Delta Stewardship Council

A CALIFORNIA STATE AGENCY

DELTA ADAPTS: CREATING A CLIMATE RESILIENT FUTURE

TECHNICAL MEMORANDUM
WATER SUPPLY

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ABBREVIATIONS

Abbreviation	Description
BCCA	Bias Correction and Constructed Analogues
BN	Below Normal [water year type]
CA	California
CALFED	CALFED Bay-Delta Program
CALSIM	California Simulation model
CALVIN	California hydro-economic model
CASCADE	Computational Assessments of Scenarios of Change for the Delta Ecosystem
CDAG	County Drought Advisory Group
CDF	Cumulative Distribution Function
CDWR	California Department of Water Resources (see also, DWR)
CEC	California Energy Commission
CMIP3	Coupled Model Inter-comparison Project Phase 3
CMIP5	Coupled Model Inter-comparison Project Phase 5
CNRA	California Natural Resources Agency
CO_2	Carbon Dioxide
CVP	Central Valley Project
CVPD	Concentration and Vapor Pressure Deficit
CVS	California Central Valley Water System
DAC	disadvantaged communities
DLIS	Delta Levees Investment Strategy
DOE	Department of Energy, U.S.
DRMS	Delta Risk Management Strategy
DSC	Delta Stewardship Council

DSM2	Delta Simulation Model 2
DUC	disadvantaged unincorporated communities
DWR	Department of Water Resources, California (see also, CDWR)
GCM	Global Climate Model
HEC-HMS	Hydrologic Engineering Center - Hydrologic Modeling System
IPCC	Intergovernmental Panel on Climate Change
LOCA	Localized Constructed Analogs
MAF	Million Acre-Feet
NDO	Net Delta Outflow
NDWA	North Delta Water Agency
NMFS	National Marine Fisheries Service
NOD	North of Delta
OEHHA	Office of Environmental Health Hazard Assessment, California
PCA	principle components analysis
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
RDM	robust decision making
RMA	Resource Management Associates
SACWAM	Sacramento Water Allocation Model
SD	Standard Deviation
SGMA	Sustainable Groundwater Management Act
SIMETAW	Simulation of Evapotranspiration of Applied Water
SJI	San Joaquin Valley Index
SLR	Sea Level Rise
SOD	South of Delta
SVI	Sacramento Valley Index
SWE	Snow Water Equivalent
SWP	State Water Project
SWRCB	State Water Resources Control Board
TAF	Thousand Acre-Feet
TUCP	Temporary Urgency Change Petition
UCLA	University of California, Los Angeles
US	United States of America
USA	United States of America
USBR	U.S. Bureau of Reclamation
VA	Vulnerability Assessment
VIC	Variable Infiltration
WAM	Water Allocation Model
WEAP	Water Evaluation and Planning model
WRIMS	Water Rights Information Management System

CHAPTER 1. INTRODUCTION

This technical memorandum presents a high-level synthesis of past studies evaluating climate vulnerability to the water supply system, an assessment of the gaps in knowledge, key management and policy questions to be addressed in this assessment, the methodology for assessing the vulnerability of water supply assets to primary and secondary climate drivers for the Delta, and results and findings from the analysis. Primary climate drivers assessed include precipitation (both the amount of precipitation and the variability of precipitation from year to year), air temperature, and sea level rise. No secondary climate drivers – such as wildfire and wind – were assessed for water supply. As shown in **Table 1**, water supply asset vulnerability was assessed for climate stressors and hazards.

Table 1. Illustration of primary climate drivers –precipitation, temperature and sea level rise, and the associated climate stressors and hazards.

Climate Driver	Precipitation	Temperature	Sea level Rise
Climate Stressors (long-term chronic environmental changes due to climate change)	Change over time in amount and variability of rainfall	Change over time in air temperature	Change over time in sea level
Climate Hazards (distinct events that either result from or are exacerbated by long-term climate changes)	Drought conditions	Drought conditions	NA

The Delta water supply vulnerability assessment focuses on the projected long-term (occurring over the next 10-50 years) shift in temperatures and precipitation over the Delta's contributing watershed (not solely over the Delta) because climate conditions in the watershed are the key driver affecting in-Delta and export water supply. Sea level within the Delta is also considered because it has an important influence on the operations of the water supply system (including management of upstream reservoir storage and releases, management of water quality requirements in the Delta, and exports of water from the Delta). The assessment also evaluates short-term conditions such as droughts, which could become more extreme due to climate change.

CHAPTER 2. BACKGROUND

One of the coequal goals of the Delta Reform Act is to provide for a more reliable water supply. The Delta Reform Act, and the Delta Plan, also establish State policy to reduce reliance on the Delta for state water supply needs as well as improve regional self-reliance (Water Code section 85021). This analysis recognizes and is consistent with this goal. However, the vulnerability assessment uses assumptions built into current water planning models. Adaptation strategies may explore alternate scenarios.

Analysis of water supply impacts requires simulation of climatic variables, translation of precipitation and snowpack into surface water flow, and modeling of managed flows from reservoirs and other infrastructure. Past studies in California generally achieve this by integrated use of Global Climate Models (representing climate variables such as temperature and precipitation), rainfall-runoff models (e.g., VIC), and system operations models (e.g., CalSim). To assess vulnerability, such analyses often describe existing conditions and future projections of water supply impacts.

In addition to studies that model and assess climate change impacts to water supply systems, there is a wealth of scientific exploration and analysis of climate changes to California's snowpack, precipitation and hydrology, water demand, and the impacts of sea level rise on Delta hydrodynamics. (See references for a list of these studies and other materials consulted).

Chapter 3. Water Supply Climate Stressors

This section describes primary and secondary climate stressors. Only primary stressors – air temperature, precipitation, and sea level rise – are quantitatively assessed in this study, while secondary climate stressors are qualitatively discussed.

3.1 Air Temperature

Climate projections of increased temperatures are more certain than those for precipitation (A. Schwarz et al., 2019). These projections show a trend toward higher mean and extreme temperatures and are likely to play a larger role in future droughts and water supply impacts due to the associated increase in evaporation and evapotranspiration. Statewide, by 2100, temperatures are projected to increase by 2-4 °C under medium emissions scenarios and up to 4-7 °C for higher emissions scenarios (Pierce et al., 2018). This increase in temperature would result in higher evapotranspiration and projected drier conditions in the spring and fall (Pierce et al., 2018). Relative temperature impacts are projected to be greatest in areas of moderate to high elevation, and therefore more likely to impact mountain snowpack (Reich et al., 2018).

Studies have identified the relative change in projected evaporative demand to be larger than changes in precipitation (Cook et al., 2014; Woodhouse et al., 2016). This impact has already been observed in the Colorado River Basin, where temperature has had a larger influence on streamflow than changes in precipitation (Woodhouse et al., 2016). In California, similar effects were observed during the 2012-2016 drought, when temperatures exacerbated drought conditions (Ullrich et al., 2018). These temperature impacts are projected to continue, and have greater impacts, in future droughts (*Ibid.*). In this study, the ratios of seasonal warming to annual warming are assumed to be the same for all scenarios, and seasonal warming is assumed to be uniform across the study area.

Air temperature increases are also projected to differentially increase, with larger relative increases at high elevations (Ullrich et al., 2018). This differential warming is due to a decrease in soil moisture and loss of snowpack (*Ibid.*). Water acts as a temperature buffer, and with decreased soil moisture and snowpack, temperature can increase more than it would otherwise. By midcentury, temperature at high elevation in the Sierra Nevada could increase by 2 °C, versus 1.5 °C at mid-elevations, and 0.8 to 1.4 °C in the Central Valley. For water supply this is projected to have relatively bigger impacts on reservoirs in the northern Sierra Nevada at lower elevation than the central and southern Sierra Nevada. Similarly, temperature is projected to increase by greater amounts in the Central Valley and Sierra versus the coast, where the ocean moderates temperature (*Ibid.*).

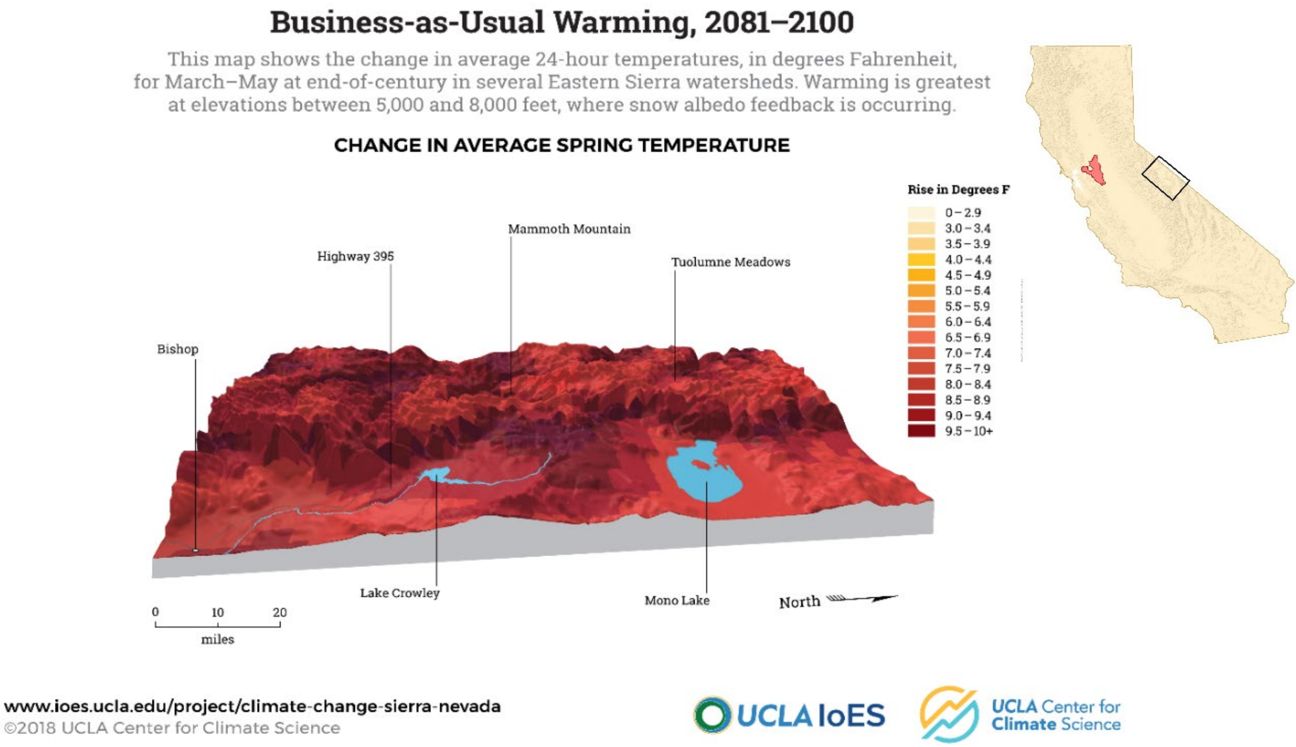


Figure 1. Potential warming in the Eastern Sierra Nevada for a business as usual climate projection case for 2081-2100.
Source: Adapted from Reich et al. 2018.

Figure 1 shows an illustrative oblique view of a cross section of the Sierra Nevada mountains from Bishop, California to north of Tuolumne Meadows, which is colorized in high-resolution according to projected rise in temperature (from 0-10 degrees F), with dark red indicating 9.5-10 degrees F. The figure indicates that temperature increases are projected across the region, but with the greatest relative increases at 5,000-8,000 feet, an important elevation band for snow accumulation and source of runoff later in the spring. The figure shows the projected change in average spring temperature in degrees Fahrenheit, from relatively less change (in yellow and orange colors) to greater increases (red to dark red colors) (Reich et al., 2018). Right inset image shows the approximate location of detail area (black rectangle) within the State of California, relative to the Delta and Suisun Marsh (dark red) (Delta Stewardship Council, 2020).

3.2 Precipitation

3.2.1 Snowpack

Snowpack provides a natural above ground water supply reservoir. On average, snowpack has historically stored approximately 15 million acre-feet (MAF) per year, or around a third of current statewide, constructed surface reservoir capacity, which is nearly 50 MAF (Rohde et al., n.d.). Snowpack is measured as Snow Water Equivalent (SWE), or the amount of liquid water the snowpack represents as liquid water. In addition to the SWE quantity, the timing of snowmelt runoff is critically important. In California, most precipitation that flows into the Delta falls in the Sierra Nevada Mountains during the months of January through March. Historically, much of the precipitation at higher elevations has fallen as snow, staying high in the watershed as a source of stored water until later in the year. This snow accumulation typically peaks in late March to early April then melts as the air temperature increases in the spring, with snowmelt runoff peaking in late spring and early summer, depending on elevation and local weather conditions. In the Sacramento River Basin, snowmelt peaks earlier than in the San Joaquin River Basin, which has higher elevation mountains. This delay in inflow to the Delta is important because it spreads flows out over time and helps align water supply with demand, which is at a maximum in the summer.

Downscaled climate projections for California consistently show an increase in temperature and a transition from snow to rain. By mid-century, peak runoff may occur a month earlier than historical conditions (Wang et al., 2018). By end of century, under a business as usual warming scenario, projections show 85 percent snow loss during drought conditions otherwise similar to 2012-2016, and two-thirds loss during wet years similar to precipitation in 2016-2017 (Reich et al., 2018). This shift is projected to decrease available water supply in two ways. First, when precipitation falls as rain, a higher proportion quickly flows off the landscape as runoff than if it fell as snow. Second, precipitation in California is concentrated in the months of December to March. Additional runoff during this period is less likely to be stored in reservoirs due to a lack of storage capacity or operating rules. If reservoir inflows increase during the winter (and decrease during spring and summer), as climate projections indicate, runoff occurring in winter is less likely to be stored in existing reservoirs. However, this is subject to a range of other factors, including inter- and intra-annual variability.

Together, earlier snowmelt and a greater rainfall-to-snow ratio is projected to contribute to a shift in the runoff pattern. Studies project that by mid-century, this will shift approximately 2.1 MAF of runoff to earlier in the year, or nearly twice the total volume of Folsom Reservoir (Wang et al., 2018). The 2012-2016 drought provided a potential preview of a future with less snowpack. However, even in future wet years, a decrease in SWE and increase in precipitation falling as rain could see a decrease in available water supply. The year 2015 had the lowest SWE on record, at 5 percent of the long-term average. However, SWE remained below normal during the wetter year of 2016. This was due to higher air temperatures, which caused more precipitation to fall as rain instead of snow. This latter case has important implications for water supply, since climate models indicate a very high confidence of increased temperature, and approximately 60 percent of precipitation falls in the Sierra Nevada (Anderson, 2017; OEHHA, 2018).

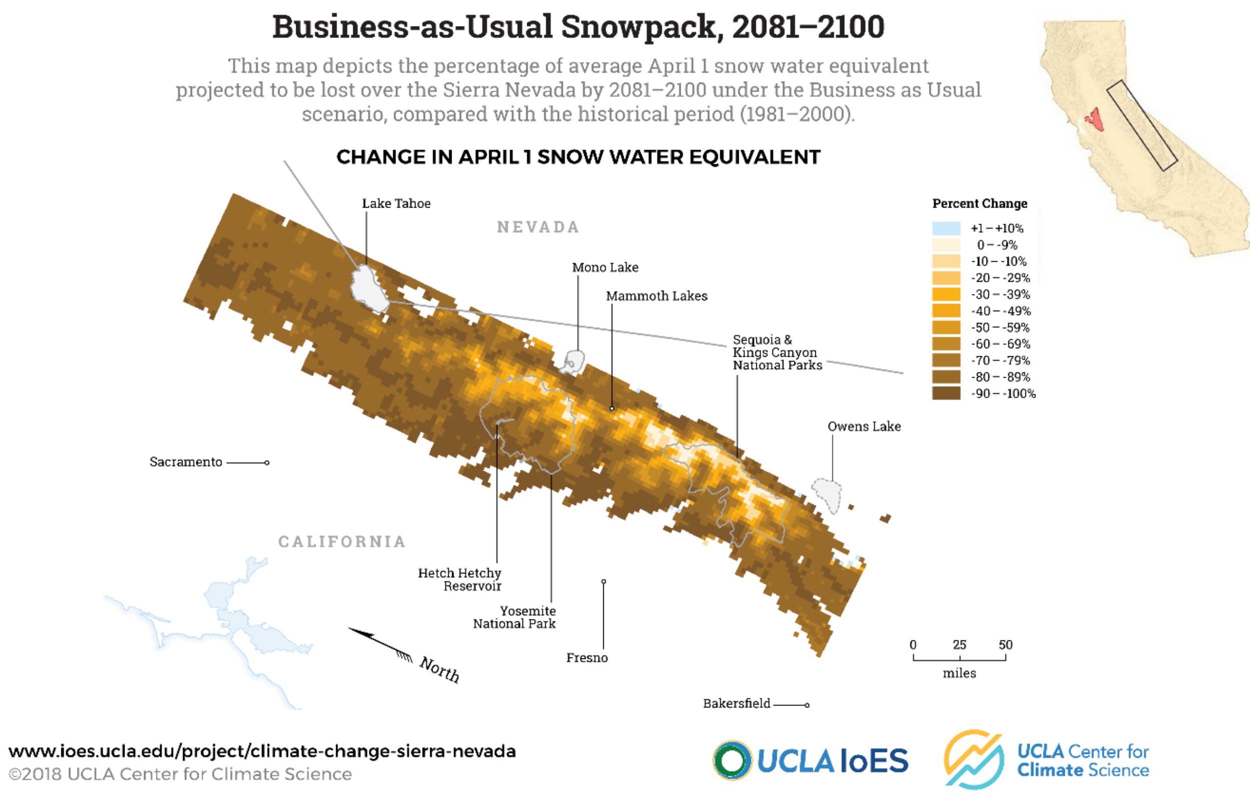


Figure 2. Projected change in Snow Water Equivalent in the Sierra Nevada for 2081-2100 under a business-as-usual climate scenario.

Source: Adapted from Reich et al. 2019.

Figure 2 presents a vertical view of the Sierra Nevada from south of Owens Lake to north of Lake Tahoe, with cells colored from yellow to brown based on the percent change in snow-water equivalent (a proxy for snowpack estimation). Darker brown areas indicate the greatest decrease in Snow Water Equivalent, most noticeable in the Northern Sierra and other areas at lower elevations. (Reich et al., 2018). Right inset image shows the approximate location of detail area (black rectangle) within the State of California, relative to the Delta and Suisun Marsh (dark red) (Delta Stewardship Council, 2020).

3.2.2 Runoff and Streamflow

Moving down from the uppermost reaches of the state's mountainous areas, streams begin to form. First, small streams, then larger ones which gradually combine and eventually merge into rivers, most of which eventually flow into a reservoir. Streamflow is driven by recent and antecedent conditions, including precipitation falling as rain and snow, snowmelt, and soil moisture.

3.2.2.1 Seasonality and Timing

The timing of precipitation, and subsequent runoff is important for determining when streamflow occurs and how much is available for supply. The majority of precipitation in California falls during the wet season (generally October to April, depending on region). Runoff peaks in winter and spring, when demand is lowest **(Lund, 2016)**. Climate studies project that precipitation patterns will increasingly shift peak runoff earlier in the winter and spring as more precipitation falls as rain instead of snow and snow is melted off earlier. This is projected to especially be the case in rain-dominated watersheds, with runoff peaking earlier and higher **(He et al., 2019a)**. In snow-dominated watersheds, relatively little change in seasonality or peak runoff is expected by mid-century (2050), but large April-July decreases in peak runoff are expected by 2100 (*Ibid*.).

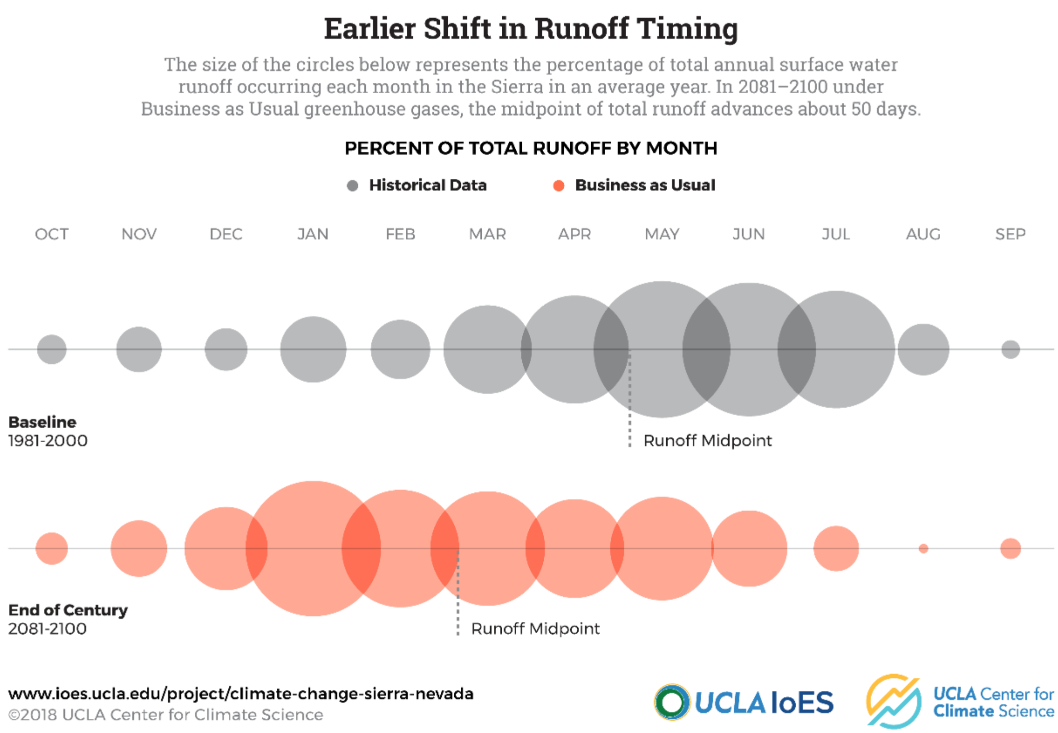


Figure 3: Projected shift in runoff by month from historical baseline to 2081-2100.

Source: Reich et al. 2018.

3.2.3 Atmospheric Rivers

Atmospheric rivers can be defined as naturally occurring, long and narrow streams of dense water vapor moving through the lower atmosphere **(Dettinger et al., 2016)**. In California, atmospheric rivers gather moisture from the tropics and transport it over the northern Pacific Ocean. When these streams of moisture are uplifted by California's mountains, they release this moisture in the form of intense rain and snow (*Ibid.*). atmospheric rivers play a key role in precipitation variability and therefore in water supply for California. Studies assessing the impact of atmospheric rivers and their impact on both intra- and inter-annual variability show that the number that occur has a large impact on whether a year is wet or dry, on water supply, and on flooding. Dettinger (2011) and Dettinger and Cayan (2014) have assessed this variability and the contribution of storms and find that more than 90 percent of major storms in observed history and more than 80 percent of floods flowing through the Delta have been the result of one or more atmospheric rivers (Dettinger et al., 2016).

Because atmospheric rivers play such a key role in delivering large portions of California's water supply, a lack of atmospheric rivers hitting California can lead to drier conditions. During the drought of 2012-2016, the presence of a persistent anticyclone, or ridge of high pressure, that occurred over the far northeastern Pacific Ocean deflected storms away from California, resulting in unusually low numbers of atmospheric rivers hitting the state.

3.2.4 Changes to Intra-annual Variability

Intra-annual variability, or the variability within a water year, has important implications for water supply. California's climate is characterized by significant variability within each year; dry summers and wet winters are the norm. However, even during California's wet periods, weeks of dry weather are not uncommon, and conditions can quickly shift to storm events that deliver heavy precipitation. A number of studies have assessed the potential for greater variability, frequency, and magnitude of seasonal precipitation (Dettinger et al., 2011; He et al., 2019b; Josué Medellín-Azuara et al., 2008)(Dettinger et al., 2011; He et al., 2019b; Josué Medellín-Azuara et al., 2008).

Dettinger et al. (2016) described potential changes to climate affecting the Delta. One significant simulated change is an intensification of storm events, with fewer days with precipitation but greater intensity of the large storms that do occur. This increase in intra-annual variability has implications for water supply. Furthermore, current infrastructure, and natural systems, have been built or adapted to the existing conditions. Although conditions experienced in the past also have high variability, projections indicate that intra-annual variability may increase substantially (Dettinger et al., 2016; Swain et al., 2018). The shift in seasonality, concentration of maximum precipitation and runoff during winter months, and increased variability and intensification of storms could strain existing water infrastructure (Swain et al., 2018).

Swain et al. (2018) uses a large ensemble of climate model simulations to quantify potential changes to wet-dry transitions under future climate scenarios. This study projects a more than three-fold increase in intra-annual wet extremes by 2100, with a smaller but still significant increase in dry extremes by end of century. In addition, simulations indicate a compression of precipitation, with 35-85 percent more (from north to south in the state) falling in the core winter months of November to March, but less falling in autumn and spring (Swain et al., 2018). However, while this and other studies have predicted an increase in extreme storms and compression of peak precipitation periods, none to date have analyzed the performance of water infrastructure and operations with these changes and sea level rise. In addition, no studies to date have quantitatively assessed the cumulative impacts of such changes for their impacts on water infrastructure, operations, and supply.

3.2.5 Inter-annual Variability and Drought

California's climate is also characterized by large changes in precipitation from year to year. Precipitation often varies from 50 percent to more than 200 percent of the long-term average and much of the precipitation each year can be attributed to only a few storms. In the Delta's watershed, half of average precipitation occurs in 15 or fewer days (Dettinger et al., 2011). Therefore, a change in number of a few storms can make a large difference in water supply.

Droughts do not have a single definition and impacts often differ by user group and area within the state. Four types of droughts have been defined by the climatological community: (1) meteorological (dry weather patterns dominate), (2) hydrological (low water supply conditions, including in streams and soil moisture), (3) agricultural (impacts to crops), and (4) socioeconomic (impacts to community water supply and demand) (National Centers for Environmental Information, n.d.). In summarizing and synthesizing previous studies on drought, we defer to the definitions of drought provided in each of the studies cited. The analysis of drought performed for this vulnerability assessment focuses on socioeconomic or water supply droughts as defined previously and described in detail below in section 13.3.

Recent studies of the 2012-2016 drought in California find that although precipitation was not the lowest on record, low precipitation combined with higher temperatures resulted in conditions of extreme aridity. Other studies indicate that such conditions may be more likely in the future (Griffin & Anchukaitis, 2014; Seager et al., 2014). Historical records demonstrate that recurrent periods of low precipitation are a regular feature of California's climate. This has been documented back to the year 800 AD by using tree ring data, which can provide a proxy for available water through their growth rate and ring width (Meko et al., 2014; Routson et al., 2011). These data show that there have been extended periods of drought in California over the last millennium. If similar periods of extended drought were to occur now, it could drastically impact water supply in the State, now home to nearly 40 million people ((Cook, Smerdon, Seager, & Coats, 2014; Griffin & Anchukaitis, 2014).

Furthermore, studies may underestimate the risk of such persistent droughts because they do not capture the full variability of multi-decadal to multi-century periods (Ault et al., 2014). Ault et al. (2014) also projected that expected climate changes using models from the Coupled Model Intercomparison Project Phase 5 (CMIP5) ensemble could result in decade-long droughts (50 percent chance of occurrence by 2050-2100).

3.3 Sea Level Rise

Several studies have estimated the effect of sea level rise on water supply and current in-Delta and export infrastructure. In general, sea level rise will increase the forcing of salinity intrusion eastward into the Delta, which would in turn require release of additional stored water from reservoirs, the reduction of export pumping from the Delta, or both, in order to counteract salinity intrusion and meet regulatory requirements. For most past studies, water quality and flow requirements are assumed as described under Decision 1641 (D-1641). D-1641 includes a wide range of water quality and flow objectives that vary by season and flow and are primarily intended to protect beneficial uses of water and fisheries, including in-Delta water use, exports, and preventing fish entrainment. D-1641 also includes a requirement for maintaining salinity of two parts per thousand (ppt) or lower at a given distance depending on time of year. This salinity level is referred to as X2 and is in place as a regulatory requirement in order to protect the water quality of Delta exports as well as maintain a low salinity zone near some of the only remaining habitat for the endangered Delta smelt (*Hypomesus transpacificus*).

Sea level rise increases the hydrostatic pressure of saline water from the ocean, effectively increasing salinity in the Delta unless fresh water is released to repel this intrusion. This action is sometimes referred to as a hydraulic salinity barrier. Modeling indicates that Delta outflow would need to increase above historic levels to maintain the hydraulic salinity barrier and in-Delta water quality, and Delta exports could decrease (A. Schwarz et al., 2019). Historically, maintenance of the hydraulic salinity barrier is the limiting factor on Delta exports in most years (Reis et al., 2019). Multiple studies of the state and Federal project operations indicate that sea level rise will increase the hydrostatic pressure that would require increasing export constrains or other tradeoffs to prevent salinity from penetrating further into the Delta (Schwarz 2019, Wang 2019).

3.3.1 Salinity intrusion and water surface elevation change throughout the Delta

Salinity intrusion is influenced by a range of factors, including sea level, tides, freshwater outflow, channel geometry, barriers or flow constrictions, exports, and water depth, movement, and vertical mixing. The last factor in particular cannot be modeled by one- or two-dimensional models and is important because gravitational circulation and horizontal and vertical flows can have a significant impact on salinity intrusion.

Several past studies employ three-dimensional models to more accurately simulate salinity under different scenarios. These include CASCaDE II (Noah Knowles & Lucas, 2015), MacWilliams et al. (2015), MacWilliams et al. (2016), Martyr-Koller et al. 2017, Gross et al. 2009, MacWilliams et al. 2015, Andrews et al. 2017, and Gross et al. 2018.

Gross et al. 2009, MacWilliams et al. 2015, Andrews et al. 2017, and Gross et al. 2018 have assessed the effect of gravitational circulation on salinity and flow patterns in the Delta. This can provide important information on how salinity dynamics may change with deeper water depth and changed geometry. Currently, many operational models assume an X2 value near the bottom of the river channel based on a surface measurement of salinity. However, these relationships may not hold with substantial sea level rise and changing geometry.

Gross et al. (2009) used the TRIM3D model to simulate salinity in the estuary, including the influence of gravitational circulation. Gross notes that gravitational circulation is an important factor in salinity transport in the estuary and Delta. This, along with outflow, heavily influences

X2 location. Although this study did not attempt to simulate salinity impacts under future climate change scenarios, it did demonstrate that models can accurately predict salinity at tidal and seasonal time scales. However, representation of the Delta and its network of channels was simplified due to the model's 200 meter (m) resolution **(Gross et al., 2009)**. The findings of this study are useful in identifying gravitational circulation as an important factor, but it does not provide a quantitative model that can be easily applied at high spatial resolution.

MacWilliams et al. (2015) applies the UnTRIM 3D model to simulate tidal and salinity dynamics in the San Francisco Estuary. The simulation was run over a three-year model period and allows for quantification of various metrics, including the location of the low-salinity zone or X2. MacWilliams et al. (2015) found that the X2 varied largely depending on geometry. This study used an unstructured grid, allowing for more find-grain simulation of processes in narrow Delta channels. Notably, the study found that it more accurately predicted salinity than correlations based on surface salinity levels (MacWilliams et al., 2015). This implies that if water surface elevation and Delta geometry change significantly, salinity dynamics may also change in a non-linear manner and require changes to system operations. The study also has implications for uncertainty in interactions and impacts from sea level rise, Delta inflows, and changed Delta geometry.

MacWilliams and Gross (2010) explored the relationship between sea level rise and X2 by modeling Delta conditions under historical operations with multiple levels of sea level rise—allowing water quality in the Delta to respond (i.e., unconstrained by regulatory requirements). This study estimated sea level rise of up to 140 cm could result in a median increase (eastward shift) of X2 of 7 km, or 7.3 km if including a 5 percent increase in tidal amplitude (MacWilliams & Gross, 2010).

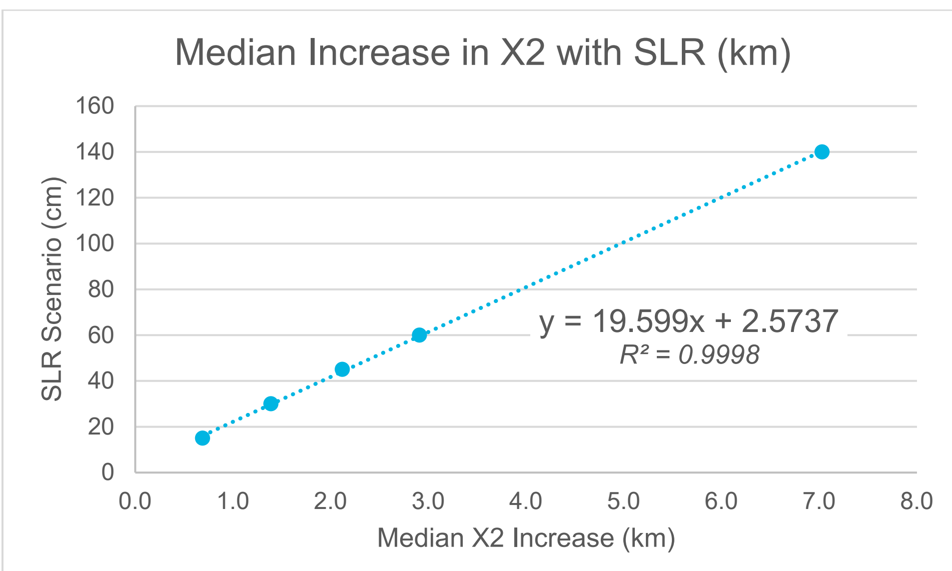


Figure 4: Median increase in X2 measured in kilometers from the Golden Gate Bridge (i.e., length of additional penetration of salinity into the Delta) with sea level rise of up to 140 cm (not including 5 percent projected increase in tidal amplitude).

