolo County released a Climate Action Plan in 2011 (Yolo 2011) which identified SLR Adaptation Measures and recommended coordination with relevant agencies and other stakeholders on understanding best available science. For Contra Costa County, the Draft Hazard Mitigation Plan includes SLR modeling from BCDC. Contra Costa County's adaptation and mitigation actions require development of "an adaptive management plan to address the long-term impacts of sea-level rise."

6. A restored Delta may provide climate refuge

Although climate change will affect many of the Delta's resources, a restored Delta may provide important future refugia in California's Central Valley. 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*." Researchers have begun to identify areas relatively sheltered from the effects of future climate change as potential refugia areas (Seavey et al. 2009; Keppel et al. 2015; Morelli et al. 2016).

The Delta has, or could have with appropriate habitat restoration, characteristics of climate change refugia. As much of California grows warmer, the Delta is projected to be one of the coolest regions in the Central Valley (Cal Adapt 2017). Dettinger et al. (1995) suggests the Delta, because of its proximity to the ocean, will remain relatively cool as inland areas of the continental US warm in the future. Lebassi et al. (2009) note that inland warming may enhance the Delta’s cooling breezes. Similarly, tidal marshes and riparian areas have higher water content compared to upland areas, so they absorb relatively more heat and can buffer organisms against extreme temperatures (Naiman et al. 2000 as cited in Seavey et al. 2009). Riparian areas are known to provide shading (Sridhar et al. 2004, Cassie 2006 as cited in Seavey et al.) and groundwater recharge, which cool water temperatures. Tidal marsh may offer similar cooling effects, though this has not been studied. Riparian habitats in the Delta can provide corridor connections to higher, cooler elevations (Seavey et al. 2009). Additional research is needed to understand the climate refuge potential of the Delta and Suisun Marsh and its use in climate adaptation. Planning for climate refuge must consider target resource needs and vulnerabilities, climate change refugia of sufficient scale and connectivity, and prioritize refugia areas (Morelli et al. 2016).

7. Restore ecosystems to promote connectivity and resilience with climate change

Ecosystems with greater connectivity, complexity, redundancy, and size will tend to have greater resilience (Millar et al. 2007; Heller and Zavaleta, 2008; Seavey et al., 2009; Baylands Goals Report 2015; Robinson et al. 2016). The ecological resilience of a system is defined by its capacity to absorb change and persist after a disturbance. Resilience at the landscape level has great value for today’s climate conditions and resilience will be an increasingly important attribute in light of climate change. Successful ecosystem restoration – including broadly management, preservation, enhancement and restoration – should promote resilience with climate change (Robinson et al. 2016). As discussed in the Delta Ecosystem and Restoration papers, riparian and wetland patches are highly fragmented in the Delta. By restoring connections between patches of the same habitat types, pathways for movement of organisms are created, allowing for connectivity of populations and maintenance of genetic exchange which confer greater resilience. Connecting habitats up and down the estuary enhances climate resilience by facilitating migration of individuals and ecosystems to, for example, areas of lower salinities or cooler temperatures. Restoring broad connections between tidal marsh and gradually sloping adjacent uplands provides the opportunity for tidal marsh to expand upslope as sea level rises. Restoring connections between channels and floodplains not only allows fish greater access to food resources and provides for nutrient exchange, but also allows fish access to more sheltered off-channel areas during the types of extreme flood events that are projected to become increasingly frequent with the changing climate.

8. Ecosystem restoration can provide climate change mitigation and adaptation

Ecosystem restoration can provide climate change mitigation and adaptation, with benefits to the ecosystem and provision of ecosystem services to Delta communities. For example, tule growing and subsidence reversal on the Delta's subsided islands would be beneficial in reducing GHG emissions that lead to climate warming and may ultimately raise elevations sufficiently to allow future restoration of tidal wetland habitat. Conversion of freshwater managed ponds in Suisun Marsh to brackish tidal marsh could result in potentially larger net GHG reductions (Kroger et al. 2017). Restoration of wetlands in front of a levee can attenuate wave energy, reducing erosion and flood water levels, thus providing an increased level of flood risk reduction. More examples of ecosystem services are provided in Table 5, below.