Source: Adapted from MacWilliams and Gross (2010), Table 5-1.

Andrews et al. (2017) used the UnTRIM model to compare hydrodynamics in the San Francisco Estuary for a pre- and post-development period. The analysis found that tidal trapping in the post-development estuary might be very different from pre-development conditions (Andrews et al., 2017) An important implication of the study is that more complex and sinuous geometry – such as in Suisun Marsh – may contribute to increased tidal trapping of salinity. The combination of sea level rise and future restoration projects could increase the strength of tidal trapping in the estuary.

Gross et al. (2018) builds on earlier work and assesses pre- and post-development variability of freshwater flow and salt intrusion. This study includes an additional "pre-project" period around 1920. The findings indicate that the pre-development estuary experienced more seasonably variable salinity because of more variable inflow from upstream. This has implications for future conditions, with many scenarios indicating more variable inflows at inter- and intra-annual time steps, because of changing climate and less ability to manage flows due to lower carryover reservoir storage.

3.4 Secondary Climate Stressors: Wildfire, Fog, and Wind

3.4.1 Wildfire

Fire activity has been increasing in the western United States, including amount of area burned, the number of large fires, and length of the fire season (Abatzoglou & Williams, 2016). This increase in fire activity is attributed both to the wildfire suppression policies of the last century, which resulted in unnaturally dense forests, increases in land development in forested areas and increasing wildland-urban interface, and to climate change (Houlton et al., 2018). Studies indicate that wildfire risk in California will increase with climate change (*Ibid*). Summer and fall wildfire activity is likely to increase in the future as summers become drier and winters become wetter (*Ibid*).

Fire can pose a serious threat to water supply (Nunes et al., 2018). Water management, water supply operations, and water storage and treatment can all be impacted by the sediment and contaminants that enter bodies of water following a wildfire (Martin, 2016). High-severity wildfires can degrade water quality due to increased sediment loads, which increase turbidity and facilitate transport of water contaminants, such as nutrients, pathogens, and heavy metals (Bladon et al., 2014).

Past studies have investigated the impacts of wildfires on watershed hydrology and water supply. For example, model results from a study by Maina and Siirila-Woodburn (2019) indicate that evapotranspiration decreases and snowpack increases after a fire, whether the fire is followed by a wet or dry year (Maina & Siirila-Woodburn, 2019). Because snowpack increases, summer runoff increases as well. Although wildfire results in an increased snowpack, snowpack melts earlier due to a greater amount of solar energy reaching it (Bladon et al., 2014). In a study investigating post-fire impacts to streamflow using 12 paired watersheds in central and southern California, Bart (2016) found that annual streamflow increased at a regional scale following wildfire (Bart, 2016). Although fire can be an important driver of watershed changes and can have impacts on water supply, assessment of the impact of potential wildfire on the Delta watershed is beyond the scope of this project.

3.4.2 Fog

California's Central Valley has thick wintertime ground fog, known as tule fog. Tule fog is important in helping create the necessary winter chill that fruit and nut trees require to be productive (Gray et al., 2019). Occurrence of this fog has been decreasing in recent decades: the number of Central Valley fog events has decreased by 46 percent, on average, over the last 32 winters, with much inter-annual variability (Baldocchi & Waller, 2014). Both the occurrence and spatial extent of tule fog has decreased (*Ibid*). However, according to Gray et al. (2019) tule fog frequency actually increased by 85 percent from 1930 to 1970 and declined by 76 percent during the past 36 winters. Gray and colleagues (2019) found that changes in air pollution, rather than climate, are the main drivers of long-term changes in tule fog. Very little research has been done examining the impacts of tule fog on water supply. Assessment of the impacts of climate change on fog in the Delta, and its impact on evapotranspiration and water supply, is beyond the scope of this project.

3.4.3 Wind

Model results from a study by Breslow and Sailor (2002) projecting the impacts of climate change on wind speeds in the U.S. found that wind speeds will decrease by 1 to 3.2 percent in the next 50 years and 1.4 to 3.2 percent in the next 100 years (Breslow & Sailor, 2002). According to Dettinger et al. (2016), there has been little research projecting climate change impacts to large-scale wind changes over the Delta, and these changes are very uncertain. However, Dettinger et al. (2016) do note that Delta breezes may become more intense. No research has been done on the impacts of wind on water supply in the Delta.

CHAPTER 4. THE DELTA LEVEE SYSTEM

A defining characteristic of the Delta is its extensive levee system that protects islands and adjacent areas from regular flooding and inundation. Many of these levees predate the State's water supply infrastructure and are at varying risk of failure (Dettinger et al., 2011; Fleenor et al., 2008; Mount & Twiss, 2005). Over the past several years, significant effort has been put into analyzing and reducing levee vulnerability. This levee system also confines the river system to static channels, in turn dramatically influencing hydrodynamics and tidal influence in the Delta. This levee system also allows for freshwater exports via SWP and CVP and other water suppliers pumps located throughout the Delta.

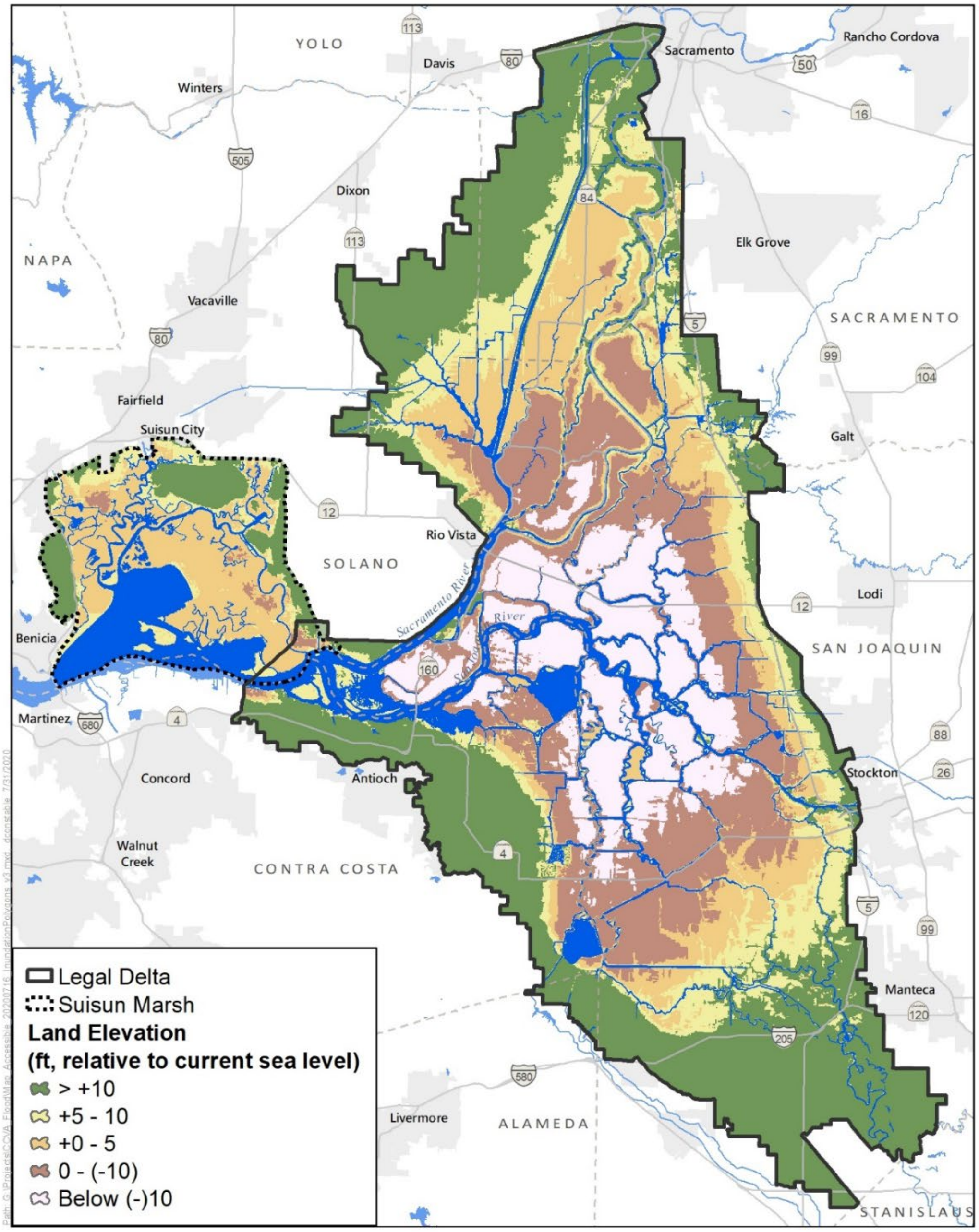
4.1 Potential Levee Failure Risk

The Delta's islands and water channels were created by levees built starting around 150 years ago. Most were not engineered, but rather formed with organic and mineral materials dredged from the adjacent channel **(CDWR, 2015b)**. Since many Delta islands are below sea level, levee failure and subsequent flooding could impact water quality and disrupt water exports especially during low inflow periods (Deverel et al. 2016, Lund 2016). When levee failures occur in the Delta, water from the adjacent channel spills onto the island until the island fills with water. Depending on the location of the failure and flow conditions during which it occurred, the water flowing on to the island may be fresh or saline water. However, in either case, the flow of water onto the island draws additional saline water into the Delta by creating a differential pressure and space into which saline water from San Francisco Bay can flow. Depending on the number of breaches, specific locations, inflows and tidal conditions at time of breach, and ability to respond, there could be widely varying impacts to water supply for in-Delta users and other users who rely on Delta water throughout the State.

Recent levee failures in the Delta have been rare. The last major levee failure occurred on Jones Tract in 2004. Levee failures can occur during any condition, including during clement weather, so-called 'blue sky' failures. However, more levees have failed in the Delta during periods of high inflow (Deverel et al. 2016). This is due to increased hydrostatic pressure on levees from higher water elevation in channels, and in some cases due to overtopping (*Ibid.*). These types of pressures are projected to increase in the future due to higher high flows from shifting precipitation patterns (*Ibid.*).

Land subsidence in the Delta provides an additional levee failure risk factor. The Delta was formed by accumulation of organic-rich plant materials, which accumulated over time. Before being converted to primarily agricultural land, wetlands and tidal marshes in the Delta created an anaerobic or partially anaerobic environment, in which microbial action and plant decay slows, allowing for accumulation of dead plants and conversion into peat-rich soils. Once these lands were drained and converted to agricultural use, exposure to oxygen in the atmosphere has resulted in continued oxidation of organic material and land subsidence. Over the past century, such subsidence has resulted in portions of the Delta subsiding to more than 25 feet below sea level. Continued subsidence will lead to increased hydrostatic forces – caused by the difference in subsided land elevation and water surface elevation in the nearby channel – and therefore increased stress on Delta levees in the future (Deverel, Ingrum, et al., 2016; Mount & Twiss, 2005). This will be further exacerbated by sea level rise and, during certain conditions, high-magnitude inflows.

Because many Delta islands are below sea level (**Figure 5**), levee failures would likely result in complete inundation of failed islands. If failed islands are not restored, the new open water areas could change the hydrodynamics around that island. Studies on this topic show that flooding of islands can result in the subsequent changes to in-Delta flow patterns, salinity intrusion, and tidal exchange (Resource Management Associates, 2020).



SOURCE: Elevation data from DWR 2017

Figure 5. Land elevation in the Delta as measured in 2017.

Figure 5 shows the Delta region according to elevation relative to current sea level on a scale of green (>10 feet above sea level) to light pink (<10 feet below sea level). The figure indicates that much of the central Delta, particularly the central region, is below mean sea level (shown in light pink and red). This region continues to subside, creating risk both with the Delta and downstream due to potential impacts to water supply. Source: Delta Stewardship Council, 2020.

4.1.1 Key Delta Levees Studies and Findings

A number of studies have assessed the probability of Delta levee failure and subsequent impacts. These include (Mount & Twiss, 2005), the Delta Risk Management Strategy (DRMS, Phases 1 and 2) (CDWR, 2009b, 2011), a study of processes affecting levee vulnerability (Deverel, Bachand, et al., 2016), the Delta Levees Investment Strategy (Delta Stewardship Council, 2017), and an ongoing analysis of levee failure and hydrodynamics (Resource Management Associates, 2020).

Mount and Twiss (2005) provided a high-level summary of processes influencing and potential impacts from subsidence and levee failure. This work took place during the CALFED process and builds on earlier studies by DWR and others during the 1970s to early 2000s. The authors calculated a levee force index, using the estimated force in the year 1900 as the baseline. They found that there will be continued subsidence through 2050 resulting in greater forces on levees and therefore an increase in potential island flooding. Furthermore, the authors found that there is a two-in-three chance of catastrophic flooding and significant change in the Delta by 2050.

The Delta Risk Management (DRMS) Phase 1 study (CDWR, 2009b) considered current and future risks of levee failure from earthquakes, storms and tidal surges, climate change (e.g., sea level rise), subsidence, and blue sky events during the next 100 years. The study also assessed the potential human health and socioeconomic impacts from such levee breaches. This was done by assessing the combined risks from these factors to come up with a mean annual probability of failure for islands in the Delta and Suisun Marsh.

DRMS Phase 2 (CDWR, 2011) assessed risk reduction options for risks identified in Phase 1. DRMS Phase 2 assessed these risk reduction options and presented four trial scenarios: Improved levees, armored pathway for through Delta conveyance, an isolated conveyance facility such as a tunnel, and dual conveyance where both an isolated conveyance facility and through Delta infrastructure would be used. DRMS Phase 2 relied on levee failure risk probabilities identified in Phase 1.

Deverel et al. (2016) considered DRMS work but noted that levee performance was better than expected. Deverel et al. (2016) hypothesized that this is because of substantial work to upgrade levees in the intervening years and increased compliance with relevant levee standards. This study provides an update on the understanding of Delta levees over the 2006-2016 period, when substantial improvements to levees were made as well as an increased understanding of levees and the processes affecting them. Notably, the last recommendation in this study called for "Additional hydrodynamic modeling to simulate a wide range of scenarios and corresponding risks and benefits to water supply and quality."

The Delta Levees Investment Strategy (DLIS) final report was released in July 2017 (Delta Stewardship Council, 2017). DLIS provides an assessment of multiple risks and benefits associated with levees, as well as a decision support tool to help prioritize investment in these levees. DLIS identified a series of priority islands for protecting human life, property, habitat, and water supply. These islands are shown by priority category in Figure 6.

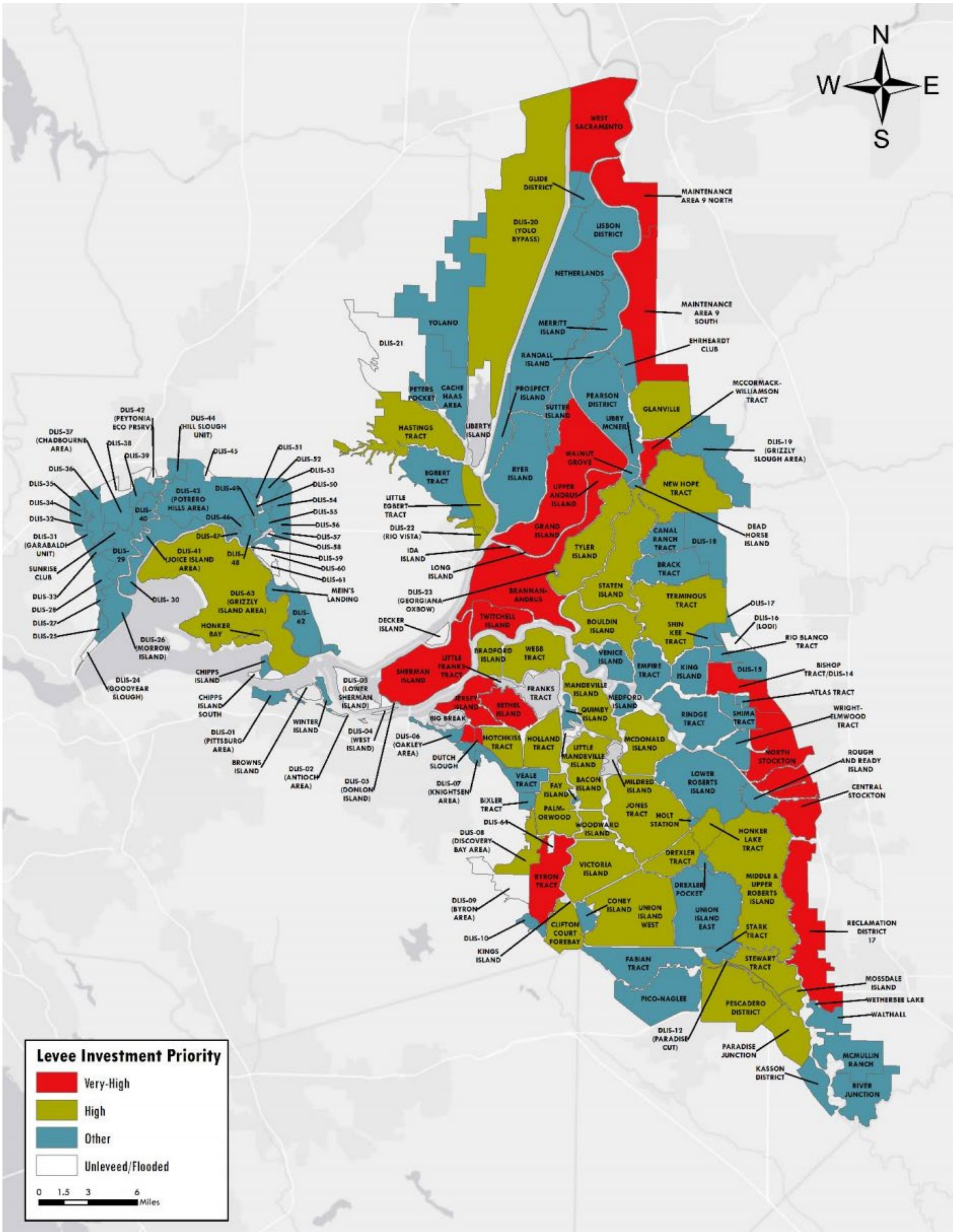


Figure 6: Delta Levees Investment Strategy (DLIS) priorities for State investment in Delta and Suisun Marsh Levees.

Figure 6 shows islands and areas in the Legal Delta and Suisun Marsh. Island colors represent a cumulative levee investment priority identified as part of the 2017 Draft DLIS. The red color represents very-high priority, green is high priority, and blue is other. High priority areas are located east of the San Joaquin river from Tracy to north of Stockton, along the east bank of the Sacramento River from the confluence with the San Joaquin to Walnut Grove, Byron Tract, Bethel Island, Jersey Island, Dutch Slough, West Sacramento, and Sacramento Pocket area south along Maintenance Area 9. Areas with a light gray background are either un-leveed or permanently flooded. Source: Delta Stewardship Council 2017.

Recent modeling by Resource Management Associates (RMA) (2020) prepared for the Delta Stewardship Council has studied the potential impacts of different combinations of levee breaches in the Delta. Model simulations have been developed to isolate the mechanisms affecting flow and salinity transport with a focus on developing metrics that can be related to the relative importance of individual islands. Hydrodynamic models are utilized to simulate the potential hydrodynamic and salinity effects of geometric changes to the Delta from two perspectives. One perspective is the immediate impact of an unanticipated levee failure event, and the second perspective is of permanent, i.e. not repaired, levee breaches. Modeling included island breaches for many locations across the Delta, both individually and in different combinations.

Findings show that island volume and surface area are important as would be expected, but also that the location of breaches has a strong influence on outcomes. Initial results also show the interrelated nature of islands, levees, and infrastructure to the water supply system as it is currently configured. Levee failure and inundation of a critical island, or a combination of islands, can have regional impacts on Delta hydrodynamics and ultimately water supply far beyond the immediate vicinity of the breaches. The outputs of this project remain in progress, but can inform the potential vulnerability of water supply to changes in hydrodynamics and salinity transport.

Evaluation of short-term impacts of levee failure events was performed using the Department of Water Resources' Water Analysis Module (WAM), which is a component of the DWR Delta Emergency Response Tool. WAM includes a one-dimensional, tidally averaged flow and transport model of the Delta coupled with operations logic to simulate disruption and recovery of the Delta water supply operations resulting from levee failure events. Thousands of simulations were performed including individual island breaches and groups of island breaches with the objective of determining importance of individual islands with regard to potential water supply disruption. The relative importance of each island was described by the days of potential export disruption, maximum change in X2 position, and days required to return water quality back to within established limits.

Simulations demonstrate that the volume of a flooded island is a good indicator of potential water supply disruption for single island failure events. When multiple island failure events are considered, the location of the island becomes more important. In particular, the larger south Delta islands such as Jones, Roberts, and Bacon stand out as contributing significantly to increased water supply disruption. The time of year when the breach event occurs, hydrology over the preceding and following months, and proximity of breaches to major waterways such as the Sacramento or San Joaquin rivers are important in assessing potential impacts from levee failures. Furthermore, this study supports past work showing large potential impacts if breaches were to occur during summer months during or ahead of a dry year.

Evaluation of longer-term impacts resulting from leaving breached islands open to tidal inundation was performed using the one- and two-dimensional RMA Bay-Delta Model. Hydrodynamic and water quality simulations of the summer spring-neap tide cycle and for January-December 2009 and July 2013. These periods were selected for representation of years including dry and critically dry periods, when water quality impacts are likely to be greatest. A spring tide, also referred to as a king tide, refers to the 'springing' of the tide when tidal range is greatest due to sun and moon alignment. A neap tide is a more moderate tide when the sun and moon are at right angles to each other. The summer spring-neap tide cycle was used to provide a range of tidal influences and isolate mechanisms affecting flow and salinity transport and with an objective of identifying importance of individual islands.

Opening new areas to tidal inundation leads to regionally varying changes in tidal range, varying mean sea level, and changed flow split between the Sacramento and San Joaquin river inflows to the Delta. In general, the volume of water exchanging with daily tides (tidal prism) measured at the Carquinez Straight does not significantly increase as Delta islands are opened to tidal exchange. Rather, the tidal prism is redistributed within the Delta depending on the size and location of breached islands (**Figure 7**).

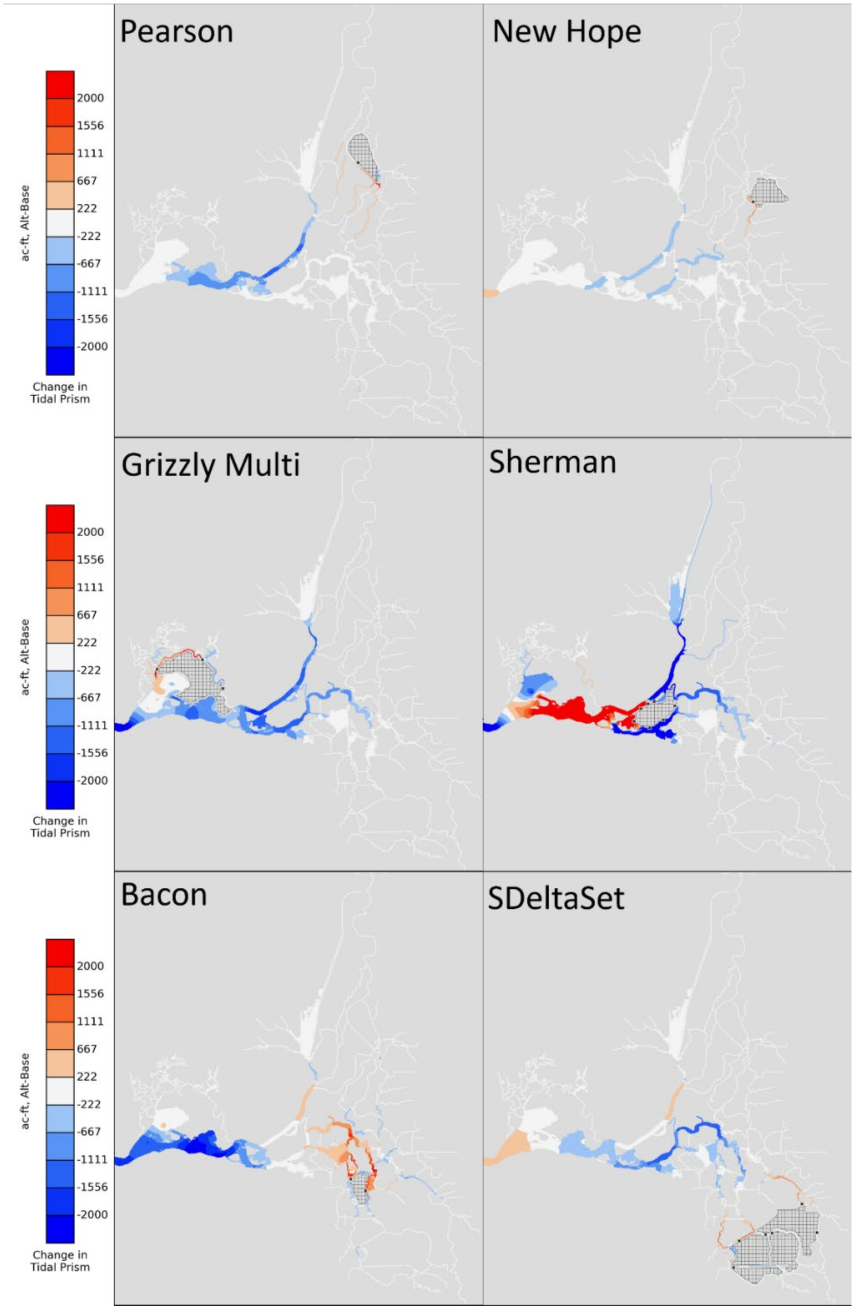


Figure 7: Changes in tidal prism for representative breach scenarios occurring in the north Delta (Pearson District), east Delta (New Hope Tract), Suisun Marsh (Grizzly Island), west Delta (Sherman Island), central Delta (Bacon Island), and south Delta (Roberts, Union Island, Fabian, Drexler Tracts shown together).

Figure 7 shows the change in tidal prism (the volume of water exchanging with daily tides) between each modeled scenario and the base case scenario of no levee breach. Cross-hatched areas indicate regions where breach would occur. The tidal prism change is delineated by a legend at left that ranges from red (+2000 acre-feet) to blue (-2000 acre-feet) (RMA, 2020).

A real world response to the impacts of a levee break is captured in the Jones Tract After Action Report (CDWR, 2004). On the morning of June 3rd, 2004, a breach occurred on Jones Tract during clement summer weather, resulting in flooding of the island. In response to the initial breach, emergency response services were quickly mobilized. Protecting lives and property and minimizing saltwater intrusion were key objectives from the start. In order to protect water quality, the Department of Water Resources (DWR) and the U.S. Bureau of Reclamation restricted pumping from the south Delta and released water from upstream reservoirs. DWR took actions to protect interior levees in order to prevent damage and potential additional levee failures from wind waves and tidal action. Ultimately, the levee breach was repaired and the island was pumped out by mid-December 2004, at a total cost of approximately $90 million. This event demonstrated the large potential impacts and response needed for even a single island failure during lower flow conditions.

CHAPTER 5. GROUNDWATER

Groundwater is an important contributor to the state's water supply; it supplies about 13% (8 MAF) of the state's total water use in average years (20% of urban and agricultural water use), and during droughts, can provide up to 60% or more for specific regions (CDWR, 2009a). From 2005-2010, groundwater contributed 38% of California's total annual water supply (16.5 MAF). During this period, in the Sacramento River and San Joaquin Valley hydrological regions respectively, groundwater contributed to 30% and 36% of agricultural water supply, 47% and 58% of urban supply, and 4% and 38% of managed wetlands supply (CDWR, 2015a). In the 2015 drought year, groundwater pumping, which mostly occurred in the Central Valley, offset approximately 70% of the water shortage (surface water shortages = 8.7 MAF, groundwater pumping = 6 MAF) (Howitt et al., 2015). As climate change progresses, changes in precipitation, greater frequency of drought, shrinking snowpack, and a shorter wet season will continue to pose threats to surface water supplies, causing greater reliance on groundwater sources for agricultural, urban, and environmental uses (Hanak et al., 2019).

Thirty-six alluvial groundwater basins in California have been identified as being highly dependent on groundwater. Of these, regions that depend on Delta water include Tulare Lake and the South Coast hydrologic regions (CDWR, 2015a). Certain areas of the Central Valley, including Lodi, Fresno, and Davis, rely almost entirely on groundwater for water supply (CDWR, 2003). Groundwater use in the Delta watershed and Delta water export regions can displace reliance on the Delta, at least in the short term. However, reliance on groundwater over the past century has resulted in extensive groundwater depletion and subsidence, especially in the San Joaquin Valley (CDWR, 2015a). Groundwater overdraft can also pose risks to reduced water quality, seawater intrusion, changes to hydrology in connected streams and rivers, and increased costs associated with water scarcity and pumping (Konikow & Kendy, 2005). The Central Valley aquifer has a depletion rate of 1.8 MAF per year.

The historical groundwater deficit of the Central Valley is 1.8 MAF/year, accounting for more than 90% of the state's groundwater overdraft (Scanlon et al., 2012) and has shown increases over the past 15 years. From 1988-2002, groundwater overdraft contributed to 8% of net water use in the Central Valley (1.3 MAF/year), and increased to 15% from 2003-2017 with the worsening droughts (2.4 MAF/year) (Hanak et al., 2019). The Sustainable Groundwater Management Act (SGMA) mandates all long-term groundwater overdraft to end by the early 2040's, forcing many regions to reduce and manage groundwater use (CDWR, 2016). Of the 15 basins subject to SGMA, 11 are considered critically overdrafted (Hanak et al., 2019). Improved management of groundwater resulting from the implementation of SGMA will likely further constrain water supplies throughout the state, potentially increasing demand for Delta water and will likely require managed replenishment of groundwater during wet periods.

More extensive management of flood flows for managed aquifer recharge, sometimes called Flood-MAR, is being evaluated by multiple entities including DWR. With more intensive use of

Flood-MAR, additional water would be removed from rivers during wet periods, reducing inflows to the Delta. However, water stored during wet periods would be available for extraction and use, potentially reducing demand for river flows and allowing additional water to flow into the Delta during drier periods.

A study of ending groundwater overdraft, as required by SGMA, found that it could result in larger reliance on Delta exports and less water supply for agriculture in the Central Valley (Nelson et al., 2016). Under full implementation and compliance with SGMA, modeling efforts suggest that water available for agriculture and urban users will be reduced by 34% and 5% respectively, resulting in statewide costs of at least $50 million per year from unmet demand. Urban users are predicted to experience less of an impact since they can purchase water from agricultural users (Dogan et al., 2019). Increases in water scarcities and associated costs will likely result in changes to agricultural practices, such as increases in fallowed land and switching to more water efficient crops. Under SGMA, it is expected that greater than 500,000 acres of irrigated cropland in the San Joaquin Valley will be fallowed (Hanak et al., 2019).

Within the Delta, groundwater level data is limited. However, data indicate that groundwater levels throughout the Delta are at or slightly below sea level and average from two to 10 feet below the ground surface (CDWR, 2015a). On many deeply subsided Delta islands, groundwater seeps out onto the surface of the island because the phreatic surface is actually above the surface of the land and therefore must be pumped out to lower groundwater levels below the root zone of crops. The impacts that salinity intrusion may have on groundwater sources in the Delta due to sea level rise remains unknown and requires further study.

In general, California surface water and groundwater systems have often not been modeled in an integrated fashion. While CalSim-III adds an important ability to dynamically model groundwater conditions that was not present in past versions of CalSim, its simulation of surface water-groundwater interactions is still quite coarse and CalSim-III's "level-of-development" simulation approach may not be well suited for simulating groundwater conditions in which impacts accrete over time and often do not "reset" periodically. Thus, there are few water supply studies that assess the potential integrated impacts of climate change on the connected surface water and groundwater systems in the Delta watershed. In addition, as noted above, FloodMAR is being investigated as a potential opportunity to capture and store flood flows, particularly under future conditions that are expected to provide more extreme winter precipitation and store those flows in groundwater basins for use during dryer conditions. Planning for and designing the infrastructure and management tools needed to successfully implement large scale FloodMAR will require new tools and processes including models that can simulate flood management operations, downstream diversion and recharge to groundwater operations, as well as the recapture and delivery of previously stored water within the water delivery system (CDWR, 2019a).

CHAPTER 6. WATER DEMAND

Water demand is influenced by a range of biophysical, economic, and social factors. These include population, changes to physical processes such as evapotranspiration driven by higher temperatures, market forces incentivizing certain crops or land uses, and regulations such as water efficiency standards.

Statewide, water in California is primarily used in three sectors: approximately 50% environmental, 40% agriculture, and 10% urban (Environmental water in this context means water that remains in rivers or streams and is not used for consumptive human use. In California, much of this environmental water is on the northwestern coast, and does not naturally flow to the Delta) (CDWR, 2015a). Approximately 25 million Californians and more than 3.7 million acres of agriculture receive at least a portion of their water from the Delta. The Delta also serves as a hub in water transfers to other areas of the state, as well as an area of critical importance for local water use by people and ecosystems. On average, 28.2 MAF of water could flow into the Delta if not diverted or used upstream. However, this average masks high inter- and intra-annual variability (Dettinger et al., 2011; Lund, 2016). The variability and timing of climatic patterns, and water demand, are projected to change in the future due to changes in climate, population, water-use patterns, and other factors.

With respect to climate change, temperature is the key driver of changes to biophysical water demands. Increased temperatures increase the rate of evapotranspiration, the process by which plants transpire water through their stomata. As the rate of evapotranspiration increases in plants, their consumptive water demand increases. Water consumed by crops does not become available for other uses (Womach, 2005), and is a significant component of regional water and flow budgets (Josue Medellín-Azuara et al., 2018). Because the agricultural sector makes up around 40% of all water use, or approximately 80% of developed water use, changes in crop consumptive water demand can have a large impact on overall water demand. Importantly, changes in water demand do not necessarily result in supply changes to offset this increase in demand. Increased demand often results in supply-demand imbalances, referred to as unmet demand. Groves and Bloom (2013) assess this in detail and conducted modeling that indicates unmet demand could peak above 10 MAF per year in the 2040s (Groves & Bloom, 2013)

A recent study by the California Department of Water Resources also assessed water demand, supply, and potential gaps between the two through the year 2100 (CDWR, 2019b). In addition to climate projections, the modeling also considered future population growth up to 150-million state residents as well as housing density, which along with population growth can influence water demand. To assess risk, the study reports vulnerability/risk as the percent of time demand would not be met under a given demand scenario. Urban demand could largely be met under most scenarios, but with a potential 6.3% gap in the Tulare Lake Region. Agricultural demand has a larger gap relative to supply. The largest gap is again in Tulare Lake Region, at 49.5% (95%

reliability threshold) or 33.7% (90% reliability threshold). Findings indicate that under most scenarios, there will be a relatively large agricultural demand gap, especially in Tulare Lake.

6.1 In-Delta Water Demand

While flows that enter and leave the Delta can vary substantially between wet and dry years, in-Delta water use has remained relatively constant at about 4% (0.9 MAF) of Delta inflows over the past century (Delta Stewardship Council, 2018). The majority of in-Delta water is used for agricultural irrigation. Over 1,800 in-Delta diversions remove water directly from channels and sloughs for irrigation use, diverting up to 5,000 cubic feet per second (cumulatively) during peak summer months. At the same time, many in-Delta water users also have to actively de-water their land by pumping water off islands to lower groundwater levels. This is necessary in order to lower groundwater below crop root zones. While Delta water users are required to report the amount of their diversions, many water users do not have flow meters, and estimate water use by the amount of water consumed by their crops (CDWR, 2007).

Crop consumptive water use, also referred to as evapotranspiration (ET), is the quantity of water evaporated from the soil and transpired during plant growth and is a significant component of regional water and flow budgets. In the Delta, the majority (60%) of total annual agricultural ET in recent years is attributed to three dominant crops: alfalfa, corn, and pasture (Josue Medellín-Azuara et al., 2018).

A project led by researchers at the Center for Watershed Sciences at the University of California-Davis found that agricultural landscapes in the Delta accounted for 477,690 acres in 2015 and estimated total annual ET from crops at 1.445 million acre-feet (MAF). In water year 2016, agricultural acres and total annual ET from crops decreased (464,742 acres, 1.379 MAF), due to land uses changes, including increased fallowed lands and changes in crop production (Josue Medellín-Azuara et al., 2018). Changes in cropping and irrigation methods, such as a trend towards increased perennial crops and more efficient irrigation systems (CDWR, 2005), will likely continue in response to water costs and regional climate patterns.

Regional and temporal land use patterns are also important in attempting to quantify crop consumptive use in the Delta. For example, the North Delta has the largest average total agriculture ET, but the Yolo Bypass has the highest average unit agricultural ET due to the production of water intensive crops (i.e. pastures, rice) (Josue Medellín-Azuara et al., 2018). Climate change impacts on ET are complex, making it difficult to accurately predict future crop water use. While ET rates increase with temperature, increased atmospheric carbon dioxide levels, cloudiness, and humidity act to reduce water consumption by plants. SIMETAW (Simulation of Evapotranspiration of Applied Water) is a simulation model that can be used to study the effects of climate change on ET. In a climate change analysis by DWR, it was concluded that temperature and carbon dioxide effects nearly offset each other, with a slightly greater effect of temperature on ET than carbon dioxide (CDWR, 2006).

Non-agricultural lands, including riparian, upland herbaceous, and floating vegetation, are also a significant component of in-Delta water consumption. In 2016, these non-agricultural land uses comprise 13% of land use in the Delta (80,000 acres), with an estimated ET from these lands of

247 thousand acre-feet per year (TAF/year), accounting for about 30% of all consumptive use in the Delta (2.0 MAF). On average, non-agricultural lands averaged higher per acre consumptive use than agricultural land use (agricultural land use averages 2.0 AF/acre) (Josue Medellín-Azuara et al., 2018).

In addition to agricultural water demands in the Delta, and the state and federal project export pumps, there are a number of local, State, and Federal water diversions located within the Delta. These are shown in the following figure (**Figure 8:**), as reported by the electronic Water Rights Information Management System (eWRIMS).

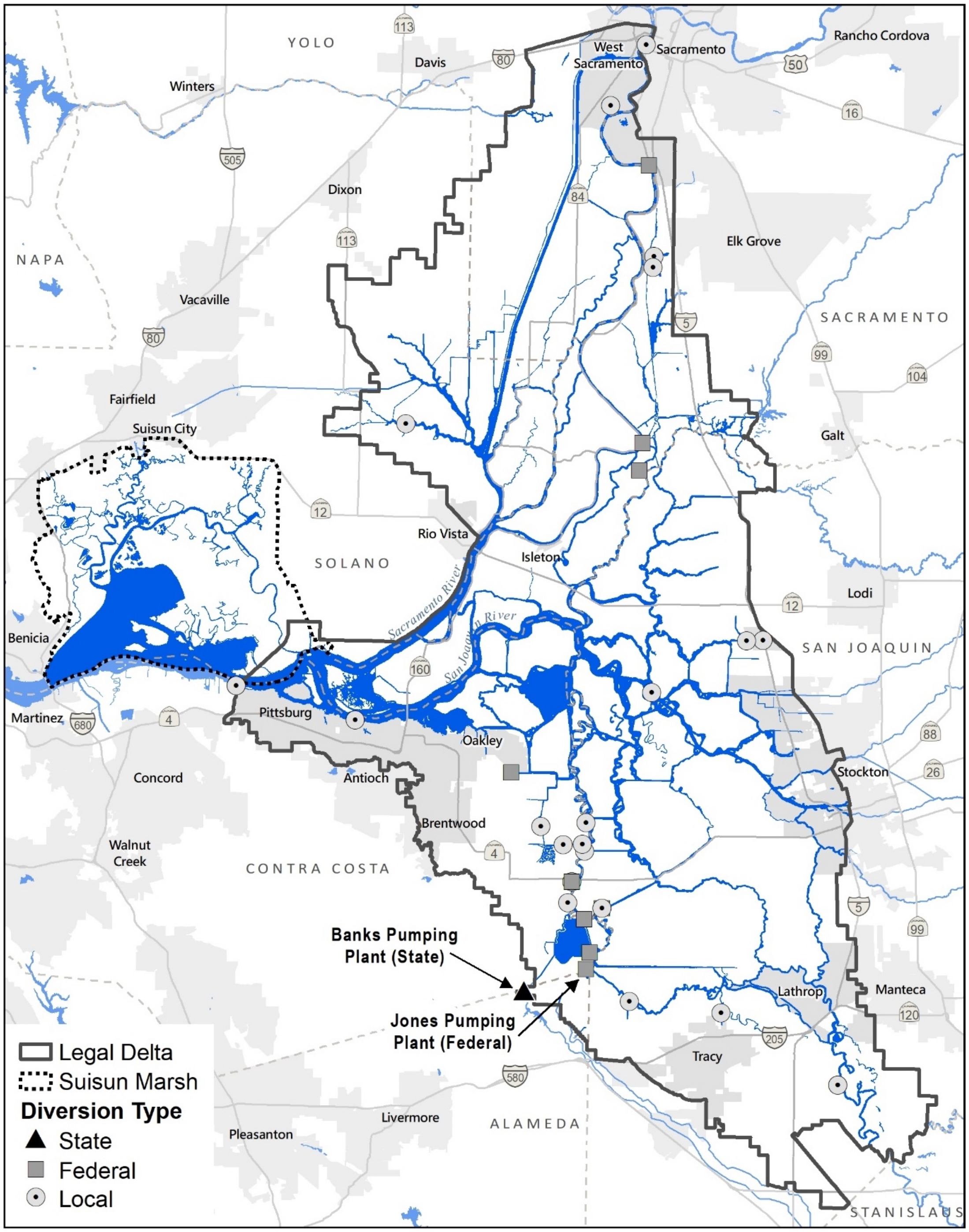


Figure 8: Major points of diversion in the Delta (State, Federal, and Local diverters).

Figure 8 shows a map of the Delta with waterways highlighted in blue and diversion point markers for local (circle), federal (square) and state (triangle) projects. Several water rights overlap spatially at some diversion points, such as to the south of Clifton Court Forebay where a Federal marker and a local one overlap, making it invisible on this map. (Data source: Adapted from eWRIMS 2019).

There are various state laws to protect water rights in and downstream of the Sacramento-San Joaquin Delta and to assure Delta water users that their local water supplies would not be depleted by the operation of the CVP or SWP water supply projects, e.g. Bay-Delta Water Quality Control Plan or D-1641, previously discussed. However, operations of the CVP and SWP also have a side effect of limiting salinity in the Delta, since portions of in-Delta waterways are used for conveyance to the south Delta export facilities, and therefore must be maintained fresh through release of stored water. While no Delta water users have a right to divert stored water, there is also not currently a way to account for potential diversions of this water. In addition to regulatory requirements, there is a contractual requirement between DWR and the North Delta Water Agency (NDWA) as part of a 1981 agreement. This agreement includes a provision that DWR will ensure a dependable water supply of suitable quantity and quality for agriculture use in the north Delta, from where NDWA diverts water, except under drought emergency provisions when the SWRCB's water quality criteria would supersede the requirements of the agreement. The potential impact of climate change on DWR's ability to meet these water quality standards and agreements requires further investigation. If substantial changes were made to the infrastructure and regulatory requirements, salinity could penetrate deeper into the Delta during summer and fall months, especially in drier years, and impact in-Delta water users' ability to divert water.

This assessment does not quantify potential vulnerability of in-Delta water users since modeling uses current regulatory requirements. Modeling up to two feet of sea level rise also projects that in-Delta regulatory requirements can be maintained in most year types.

CHAPTER 7. WATER RIGHTS

Water rights in the Delta are primarily riparian or appropriative. Riparian rights do not specify specific limits in use, other than that any diverted water must be used beneficially on property adjacent to the river course. Appropriative water rights have also been granted for parcels within the Delta, including parcels that have a riparian right. During the 2012-2016 drought the Office of the Delta Water Master, within the SWRCB, began a process to analyze overlapping water rights, and potential duplicative reporting of water diversions. This work remains ongoing.

A 2014 study estimated that appropriative water rights represent approximately 324 MAF of annual water diversions, or around five times the mean annual runoff statewide (Grantham & Viers, 2014). Excluding non-consumptive hydropower allocations, more than 88 MAF are allocated to appropriative rights in the Delta, or approximately three times the average unimpaired flow of the system (DWR 2007, In: Grantham and Viers, 2014).

Climate change projections indicate that changes in hydrology will shift the timing of flows, reducing available water during some periods of the year and increasing water availability at other times of the year. Work by Schwarz et al. (2015) indicates that junior water rights holders in the Delta watershed are likely to be curtailed more frequently and for longer periods in the future due to climate change impacts (A. M. Schwarz, 2015). By midcentury, such curtailments could increase by as much as 20%, rising to 26% above historic levels by the end of the century (Ibid.).

As part of California's Fourth Climate Change Assessment, researchers assessed the potential impacts to water rights and ability of the State Water Resources Control Board (SWRCB) to respond to future conditions (Nylen et al., 2018a, 2018b). The SWRCB keeps records of water rights in the state and arbitrate conflicts on how to allocate water to rights holders during times of scarcity. During past droughts the SWRCB has responded in different ways, partially due to lack of contingency planning (Nylen et al., 2018b). Researchers suggested that ahead of future droughts, the SWRCB could adopt such contingency planning and continue to prioritize water rights enforcement between droughts (among other actions) (Nylen et al., 2018a).

CHAPTER 8. Climate Change Impacts on Statewide and in-Delta Water Supplies

The complex system of watersheds, rivers, reservoirs, levees, pumping plants, regulations, and operations that allow water from the Sacramento and San Joaquin river watersheds to be stored, conveyed, and delivered to meet the needs of California water users is one of the most complex and sophisticated water systems in the world (Ray et al., 2020). Assessing the climate change vulnerability of such a complex system requires integrated modeling of multiple processes. Past modeling studies of the water system, discussed below, have yielded substantial insights for policy-making and public discussion. Each of these studies has involved the use of an integrated set of models to evaluate climate variables such as temperature and precipitation, hydrologic conditions such as streamflow and soil moisture, water system operations such as reservoir storage and water deliveries, and in some cases economic outputs such as the value of water deliveries.

Despite the value of past studies on climate and water supply, there are limitations in fully integrated modeling analyses. Most studies in this area have focused on select variables (e.g., changes in physical climate) while holding other factors static (e.g., existing infrastructure and operating rules). Integrated approaches require very specific assumptions to be made, for example on the magnitude and frequency of atmospheric rivers (if these are modeled at all), on reservoir operational decisions in the future, on drought, and multi-year antecedent conditions. In addition, future projections indicate a potential for more extreme whiplash between periods of drought and extreme precipitation, such as during the 2012-2016 drought, followed by heavy precipitation in 2017, when the Oroville Dam spillway failed during emergency releases. Modeling such specific series of events (multiple dry years, followed by heavy wet years) is not the focus of this or most analyses that have been conducted on water supply. Such an approach would require specific scenarios and assumptions and is beyond the scope of this study.

8.1 Integrated Water System Modeling

Assessing water supply impacts to the Delta cannot be done without consideration of the entire water supply system. Inflows to the Delta are managed and controlled by upstream reservoirs and tuned to meet regulatory requirements in the rivers and in the Delta. Water exports from the Delta are made only after other upstream and in-Delta conditions have been satisfied. Thus, the suite of studies summarized below all employ some form of system operations model that simulates how system operators would manage reservoir storage and releases under a range of climatic and hydrologic conditions specified within each study. CalSim-II, CalSim-III, CalLite, and WEAP are examples of system operations models that have been used in California. In addition, CALVIN, an economic optimization model of California's water system has been used to envision alternative outcomes and water distributions without economically inefficient institutional barriers

8.2 Reservoir Storage Impacts

Constructed surface water reservoirs play an important role in water management. Reservoirs provide both inter- and intra-annual water storage, help attenuate flood flows, provide environmental flow regulation, recreational opportunities, and power generation services. California has approximately 40 million acre-feet of above ground water storage in the form of constructed reservoirs (Department of Water Resources, 2019a). These include major reservoirs that supply the State Water Project (SWP) (e.g., Oroville), Federal facilities (e.g., Shasta, Folsom, Millerton), and hundreds of smaller reservoirs that serve local water agencies and power companies and contribute to downstream flows and subsequent reuse.

California's 40 million acre-feet of above ground storage is a relatively small amount compared to the total runoff of the watersheds feeding those reservoirs. In addition, almost all of California's major reservoirs are multi-purpose reservoirs—providing both water supply and flood protection benefits (among other benefits). Because California's major reservoirs are managed for both water supply and flood protection benefits, reservoir operations often require trade-offs. Between November and March, most reservoirs are managed according to reservoir rule curves. Rule curves specify the minimum storage space or flood accommodation space that must be maintained in a reservoir during the wet season. To meet these requirements, reservoir operators have to release water if reservoir water levels go above the prescribed rule curve-established level. This means that high flows entering reservoirs between November and March often can't be stored for later use during water supply operations in April through October. Many of California's major reservoirs are also managed for other benefits that were not in their original design parameters such as environmental benefits from cold-water pool storage and releases. (A cold-water pool release is intended to maintain adequate quality aquatic habitat for spawning salmonids. For Shasta Reservoir, this requirement was added by the National Marine Fisheries Service (NMFS) 2009 Biological Opinion).

The RAND Corporation prepared a study in 2013 for DWR related to the 2013 Update to the California Water Plan. The study's robust decision making (RDM) approach used performance metrics to quantify the likely performance of the water-management system across multiple scenarios. This study assessed 36 future scenarios, 12 different future climate sequences derived from global climate models combined with three different assumptions of future land use, through the year 2050. The study was a proof of concept and focused on vulnerabilities to urban water supply, agriculture water supply, and frequency of meeting in-stream flow requirements. However, it also highlighted potential vulnerabilities to reservoir volumes. The model also constrained groundwater storage volume to not fall below historic lows of approximately 90 MAF. Using this constraint and other scenario factors, the study found that reservoir values could vary widely, but in many scenarios decreased significantly by mid-century (Figure 3.3, Groves and Bloom, 2013). Modeling of the 36 future scenarios indicated that 15 (38%) were vulnerable to not meeting performance metrics for water supply (Groves and Bloom, 2013).

The U.S. Bureau of Reclamation prepared a climate impact assessment on the Sacramento and San Joaquin basins to assess the risks and impacts of climate change to major Reclamation basins in California (U.S. Bureau of Reclamation, 2016). This study looked at two major uncertainties: climate and socioeconomics, as they relate to future impacts to water supply. The study developed three socioeconomic scenarios (expanded growth, current trends, and slow growth) in combination with a reference climate (no climate change) and five ensemble climate scenarios (18 combinations of socioeconomic conditions and climate conditions). In addition, the study utilized a current trends socioeconomic scenario in combination with twelve Climate Change Technical Advisory Group climate scenarios (12 scenarios). The study found that the seasonal shift of earlier runoff and more precipitation falling as rainfall due to warmer temperatures would have a negative impact on California's reservoirs and therefore water supply. More specifically, the shift and concentration of runoff to earlier in the spring or winter could result in reservoirs filling more quickly at a time when downstream demands are low. Under current reservoir operation criteria (rule curves), reservoirs could be required to spill excess water during these earlier periods to vacate water supply capacity in lieu of flood capacity and be less likely to refill due to less snowmelt later in the spring. In this case, flood risk could increase during the winter and water supply decrease later in the year when demand is greater (U.S. Bureau of Reclamation, 2016). This decrease in water supply reliability was captured using end-of-September storage as an indicator.

End-of-September storage, sometimes called "carryover storage" provides a metric of the amount of water held in storage at the end of the water year as a hedge against dry winter conditions. This study simulated potential end-of-September reservoir storage as compared to a reference no climate change/2006 historic demands socioeconomic scenario, with a focus on how frequently storage was less than the 10th percentile of historic levels. This study found that for reference conditions, end-of-September storage could be less than this value in up to 17% of years for 2040-2069 and up to 13% for 2070-2099. Although somewhat counterintuitive, this change is partially driven by a decrease in agricultural demand caused by an increase in CO_2 concentration and Vapor Pressure Deficit (CVPD). Together, these changes have a marked effect on simulated evapotranspiration and agricultural water demand later in the century (U.S. Bureau of Reclamation, 2016). Across the full range of scenarios throughout the twenty-first century, storage could be less than the 10th percentile of historic level in up to 53% of years in the Sacramento Valley, up to 44% of years in the San Joaquin Valley, and up to 42% of years in the Tulare Lake region. These impacts reflect differences across climate scenarios, as well as differences between these regions. In the best-case scenarios, there is little change from historical conditions, while under other scenarios approximately one-in-two years is below the 10th percentile of historic storage.

Since these two earlier studies, two DWR studies have taken account of newer climate change modeling developed from the Coupled Model Intercomparison Project Phase 5 (CMIP5). Both studies were published in the Fourth California Climate Change Assessment. Wang et al. 2018 Evaluated reservoir storage changes in the four major North of Delta reservoirs: Lake Shasta, Trinity Lake, Lake Oroville, and Folsom Lake. The study determined that despite higher overall precipitation, seasonal runoff shifts, sea level rise, and applied agricultural water demand would all decrease North of Delta reservoir storage (**Figure 9**). The seasonal shift in runoff, due to earlier snowmelt and more precipitation falling as rain, would create the greatest impact on North of Delta reservoirs. This is followed by changes in applied water demand, and additional outflow requirements to repel salinity due to sea level rise. Ultimately, one of the study's conclusions is that North of Delta carryover storage would diminish by 1.5 MAF by the middle of the century under an ensemble mean (Wang, et al, 2018).

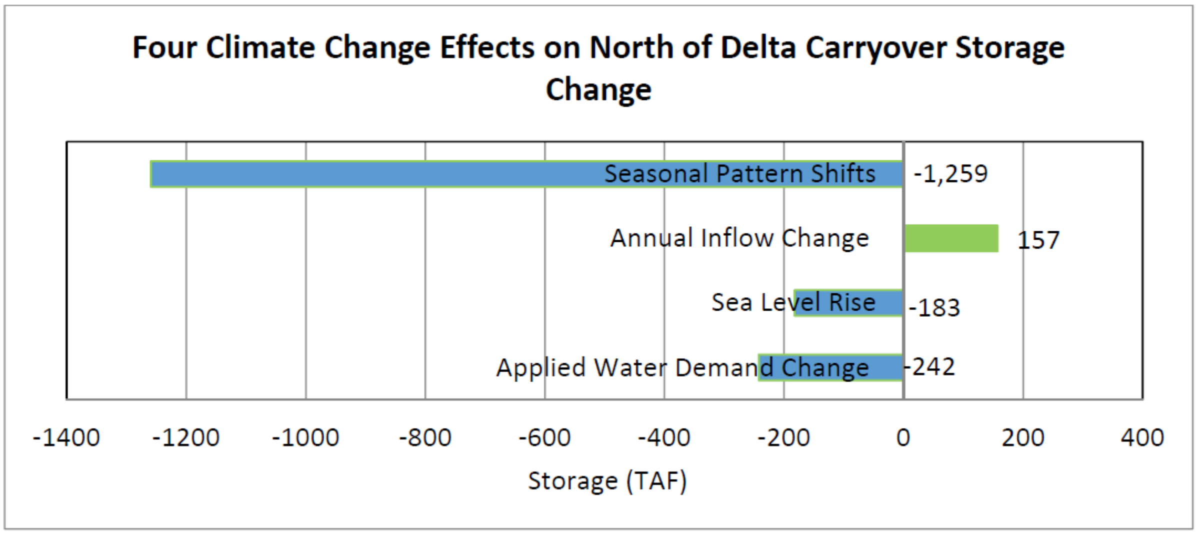


Figure 9: Potential change in north-Delta carryover storage.

Figure 9 shows changes in North of Delta carryover storage from four climate change effects or related impacts. The largest decrease shown above is a decrease in seasonal pattern shifts (-1,259 TAF), followed by applied water demand change (-242 TAF), then sea level rise (-183 TAF). An increase in carryover storage from annual inflow change is shown in green noting a positive change (157 TAF). Source: (Wang et al., 2018).

A study by Schwarz et al. (2018) also assessed water supply and reservoir storage. This study used a bottom-up decision scaling approach to assess how the water supply system may behave under different climatic conditions. The study simulated end-of-April and end-of-September reservoir storage North of Delta under a range of precipitation and temperature combinations. The performance of the water system under these conditions was then combined with the likelihood that such conditions will occur in the future. The study indicates that by 2050 North of Delta storage at the end of April would be most impacted in the driest 25 percent of years falling by about 300,000 acre-feet in those years (**Figure 10**a). North of Delta end of September storage would be impacted to a much greater extent with storage levels falling by around a 1 million acre-feet (roughly 20 percent) in nearly all year types (**Figure 10**b) (A. Schwarz et al., 2018).

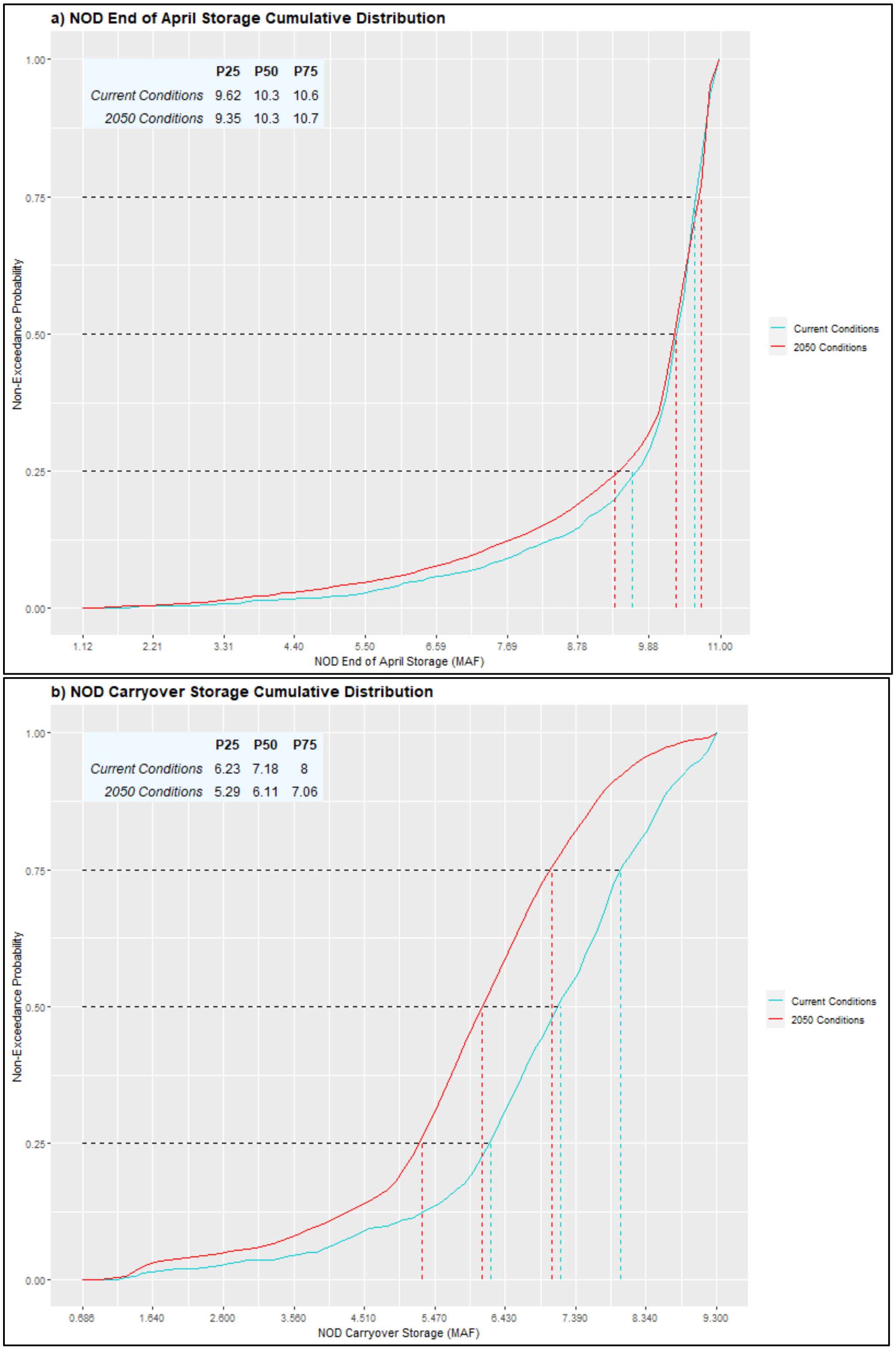
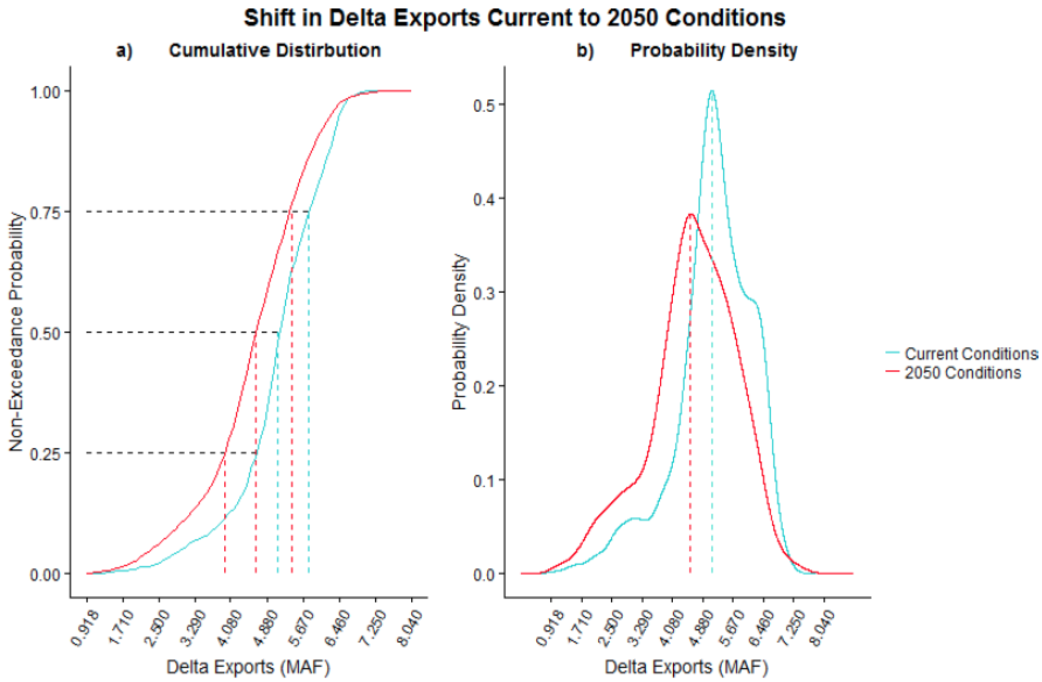


Figure 10 a-b: Projected shift in North of Delta storage for April and September, current to mid-century conditions. NOD = North of Delta, MAF = million acre-feet.

Figure 10 compares cumulative distribution functions (CDFs) for water storage in North-of-Delta reservoirs at two annual time points – April (a) and September, or carryover (b) - based on current (blue lines) and 2050 conditions (red lines). The CDFs show non-exceedance probability throughout the range of storage volumes at each location, which indicate how likely each volume is to occur under those conditions. Source: (Schwarz, et al, 2018).

8.3 Water Delivery Impacts

Water delivery is influenced by the balance of water demands and inter- and intra-annual hydrologic variability that affects supply. Complicating this are salinity impacts, regulatory requirements, and infrastructure capability. Water operations managers work to provide a reliable supply through an integrated system of surface water reservoirs, ground water, and conveyance facilities throughout the State. Studies by Schwarz et al. (2018), Wang et al. (2018), and the U.S. Bureau of Reclamation (2016) have found that sea level rise, combined with changes in hydrology will result in decreases to Delta exports. Of these factors, modeling of future conditions under climate change show that a shift in seasonal flow pattern is a major factor affecting water supply, with sea level rise a secondary factor (A. Schwarz et al., 2018; Wang et al., 2018). Wang et al. (2018) estimated that Delta exports will be reduced by 500,000 acre-feet per year on average. Schwarz et al. (2018) projected similar reductions in Delta exports by midcentury, but additionally found that the most significant reductions in Delta exports would be felt in the driest years—with reductions of 15% (nearly 700,000 acre-feet) coming in the years falling in the lowest quartile (see **Figure 11**).



	P25	P50	P75
Current Conditions	4.63	5.11	5.8
2050 Conditions	3.94	4.63	5.41

	Mode
Current Conditions	5.11
2050 Conditions	4.56

Note: MAF = million acre-feet, taf = thousand acre-feet
The cdf (left) indicates a decrease in median future Delta exports of approximately 500 taf (9 percent) relative to current conditions, with greater (approximately 700 taf or 15 percent) decreases at low flow conditions and relatively lower (approximately 400 taf or 7 percent) decreases at high flow conditions, and the pdf (right) indicates a decrease in the mode of Delta exports of approximately 560 taf or 11 percent.

Figure 11 a-b: Projected Delta exports for current mid-century conditions.

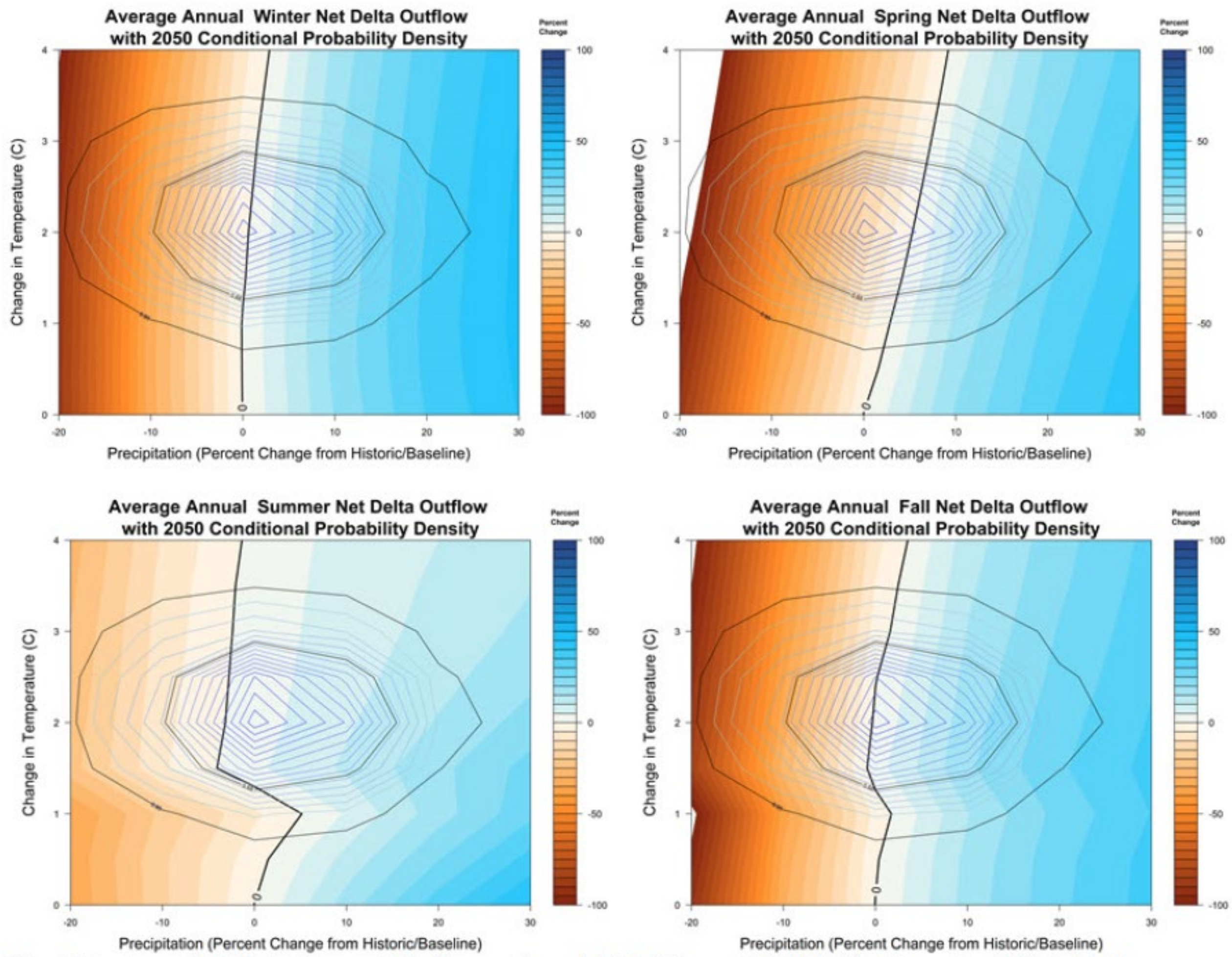
Figure 11 shows modeled changes in Delta exports by midcentury in a cumulative distribution (a, left) and probability density (b, right). Current conditions are represented in blue, 2050 conditions are in red. Both figures indicate that Delta exports will decrease due to climatic factors and become more variable, and decrease the greatest in drier years when the system is already the most constrained (area below the 25th percentile) (A. Schwarz et al., 2018).