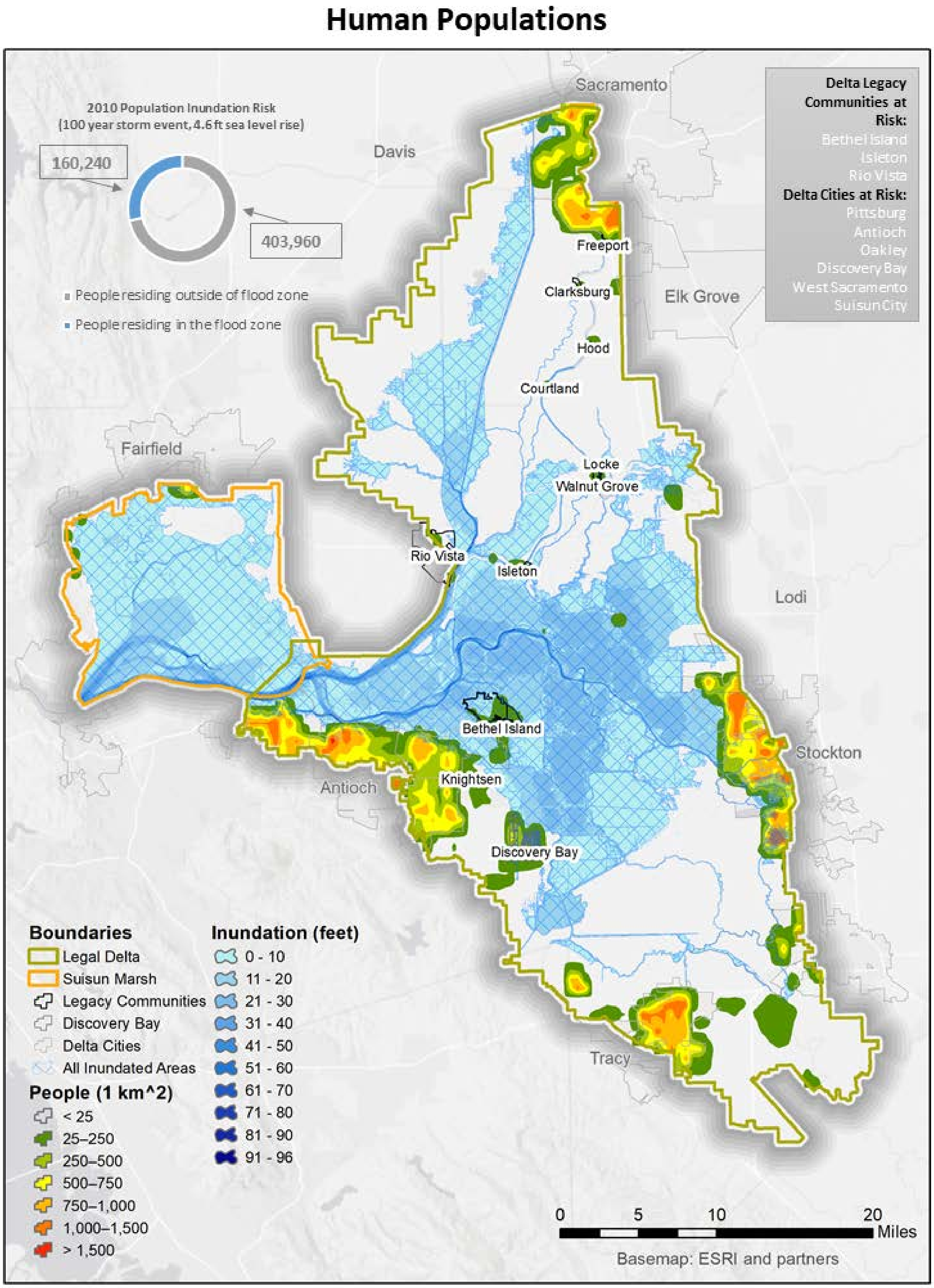
Table 5. Climate-Related Ecosystem Services from Restoration and Natural Infrastructure