8.4 Delta Outflow and Salinity Impacts

In California's highly managed water system, Delta inflows are the result of both upstream flows, and reservoir management. Delta outflows are an important metric because they are used to counteract salinity intrusion during drier periods, are necessary to maintain exports from the South Delta, and have large impacts on habitat conditions within the Bay-Delta estuary. In addition, sea level rise is of critical importance to Delta flows. Increases in sea level drive the need for greater Net Delta Outflow (NDO), or the net amount of water that flows out through the Delta and to San Francisco Bay. Sea level rise is likely to increase the required NDO in order to maintain salinity for in-Delta use and Delta exports to water users. Furthermore, this is likely to occur independent of changes in precipitation patterns, so is more certain to occur and result in increased NDO and decreased exports.

Upstream conditions that influence NDO change throughout the year. Winter NDO is driven primarily by rainfall events and the resulting high flows in rivers flowing into the Delta. Spring NDO is driven by snowmelt and is sensitive to temperature changes that result in changes in spring snowpack conditions. Summer and fall NDO are driven primarily by regulatory and water quality requirements. The impacts of climate changes on summer and fall NDO conditions should be understood in the context of California's regulatory system: regulatory requirements are given high priority, meaning that system operators meet regulatory requirements first, at the expense of other system water demands (Schwarz et al. 2018).

The climate response surfaces below from Schwarz et al 2018 for each seasonal NDO condition indicate that temperature changes have little effect on winter and fall NDO and a relatively weak influence on spring NDO. In the summer NDO response surface (bottom left) and, to a lesser extent, in the fall NDO response surface (bottom right), discontinuities in the system performance at 0.5 °C, 1.0 °C, and 1.5 °C (0.9 °F, 1.8 °F, and 2.7 °F) are evident. These are caused by the implementation of sea level increases in the model. The significant discontinuity between 1.0 °C and 1.5 °C is the result of the shift from a 15 cm sea level rise parameterization to a 45 cm sea level rise parameterization, highlighting the effect of higher sea level on NDO particularly in Summer.



Note: Winter (upper left), Spring (upper right), Summer (lower left), Fall (lower right). Solid black lines show historical values.

Figure 12: Annual average net outflow by season for 2050.

Figure 12 includes four response surfaces showing predicted average annual net Delta outflow for each season based on precipitation and temperature, using 2050 conditional probability density. Vertical black lines show the temperature and precipitation combinations at which no change in performance from historical values would be expected. Areas to the left of the lines indicate performance worse than historical (-100% to 0% change in outflow, in orange color scale), and areas to the right indicate performance better than historical (0% to 100% change in outflow, in blue color scale). Conditional probability density is shown in concentric circles that indicate confidence intervals. With no change in precipitation and an increase of 2 degrees Celsius, performance could be notably worse in the spring (A. Schwarz et al., 2018).

8.5 Shortages and Restrictions

The water management system in California is robust and historically has been able to adapt to 1-2 years of dry and critical conditions. Even during the extended drought of 2012-2016, the water management system was able to adaptively cope and maintain critical water supplies with relatively little economic impact (Howitt et al., 2014; J. R. Lund, 2016; Nelson et al., 2016).

However, extended periods of drought, or multiple periods of drought without full recovery in between, could severely strain the current water management system causing significant economic and societal impacts. One extreme expression of this strain is when reservoirs cannot physically provide outflow or when system operators cannot meet regulatory requirements without risking dead storage or dead pool storage, or the minimum level a reservoir can make available for outflow.

Below dead pool, the reservoir may retain water, but is not accessible due to the elevation of an outlet or pipe intake locations. In reality, reservoir operators will make every effort to avoid such conditions. However, because models often do not include the ability of operators to deviate from rules, modeling results of the water system under stressful conditions often show dead storage occurrences. Analyzing the relative frequency of dead pool occurrences in baseline and simulated future climate conditions can indicate the risk of conditions occurring where not all requirements can be met (Wang et al., 2018). These also may provide a useful proxy metric for when extraordinary management actions might be needed, such as use of Temporary Urgency Change Petitions.

Based on data for 1922 to 2015, a base case scenario used CalSim-III to estimate the occurrence of dead storage conditions. This metric is quantified as dead storage months, or the number of dead storage occurrences system wide across the entire time period. Because there are multiple reservoirs, a single month can have more than one event, i.e. if dead pool conditions occurred in more than one reservoir. Wang et al. (2018) found that for the 94-year historical period, the model simulated 44 instances of dead pool conditions, whereas there were 228 instances of dead storage conditions in simulations under mid-century climate conditions (Wang et al., 2018). This is an increase of 420 percent (Ibid.). Of the SWP and CVP reservoirs modeled, Shasta and Trinity emerged as the most likely to be impacted in terms of dead storage (**Figure 13**), at approximately 80 months cumulative dead storage by mid-century for each. This indicates that it may be much more difficult to meet in-Delta water quality requirements and maintain exports from the south Delta.

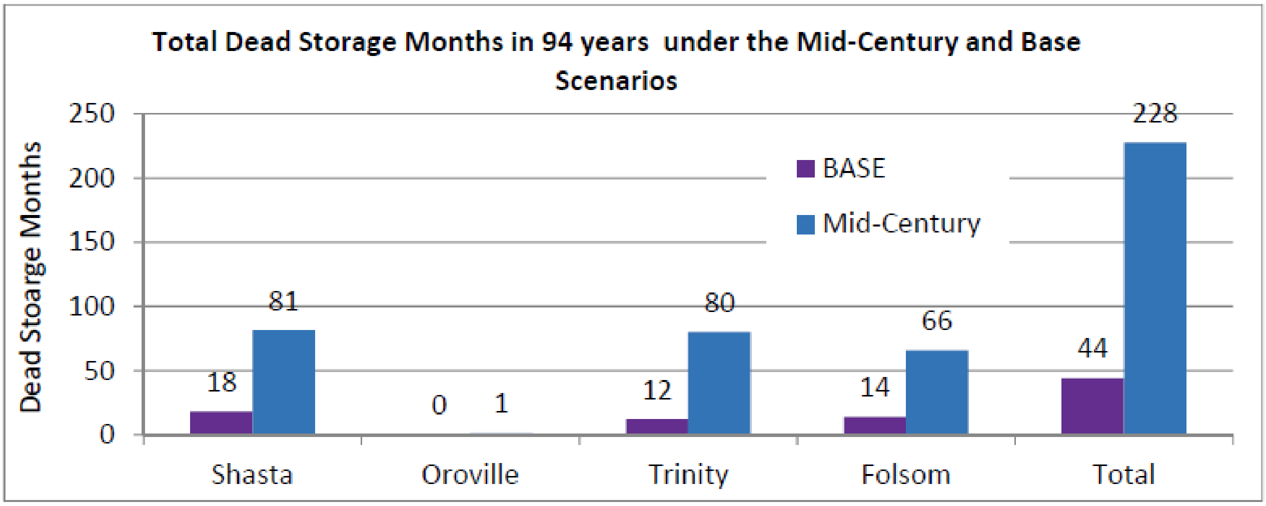


Figure 13.Projected dead-storage occurrence for the Base and Mid-Century Scenarios (Wang, et al, 2018).

Figure 13 shows a bar chart for cumulative months of dead storage over 94 years between base (purple, left) and mid-century (blue, right) at four different reservoir locations and a summed total.

Another way that models can simulate and report these stressed conditions is by using a system shortage metric that tracks when there is not adequate water in the system to be able to meet all system regulations and demands. Historically, such shortages have been relatively rare and short in duration (A. Schwarz et al., 2019). Some of the most recent examples occurred during the drought conditions of 2014 and 2015, when the Department of Water Resources applied for Temporary Urgency Change Petitions (TUCPs) to relax Delta water quality and outflow requirements (A. Schwarz et al., 2019). Work by Schwarz et al. (2018) indicates a probability of 87% that the water supply system will have greater frequencies of shortages by midcentury (Ibid.). Modeling indicates that with warming of each 1°C, shortages may increase by 10,000 acre-feet per year (Ibid.). Modeling further projects that by midcentury there may be little change in precipitation, but a 2°C increase in temperature, which could result in average shortages of closer to 50,000 acre-feet per year (Ibid.).

8.6 Vulnerable Populations

AB 685 (2012) made California the first state to recognize the human right to “safe, clean, affordable, and accessible water for human consumption, cooking, and sanitary purposes” (State Water Policy, 2012). While AB 685 was an important milestone in the effort to ensure safe and affordable water for all, some California residents still lack access to or are unable to afford safe water. This is especially pronounced for small water suppliers, rural communities, disadvantaged communities (DACs) and areas with a higher proportion of vulnerable populations (CDWR, 2020). However, here the term “vulnerable” is used as a general description to describe populations that may be particularly vulnerable to drought, including the above categories.

Droughts can exacerbate existing water quality issues. Communities served by non-public water systems, such as private domestic wells and small water systems with fewer than 15 service connections, tend to be most vulnerable to degraded water quality due to drought because these systems are not regulated or monitored as strictly as public systems (Feinstein et al., 2017). Public health violations in California's public drinking water systems and wastewater utilities are relatively rare, but most of the violations are in small, rural water systems (systems with 15-999 connections) (Hanak et al., 2014). Many small water systems throughout California rely on groundwater, and some of these systems use groundwater that is highly contaminated (*Ibid.*). Some larger community water systems rely on contaminated groundwater as well: out of 3,037 community water systems in California, 265 rely on at least one contaminated groundwater well and violated at least one maximum contaminant level (MCL) between 2002 and 2010 (*Ibid.*). At least eight of these systems are within or partially within the Delta, including both small, rural water systems and systems for cities—including Manteca and Lathrop. A quantitative assessment of the specific vulnerabilities and potential water supply impacts to vulnerable populations is beyond the scope of this assessment. In the sections below, available information related to water supply system characteristics and population vulnerability are discussed to identify how these characteristics can interact to increase water supply risks and impacts.

8.6.1 Risks to Small Water Suppliers and Rural Communities in the Delta

In addition to being at-risk for reliance on contaminated groundwater, small water suppliers and rural (or self-supplied) communities also have particular vulnerabilities to drought and water supply shortages. A 2021 DWR report identified small water suppliers and self-supplied communities most at risk of drought and water supply shortage, incorporating future climate change-related risks (DWR 2021). The report determined risk scores for both small-scale water systems (Figure 14) and census block groups based on their water source (Figure 15) (DWR 2021). The two sets of risk scores range from 0-100 (with a higher score indicating a higher risk level) and were calculated separately using separate indicators and different methodologies. Risk scores are derived from a set of indicators developed from a stakeholder advisory group (County Drought Advisory Group, or CDAG), and represent estimated risk through three components: 1) exposure of suppliers and communities to current and future hazardous conditions and events 2) the physical and social vulnerability of suppliers and communities to the exposure, and 3) recent history of shortage and drought impacts. The social vulnerability indicators include income and poverty levels; percentage of population over age 65; percentage of population 17 years of age or younger; percentage of population 5 years of age or younger; percentage of mobile homes; vehicle access; education level (percentage of population over age 25 with no high school diploma); linguistic isolation; unemployment level; percentage of population that are renters; percentage of population with single parent with children under age 18; and percentage of population living in group quarters (such as correctional facilities, nursing facilities, and other group living facilities). (Many of these indicators are similar to those used in the Council's social vulnerability index used in the vulnerability assessment).

Scores for suppliers and rural communities were evenly distributed throughout the range; the mean and median for small water supplier scores were 55, and the mean and median for self-supplied communities were 42, indicating that both sets of scores have a normal distribution.

Relative to the State as a whole, most of the Delta's small water suppliers and self-supplied communities appear to be at lower risk of drought and water shortages. The Delta has one hundred twenty-nine of the 4,572 small water suppliers identified in California, with an average risk score of 55.99. Thirty-eight of these suppliers are in the top fifty percent for risk statewide, and six have a score above seventy, falling in the top eleven percent for risk statewide (labeled in Figure 14). Five of the six small water suppliers in the Delta with risk scores above 70 are located in Contra Costa County. Twelve out of California's fifty-eight counties contain one or more census block groups with a risk score higher than 90. The ten counties with the most at-risk block groups are all outside of the Delta: Tulare (2 block groups with risk scores >90), Fresno (1), Del Norte (1), Kern (3), Merced (1), Riverside (1), Stanislaus (1), Mendocino (1), Kings (1) and Madera (1). Out of the five Delta counties, Solano County has the most block groups with high risk scores (Figure 15).

The DWR report emphasizes that scores below the top 10 percent do not mean that a community is not at risk, as all communities in California are susceptible to drought and supply shortages to some extent, but that these regions should prioritize adaptation action. DWR recommends that small water suppliers (serving 15 to 2,999 service connections) and rural communities (defined as having fewer than 15 service connections) develop emergency response plans and a drought supply evaluation, as well as drought and water shortage contingency plans (CDWR, 2020).

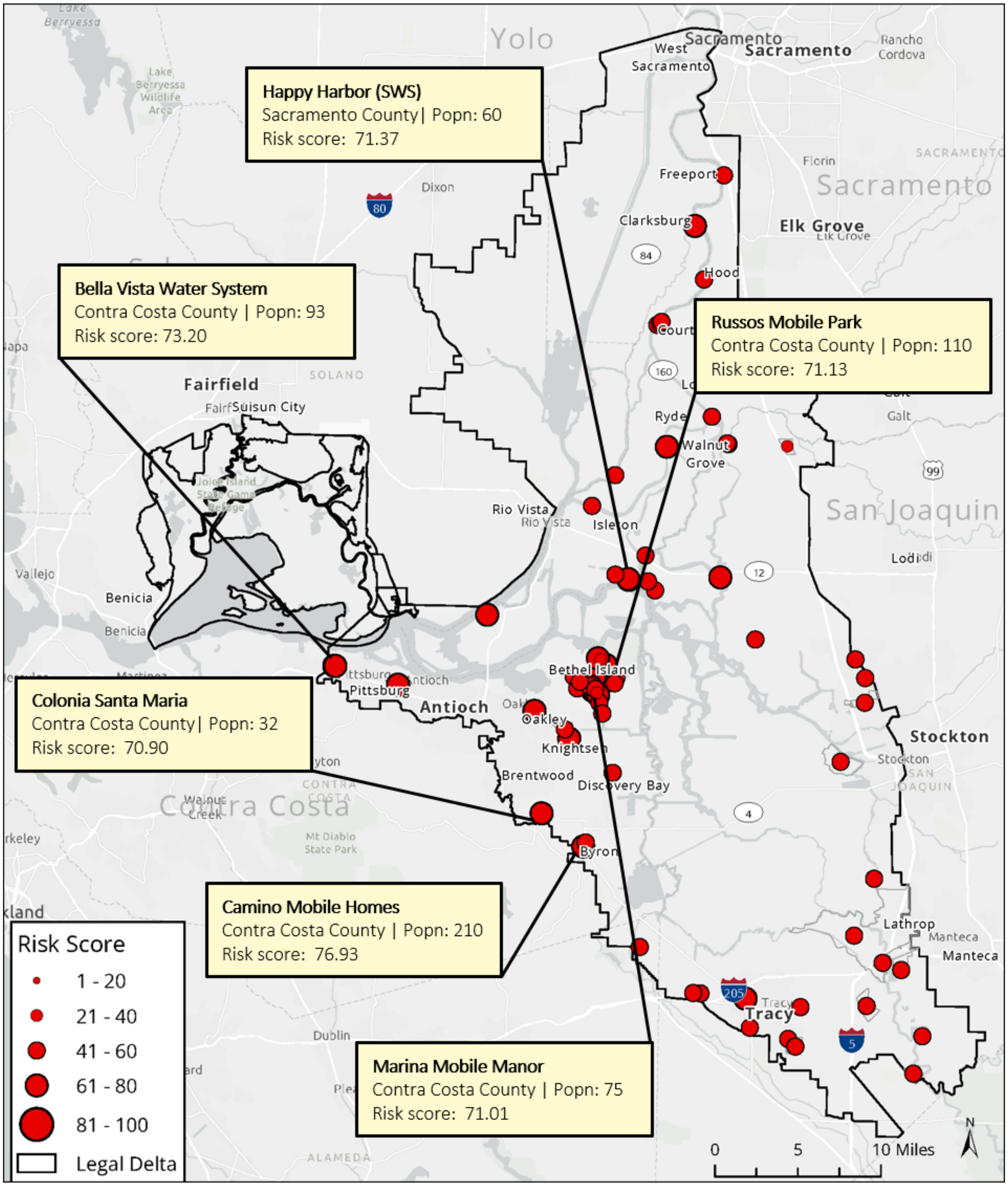


Figure 14: Map of the Delta where small water suppliers are indicated with red circles proportional in size to risk scores.

Six of the small water suppliers in the Delta have a score above seventy, falling in the top eleven percent for risk statewide. These six small water suppliers are labeled with the supplier name, location, population served, and risk score. These suppliers provide water to approximately 580 people in the Delta. Water system boundary data were last updated on October 29, 2020 (SWRCB, 2020).

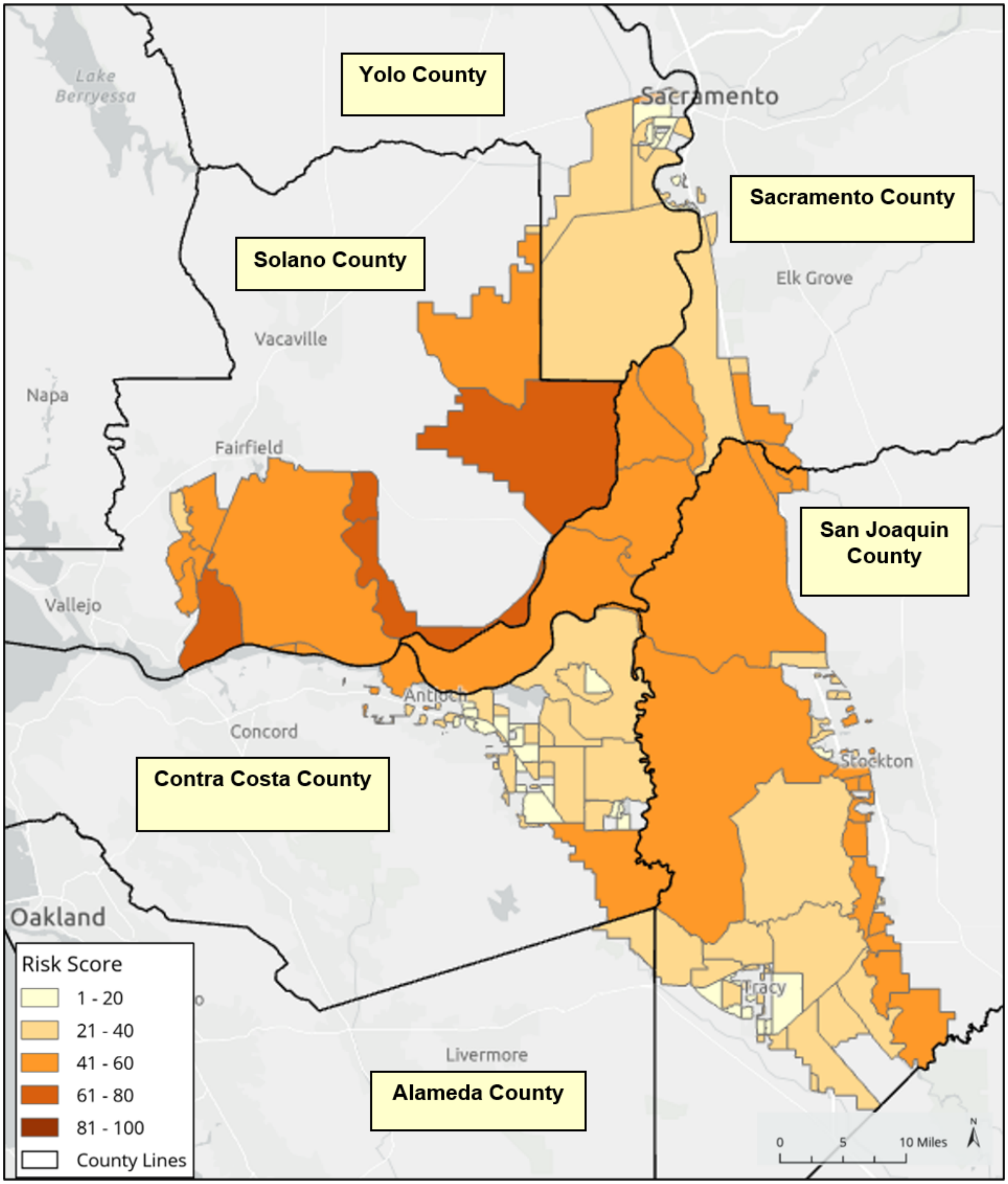


Figure 15: Drought and water shortage risk scores for self-supplied/rural communities within the Legal Delta and Suisun Marsh.

Figure 15 shows census block regions within the Delta boundaries that are colorized based on risk score. County boundaries are also indicated and labeled. All Delta counties except Sacramento County contain at least one block group scoring in the top ten percent of at-risk census block groups in the state. Of the 242 block groups in the top ten percent statewide, there are two in San Joaquin County, two in Contra

Costa County, four in Solano County, three in Alameda County, and two in Yolo County. This map omits census block groups with no residents and those with no records for domestic wells (SWRCB, 2020).

8.6.2 Disadvantaged Unincorporated Communities

As part of the effort to address drinking water contamination issues, there is a push to consolidate small water systems with larger systems. In California more than one hundred such consolidations have already taken place or are ongoing (Nylen et al., 2018b). Various California laws encourage water system consolidation, including SB 244 (2011)—which requires cities, counties, and local agency formation commissions to identify and plan for providing infrastructure and services to disadvantaged unincorporated communities (DUCs) —and SB 88 (2015), which gives the SWRCB the authority to mandate certain water system consolidations when a water system "consistently fails to provide an adequate supply of safe drinking water" (SB 88, 2015, p. 88; SB 244 - Disadvantaged Unincorporated Communities, 2011, p. 244).

While connecting DUCs to systems with safer drinking water supplies is an environmental justice priority, connecting to existing water systems that rely on exports from the Delta could increase water demand and reliance on the Delta. Under current Delta Plan regulations, water system consolidations that increase reliance on Delta water supplies could be inconsistent with Delta Plan policy WR P1, which requires reduced reliance on Delta water through improved regional water self-reliance (Reduce Reliance on the Delta through Improved Regional Water Self-Reliance, 2013). These two state goals have the potential to conflict irrespective of climate change; however, climate change may cause longer, more intense periods of drought, increasing the urgency to connect DUCs as well as to reduce reliance on Delta water supplies.

Consolidation can also present high up-front costs, serving as a potential barrier (US Water Alliance & UNC Environmental Finance Center, 2019). In some cases, receiving systems have charged excessive rates to customers of the incorporated system, charging rates that are 150% of rates charged to existing customers (Nylen et al., 2018b). Low-income households may not be unable to afford these rate increases.

8.6.3 Drinking Water Affordability

Drinking water affordability is one of the tenets of human right to water, but is already a challenge for many low-income households in California. Much of the state's water supply infrastructure is old, with extensive deferred maintenance (Hanak et al., 2014), and utilities will likely need to increase rates to repair, rehabilitate, and upgrade their systems. Climate change, along with other factors, will compound this need (*Ibid*).

Climate change will increase the risk of drought in California (Diffenbaugh et al., 2015) and droughts can cause the cost of water to go up (Feinstein et al., 2017). In the short-term, drought can increase water rates because water utilities may have to enact temporary drought charges to cover the costs when mandatory or voluntary restrictions lead to declining water use (*Ibid*). Longer-term, utilities are weighing options to adapt to increased frequency and intensity of droughts by diversifying their water supply portfolios, purchasing or developing costlier water, or pumping groundwater from greater depths (*Ibid*). Increased frequency of droughts may also cause toxic algal blooms and degrade raw water quality, affecting raw water supplies and requiring upgraded drinking water treatment systems.

Climate change may raise costs of water supply in other ways as well. Increased temperatures in summer months can decrease the quality of raw water supplies, necessitating new drinking water treatment systems to continue meeting state and federal standards. As described in section 3.3 above, sea level rise will require additional water releases from upstream dams in order to maintain X2, which could further necessitate diversification of raw water supplies for utilities that depend on Delta water. For example, the City of Antioch has proposed building a desalination plant so that it can draw water directly from the San Joaquin River even when salinity in the river exceeds allowable drinking water levels.

8.6.4 Vulnerable Populations Outside of the Delta

Reduced water supplies from the Delta due to climate change will likely also have impacts on vulnerable populations outside of the Delta. The Crop Yield and Agricultural Production Technical Memorandum discusses potential impacts of reduced Delta water exports on the agricultural economy of the Central Valley, which depends in large part on Delta water. Negative impacts to the agricultural economy would especially impact rural, low-income communities, including migrant farmworkers (Gowda et al., 2018). As discussed above in section 8.7.3, climate change may exacerbate existing water affordability issues by leading to increased water rates charged by utilities for a variety of reasons. In addition to the rising water supply costs discussed above, urban agencies that use CVP and SWP exports may experience economic losses as a result of reductions in Delta exports due to climate change (see section 5.4.3.1 of the vulnerability assessment, Delta Exports), which could further increase water supply costs. Without programs to mitigate these costs, increased water rates charged by these urban water agencies would especially impact low-income ratepayers.

CHAPTER 9. WATER YEAR TYPING AND WATER SUPPLY OPERATIONS

9.1 Water year typing methodology

In California, water supply conditions are described by water year and water year type. The water year runs from October 1 to September 30. This convention maintains the grouping of the wet parts of the year (October-April) in the same water year. Thus, water year 2020 includes the last three months of calendar year 2019 to capture early winter precipitation that would contribute to conditions later in 2020. DWR also characterizes each water year by one of five water year types, as quantified by an index of unimpaired runoff. From the highest to lowest runoff, these include: Wet, Above Normal, Below Normal, Dry, and Critical. This index can be calculated for – and differ between – the Sacramento Valley and San Joaquin Valley (four river indices), as well as for the Central Valley as a whole (eight river index), and for other individual basins throughout California that have their own water year classifications and calculation methodologies. The eight-river index is used for defining water year types as relevant to the Bay-Delta Water Quality Control Plan. The specific definitions for each water year type were first defined in the 1995 SWRCB Bay-Delta Water Quality Control Plan. The definition of water year type is important because it dictates the regulatory flow requirements for portions of the year as described in SWRCB D-1641 Bay-Delta Water Quality Control Plan that affect water supply.

Water supply operations in the Delta and throughout the Delta watershed are most directly regulated by the Bay-Delta Water Quality Control Plan (D-1641) and requirements established by the 2019 Biological Opinions and 2020 California Endangered species Act incidental take permit for long-term operations of the State Water Project. D-1641 includes water quality objectives that apply throughout the year (SWRCB, 2000). Water quality objectives for municipal and industrial beneficial uses include mean chloride requirements that differ by water year type and compliance location. In addition, for a combination of five identified compliance locations the standards apply during all water year types and throughout the year. Similarly, water quality objectives (electrical conductivity) for agricultural beneficial uses differ by compliance location and water year type, as well as unit (e.g. maximum 14-day running average of mean daily electrical conductivity). Select units apply to all water year types, for portions of the year. It should be noted that the SWRCB is reviewing a potential change to agricultural water quality objectives (for more specifics, see SWRCB 2000, pp. 183-87).

Flow objectives for fisheries protection are required year-round but vary by month. During January through June, flow requirements differ by the eight-river index. For July through December, the flow requirements depend on the water year type classification (SWRCB 2000, pp. 183-87).

Water exports are generally more limited during below normal, dry, and most especially critical water year types, especially during the Fall months. Although the specific impact also differs by antecedent conditions, such as reservoir storage, south of Delta export operations have historically been most negatively affected by multiple years of drier conditions, and in critical years. In-Delta water supply operations have been relatively spared because the water projects must meet D-1641 flow and water quality objectives, unless granted specific exemption through a Temporary Urgency Change Petition.

9.2 Future adaptations to water year typing

Categorizing water years into similar types was developed to aid management decisions and simplify complex hydrology into a numerical index. Two indices used in the Delta region, the Sacramento Valley Index (SVI) and the San Joaquin Valley Index (SJI), classify years into five categories (mentioned above) by comparing runoff in the current year to average historical runoff (Null & Viers, 2013). Water year types determined by these indices form the basis for determining regulatory requirements (as described above), which then influence how much water will be allocated to exports via the State Water Project (SWP) and Central Valley Project (CVP), agricultural uses and environmental flow objectives. The simplification of this complex system means that there are inherent limitations in water year typing. One of these limitations is the fact that the classification thresholds were developed under the assumption of a stationary climate. Therefore, as the timing and amount of runoff change in response to warming conditions, the relative frequency of occurrence of each water year type will change. This will cause a deviation from the original water year type distribution and potentially change the meaning and application of this classification scheme.

Null and Viers (2013) found that when modeling water year indices under climate change conditions, the distribution of water year types changed over time. By the end of the century, projections indicate that the distribution of water year types will shift with more years classified as critical in both the SVI and SJI (**Figure** 16). This would in turn change the management of the system because more years would be managed under requirements for critical years changing the distribution of impacts and the burden of climate-driven water scarcity among water uses. A disproportionate amount of this burden would fall on environmental flows. Null and Viers (2013) conclude that under more persistently dry conditions, the Delta watershed would fail to provide adequate baseflow and hydrologic variability required to support ecosystems. Arnold et al. 2019, conducted similar analyses of shifting climate conditions on water year type distribution and found similar results (Arnold et al., 2019).

Because water year type classifications are so important for setting management constraints that impact water allocations, adapting these frameworks to climate change is important for anticipating and managing climate change impacts. Null and Viers (2013) suggest adjusting water year type thresholds based on changing flow regimes to maintain historical water year type distributions (**Figure 17**). This would not make more water available, but would influence management regimes and maintain the distribution of water scarcity burdens across potential future conditions.

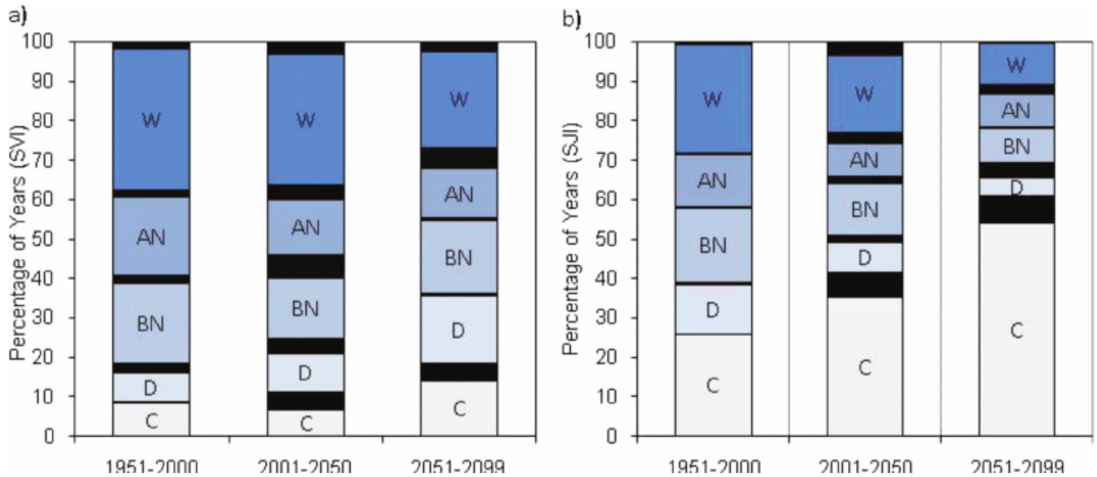


Figure 16 a-b. Modeled distribution of water year types using historical thresholds.

Figure 16 compares the difference in the percentage of water years of each type between using the SVI (a) and the SJI (b) with historical thresholds. Five water year types are shown (C = critically dry, D = dry, BN = below normal, AN = above normal, W = wet) for each time period, with the height of each segment corresponding to the percentage of years categorized as that type. Water year type is colorized from light blue (C) to dark blue (W), and black bands show uncertainty between estimates. An increase in the proportion of critical years and decrease in the proportion of wet years is visible over time from the historical to future period through 2100 (Null and Viers, 2013).

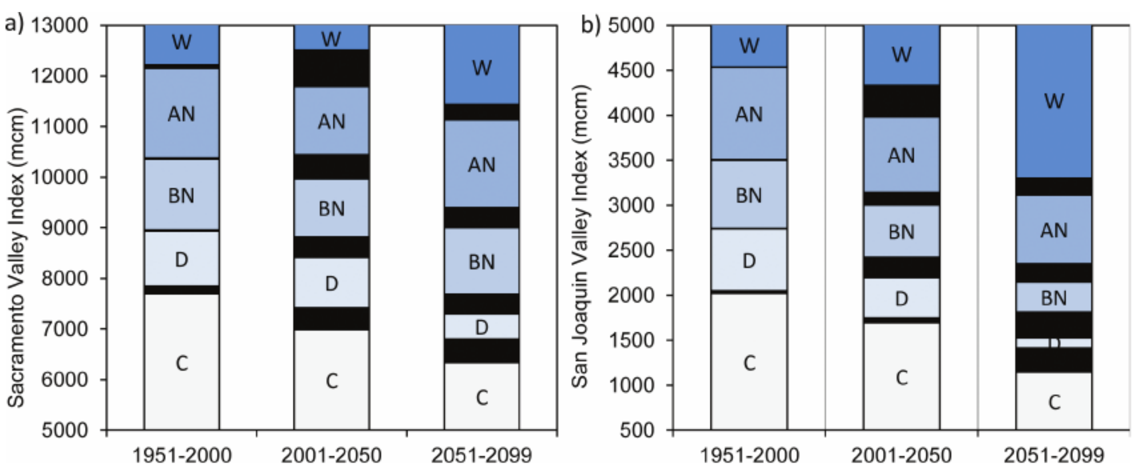


Figure 17 a-b. Modeled change to water year classification thresholds using historical percentages of years per category.

Figure 17 compares the difference in the percentage of water years of each type between using the SVI (a) and SJI (b) with historical percentages of years per category. Five water year types are shown (C = critically dry, D = dry, BN = below normal, AN = above normal, W = wet) for each time period, with the height of each segment corresponding to the percentage of years categorized as that type. Water year type is colorized from light blue (C) to dark blue (W), and black bands show uncertainty between estimates. For future periods, changing thresholds would result in a wider range for years to be considered wet and a smaller range to be considered critical (Note scale change between figures).

CHAPTER 10. DATA AND KNOWLEDGE GAPS

This synthesis has provided an overview of relevant research conducted to date and highlighted that the Delta watershed has been the focus of substantial research on climate and water resources. In addition, ongoing research will continue to refine and improve our understanding of climate change impacts on Delta water supplies. Based on the science synthesis provided above, the Council has identified key data gaps that should be prioritized to better assess the potential water supply impacts of climate change in the intermediate (mid-century) and longer term (year 2100). Key data gaps for Delta water supply include:

- Evaluation of Delta water operations with sea level rise conditions above 1.5 feet, extending up to the point at which changes to current operations and regulations may be required.
- Evaluation of the impacts of changes in inter-annual variability of precipitation that are de-coupled from changes in mean annual precipitation.
- Better integration of surface water and groundwater interactions in water operations modeling and accurate characterization of future groundwater management actions.
- Better integration of water supply and flood modeling throughout the Central Valley water system, allowing analysis of climate change adaptation strategies for managing the loss of snowpack and more extreme winter flow events.
- Extension of Delta levee failure analyses to evaluate the additional impacts to water supplies if the geometry and hydrodynamics of the Delta were altered by levee failures that were not repaired.
- Evaluation of cascading water system and flood infrastructure vulnerabilities and failures. Climate change will place greater stress on water management infrastructure that provides multiple benefits such as reservoirs that serve water supply and flood protection purposes. A failure of flood protection infrastructure could have cascading impacts to the water supply system and aquatic ecosystems that have rarely been explored in an integrated manner.
- Exploration of the use of water-year typing in California to categorize hydrologic conditions and inform regulatory constraints on water management operations and Delta conditions. Climate change is likely to significantly shift the distribution of water year types in California potentially changing the frequency and distribution of regulatory constraints (Arnold et al., 2019) (Null and Viers, 2013).

- Scenario-based consideration of multiple, cascading stressors and cumulative impacts. For example, multi-year droughts followed by years with increased atmospheric intensity and extreme flooding, decreased reservoir storage due to drought and flood buffer requirements, levee failures, and sea level rise.

Chapter 11. Policy and Management Questions

New analyses conducted for the Delta Adapts project cannot fill all data and knowledge gaps identified above. The Council, in consultation with its Technical Advisory Committee, has selected a limited set of policy and management questions to guide the new analyses conducted for this project. The analyses conducted to address each management question are intended to incrementally improve our knowledge and understanding of Delta water supply vulnerability to climate change; can be conducted with existing resources, tools, and data; build on the work of previous research by the academy and state agencies; and can provide policy and decision relevant information to inform Delta climate change adaptation strategies.

1. **What are the impacts to the water supply system of sea level rise greater than 1.5 feet (45cm)?**

   Past integrated modeling of the Delta water supply system that includes projections of sea level rise has been limited to an increase in sea level of 45 cm (1.5 feet). This study expands the analysis conducted by Schwarz et al. (2018) by adding 30 cm (1 foot) and 60 cm (2 foot) sea level rise scenarios in addition to use of refined scenarios of 0, 15 cm (6 inches), and 45 cm (1.5 foot) that were previously evaluated. The analysis completed for this project adjusts the sea level rise implementation scheme used by Schwarz et al. (2018) and Selmon et al. (2019) to include the additional increments of sea level rise, thus providing a higher resolution treatment of sea level rise impacts and a higher upper bound of sea level rise. This additional analysis represents the deployment of all of the available sea level rise scenarios configured to work with CalSim-III and CalLite.

2. **How sensitive is the Delta water supply system to projected changes in the interannual variability of California precipitation?**

   The approach and analysis conducted by Schwarz et al., 2018, (Selmon et al., 2019) explored a wide range of hydrologic interannual variability by using an 1,100 year paleo reconstruction of streamflow. While this represented one of the largest explorations of historical interannual variability ever conducted for the Delta water supply system, it did not explore potential changes in interannual variability outside of the historical range. Because of the growing evidence suggesting that climate change may result in changes to California's precipitation variability, this analysis replaces the perturbation of the amount of annual amount of precipitation projected with climate change with a perturbation of interannual variability of precipitation projected with climate change to explore water supply impacts driven by changes in the interannual variability of precipitation. This analysis differs from previous analyses that have evaluated downscaled GCM projections that indicate greater interannual variability because it will explore interannual variability change independent of changes in average annual precipitation, temperature, and sea level rise.

3. Of the key climate stressors to the water supply system, which drive system vulnerability and which might be most important to monitor to identify observable changes?

   Because projections of climate change provide significant ranges of potential changes for each climate change stressor (temperature, precipitation change, and sea level rise), and both the amount of change and rate of change in these stressor may differ, understanding which stressor or stressors the Delta water supply system is most sensitive to provides important insight into which changes would cause the most impact and provide important information for monitoring and potential adaptation investments. The analyses conducted for this study evaluates and summarizes water supply changes that would result from changes in any one of the following variables with no change in any of the other variables: increases in temperature, increases in sea level rise, changes in the amount of precipitation, and changes in the variability of precipitation.

CHAPTER 12. DELTA ADAPTS WATER SUPPLY ANALYSIS METHODS

12.1 Water Supply Performance Metrics

For this study, we have selected a limited set of system performance metrics to gauge the impacts of climate stressors on the water supply system. Performance metrics are quantifiable conditions that provide information about how the managed water supply system is performing relative to a quantified baseline condition. Each of the metrics provide information about a different part of the water supply system that may be of specific interest to groups of stakeholders as noted below. In addition, climate changes have different impacts on the system depending upon which performance metric is being considered.

Delta Exports

Delta exports provide a measure of water supply available to south of Delta water users. When defining “Delta water supply” as an asset, this performance metric provides information about the portion of that asset that is exported from the Delta, in-Delta water supplies make up the balance of this asset class.

North of Delta Storage

North of Delta (NOD) storage includes the major storage reservoirs of the SWP and CVP including, Lake Shasta, Lake Oroville, Folsom Lake, and Trinity Lake. Storage volumes fluctuate throughout the year but two points during the year are traditionally used to gauge storage. April storage values provide a measure of stored water at the end of the runoff season, when winter rains are largely finished, and reservoirs begin to release more water than is entering the reservoirs from upstream. This metric is important for water deliveries and reservoir releases for environmental purposes. End of September storage, also called carryover storage, provides a measure of the amount of water in storage at the end of the irrigation season and before winter rains begin. This metric is helpful for understanding the amount of water storage that is being carried from one year to the next and provides an important hedge against dry winters and longer-term droughts. Carryover storage is also important for downstream river water temperature control for salmonid rearing and survival conditions. Each metric shows very different sensitivity to climate factors

System Shortages

System shortages provide a mechanism for the modeled system to account for conditions in which there is not enough water in the system to meet all required conditions. CalLite, the model used in this analysis, uses a complex algorithm based on real world operations to make decisions about when water is stored or released from reservoirs, how much water is delivered to contractors, and how much should flow out to the ocean. CalLite uses a system of constraints and penalties to weigh tradeoffs between these decisions. At every time step, the model attempts to meet all constraints and minimize penalties. Similar to conditions during a drought in the real system, the model is often not able to meet all constraints at all times, such as temperature control operations at upstream reservoirs. When a constraint must be relaxed, the model tracks the amount of water that would have been needed to meet the constraint—this is called a shortage. In the real world, operators usually see potential shortage conditions coming and can apply for a Temporary Urgency Change Petition from the Water Resources Control Board—allowing the regulatory restriction to be relaxed for a defined period of time and to a pre-defined level. These real-world decisions weigh political and economic considerations that cannot be simulated. Thus, the shortage accounting in CalLite provides a proxy for these real-world conditions. The frequency of shortages indicates how often such conditions might occur, and the size of the shortage indicates the severity of the condition and the complexity of the tradeoffs that would need to be considered. Because shortage conditions may also result in relaxations of the Delta water quality standards and could result in periods of increased salinity in the Delta, larger shortages may also serve as a useful proxy for periods of reduced in-Delta water supply availability. Minor shortages often occur in parts of the system for short durations and would have limited impacts. As such, a threshold of 50,000 acre-feet per month was used to screen out minor shortages.

12.2 Delta Water Supply System Exposure

Delta water supplies are exposed to changing climate conditions in multiple ways. In the watersheds that flow into the Delta, higher temperatures and changes in precipitation are expected to change streamflows, snowpack, and runoff available for capture in reservoirs. In the Delta, freshwater inflows interact in the Delta's complex channels and sloughs and are influenced by diversions, return flows, sea level, and tides. Throughout the areas that rely on water exported from the Delta, demand for Delta water supplies will be affected by higher temperatures and changing precipitation. Exposure to climate change for these areas has been estimated using data from an ensemble of 36 projections from the Coupled Model Inter-comparison Project Phase 5 (CMIP5) to develop probabilistic climate information. The ensemble of models indicates a range of future outcomes in temperature and precipitation (Figure 18 and Figure 19).

Using the CMIP5 ensemble, the relative likelihood (probability density) of each climate state was calculated. This was done by:

1. Calculating the future mean change in standard deviation of precipitation and mean change in temperature for each climate projection[1] as the difference between a baseline condition (1981-2010) and 30-year rolling time horizons 2036-2065 shown in **Figure 18**.

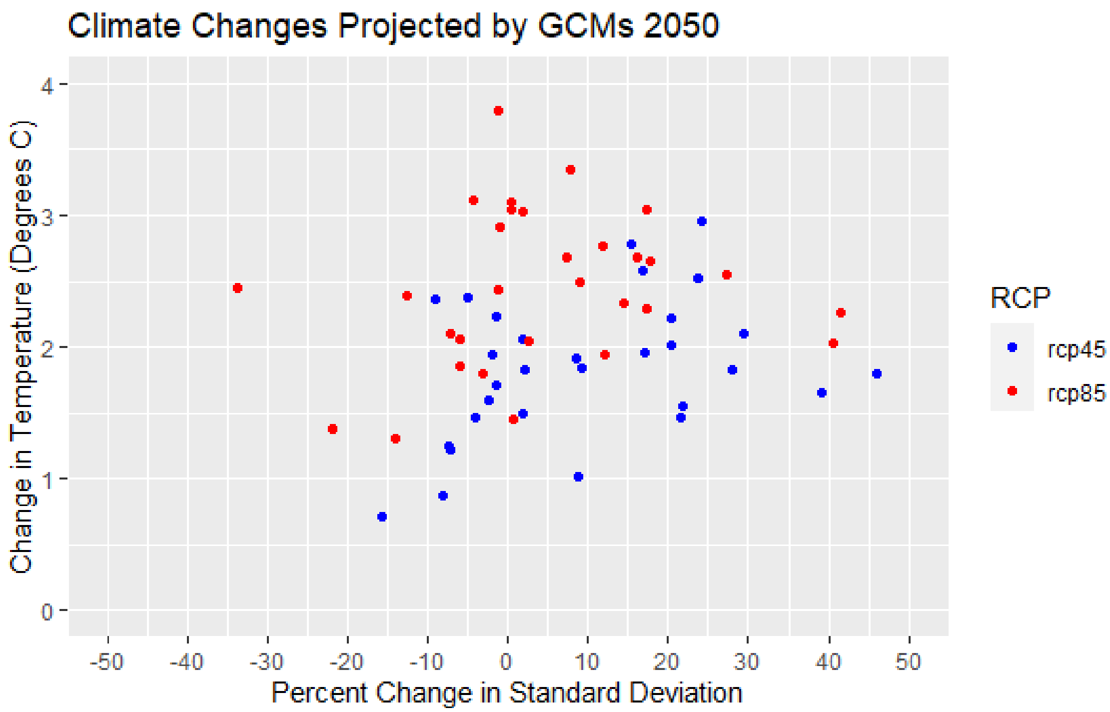


Figure 18: Projected change in average temperature and standard deviation of precipitation over Delta watershed area by 2050.

Blue dots show CMIP5 GCMs run with RCP4.5, red dots show CMIP5 GCMs run with RCP8.5.

2. Mean changes from the full ensemble of GCMs were then reduced to 24 data points (12 data points for each RCP) to account for potential sampling biases because of the structural similarities in GCMs (Knutti, Masson, & Gettelman, 2013). In so doing, all model

[1] In the design of this study, the decision was made to include as much information from the CMIP5 archive as possible, relying on the assumption that because we want to stress test the system we should consider the widest possible range of potential climate changes. Thus, we have not employed any method of model selection, weighting, or culling. Previous efforts using similar approaches (e.g., Schwarz et al. 2018) have analyzed the sensitivity of results to this assumption versus using an alternative culled set of GCM's (CCTAG, 2010) and shown that the differences in the results are small relative to other uncertainties and the range of potential outcomes. Full results of our analysis using the 10-model ensemble suggested by CCTAG are available upon request.

runs were weighted equally and combined by arithmetic averaging within each model group[2].

3. The computed 24 data points were used to define a probability density function (PDF) following the methodology used by Whateley, Steinschneider, and Brown (2014).
4. The Gaussian PDF was used to obtain the contingent normalized probability weights of the 88 plausible mean temperature and standard deviation of precipitation changes, hereafter referred to as the GCM-informed PDF.

Similar approaches have been taken by others ((Ray et al. 2020); (Selman et al. 2019); Schwarz et al 2018); (Borgomeo, Farmer, & Hall, 2015); (Steinschneider, McCrary, Mearns, & Brown, 2015); (Tebaldi, 2005)).

Figure 19 shows the GCM-informed PDF for climate change (temperature and precipitation) at 2050 over the Delta watershed area. By expressing the range of climate changes in the future as probabilistic possibilities, one can get a deeper understanding of the range of potential exposures and the likelihood of experiencing those levels of exposure.

[2] Knutti et al (2013) demonstrate that many of the individual GCM's submitted to the CMIP5 archive are not truly independent, but rather exchange ideas and code with other models. This results in the GCMs lacking true independent from each other. The grouping of GCMs into "families", helps reduce the over-weighting of model outputs that are derived from similar codes that have been embedded in multiple models.

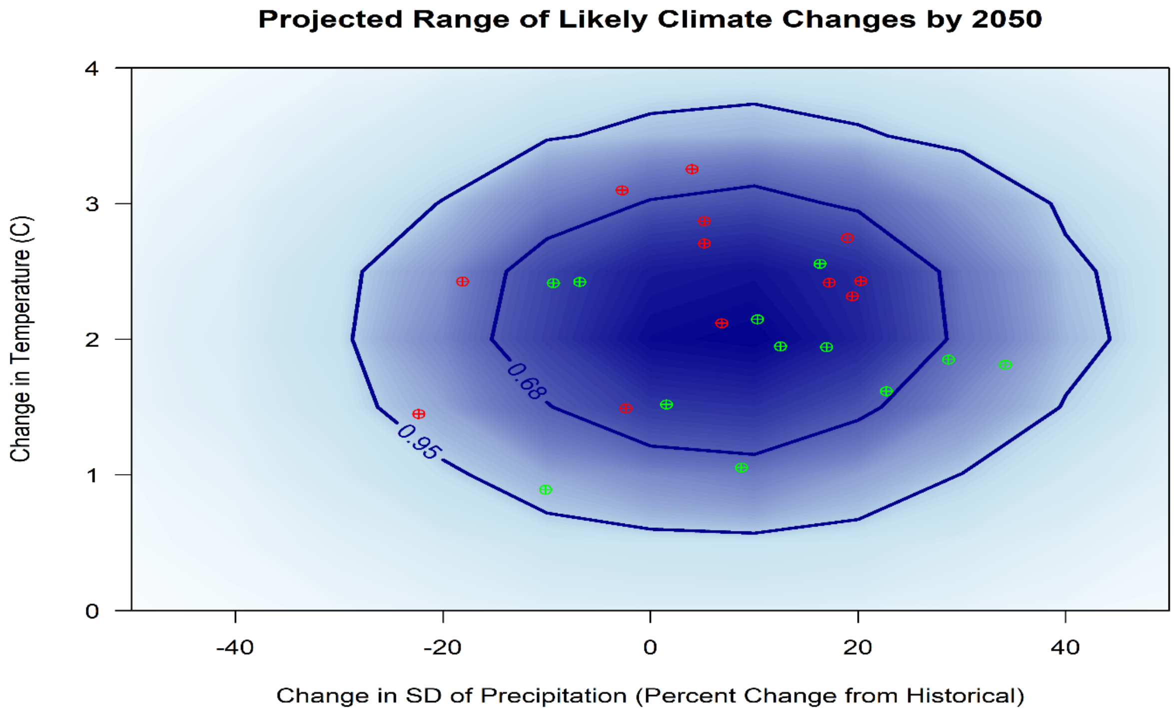


Figure 19: GCM-informed PDF for climate change (temperature and precipitation) at 2050 over the Delta watershed area.

Deeper blue colors toward the center represent greater model agreement and therefore a higher probability of climate states in that region of the figure. Lighter blue colors represent future conditions projected by fewer models but still considered possible. Green dots show CMIP5 GCMs run with RCP 4.5, red dots show CMIP5 GCMs run with RCP8.5. Concentric circles represent the probability density function, with ninety-five percent and sixty-eight percent confidence bounds shown.

12.3 Delta Water Supply Assets

Delta Water supply assets evaluated for this assessment include water exported from the Delta to serve water supply needs throughout the State and in-Delta water diversions. The vulnerability of water supply infrastructure assets including water diversion, conveyance, treatment, and storage facilities are discussed elsewhere because these infrastructure components are more sensitive to climate change-driven flood exposure than to the climate impacts evaluated here.

CHAPTER 13. WATER SUPPLY SYSTEM ANALYSIS APPROACH

For primary climate drivers, water supply asset vulnerability was assessed using a bottom-up approach known as decision scaling. Decision scaling uses data and stakeholder input to identify key uncertainties (UMass Amherst, 2019). Decision scaling differs from the traditional, top-down climate impact analysis approach. In the top-down approach, the analysis begins with selection and downscaling of a discrete number of climate model projections, using these to conduct hydrologic modeling of runoff, passing this through an operational model such as CalSim or CalLite, and assessing water supply outcomes. Conversely, decision scaling starts with the question: How does the system behave as a result of changes in the character of uncertain climate variables e.g., how do metrics of performance like water available for delivery change when temperature of the watershed increases? This approach is often more flexible for exploring uncertainties because it can incorporate a very large number of GCMs, emissions scenarios, and other uncertainties and those data can be updated simply and quickly as new data become available. In addition, decision scaling allows a decision maker to consider how the system may behave whether such climate change occurs in the next five years, next 50, or in 2100. Although a relatively novel approach in California, it is gaining traction and has been widely used elsewhere. The California Department of Water Resources recently completed a climate change vulnerability assessment that uses this approach (A. Schwarz et al., 2018; Selmon et al., 2019). The analysis conducted for this study builds on and expands the work completed by DWR and was done in collaboration with DWR. Detailed information about the data, process, and methodology used by DWR is available at: https://water.ca.gov/-/media/DWR-Website/Web-Pages/Programs/All-Programs/Climate-Change-Program/Climate-Action-Plan/Files/CAPIII-Decision-Scaling-Vulnerability-Assessment-Report.pdf. Additional information about the specific additional analysis conducted for this assessment is provided below.

For this vulnerability assessment, the decision scaling analysis is achieved by perturbing external climatic factors that affect water resources, such as precipitation, temperature, and sea level. Assessing different combinations of these factors creates a better understanding of which factors are most important and how the system may behave under different conditions. The findings of this study provide broad context on water supply vulnerabilities at various points in the future. This information can in turn be used by decision-makers to assess the relative vulnerability of water supply, and when actions to address these vulnerabilities may need to be taken. In addition, the outputs of this study can help assess the resilience of the current water supply system, including which specific factors have the greatest impact on supply, how long current regulations can be maintained, and what implicit tradeoffs there are in meeting these regulations.

While this analysis builds on existing work, it adds two critical improvements that help address key knowledge gaps identified above. First, additional analyses evaluate refined and additional sea level rise conditions that increase the evaluated sea level rise range up to 60 cm (~2.0 feet). Second, this analysis evaluates the vulnerability of the water supply system to changes in interannual precipitation variability. This allows for improved understanding of how the system responds to potential increased variability—even if average precipitation and other variables remain constant.

The analysis being conducted for this vulnerability assessment evaluates how the system would perform with existing water quality regulations, existing infrastructure, and operations. This analysis does not propose or evaluate any specific regulatory, infrastructure, or operational changes. Although important, these details are beyond the scope of the vulnerability assessment. Some of these factors are likely to be analyzed in the adaptation phase of this project.

13.1 Additional Sea Level Rise Analysis

This study expands upon the analysis conducted by Schwarz et al. (2018), Selmon et al. (2019), and Ray et al. (2020) by adding 30 cm (6 inches) and 60 cm (2 foot) sea level rise scenarios. The analysis also includes refined scenarios from those previously evaluated for 0, 15 cm (6 inches), and 45 cm (1.5 foot). In addition, analysis of impacts of SLR above 60 cm (2 foot) is discussed qualitatively.

Artificial Neural Networks (ANNs) for 0 cm, 15 cm, 30 cm, 45 cm, and 60 cm have been obtained from DWR (September 2019, provided by the office of Erik Reyes). The ANNs were trained using data from DSM2 simulations using the Martinez stage as the stage boundary. These ANNs are the best available at this time. Each sea level rise scenario has been paired with a regional temperature condition. A detailed description of the methodology for reaching these levels is provided in https://water.ca.gov/-/media/DWR-Website/Web-Pages/Programs/All-Programs/Climate-Change-Program/Climate-Action-Plan/Files/CAPIII-Decision-Scaling-Vulnerability-Assessment-Report.pdf.

Table 2. Sea level rise discretization used in climate change simulations

Regional temperature increase from baseline conditions [1980-2010] (degrees C)	Sea level rise increase (cm)
0.0	0
0.5	15
1.0	30
1.5	45
2.0-4.0	60

This additional analysis represents the deployment of all the available sea level rise scenarios configured to work with CalSim-III and CalLite. This analysis evaluates sea level rise up to 60 cm above current observed levels. Evaluation of sea level rise beyond 60 cm was not possible due to data availability and modeling limitations. Modeling using the CalSim family of models (CalSim-II, CalSim-III, CalLite) require sea level parameterizations that provide the ocean and Delta boundary conditions that affect water system operations throughout the water system. These parameterizations are currently only available for 0, 15, 30, 45, and 60 cm of sea level rise. Parameterizations above 60 cm have not been developed because of uncertainties related to Delta levee geometry and hydrodynamics that are considered highly uncertain at sea levels above 60 cm—changes in channel geometry, island flooding, and implementation of restoration projects would all need to be specified to develop additional ANNs for higher levels of sea level.

Other studies have considered higher sea level rise values using other methodological approaches. A key limitation of these other studies is that they are not able to simulate dynamic operational changes to the system resulting from sea level rise. CalLite, the model used in this analysis, is able to simulate how operations of the system would change to respond to higher sea levels.

13.2 Inter-annual Variability Analysis

The CalLite decision scaling platform, initially developed by DWR in collaboration with the University of Massachusetts Amherst, has been used to explore exposure, sensitivity, and vulnerability of the California Central Valley Water System (CVS)[3] to climate change (Ray et al 2020; Selman et al 2019; Schwarz et al 2018). Whereas DWR's vulnerability assessment focused on two variables of climatic change – average annual temperature and precipitation – this analysis extends the climatic perturbation scheme to incorporate changes in the interannual variability of precipitation.

[3] The California Central Valley Water System (CVS) is defined as the interconnected system of natural river channels and man-made facilities that comprise the Central Valley Project (CVP) and the State Water Project (SWP)

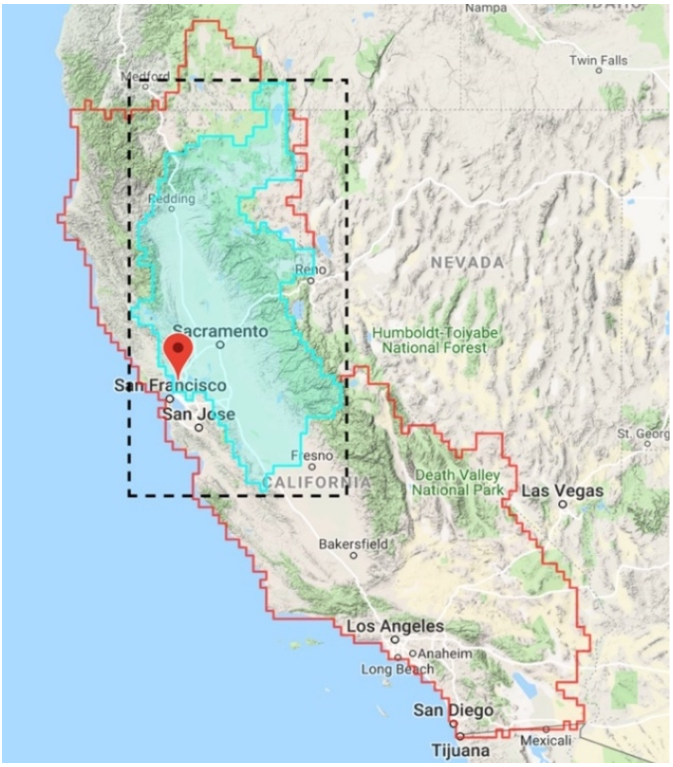


Figure 20. Geographic extent of the region contributing flow to the Central Valley Water System (CVS).

The CVS watershed is shown in Figure 20 as a polygon highlighted in blue. A bounding box (rectangle drawn with a dotted black line) indicates the area over which annual precipitation from 32 GCMs (RCPs 4.5 and 8.5) from the CMIP5 archive were spatially averaged.

The extension to interannual variability is achieved through a method of systematically perturbing annual streamflow sequences developed in prior work. The novel perturbation method, distinct from previously explored changes in the average *amount* of annual precipitation, holds long-term average annual precipitation constant while adjusting annual precipitation and streamflow to explore changes in the frequency of wet and dry years.

Projected Changes in Interannual Variability of Precipitation

GCM projections are used here as the primary source of information to determine the magnitude and range of potential exposure to long-term, persistent hydrologic changes in interannual variability. Bias-corrected, re-gridded GCM projections4 at their native scale are processed to develop annual precipitation amounts spatially averaged over the area contributing flow to the CVS (**Figure 21**). A list of the GCM models contained in the Intergovernmental Panel on Climate Change's (IPCC's) Fifth Coupled Model Intercomparison Project (CMIP5) archive and used in this analysis is provided in Appendix A. In addition, the U.S. Bureau of Reclamation also assessed and made available downscaled climate projections for CMIP5 (as well as CMIP3) (U.S. Bureau of Reclamation, 2014).

Shown in **Figure 21** is the percent change in the standard deviation of annual precipitation for each ensemble member calculated for thirty-year periods centered on 1996 (i.e. 1982-2011) through 2085 (i.e. 2071-2100) relative to a baseline period of 1981-2010. Both Representative Concentration Pathway (RCP) scenarios used in this assessment (RCP4.5 and RCP8.5) trend towards increased interannual variance in precipitation, reaching an ensemble mean of

[4] Retrieved from "Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections" archive at https://gdo-dcp.ucllnl.org/downscaled_cmip_projections/

approximately 15 percent increase in standard deviation by 2050 and towards an increase of 20 percent standard deviation by 2085.

Figure 21 also indicates that based on the envelope of variability, this difference may not be statistically significant. Nonetheless, an increase in the variability of precipitation resulting from climate change is consistent with a number of other studies looking at different lines of evidence and physical climatic responses, as discussed above in section 3.2.2. This analysis suggests that, regardless of the physical mechanism driving changes in interannual variability of precipitation, evaluation of the envelope from a 50 percent increase in standard deviation of precipitation to a 50 percent decrease in standard deviation of precipitation would cover over 95 percent of the potential future conditions likely to occur over the Delta watershed.

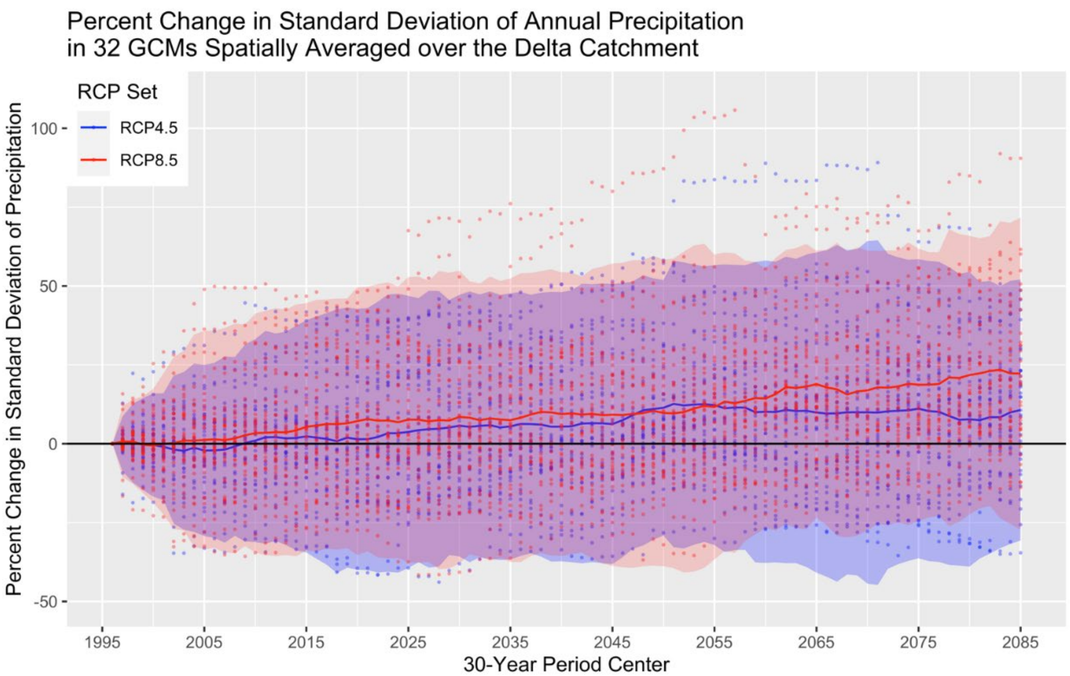


Figure 21: Percent change in the standard deviation of annual precipitation from 32 GCMs (RCPs 4.5 and 8.5) spatially averaged over the Delta catchment for 30-year periods centered on 1996 through 2085 relative to a baseline period 1981-2010.

Blue line represents the ensemble mean for RCP 4.5, and the blue shaded region indicates the 95 percent confidence interval (two standard deviations) for that scenario. Red line represents the ensemble mean for RCP 8.5, and the red shaded region indicates the 95 percent confidence interval for that scenario. The purple region shows where the two 95 percent confidence intervals overlap. Red and blue dots represent individual percent changes in standard deviation of precipitation, and horizontal black line represents a 0 percent change scenario.

13.2.1 Method of Perturbing Interannual Variance in Precipitation

The decision scaling platform built for bottom-up climate change vulnerability assessment of the CVS uses the paleo-dendrochronology reconstructed record of the Sacramento 4-river (SAC-4) annual streamflow (900–2013) (Meko et al. 2014) coupled with historical daily temperature and precipitation from Livneh et al. (2013) to develop 1,100-year climate traces of plausible alternative precipitation and temperature. The reconstructed SAC-4 annual flow provides information about long-term variability through an 1,100-year record of the wet and dry cycles that the CVS has experienced.