Ecosystem Service	Description
Protection from SLR	Wetlands can provide key services like wave attenuation, storm surge attenuation, and maintenance of shoreline elevation (BEHGP 2016; Shepard et al. 2011; Hale et al. 2009; Cahoon et al. 2006; Callaway et al. 2011; Parker et al. 2011). Wider and more extensive marsh plain in tidal wetlands and in floodplains increases protection of upland habitat and human structures from flooding and storm surges, which are predicted to worsen with climate change (Cayan et al. 2008). Using Radke et al. 2017 projections, an estimated 160, 000 people are at risk of inundation, and of those, about 24,000 are highly vulnerable people, see Figure 11 and Figure 12. Depending on location, wetland restoration could provide protection from SLR to human populations.
Reduction of risks of levee failure	When wetlands behind levees are drained and dry out, organic matter in the soil oxidizes, which can cause subsidence, reduce levee stability, and increase the risk of levee failure during flooding, resulting in saltwater intrusion into aquifers and farmlands (Mount and Twiss 2005). Restoration of wetted conditions eliminates ongoing subsidence and can slowly build up land elevations, somewhat reducing the risk of levee failure.
Natural flood management	Improved floodplain connectivity to rivers will restore the ability of floodplains to absorb flood flows and provide a reservoir of water to support resiliency of both wildlife and people to help species withstand droughts (Bales et al. 2016).
Carbon sequestration and climate change mitigation	In 2016, the California State Legislature passed Senate Bill 32 (SB 32 2017), which codifies the 2030 GHG emissions reduction target of 40 percent below 1990 levels. Within the California Air Resources Board Final Proposed 2017 Scoping Plan Update (CARB 2017), the high target for carbon sequestration through wetland restoration in the Delta is recommended as 30,000 acres by 2030. This target is complimented by the carbon offset methodology that quantifies GHG emissions reductions from the Restoration of California Deltaic and Coastal Wetlands approved by the American Carbon Registry (ACR) (ACR 2017). In the Bay-Delta area, drained and cultivated organic soils continue to oxidize, subside and emit an estimated 1.5 to 2 million metric tons of CO_2-equivalent annually — equal to annual emissions from over 300,000 passenger vehicles (ACR 2017). Carbon market revenues provide an incentive to landowners to convert their most subsided and marginal agricultural lands to wetlands or to produce wetlands crops such as rice, which will reduce land subsidence and reverse it over time. Of interest to tidal restoration, recent research by Kroeger et al. (2017) find that tidal restoration to reduce emissions from fresh or brackish managed wetlands has a much greater impact per unit area than wetland creation or conservation to enhance sequestration.

Source: Table adapted from US Bureau of Reclamation et al. 2013b, Appendix 5.A.1.