The coupling is performed by matching a paleo reconstructed SAC-4 streamflow (900-1949) with the closest analogue SAC-4 streamflow simulated from the historical daily gridded climate data (1950-2003). The historical gridded meteorological data is then taken as the gridded meteorological data for the paleo-historic year (900-1949) to create an 1,100-year record of gridded temperature and precipitation that would produce streamflows matching the 1,100-year streamflow record produced by Meko et al. (2014).

The coupling method provides the meteorological data needed to explore potential future climate changes. Perturbation of the meteorological variables allow for exploration of potential climatic changes to these variables. Incremental perturbation of the standard deviation of the paleo SAC-4 record increases (or decreases) the frequency of sampling analog years from the historical simulated streamflow, thereby altering the variance in annual precipitation once coupled with the daily historical precipitation.

Since the paleo SAC-4 streamflow exhibits significant multi-decadal variability in the 30-year mean streamflow, care must be taken not to alter the mean of any 30-year portion of the 1,100-year record. Figure 22 shows the results of two methods of perturbing the standard deviation of the streamflow record: (1) the “full” method perturbs flows of the entire 1,100-year record at once, while (2) the “30-yr-block” method perturbs flows by stepping through the 1,100-year record in 30-year blocks. Compared to the “full” method, the “30-yr-block” method better preserves the 30-year rolling mean and so is chosen as the most suitable method. Preservation of the 30-year rolling mean was considered important to capture and preserve the low-frequency variability in precipitation. Using the 30-yr-block method, annual flows are perturbed by:

$$Q' = ((Q - Q_u) * SD_{factor}) + Q_u$$

Where Q' is the perturbed annual flow, Q is the annual flow, Q_u is the mean of the 30-year block, and SD_{factor} is the standard deviation scaling factor. This equation is a version of the Thomas-Fiering streamflow generator (Thomas and Fiering, 1962) that is modified to change the underlying statistics of the sequence over time.

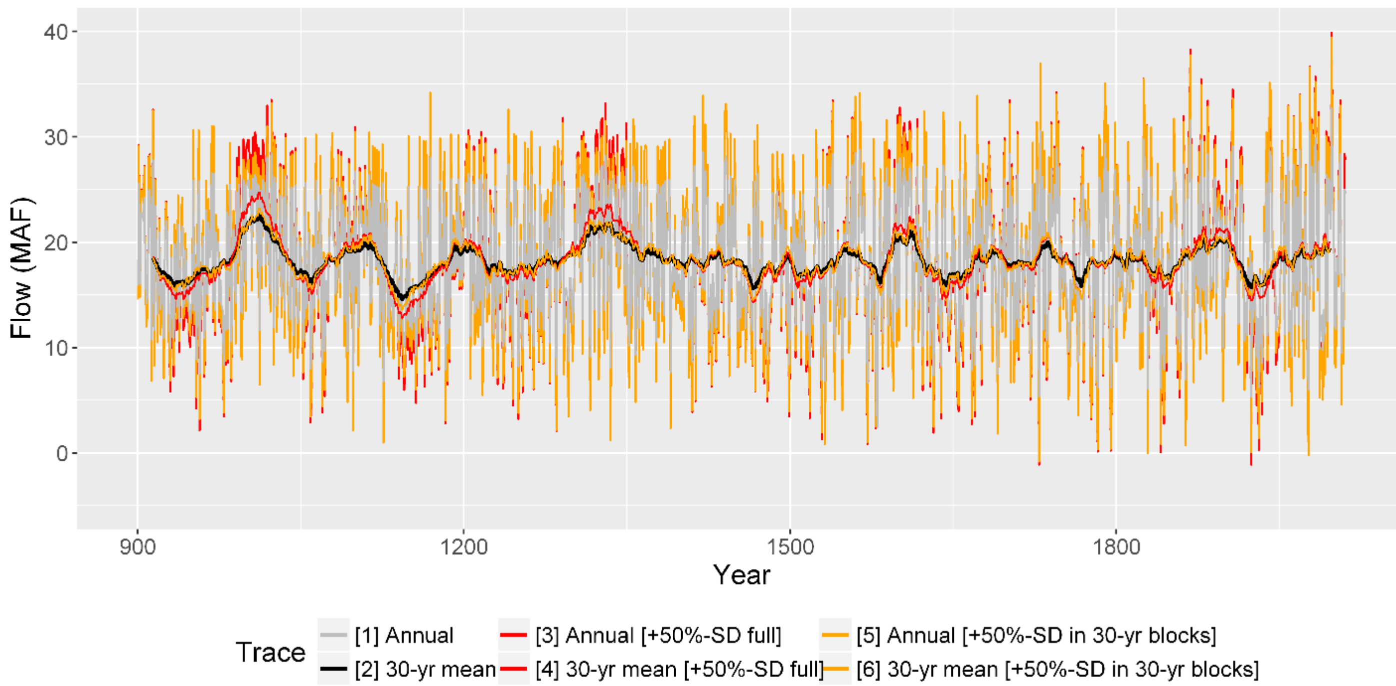


Figure 22. Time series of paleo reconstructed flows with two perturbation methods and 30-year rolling mean.

Figure 22 shows the range of reconstructed flows over the time series from 900-2000. Three lines in the middle symbolize the 30-year mean (black), the 30-year mean +50 percent standard deviation (SD) (red), and the 30-year mean +50 percent SD calculated in 30-year blocks. Above and below the means are annual flow (gray), annual flow +50 percent SD (red), and +50 percent SD calculated in 30-year blocks (orange).

Figure 23 shows the influence of the paleo streamflow standard deviation perturbation on the frequency of sampled historical simulated annual flows for the 50 percent (1.5) standard deviation and -50 percent (0.5) standard deviation change factors respectively. The 50 percent standard deviation results in more frequent sampling of historical flows further from the mean and the -50 percent standard deviation has the inverse effect (i.e. more frequent sampling of flows closer to the mean). After coupling the perturbed SAC4 annual sequence with the historical years of daily temperature and precipitation, the process yields daily hydroclimate sequences that have greater (or reduced) variability of interannual precipitation compared to historical.

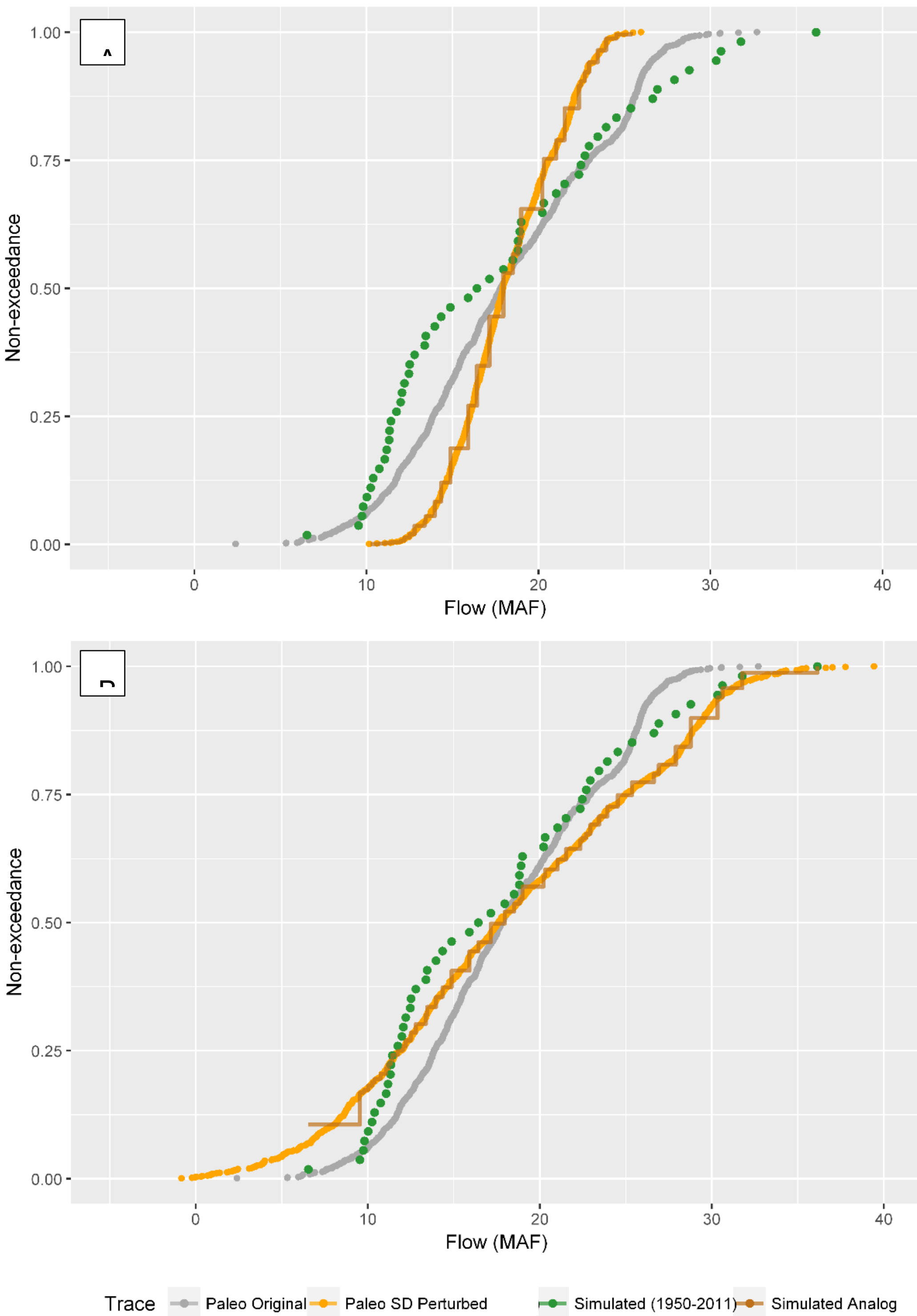


Figure 23. Empirical cumulative distribution of historical simulated streamflow (green), original paleo reconstructed streamflow (grey), perturbed paleo reconstructed streamflow (orange) with -50 percent standard deviation (top panel A) and +50 percent standard deviation (bottom panel B), and the sampled historical simulated analogs (brown).

13.3 Drought Analysis

Droughts are a regular component of California's hydrology. California's most significant historical statewide droughts observed and recorded in our written records were the six-year drought of 1929-34, the two-year drought of 1976-77, the six-year drought of 1987-92, and the five-year period from 2012-2016 (Jones, 2015). These droughts stand out in the observed record due to their duration or severe hydrology. However, evidence of droughts of similar severity and even greater duration can be found in proxy records of climate dating back centuries. The period of historically recorded hydrology of little more than a century does not represent the full range of the climate system's natural variability. Paleoclimate information, such as streamflow or precipitation reconstructions developed from tree-ring chronologies, provides a long-term perspective on climate variability (Jones, 2015).

While we have several data sources and methods for measuring drought, there is no standard definition of drought. There are a number of ways that drought can be defined: meteorological droughts describe periods of below average precipitation; hydrologic droughts describe periods of below average streamflow, runoff, and soil moisture which often include temperature effects; and water supply droughts describe periods of water supply shortage during which not all needs and uses of water can be met. Unlike flooding or other natural disasters, drought is a gradual phenomenon, unfolding over multiple years. It is often difficult to determine when a drought has begun or ended. While drought emergencies have been declared by California governors twice during the last 20 years (2009, 2014), neither used quantitative measures for the start or end of the emergency.

The analysis conducted for this vulnerability assessment focuses on water supply drought. And uses criteria for identifying drought conditions based on conditions observed during the most recent drought from 2012-2016. While these criteria do not describe every potential condition that could be considered a drought, they provide a useful reference point for drought conditions that were experienced very recently.

While the hydrology of historical droughts can readily be compared from one event to another, the same cannot be said of their impacts, due to changes in California's institutional setting and level of development (Jones, 2015). Focusing on water supply conditions allows for consideration of multiple factors in exploring vulnerability and risk. Water supply droughts are affected by meteorology and climatology, which influence hydrology and soil moisture, but they are also affected by water management decisions and operations, societal actions such as population growth and water conservation, and water management regulations. This analysis allows us to explore how today's water management systems would perform under historical meteorological and hydrological conditions, overlaid with today's demands, regulations, and level of development. It also allows us to explore how those historical climate conditions might shift with climate change and how our water management system would be able to function under such conditions.

The drought analysis presented here explores two different aspects of climate change impacts on drought: Changes in drought severity and changes in drought frequency.

13.3.1 Drought Severity Analysis

Climate change will likely result in higher temperatures, more variable precipitation, and higher sea levels. To look at how these climate stressors could exacerbate future droughts we look at a drought period similar to the 2012-2016 drought and model how that drought would be likely to affect Delta water supplies, were it to occur again with future climate conditions.

The meteorological and hydrological data used for this study does not include data from the 2012-2016 drought, however, the 1,100-year record includes several other periods of similar hydrologic conditions. The following steps were followed to identify a historical analogue period for the 2012-2016 drought.

1. Full natural flow into and storage values at major SWP and CVP rim reservoirs (Shasta, Oroville, Folsom, and Millerton) were downloaded from https://CDEC.water.ca.gov for the entire period of available data.
2. Combined full natural flow into rim reservoirs over the 2012-2016 period was compared to simulated flow into rim reservoirs using the reconstructed flow data described above in section 13.2.
3. Five-year periods throughout the paleo-historical record that matched the observed 2012-2016 period in cumulative reservoir inflow deficit were extracted and compared to observed inflow conditions (Figure 24).
4. The historical drought period 977-981 was chosen as the most similar drought analogue for 2012-2016 because of its similarity in the sequence of inflow deficit and consistency with the 2012-2016 antecedent reservoir storage conditions in September of the year prior to the drought beginning.

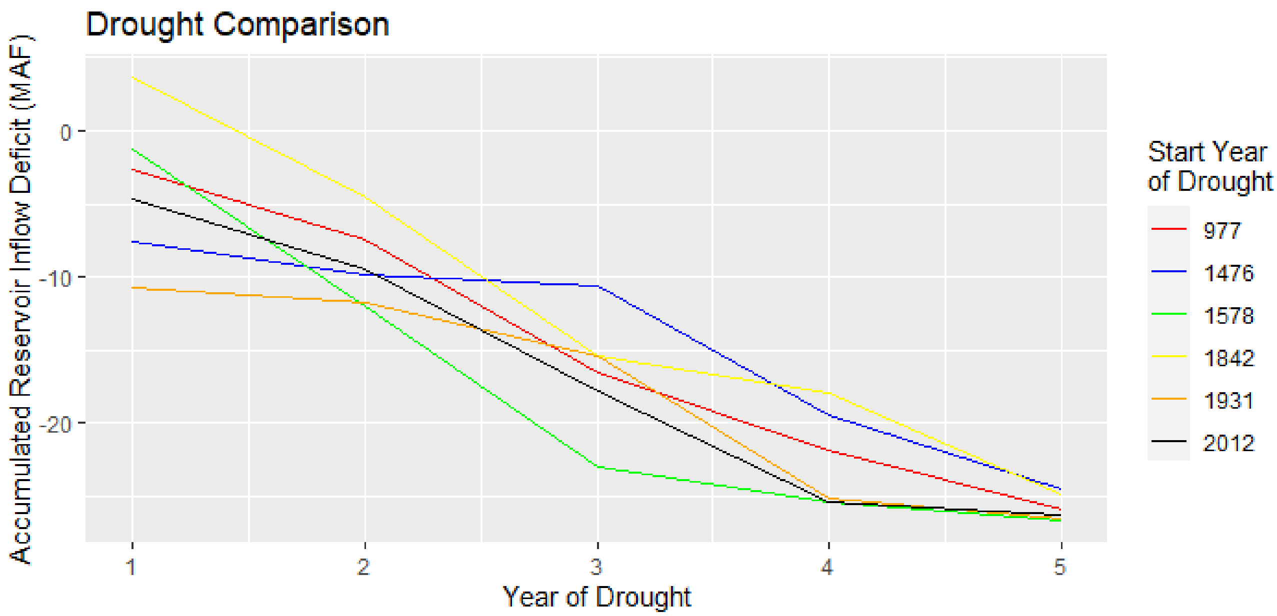


Figure 24: Comparison of simulated drought periods with observed drought conditions 2012-2016.

Accumulated inflow deficits for six five-year drought periods are shown with starting years in 977 (red), 1476 (blue), 1578 (green), 1842 (yellow), 1931 (orange), and 2012 (black).

The drought chosen for this severity analysis, 977-981, is a slightly less severe drought (hydrologically) then 2012-2016. However, in historical context, these two periods were remarkably similar. 977-981 provides a useful example of past hydrological conditions that can be simulated and perturbed with future climate shifts to evaluate potential water supply vulnerabilities if this series of conditions were to repeat under future climate conditions.

13.3.2 Drought Frequency Analysis

In addition to increasing drought severity, droughts may also become more frequent under future climate conditions. In order to explore the potential vulnerabilities to Delta water supplies of increasingly frequent droughts, we have identified some of the key characteristics of the 2012-2016 drought, and used those to identify similar conditions within the historical record to understand how common such conditions are today and how common they are likely to be under future climate conditions. The following steps were followed to establish criteria for water supply drought frequency analyses.

1. Delta exports were downloaded for the period 1984-2019 from the DWR Dayflow dataset (https://data.ca.gov/dataset/dayflow)
2. Dayflow Delta export data 2012-2016 were evaluated and the following criteria calculated to define key drought metrics:
    a. **Define length** (Determine when a drought has started and ended): Between 2012-2016, no year produced greater than 5 million acre-feet of total Delta export. In

2017, 6.4 million acre-feet of water were exported from the Delta, ending the drought.

In the analogue historical climate (adjusted to be consistent with today's temperatures) and run through the existing water supply system with today's water demands, level of development, and regulations, there are eight periods (of varying length from 5-8 years) that meet this criterion (**Figure 25**).

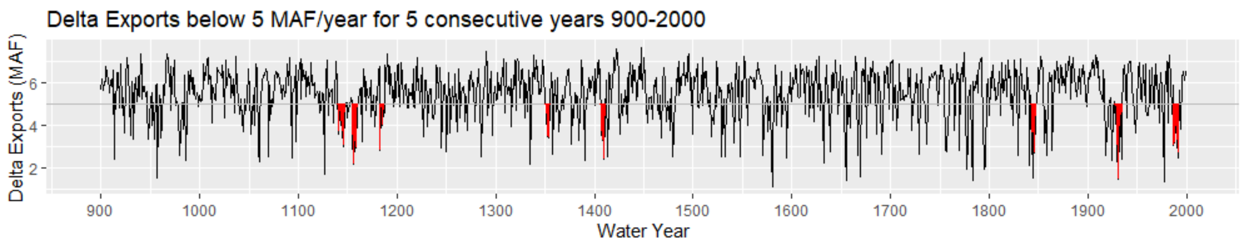


Figure 25: Delta Exports, continuous periods of 5-years or more during which exports remained below 5 MAF shown in red.

b. **Define severity/depth** (Determine when conditions are severe enough to consider the period a drought): Between 2012-2016, the total cumulative Delta exports were 16.7 million acre-feet or an average of 3.34 million acre-feet per year.

   In the analogue historical climate (adjusted to be consistent with today's temperatures) and run through the existing water supply system with today's water demands, level of development, and regulations, there are only 2 periods that meet both criteria a and b. (**Figure 26**).

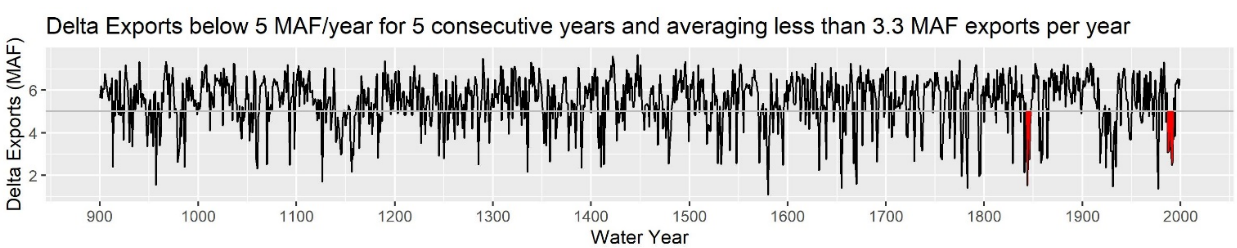


Figure 26: Delta Exports, continuous periods of 5-years or more during which exports remained below 5 MAF and average Delta Exports over the duration of the drought were below 3.3 MAF per year shown in red.

A Poisson probability distribution is used to calculate the probability and expected length of droughts occurring over any specified timeframe using the equation:

$$f(k;\lambda) = \Pr(x = k) = \lambda^k e^{-\lambda}/k!$$

where λ is the Poisson distribution parameter, *e* is Euler's number (*e* = 2.71828...), k is the number of events (droughts meeting the criteria above) occurring during the specified timeframe, and *k*! is the factorial of *k*.

The Poisson probability distribution is a discrete probability distribution that expresses the probability of a given number of events occurring in a fixed interval of time or space if these events occur with a known constant mean rate and independently of the time since the last event. The distribution allows us to calculate a mean rate of drought over the entire 1,100-year simulation period and then calculate how many droughts would be expected to occur (and the expected value of their average length) during any time interval, e.g., 50 or 100 years that may be more easily communicated.

Using the Poisson distribution allows estimation of changes is the frequency of droughts under future climate conditions. For each 1,100-year simulation, conditions that meet the two criteria listed above are identified (the number of droughts and the total length of each drought are recorded over the 1,100-year period). With these data, the λ for each simulation is calculated. The Poisson distribution was then used to calculate the probability of at least one drought occurring during specified timeframes (i.e., 50, 100 years). The expected value of the number of years with drought conditions was also calculated by multiplying the number of droughts but the average length of the droughts. The expected value of years with drought conditions was divided by the length of the time frame to arrive at a value for number of years with drought conditions per year. (While this number is quite hard to understand, when it is compared to the historical value for number of years with drought conditions per year it reveals the factor of change between historical and potential future conditions.)

As with the drought severity analysis, this analysis does not evaluate changing frequency of all different kinds of drought conditions, rather we define and describe specific characteristics of the most recent water supply drought (2012-2016) and then evaluate the change in frequency of experiencing those conditions.

13.4 Regulatory and Operational Assumptions

All modeling done for this study assumes current water quality regulations remain in place, including Decision 1641 (D-1641) of the Bay-Delta Water Quality Control Plan. D-1641 includes a wide range of water quality and flow objectives that vary by season and inflows at defined locations. These objectives are primarily intended to protect beneficial uses of water and fisheries, including in-Delta water use, exports, and preventing fish entrainment. D-1641 also includes a requirement intended to maintain salinity of two parts per thousand (ppt) or lower at specified distances from the Golden Gate Bridge, depending on time of year. This salinity level is referred to as X2 and is a regulatory requirement to protect water quality as well as maintain a low salinity zone near some of the only remaining habitat for the endangered Delta Smelt.

Regulations are implemented as they have previously been parameterized in CalLite, no modifications to regulatory constraints or operations have been implemented in these simulations. This is similar to most existing water supply and climate change studies conducted to date.

Regulations and water management operations could change in the future to address changes in climate or to adjust protections for threatened and endangered species. Although alternative regulatory and operational regimes could be explored, doing so would be speculative. Such analyses are not appropriate to this vulnerability assessment.

13.5 Other Methodological Considerations

The methods employed in this study have associated considerations and limitations that must be kept in mind. Several of these are briefly described here, and under section 14.4, *Other Water Supply System Risks and Potential Vulnerabilities.* First, the operational model CalSim uses a monthly time step. Although this captures past and potential future operational rules and decisions well, it is dependent on historical hydrology for calibration. A shift to larger inflow peaks could affect operations through requiring additional reservoir releases and affecting the proportion of runoff that can be effectively captured during the wet season. Similarly, projected potential shifts in temperature and precipitation patterns may have a larger than expected impact on flooding and water supply. The methods used here use current operational rules in order to avoid speculation. However, as precipitation and temperature shifts runoff patterns, this could result in changes in operational rules for reservoirs and overall changes in storage and water supply.

Second, climate projections for water supply ultimately depend in part on the accuracy of GCMs, and assumptions or models used to translate large scale changes to more localized impacts. Although the bottom-up methodology used in this study provides a way to update the analysis more quickly as GCMs are updated – as well as capture a wide range of GCMs – it still depends on the currently best available GCM projections.

Third, this study analyzes both the individual contributions of temperature, precipitation, and sea level rise to impacts on water supply system performance and combinations of impacts occurring simultaneously. Considering climate stressors individually can help demonstrate the relative contribution to impacts of each stressor, highlighting the different ways in which changes in one stressor affect the system versus the ways in which another stressor may affect the system. This analysis can also be informative for planning and decision making because there are different levels of confidence or certainty about different climate stressors, for example, there is unanimity across all GCMs that temperatures will increase over California, while there is less certainty about how precipitation will change. These stressors are related and have compounding effects. For example, increased temperature is associated with sea level rise. As such, considering these stressors independently likely understates the potential combined impacts that could occur. Nevertheless, the methodologies used here provide a robust analysis of the combined factors, as well as separate consideration for potential individual contributions to water supply impacts.

CHAPTER 14. RESULTS

14.1 Water Supply System Sensitivity

This section explores how different water supply performance metrics respond to changes in three key climate change stressors: temperature, precipitation, and sea level rise. We assessed the sensitivity of Delta exports, April storage, carryover storage, and system shortages to the following climate stressors: temperature increases from 0-4° C, sea level rise scenarios of 0, 30, 45, and 60 cm, precipitation changes from -20 percent to +30 percent with no change from historical levels of variability, and precipitation variability of -50 percent to +50 percent change in the of standard deviation of annual precipitation with no change from the historical amount of precipitation. These ranges were developed by evaluating the spread of GCM projections for mid-century for each climate stressor, and then defining the range so that it was inclusive of plus or minus two standard deviations of the mean amount of change projected by the ensemble of models. Each climate change stressor was explored through system simulations which explored the impact of those stressors independent of the other stressors so that the impact of the stressor in question could be isolated from the impacts to the system of other stressors or the impacts to the system of multiple stressors working in similar or contradictory directions. This allows for the evaluation of impacts to the system of each factor independently. Varying temperature, precipitation, and sea level rise independently allows for identification of drivers of water supply system performance. Although temperature and sea level rise are correlated, this analysis shows that temperature change is likely to have a much larger impact on water supply than sea level rise, despite the correlation.

We performed a principal components analysis (PCA) on annual values for each stressor and performance metric, in order to assess the relationship between performance metrics of interest and each climate stressor: temperature change, precipitation change (amount only, precipitation variability was not evaluated by PCA), and sea level rise. This allows visualization of which stressors have the highest correlation to system performance and which stressors exert the strongest effect on the system overall. PCA revealed similar trends across all four performance metrics. All metrics had a moderate to strong correlation with precipitation change (with no variability change) and a weak correlation with temperature increases. A notable finding was that exports and storage metrics were weakly correlated with sea level rise, while shortages showed moderate to strong correlation with sea level rise.

To visualize how the distribution of exports, storage, and shortages are affected by climate stressors, we graphed cumulative distribution functions (CDFs) that show the cumulative distribution of performance metric data throughout the range of each climate variable. This is a method to approximate the sensitivity of each metric to climate stress. Violin plots were also included as a different way to visualize the influence of climate stressors on the distribution of performance metric data.

14.1.1 Principal Components Analysis (PCA) of the Effect of Climate Stressors on Water Supply Performance Metrics

Principal component analysis (PCA) assesses variability amongst multiple dimensions of data by compressing them into two axes. Performing PCA on climate stressors that affect performance metrics allows visualization of the relationships between these variables (Precipitation variability was not explored using PCA). Dimension percentages (Dim1 and Dim2) indicate the amount of variance accounted for by each principal component; a higher combined percentage means that more of the overall variance in the data can be captured by just two dimensions. Vectors closely aligned with the dotted axes indicate variables with strong influence on that component. The most important variables to each component are indicated by contribution percent ('contrib', as noted in the legend on the following figures) and vector length. Adjacent vectors indicate positively correlated variables, opposite direction vectors indicate negative correlation, and orthogonal vectors indicate lack of correlation. While PCA does not allow us to infer causality between variables, it enables visualization of relationships within the data that may not be otherwise apparent.

Delta Exports

Principle components 1 and 2 (Dim1 and Dim2) combined account for 65.5 percent of the variance in the dataset. Exports and precipitation showed a positive correlation with each other, and both have a strong influence on principal component 1 (Dim1), which accounts for a higher percentage of the variance in the dataset than Dim2. Temperature and sea level rise are also correlated with each other, have a low contribution to Dim2, and have little to no correlation with exports and precipitation. Temperature and sea level rise are slightly negatively correlated with exports, but precipitation is the most relevant variable to this metric. However, because sea level rise and temperature are correlated, they are likely exerting a similar influence on the system and may reinforce each other, potentially leading to compounded impacts on exports.

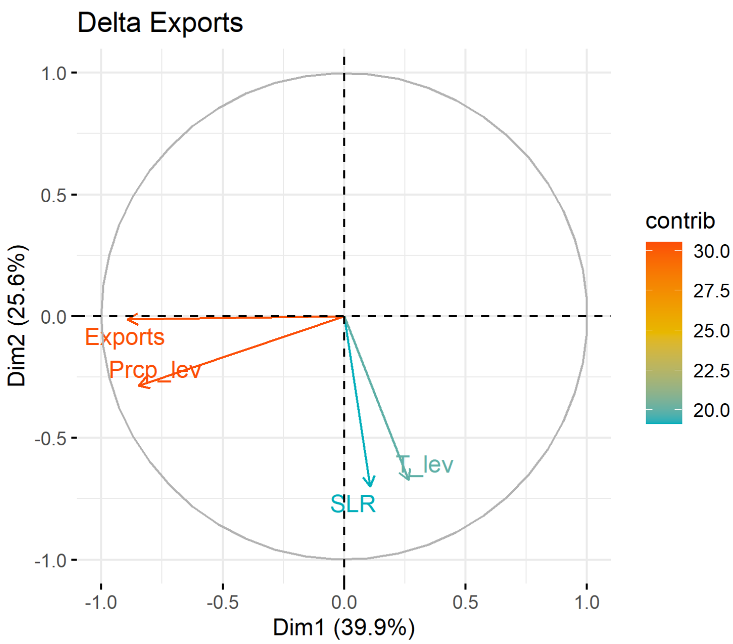


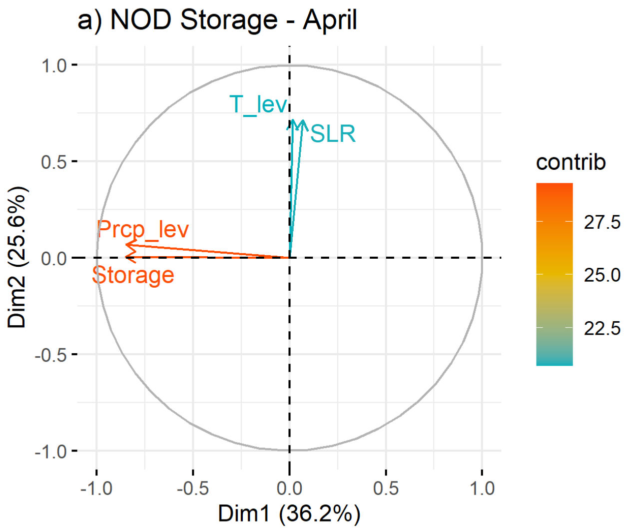
Figure 27: PCA factor map for climate stressor variables and Delta Exports.

Data from four variables (export volume, precipitation, sea level rise, and temperature) are compressed into two axes (Dim1 and Dim2) which each account for a percentage of variance in the data. Overall contribution of variables to the model ranges from 20 percent (blue) to 30 percent (orange). The arrows indicate the relative contribution of each variable and the correlations between them. Exports and precipitation (center-left, orange arrows pointing to left) are more closely correlated. Sea level rise and temperature (center-bottom, blue arrows point down and to right) are more closely correlated and are weakly correlated with export levels.

North of Delta Storage

For April storage, principal components 1 and 2 accounted for 61.8 percent of the variance in the dataset, with Dim 1 accounting for a higher percentage of the variance. Precipitation and storage are highly positively correlated, and have a strong influence on Dim1, which accounts for a higher percentage of the variance in the dataset than Dim2. Temperature and sea level rise are also highly correlated with each other and have a minimal influence on Dim2. These variable clusters are orthogonal (not correlated) with each other. Precipitation and storage had overall higher contribution percentages to the system than temperature and sea level rise.

For carryover (September) storage, principal components 1 and 2 accounted for 65.4 percent of the variability in the dataset, with Dim1 again accounting for a higher percentage of the variance. Precipitation and storage are less correlated than they are for April storage, but are still positively correlated. Carryover storage shows precipitation with a lower contribution to Dim 1 than April storage, indicating that precipitation has more influence on storage in the spring versus fall. Sea level rise and temperature are correlated with each other and have a low contribution to Dim2 here as well and have a slightly stronger negative correlation with storage than seen in April. This indicates that precipitation is less related to carryover storage, and sea level rise and temperature have a larger influence than in April storage. It is also interesting to note that the PCA map for carryover storage is almost identical to that for Delta exports, suggesting that these performance metrics are influenced in the same ways by the same climate stressors.



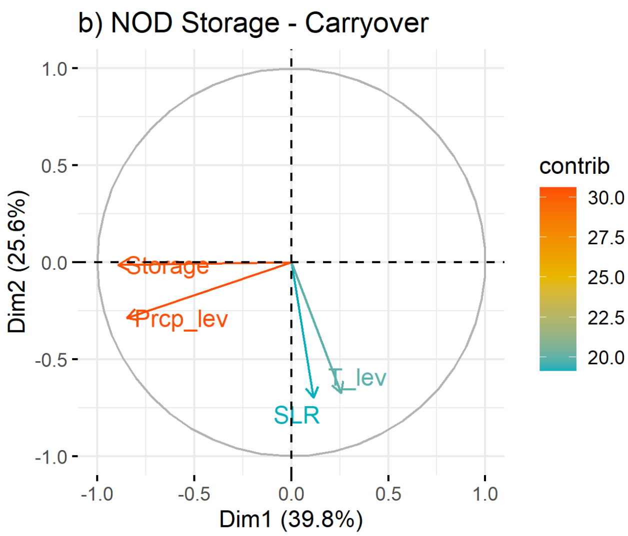


Figure 28 a-b: PCA factor maps for climate stressor variables and North of Delta storage in April and September.

Data from four variables (storage volume, precipitation, sea level rise, and temperature) are compressed into two axes (Dim1 and Dim2) which each account for a percentage of variance in the data. Overall contribution of variables to the model ranges from 20 percent (blue) to 30 percent (orange). The arrows indicate the relative contribution of each variable and the correlations between them. Storage and precipitation (orange arrows pointing to the left) are more closely correlated. Sea level rise and temperature (blue arrows pointing up and down) are closely correlated with each other and are not (April) or weakly (carryover) correlated with storage.

System Shortages

When all data were included, principal components 1 and 2 accounted for 54.7 percent of the variance in the data, and slightly more variance accounted for by Dim1 over Dim2. Shortages and precipitation are negatively correlated and moderately influence Dim1. Both are orthogonal to temperature, which is highly influential on Dim2 and appears to act as a variable largely independent of the others. Sea level rise is strongly correlated with shortages but had an overall low contribution to Dim1.

Filtering data to shortages greater than 50,000 acre-feet resulted in little change to the percent of variance accounted for, a slightly weaker correlation between precipitation and shortages, and a stronger correlation between temperature and precipitation. Comparing the filtered dataset to the dataset containing all shortages, shortage and precipitation have a similar influence on Dim1, temperature has a lower contribution to Dim2, and sea level rise has a higher contribution to Dim1, (but was more weakly correlated with shortages). While none of the climate stressors were strongly associated with shortages greater than 50,000 acre-feet, sea level rise was more correlated with and exerted a stronger contribution to shortages than any of the other performance metrics we examined. Therefore, sea level rise may be having only a marginal impact on deliveries and reservoir storage but a larger impact on system shortages. This may be an indication that current water supply operations (as modeled) may be simulating water supply operations that place the system closer to the threshold between meeting all requirements and shortages in dry years, thus, creating additional risks of increased shortage conditions as sea levels rise and hydrologic conditions become more extreme.

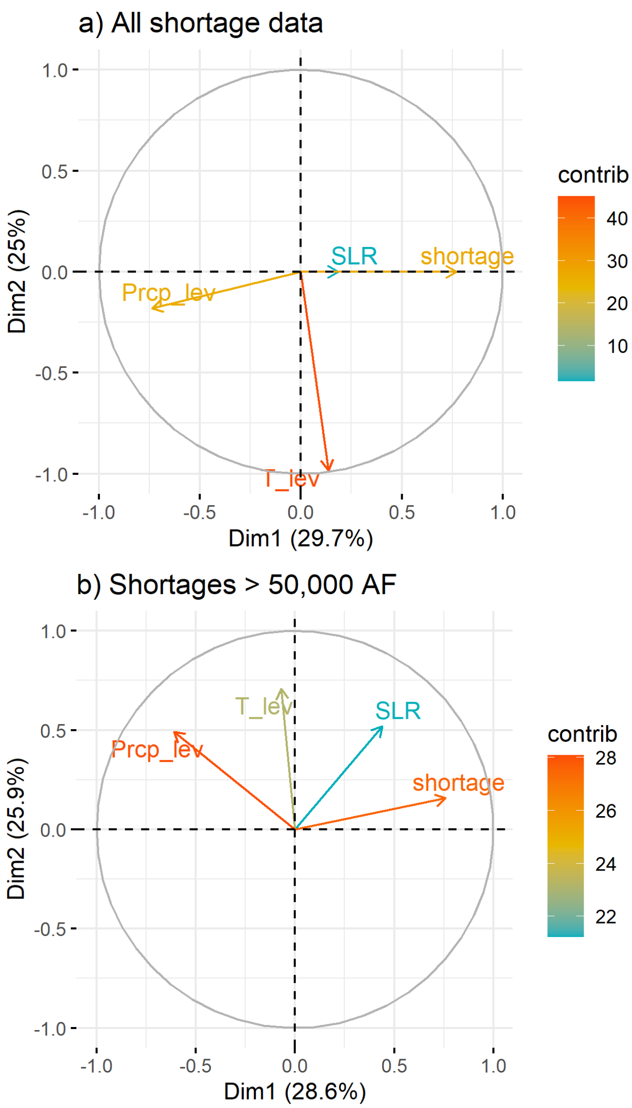


Figure 29 a-b: PCA factor maps for climate stressor variables and system shortages for all shortages and with shortages under 50,000 acre-feet filtered out.

Data from four variables (shortage, precipitation, sea level rise, and temperature) are compressed into two axes (Dim1 and Dim2) which each account for a percentage of variance in the data. Overall contribution of variables to the model ranges from 20 percent (blue) to 30 percent (orange). The arrows indicate the relative contribution of each variable ('contrib' percent) and the correlations between them. Overlapping arrows indicate strong positive correlation, opposite direction indicates negative correlation, and orthogonal vectors indicate low or weak correlation.

Overall, each PCA factor map showed precipitation change having the strongest correlation with each water supply metric (exports, storage, and shortages). PCA for storage and exports demonstrated high correlation between sea level rise and temperature, although neither were strongly correlated with these water supply metrics. This suggests that while precipitation change is the largest driver of every performance metric, the strong positive correlation between temperature and sea level rise could have a compound effect on performance that should be considered. Interestingly, mapping the influence of climate stressor variables on system shortages revealed a moderate- to strong-positive correlation between sea level rise and shortages, indicating that sea level rise may be an important driver of this metric.

14.1.2 Sensitivity of Water Supply Performance to Climate Stressors

We visualized the distribution of each performance metric using cumulative distribution functions (CDFs) and violin plots to determine how climate stressors (temperature change, sea level rise, change in average amount of precipitation, and change in the variability of precipitation) would affect the system across the range of conditions if no other change in the conditions occurred (e.g., the SLR plots below represent data where all other variables are maintained at their historical unperturbed levels, while sea level rise values are successively increased from 0 to 60 cm). The CDFs allow us to plot the full range of system performance. E.g., Delta exports range from a minimum of about 1 million acre-feet in the most severe drought conditions to almost 8 million acre-feet in the wettest conditions. Plotting performance CDFs across different scenarios of warming, precipitation change, and sea level rise allows us to see how each climate stressor affects system performance across the full range of performance. Some climate stressors impact the entire range of performance while other stressors have a disproportionate effect on the lower end of performance. The distance between the lines on each CDF indicate the sensitivity of the system: the farther apart the lines are (and the farther they are from the baseline in black), the greater the effect of that particular climate stressor. Violin plots, an alternative to box plots, also show the distribution of performance data throughout its range, for each level of the four climate stressors.

Delta Exports

Sea level rise has a fairly minor effect on exports across all levels of export performance (Figure 30a, Figure 31a) Temperature has a larger effect on export values throughout the data range, but particularly on exports above ~4 MAF, where the curves have more separation (Figure 30b). Incremental decreases in performance occur with each step in warming, indicating that warming reduces the export capacity of the system overall (Figure 30b, Figure 31b). However, the largest difference in performance occurs between 0 and 0.5 °C, which is likely due to the loss of snowpack that occurs in the initial warming steps. Exports continue to decline as temperature increases, but the effect of increasing temperature on exports appears to diminish slightly with each increased step of warming.

While all four stressors show a noticeable shift in export volume from the baseline, the most significant effect occurs from precipitation change (Figure 30c, Figure 31c). Changes in the amount of precipitation affect Delta export performance across the entire range of performance. Altering precipitation affects export volumes relatively equally between each 10 percent step, with the largest change in performance occurring as a result of decreasing precipitation from -10 percent to -20 percent (Figure 30c). This indicates that performance becomes increasingly sensitive to precipitation changes in drier scenarios, and that export volumes are highly influenced by precipitation changes. Further, exploration of variability in precipitation (as shown by percent change in standard deviation from baseline) indicates that performance is more sensitive to changes in variability during dry years than in wet years (**Figure 30**d). Lower variability in precipitation leads to increased export volumes below about the 30th percentile of performance; higher variability in precipitation leads to decreased export volumes below about the 30th percentile of performance. Decreased exports become more likely with increased variability (**Figure 30**d, **Figure 31**d).

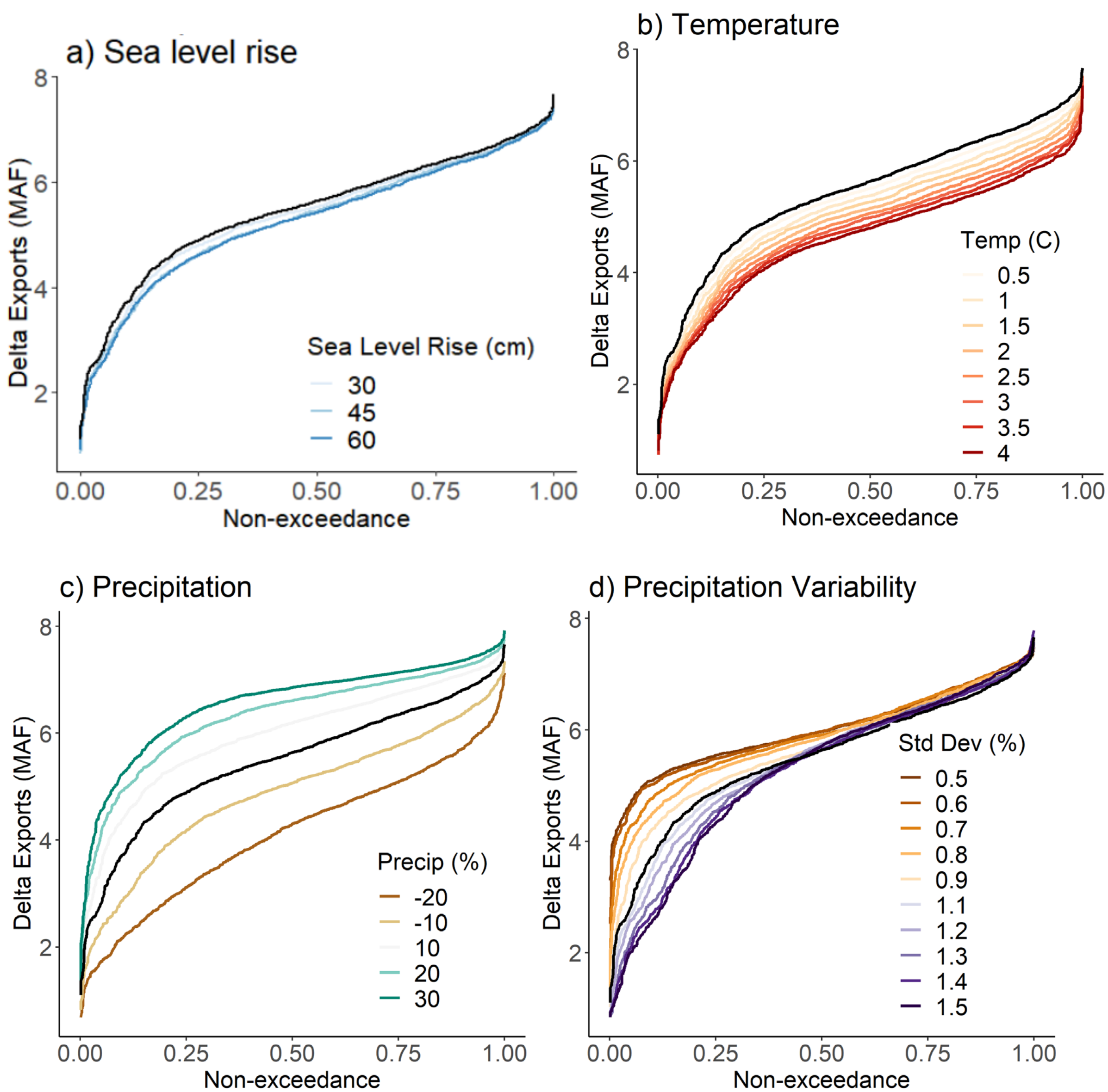


Figure 30 a-d: Cumulative distribution functions (CDFs) showing independent effect of changes in sea level rise, temperature, and precipitation to Delta exports in millions of acre-feet.

Figure 30a shows a CDF for the effect of sea level rise on Delta Exports volume ranging from 0 cm SLR (light blue) to 60 cm SLR (dark blue). Figure 30b shows a CDF for the effect of temperature increases on Delta Exports volume ranging from 0.5 degrees C (light orange) to 4 degrees C (dark red). Figure 30c shows a CDF with a divergent color scheme for the effect of precipitation on Delta Exports ranging from -20 percent (dark brown) to +30 percent (green). Figure 30d shows a CDF with a divergent color scheme for the effect of precipitation variability on Delta Exports ranging from 50 percent (dark orange) to 150 percent (dark purple) standard deviation. Black curves indicate a baseline of zero change.

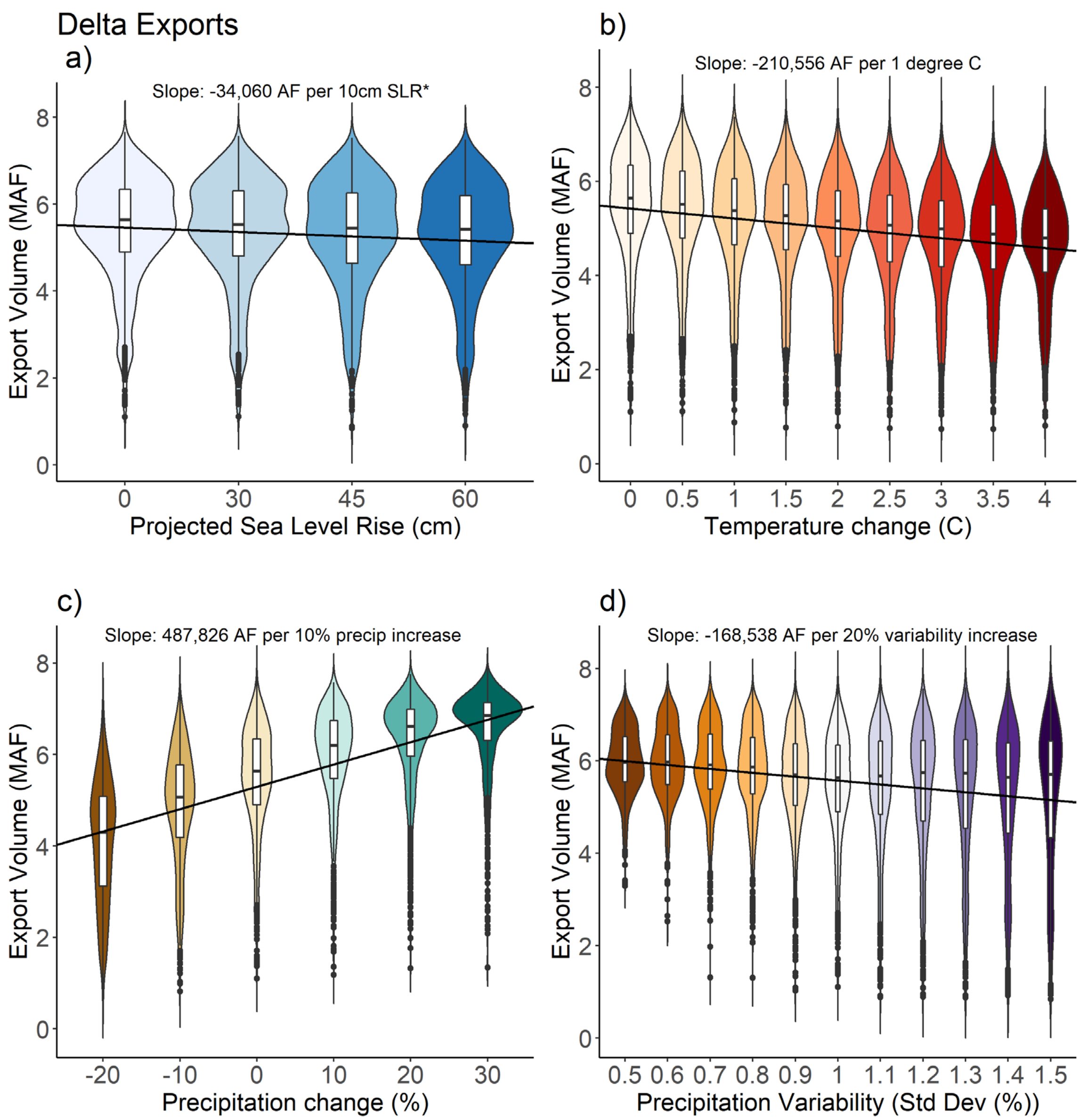


Figure 31 a-d: Violin plots showing independent effect of changes in sea level rise, temperature, and precipitation on Delta exports in millions of acre-feet.

Figure 31 has four subplots, each showing a series of violins using the same color schemes as in the previous figure. Box plot inside violins shows the interquartile range and median, and vertical lines show the range of data (including outliers exceeding the upper and lower interquartile range, indicated by black dots). Width of each violin indicates the probability of data points occurring throughout that range (wider = high probability, thinner = lower probability). Figures have a linear trendline based on a regression between the performance metric and each climate stressor, and trendline slope is noted (p>0.01 for all).

** Standard error > 0.01.*

North of Delta Storage - April

April North of Delta (NOD) storage does not appear to be highly sensitive to sea level rise or temperature, largely due to seasonal management regimes (Figure 32a-b Figure 33a-b). During the winter months (December through April) when storms are frequent, reservoirs are kept artificially low to maintain space for flood control. Increased temperatures can shift snow events to rain events, or cause earlier snowmelt, thus creating more flow into reservoirs, however, that water typically cannot be stored because of flood control management during this time of the year.

Precipitation change has a large effect on the system (Figure 32c, Figure 33c). There is a greater difference in performance between -20 percent and -10 percent precipitation than between the baseline and -10 percent, (Figure 32c) indicating that exceptionally dry periods have an outsize influence on storage April reservoir storage. The influence of increased precipitation levels beyond 10 percent have more limited impact on April reservoir storage levels. This is likely due to the storage limitations of existing infrastructure (i.e., additional precipitation cannot be captured because reservoirs are already at capacity much of the time). Changes in precipitation variability have a larger effect on performance during dry years than in wet years for this metric as well, but all hydrologic conditions show sensitivity to variability. Less variability results in higher storage levels (Figure 32d, Figure 33d).

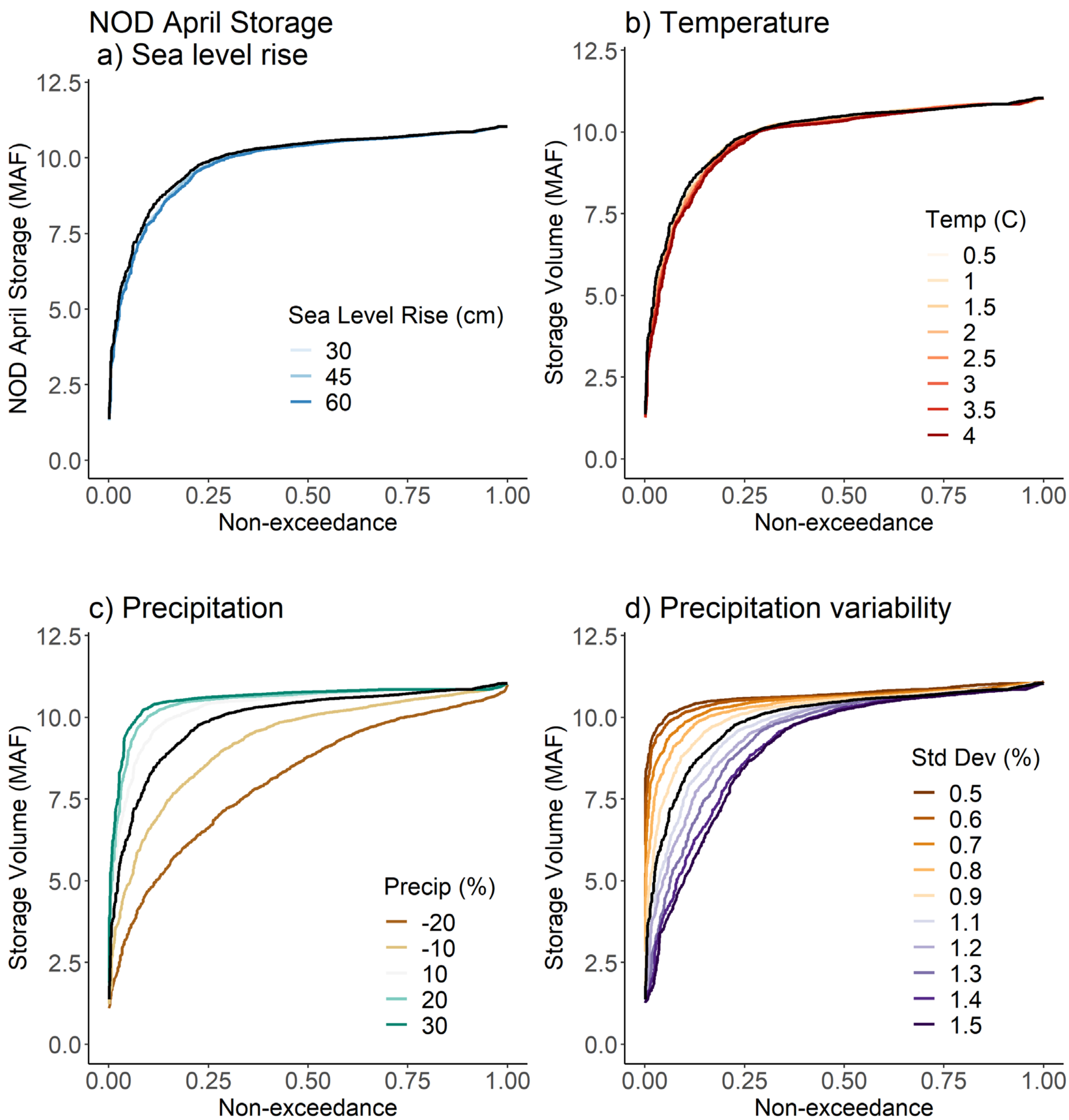


Figure 32 a-d: Cumulative distribution functions showing independent effect of changes in sea level rise, temperature, and precipitation to North of Delta April storage in millions of acre-feet.

Figure 32a shows a CDF for the effect of sea level rise on NOD April storage volume ranging from 30 cm SLR (light blue) to 60 cm SLR (dark blue). Figure 32b shows a CDF for the effect of temperature increases on storage volume ranging from 0.5 degrees C (light orange) to 4 degrees C (dark red). Figure 32c shows a CDF with a divergent color scheme for the effect of precipitation on storage ranging from -20 percent (dark brown) to +30 percent (green). Figure 32d shows a CDF with a divergent color scheme for the effect of precipitation variability on storage volume ranging from 50 percent (dark orange) to 150 percent (dark purple) standard deviation. Black curves indicate a baseline of zero change.

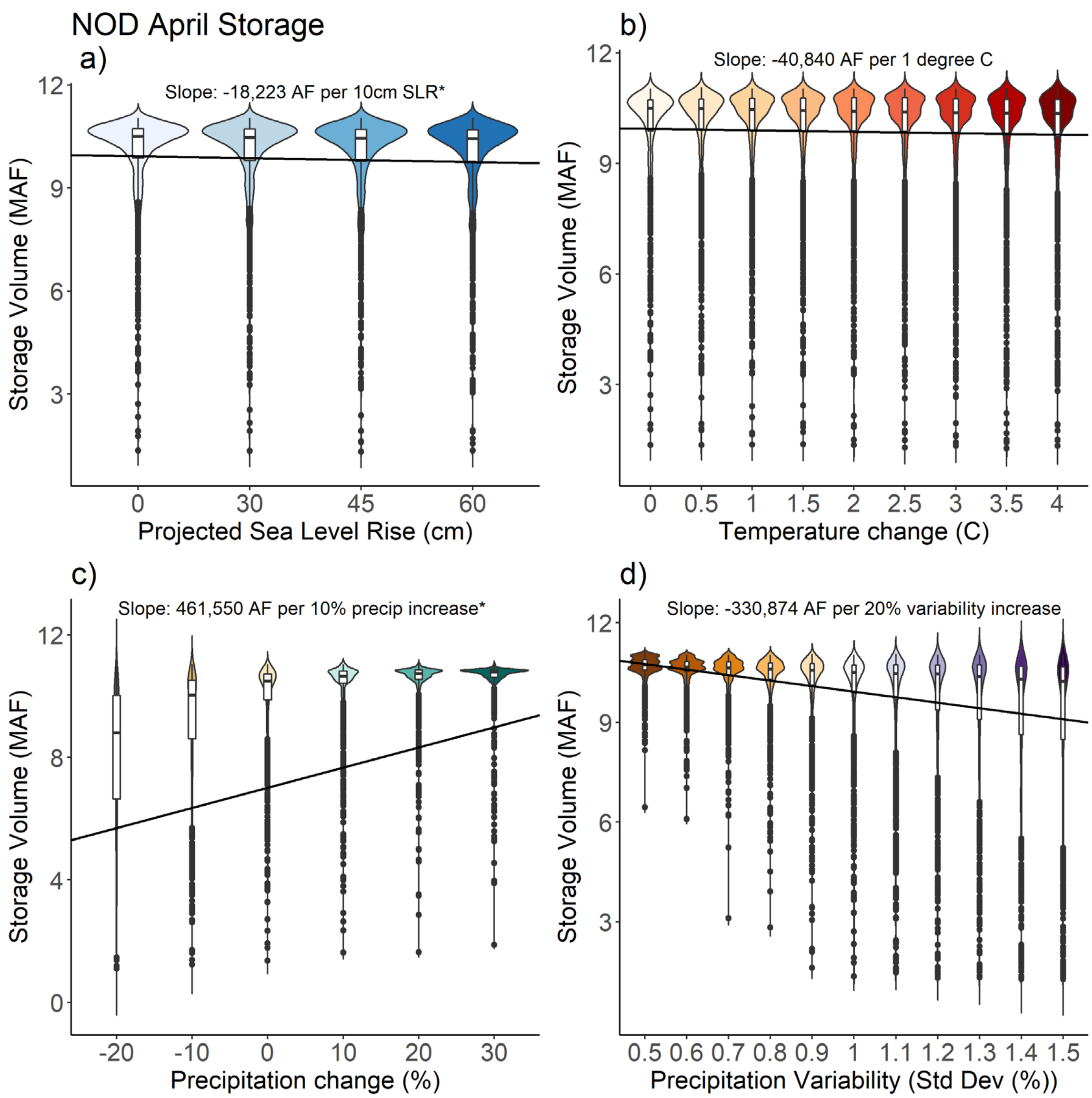


Figure 33 a-d: Violin plots showing independent effect of changes in sea level rise, temperature, and precipitation on North of Delta April storage volume in millions of acre-feet.

Figure 33 has four subplots, each showing a series of violins using the same color schemes as in the previous figure. Box plot inside violins shows the interquartile range and median, and vertical lines show range of data (including outliers exceeding the upper and lower quartile range, indicated by black dots). The width of each violin indicates the probability of data points occurring throughout that range (wider = high probability, thinner = lower probability). Figures have a linear trendline based on a regression between the performance metric and each climate stressor, and trendline slope is noted (p>0.01 for all except SLR).

** Standard error > 0.01.*

North of Delta Storage – Carryover

Overall effects for each climate stressor are similar to those seen for Delta Exports. Sea level rise sensitivity is minimal (**Figure 34**a), while temperature has a large effect on storage (**Figure 34**b), particularly for the initial increases in warming. Precipitation has a significant impact on carryover storage at all levels across the performance range, with the 20 percent decrease has a particularly large effect on carryover storage volume throughout the performance range (**Figure 34**c). Effects of precipitation variability on performance are similar to those seen for Delta Exports, with dry years more affected by precipitation variability and increased variability leading to lower storage volume (**Figure 34**d). Notable, impacts of precipitation variability appear to stretch further across the performance range for carryover storage then were observed for Delta exports. For carryover storage, precipitation variability impacts performance up to about the 65th percentile **Figure 34**d).

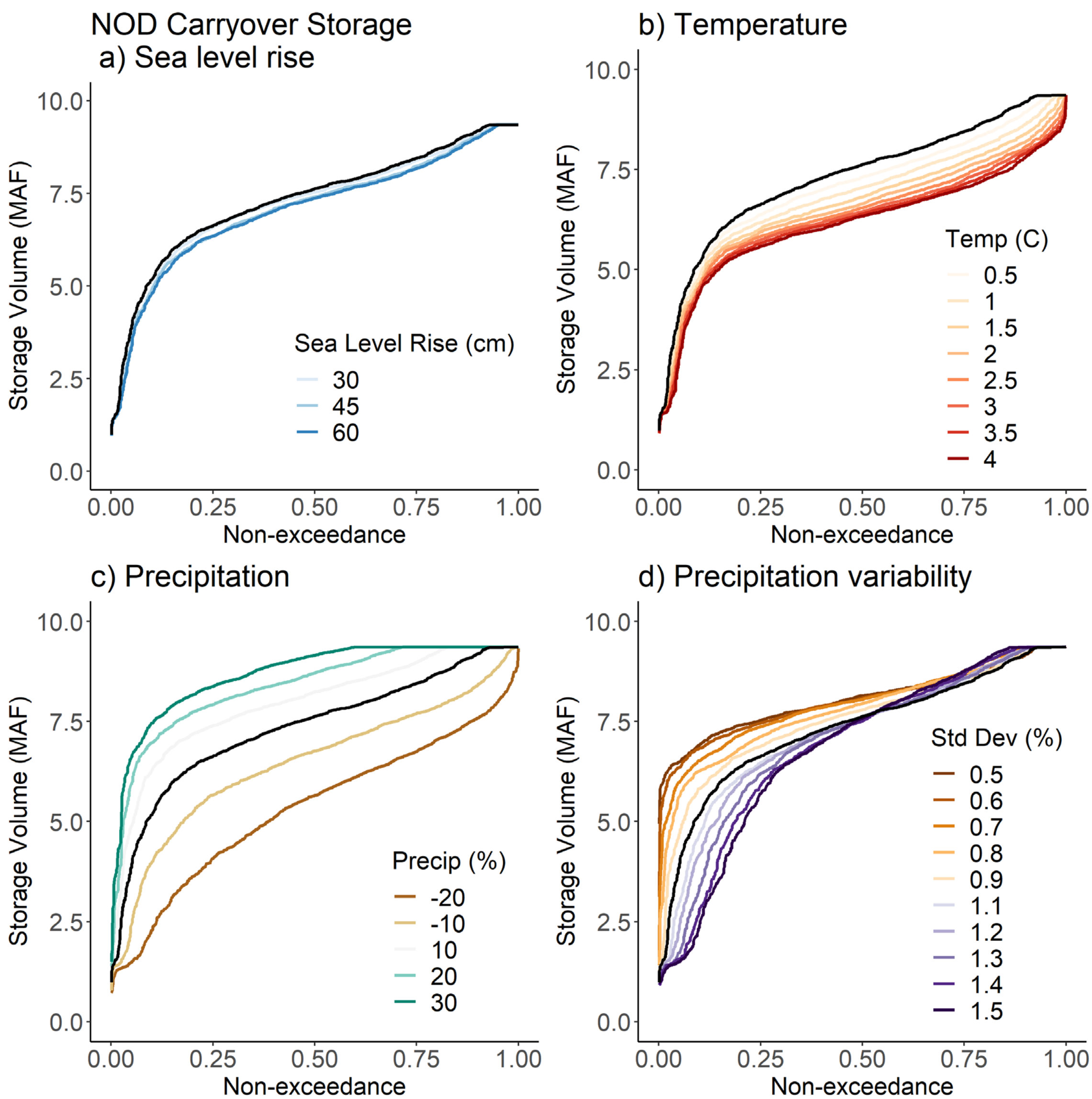


Figure 34 a-d: Cumulative distribution functions showing independent effect of changes in sea level rise, temperature, and precipitation to North of Delta carryover storage in millions of acre-feet.

Figure 34a shows a CDF for the effect of sea level rise on NOD carryover storage volume ranging from 30 cm SLR (light blue) to 60 cm SLR (dark blue). Figure 34b shows a CDF for the effect of temperature increases on storage volume ranging from 0.5 degrees C (light orange) to 4 degrees C (dark red). Figure 34c shows a CDF with a divergent color scheme for the effect of precipitation on storage ranging from -20% (dark brown) to +30% (green). Figure 34d shows a CDF with a divergent color scheme for the effect of precipitation variability on storage volume ranging from 50% (dark orange) to 150% (dark purple) standard deviation. Black curves indicate a baseline of zero change.