Figure 11. Inundation Risk to Human Populations

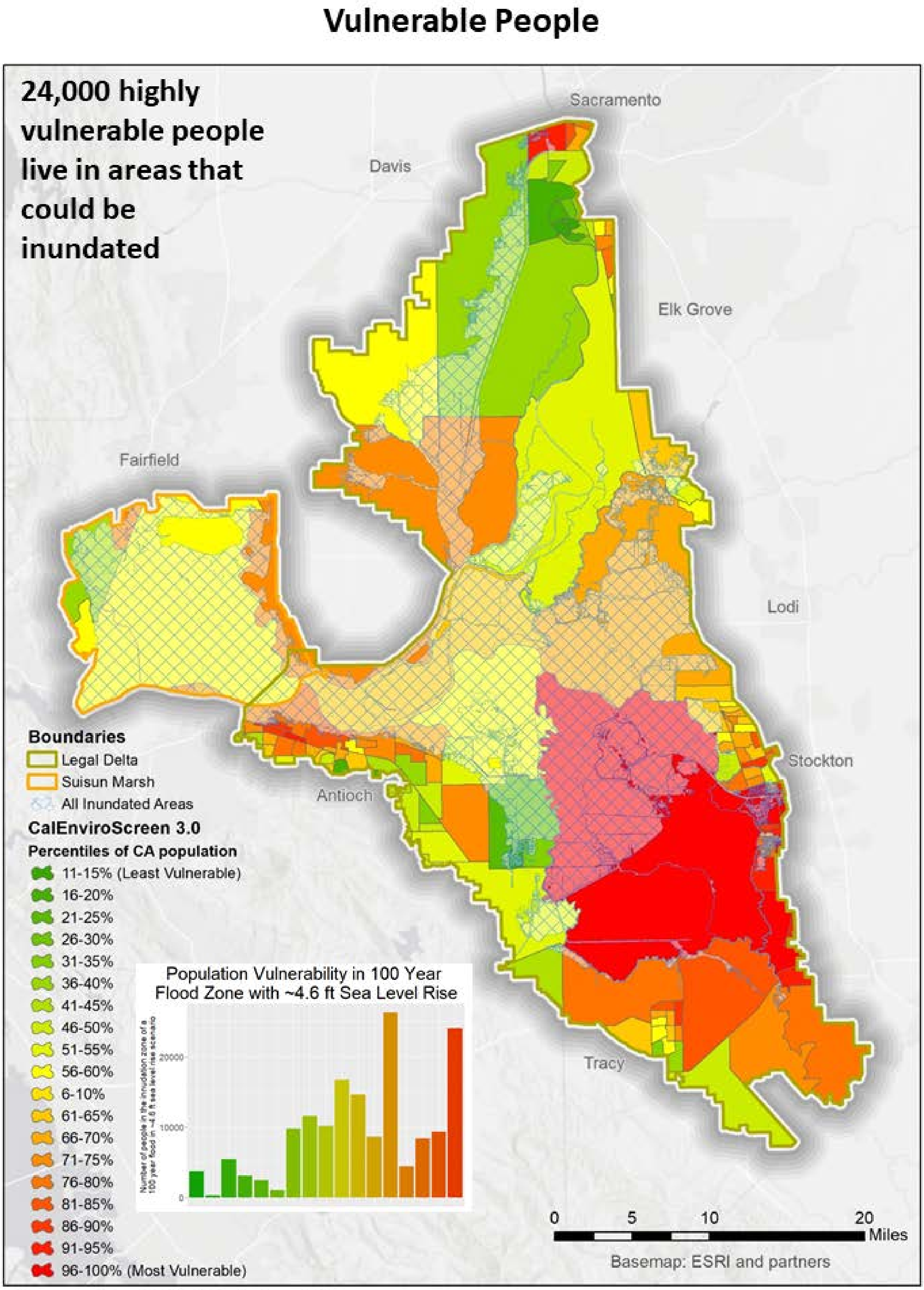
Source: Radke et al.*, 2017*



Sources: Radke et al 2017; SEDAC 2010; Delta Reform Act 2009; CalTrans 2015; Delta Plan 2013.
Disclaimer: This map reflects a risk-based approach of where inundation could impact human populations currently in the Delta and Suisun Marsh and does not incorporate population growth.

Figure 12. Inundation Risk to Vulnerable People

Source: Radke et al.*, 2017*



Sources: Radke et al 2017; CalEnviroScreen 3.0.

Disclaimer: This map reflects a risk-based approach of where inundation could impact vulnerable human populations currently in the Delta and Suisun Marsh and does not incorporate any demographic shifts.

9. Restore with tomorrow's climate in mind

Numerous researchers recommend that ecosystem restoration be designed toward future climate effects rather than today's climate (e.g., Pressey et al. 2007; Sgro et al. 2010; Cloern et al. 2011, Bayland Goals Project Update 2015, Robinson et al. 2016). For example, in the Delta, this means anticipating future locations of tidal wetlands and wetland restoration opportunities that include consideration of SLR, future locations of fresh, brackish, and saline habitats with salinity intrusion, and planning and designing restoration projects based on those estimated future conditions.

10. Restore natural processes sooner to build climate resilience

The sooner habitat and process restoration occurs, the sooner ecological and human benefits begin accruing. Beyond this basic consideration, the timing of restoration can be important for long-term feasibility. With SLR, the elevations at which tidal wetlands can be restored will increase over time. Combined with the ongoing subsidence of most Delta islands (which is currently occurring faster than SLR), many areas at elevations suitable for tidal wetland restoration today will be too low for restoration decades from now. Similarly, the strategy of using subsidence reversal to raise ground elevations prior to reintroduction of tidal processes requires a decades-long lead time. Any delays in beginning subsidence reversal delay the date of tidal restoration. Restoring earlier in this century also provides time for recovery of target aquatic and terrestrial populations, building ecosystem resilience while the stressors of climate change and SLR are more moderate.

Looking forward, restoring resilient tidal marsh in the Delta and Suisun requires restoration of the biophysical processes that maximize accretion with SLR. This means restoring appropriate conditions for vegetation colonization and sedimentation. Vegetation can persist at lower elevations than it can establish (Williams and Orr 2002; Kirwan and Megonigal 2013). Thus, restoring earlier in this century allows restoration to occur at elevations appropriate for vegetation establishment and time for accretion to occur prior to more rapid SLR later in the century. Tidal wetlands that are higher in the tidal frame (higher in elevation) have more elevation to lose before the plants reach critical thresholds and "drown." So if restored marshes have time to build to higher elevations they will last longer with SLR (Cahoon et al. 2006). For this reason, restoring earlier this century is a key recommendation of the San Francisco Baylands Ecosystem Habitat Goals Update (2015).

The State of California (CNRA and OPC 2018) recently released guidance for SLR adaptation planning based on location, lifespan of the given project or asset, SLR exposure and associated impacts, adaptive capacity, and risk tolerance/aversion. While habitats supported by natural physical and biological processes generally have high adaptive capacity to evolve in response to SLR given their recognized importance to the Delta (high risk aversion) and desired sustainability (long time frame), the guidance suggests use of a high SLR estimate for planning. Stated another way, planning for a given amount of SLR means starting earlier.

11. Monitoring and adaptive management are necessary

Climate scientists working in the Delta note the need for adaptive and flexible decision making and management that is responsive to the emergence of new models, analyses, and insights on climate change effects (Cloern et al. 2011 and Dettinger et al. 2016). Such decision making must be based on integrated monitoring systems which are essential for detecting and responding to ecological regime shifts, integrated modeling, and integrated assessments of vulnerabilities and management actions.

Implementing the Delta Plan within a rigorous adaptive management (AM) framework will be important for managing uncertainty in the effects of climate change and biological responses. The Delta Reform Act (Water Code 85052) specifies the use of AM and the Delta Plan (Appendix 1B) identifies a nine-step program of AM as a means of addressing the uncertainty inherent in ecosystem restoration. While the Delta Reform Act and Delta Plan recognize the importance of AM and proposes it, a review by the Independent Science Board in 2013 found few examples of where AM was being implemented, rigorously planned, or coordinated regionally (Delta Independent Science Board 2013). One such positive example is the Department of Boating and Waterways' (California State Parks) management of invasive aquatic plants. AM is a relatively new flexible management approach and, while it is potentially powerful, it requires dedicated and coordinated efforts to implement successfully. Any limitations in implementing effective AM in the Delta will hinder efforts to meet the ecosystem goals of the Delta Plan with the shifting baseline and additional uncertainties of climate change.

9. Considerations for amending Chapter 4 of the Delta Plan

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

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

1. Climate change science has rapidly progressed since the 2013 Delta Plan. Climate change considerations, impacts, and studies need to be better integrated throughout Chapter 4, which currently has a limited discussion of climate change. Discussions of the Delta setting and restoration strategies should incorporate how climate change may exacerbate a present stressor or how it may affect the success in restoring the ecosystem, as appropriate. Ultimately, discussions in Chapter 4 should be expanded to cover ways that climate change may affect the ecosystem and the benefits and services that people receive, including how water exports may be reduced in order to meet regulatory requirements in the Delta for an ecosystem that is evolving in response to climate change. Discussions in Chapter 4 should also incorporate how to approach ecosystem restoration to increase resilience to climate change.

2. The findings from this science synthesis do not foundationally change Recommendations for ecosystem restoration made in Chapter 4 of the Delta Plan. Rather, the changes expected with global warming generally increase the criticality of, and need for, Recommendations in Chapter 4, with additional considerations to look forward with climate change. For example, the magnitude of uncertainty around how individual species and the Delta ecosystem will respond to climate change underscores the importance of restoring the Delta – in the broadest sense including management, preservation, enhancement and restoration – and integrating an adaptive approach to management. The likely scale of the effects of climate change on the Delta's native species make restoring for ecological resilience through managing flows; managing non-native species; restoring aquatic and terrestrial habitats, hatcheries, and fisheries; and improving water quality even more critical, though the relative emphasis of particular actions will shift.

3. Climate change and SLR will change where habitats will be located and restored in the future, and make restoration of certain functions (such as thermal and high water refuge) and processes (such as organic and inorganic deposition) more valuable. Delta Plan policies should be reviewed with an eye towards restoring with future climate conditions in mind, as required for effective restoration and consistency with updated State climate change guidance.

    a. Policy **ER P2** Restore Habitats at Appropriate Elevation: SLR will affect where intertidal habitat can be restored, as these areas will migrate upslope over time.

    b. Policy **ER P3** Protect Opportunities to Restore Habitat: Areas protected for potential restoration could be expanded or shifted to provide additional SLR accommodation space, climate refuge, connectivity for ecosystem and animal migration, and restoration of natural processes to improve overall ecosystem resilience to climate change. Land management to halt or reverse ongoing subsidence could be used to protect or create potentially restorable areas.

   c. Policy **ER P4** Expand Floodplains and Riparian Habitats in Levee Projects: The reaches prioritized for potential levee setback could be expanded to enhance climate resilience benefits, such as flood risk reduction from more extreme flood events. In addition, connecting riparian habitats continuously through the Delta would provide resilience to future shifts in salinity by establishing habitat along the salinity gradient.

4. Climate change may affect topics covered in other Delta Plan chapters, such as ecosystem water quality in Chapter 6, and the Delta as evolving place in Chapter 5. These chapters are not being amended at this time. Improving ecosystem water quality will require a better understanding of the ability to manage for fisheries water quality requirements with climate change and incorporation of this understanding into water quality requirements. Functional flows for quantified environmental needs should be managed in a manner that incorporates expected changes in precipitation, runoff, and SLR.

5. Because climate-induced changes to environmental conditions are expected to occur, both gradually and in extreme events, performance measures identified in the Delta Plan may need to adapt to a changing baseline, as quantifiable targets based on today's climate conditions may no longer be appropriate. The timeframes for achieving certain performance measures may also need to be accelerated to ensure that Delta ecosystems have the resilience needed to adapt to climate change.

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