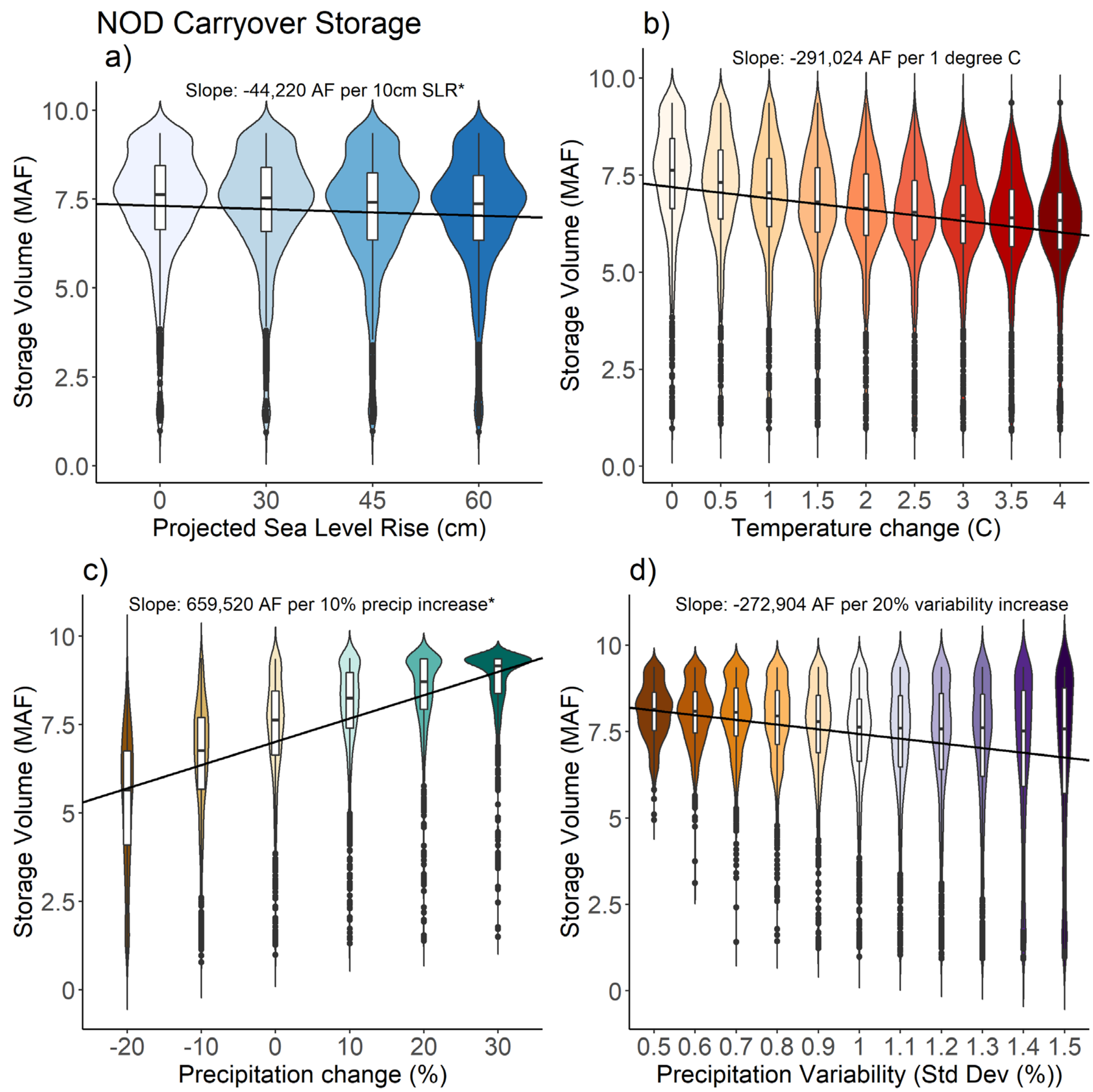


Figure 35 a-d: Violin plots showing independent effect of changes in sea level rise, temperature, and precipitation on North of Delta carryover storage volume in millions of acre-feet.

Figure 35 has four subplots, each showing a series of violins using the same color schemes as in the previous figure. Box plot inside violins shows the interquartile range and median, and vertical lines show range of data (including outliers exceeding the upper and lower interquartile range, indicated by black dots). The width of each violin indicates the probability of data points occurring throughout that range (wider = high probability, thinner = lower probability). Figures have a linear trendline based on a regression between the performance metric and each climate stressor, and trendline slope is noted (p>0.01 for all).

** Standard error > 0.01.*

System Shortages

In order to assess the impacts of changes to climate stressors on shortages, we graphed CDFs on a log-scale to be able to identify changes in performance. The inset tables provide additional information about the number of years in which shortages were observed under each condition. Each inset table shows the percent change in the number of years with shortages greater than 50,000 acre-feet from the baseline for each scenario. For example, 30cm of sea level rise results in 6.7 percent more years with large shortages.

Sea level rise and precipitation amount have the greatest effect on system shortages. Effects are greatest on shortages between 100,000 and 1 million acre-feet. Sea level rise scenarios at 45 and 60cm have essentially the same effect (Figure 36a, Figure 37a). Temperature increases showed very little overall effect on shortages (Figure 36b, Figure 37b). Precipitation has the most significant impact on shortages, with large shifts between -10 percent and -20 percent and between 10 percent and 20 percent (Figure 36c, Figure 37c). For scenarios with low interannual variability in precipitation (change in standard deviation less than 1), there were far fewer years with large shortages, whereas high variability resulted in increased years with large shortages (Figure 36d, Figure 37d).

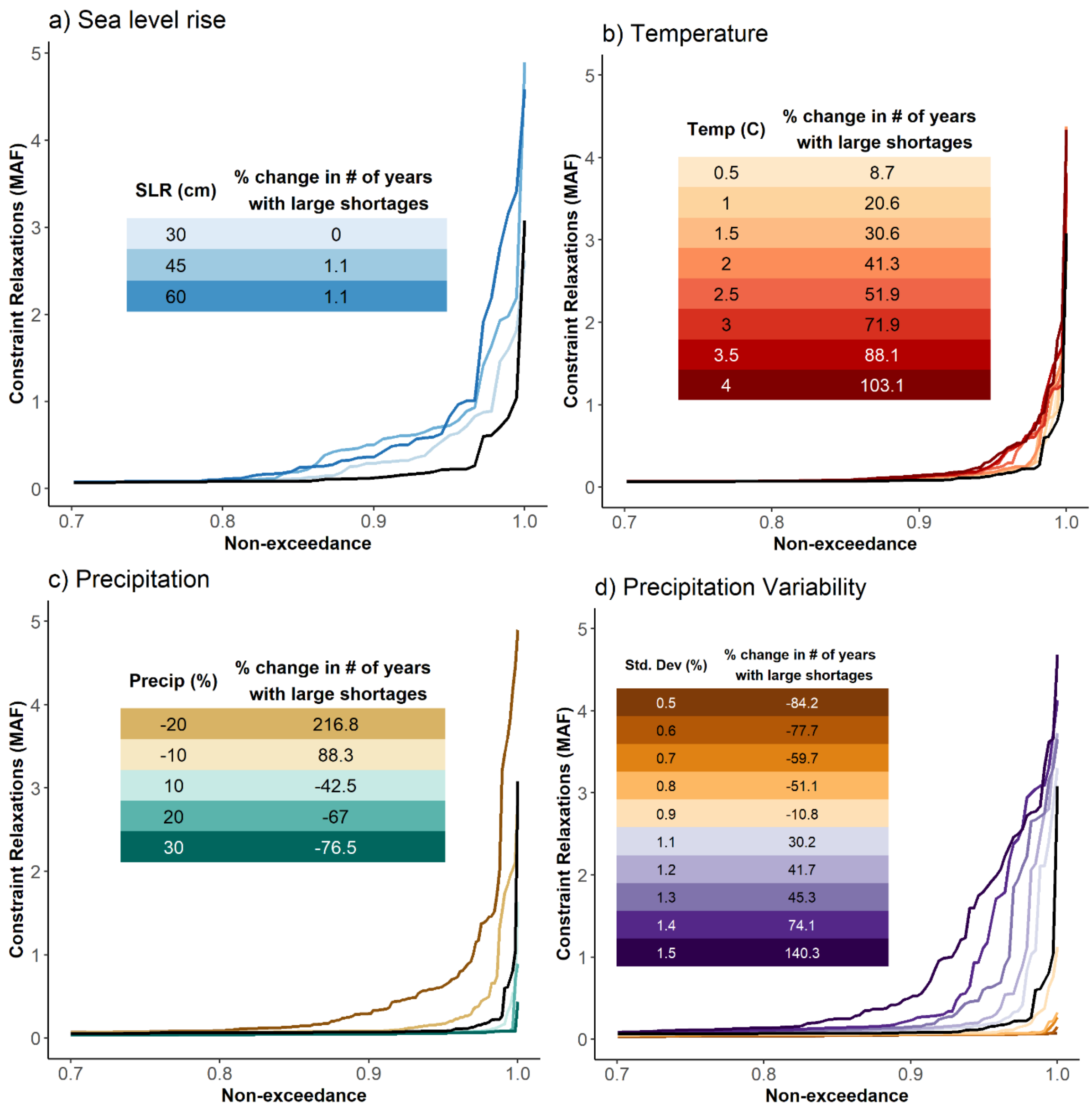


Figure 36 a-d: Cumulative distribution functions showing independent effect of changes in sea level rise, temperature, and precipitation on constraint relaxations (or system shortages) in millions of acre-feet.

Figure 36a shows a CDF for the effect of sea level rise on shortage volume ranging from 30 cm SLR (light blue) to 60 cm SLR (dark blue). Figure 36b shows a CDF for the effect of temperature increases on shortage volume ranging from 0.5 degrees C (light orange) to 4 degrees C (dark red). Figure 36c shows a CDF with a divergent color scheme for the effect of precipitation on shortage volume ranging from -20% (dark brown) to +30% (green). Figure 36d shows a CDF with a divergent color scheme for the effect of precipitation variability on shortage volume ranging from 50% (dark orange) to 150% (dark purple) standard deviation. Black curves indicate a baseline of zero change. Tables indicate the percent change in the number of years with a shortage >50k acre-feet over the baseline for each scenario of changing stress.

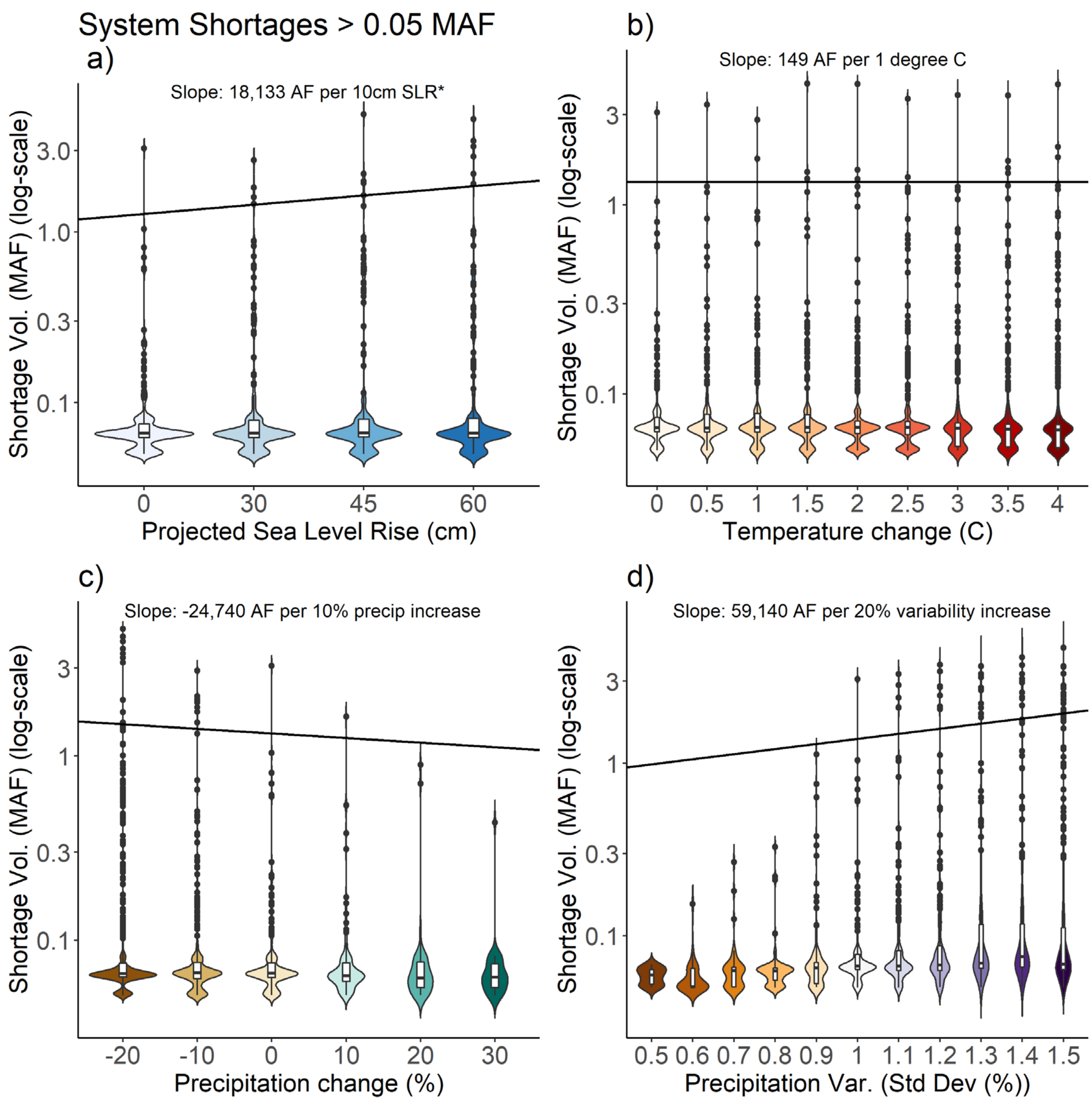


Figure 37 a-d: Violin plots showing independent effect of changes in sea level rise, temperature, and precipitation on system shortage volume in millions of acre-feet.

Figure 37 has four subplots, each showing a series of violins using the same color schemes as in the previous figure. Box plot inside violins shows the interquartile range and median, and vertical lines show range of data (including outliers exceeding the upper and lower interquartile range, indicated by black dots). The width of each violin indicates the probability of data points occurring throughout that range (wider = higher probability, thinner = lower probability). Figures have a linear trendline based on a regression between the performance metric and each climate stressor, and trendline slope is noted ($p>0.01$ for precipitation and precipitation variability, $p>0.01$ for SLR and temperature). All y-axes are on a log scale to better visualize differences in data distribution across scenarios.

** Standard error > 0.01.*

14.1.3 Discussion of Sea Level Rise Sensitivity Above 2 Feet

Several studies have estimated the effect of sea level rise on water supply. In general, sea level rise will increase the forcing of salinity intrusion eastward into the Delta. In order to meet current regulatory requirements and provide sufficient quality water for export, this would require release of additional stored water from reservoirs, the reduction of export pumping from the Delta, or both. While the results shown above indicate that increases in SLR will have a relatively minor impact on water supply (in comparison to projected changes in temperature and precipitation), sea level rise increases beyond 3-4 feet at the Golden Gate Bridge, could result in non-linearities in the system response - i.e., a point could be reached at which sea level begins to have much more significant impacts on system performance than the more or less linear trend in impacts shown above.

Sea level rise increases the hydrostatic pressure of saline water from the ocean, effectively increasing salinity in the Delta unless fresh water is released to repel this intrusion (sometimes referred to as a hydraulic salinity barrier). Regardless of whether additional freshwater is released to counteract salinity intrusion, an increase in sea level will increase water levels in channels throughout the Delta. This increase in channel depth increases the potential for salinity dynamics to change (Gross et al. 2009, MacWilliams et al. 2015, Andrews et al. 2017, and Gross et al. 2018). Increased in-channel depth of water can change channel geometry and allow for salinity wedges and gravitational circulation. Salinity wedges are intrusions of more saline water along the channel bottom and are driven by the density difference between freshwater and seawater. The amount of salinity intrusion into the Delta is influenced by the water depth and river flow velocity. Gravitational circulation involves seawater intruding below freshwater, with a portion joining freshwater outflow, and creating space that draws in additional saline water deep in the channel. This circulation of saline water is driven by tidal energy, but is also affected by channel depth. Both factors can draw saline water further into the Delta and require larger amounts of freshwater to flush out and meet current water quality requirements. Sea level rise would increase channel depth and tidal energy in the Delta and is expected to increase salinity. However, the effect on salinity is hypothesized to remain linear at lower levels, when compared to no sea level rise. This effect is also hypothesized to increase more rapidly above a to-be-determined threshold (MacWilliams et al., 2015).

Modeling work conducted for the Bay-Delta Conservation Plan included sea level rise scenarios up to 140 cm (4.6 feet). However, this modeling did not include an operational response. Rather, it was conducted to estimate salinity intrusion and calibrate other models (DSM2). In addition, past work has found that up to 140 cm the salinity impacts of sea level rise appear to be approximately linear (MacWilliams et al., 2016). Up to this level, a regression equation could potentially be used to estimate outflow required to meet water quality objectives.

14.2 Water Supply System Asset Vulnerability to Combined Climate Stressors

Section 14.1, above, discusses how sensitive the Delta water supply system is to each of the climate stressors we evaluated. These evaluations looked at each climate stressor in isolation i.e., no other climate changes occurring. However, climate change is already and will likely continue to drive multiple simultaneous changes to each of the stressors. Changes to one stressor will likely reinforce or exacerbate the changes driven by other stressors making the impacts to the system greater than the sum of impacts from individual stressors. In this section we highlight key findings about the likely impacts to Delta water supplies resulting from the combined impacts of all stressors. For the results below, conclusions are drawn from simulations of the system with changes in temperature, variability of precipitation, and sea level rise all simultaneously occurring throughout the Delta and Delta watershed. The estimates of climate impact reported here provide our best estimate of the likely impacts by 2030 and 2050, as with all estimates of future conditions, actual conditions may end up being better or worse. These estimates are developed by estimating climate impacts across a very wide range of potential climate conditions and then calculating the likely level of impacts by weighting each impact by its relative likelihood of occurrence (as described above).

For each of the four performance metrics (Delta exports, North of Delta reservoir storage in September and April, and system shortages) the mean and standard deviation of the system performance metric is plotted as a response surface to show the sensitivity of long-term system performance over the range of changes in temperature and interannual precipitation variability. On the response surface, the black line represents performance at historical levels; warm colors represent performance worse than historical levels while cool colors represent performance better than historical levels. (In this context better and worse describe the societal values applied to the specific performance metrics, e.g., more carryover storage or Delta exports are better, more shortages are worse.) Changes in color represent sensitivity to a change in climate. The two response surfaces present different aspects of the impacts of climate change. The response surface of mean system performance indicates the direction of change (improving or diminishing performance) of the system overall. The response surface of standard deviation of system performance shows how much more or less variable or reliable the system will be. These two different aspects of performance are important because water supplies depend both on amount of available water and the reliability of that amount of water year after year. For many water suppliers, especially those with minimal storage capacity, higher interannual variability of water supplies will be an additional adaptation challenge.

Results are also presented for annual performance of each metric. These values are presented as cumulative distribution functions (CDF) and probability distribution functions (PDF) to show system performance change across the entire distribution of hydrologic conditions from the wettest years to the driest years. The CDF provides the probability that the system performance will be at or below any given value of system performance, while the PDF provides a measure of the relative likelihood of one level of performance over another or the probability that system performance will fall within a given range. The CDF and PDF take into account the yearly system performance data across all 99 different combinations of temperature and interannual precipitation variability and weights them by the conditional GCM-informed probability density associated with the combination of temperature and interannual precipitation change that produced the simulation. The CDF and PDF for each performance metric can be calculated at current conditions and at any future time period. Comparing the CDF and PDF for current conditions and mid-century conditions illustrates the shift in the distribution of annual performance.

14.2.1 Delta Exports

Figure 38(a) shows an approximately 7 percent decline in average annual exports per degree (°C) of temperature increase. The sensitivity to increasing temperatures is associated with snowpack loss and the reduction of North of Delta carryover storage, which is visible in the strong similarities of the response surfaces between both performance metrics. Average annual exports are comparatively more sensitive to decreases in interannual precipitation variability (approximately 2.5 percent average annual export increase per 10 percent reduction in interannual precipitation variability) than to increases in interannual precipitation variability (<1 percent improvement in average annual exports per 10 percent increase in interannual precipitation variability). Increases in interannual precipitation variability tend to exacerbate the sensitivity of average annual Delta exports to temperature changes, as indicated by the increasing horizontal slope of the color bands as interannual precipitation variability rises. Figure 38(b) indicates annual standard deviation in Delta exports is highly sensitive to both increases and decreases in interannual precipitation variability, with approximately 5 percent increase in average annual export variability per 10 percent increase in interannual precipitation variability and approximately 13 percent reduction in average annual export variability per 10 percent decrease in interannual precipitation variability.

The 2050 conditional probability density, shown overlying the response surface in Figure 38(a) and (b), indicates that there is 95 percent confidence that annual Delta exports will be reduced by 2050 based on current GCM projections. There is a 68 percent chance that those reductions will be between 10 and 20 percent for annual exports with a similar increase in the annual export variability, thus, indicating that there is high confidence that these impacts will be significant and will require substantial adaptation to maintain resilience.

The CDF and PDF of annual Delta exports, shown in Figure 39 (a) and (b), indicate a large overall performance decline at 2050 compared with current conditions. Reductions in exports are more severe during drier years with a decline of 0.94 MAF at the 25th percentile of annual exports compared with current conditions, which is nearly double the 0.53 MAF decline at the 75th percentile. The widening of the PDF of annual exports at 2050 compared to current conditions indicates greater variability in exports. Years with less than 4 MAF of Delta exports increase from about 12 percent of years under current conditions to 25 percent of years at 2050.

Figure 38 a-b: Delta Exports - Sensitivity of Long-term Performance.

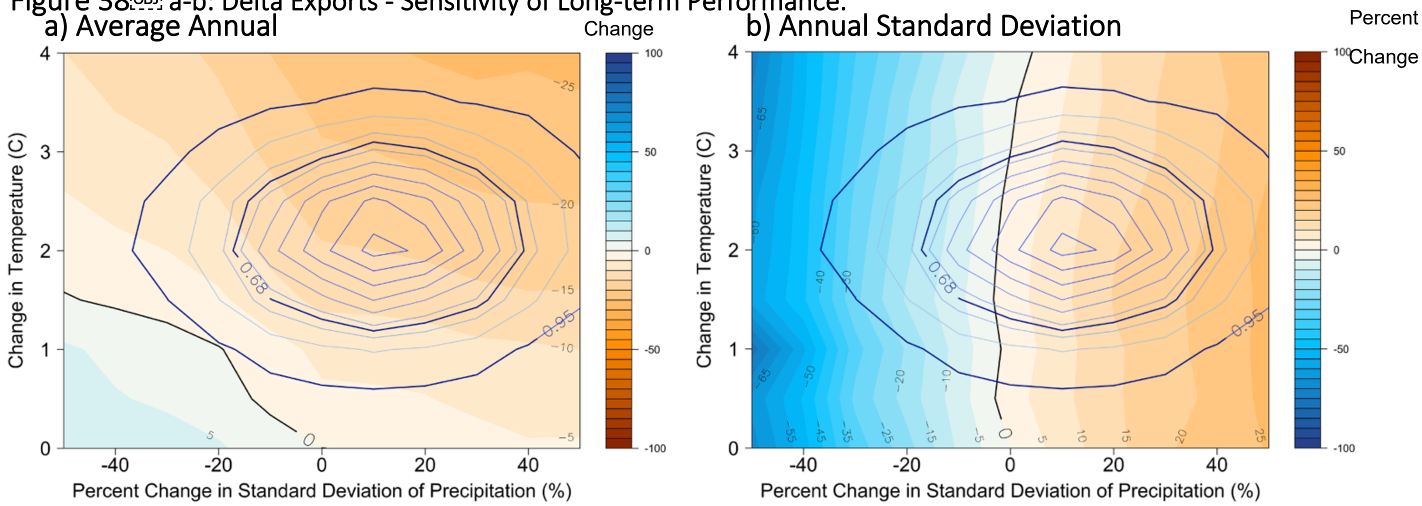
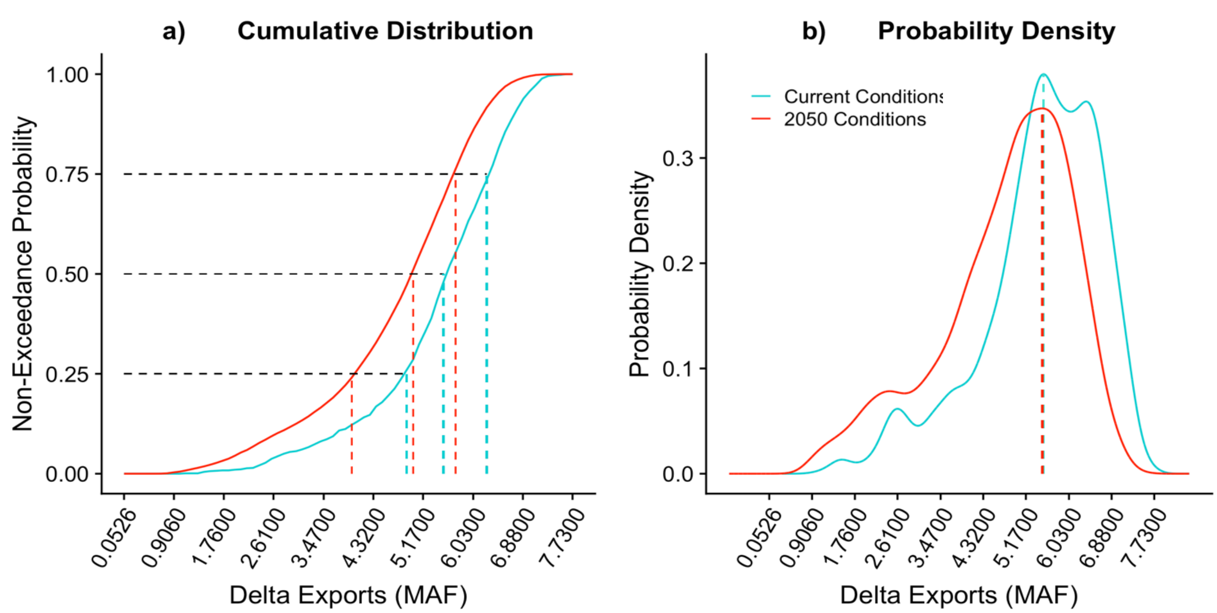


Figure 38 includes two response surfaces showing average annual Delta export volume and annual standard deviation under a range of scenarios of changes in temperature and precipitation. Straight black lines show the temperature and precipitation combinations at which no change in performance from historical values would be expected. Area to the right of the lines indicate performance worse than historical (-100% to 0% change in exports, in orange color scale), and areas to the left indicate performance better than historical (0% to 100% change in exports, in blue color scale). Conditional probability density is shown in concentric circles that indicate confidence intervals.



	P25	P50	P75
Current Conditions	4.89	5.52	6.26
2050 Conditions	3.95	5	5.73

	Mode
Current Conditions	5.52
2050 Conditions	5.5

Figure 39 a-b: Delta Exports – Annual performance at 2050.

Figure 39 shows modeled changes in annual performance of Delta exports by midcentury in a cumulative distribution (a, left) and probability density (b, right). Current conditions are represented in blue, 2050 conditions are in red. Both figures indicate that Delta exports will decrease due to climatic factors and become more variable. While the value of the mode only shifts by approximately 20,000 acre-feet (0.02 MAF), the frequency of that value occurring drops indicating that the certainty with which we can predict or rely on exports will diminish. See Figure 45(b) for the frequency and size of shortages that are projected to occur.

14.2.2 North of Delta End-of-April Storage

North of Delta end-of-April storage is more sensitive to interannual precipitation variability than temperature and sea level. **Figure 40**(a) shows an approximate 1.8 percent improvement in average North of Delta end-of-April storage per 10% increase in interannual precipitation variability. The interannual variability of North of Delta end-of-April storage is more sensitive to decreases in interannual precipitation variability, showing a nearly 100 percent reduction (maximum of the color bar range) with a 30% decrease in interannual precipitation variability. The interannual variability of North of Delta end-of-April storage rises by about 8 percent per 10 percent increase in interannual precipitation variability.

The CDF and PDF of North of Delta end-of-April storage (**Figure 41** a and b) provide context for the sensitivity to changes in interannual precipitation variability. Increases in interannual precipitation variability result in greater frequency of lower storage conditions owing to deeper and more frequent years with below average runoff. Volumetrically, this is expressed by a 0.45 MAF drop in North of Delta end-of-April storage for the 25th percentile at 2050 climate conditions compared to current conditions. Increases in interannual precipitation variability also result in more frequent years of above average runoff; however, since reservoir rule curves limit reservoir capacities to reduce flood risk, corresponding increases in storage at the higher annual performance percentiles are not realized. The PDF of end-of-April storage at 2050 shows this effect with a slight upward shift of 0.2 MAF in the mode of the distribution.

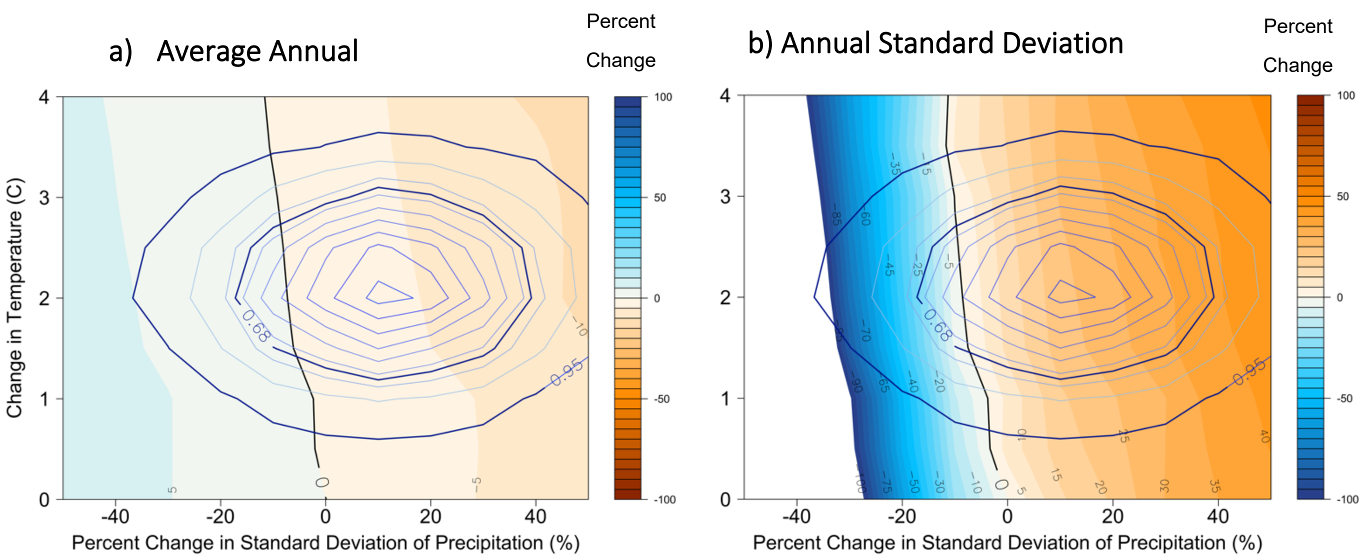
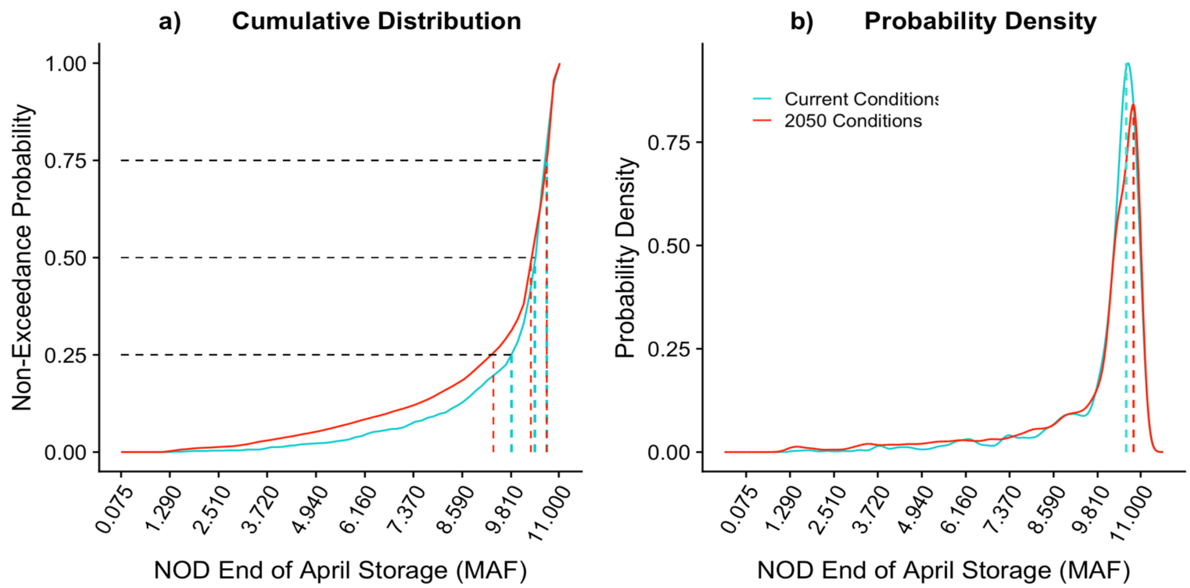


Figure 40 a-b: North of Delta April Storage - Sensitivity of Long-term Performance

Figure 40 (above) includes two response surfaces showing average annual April NOD storage volume and annual standard deviation under a range of scenarios of changes in temperature and precipitation. Vertical black lines show the temperature and precipitation combinations at which no change in performance from historical values would be expected. Areas to the right of the lines indicate performance worse than historical (-100% to 0% change in storage, in orange color scale), and areas to the left indicate performance better than historical (0% to 100% change in storage, in blue color scale). Conditional probability density is shown in concentric circles that indicate confidence intervals.



	P25	P50	P75
Current Conditions	9.82	10.4	10.7
2050 Conditions	9.37	10.3	10.7

	Mode
Current Conditions	10.6
2050 Conditions	10.8

Figure 41 a-b: North of Delta April Storage – Annual Performance at 2050.

Figure 41 shows modeled changes in annual performance of April NOD storage by midcentury in a cumulative distribution (a, left) and probability density (b, right). Current conditions are represented in blue, 2050 conditions are in red. Both figures indicate a low probability that April NOD storage will decrease due to climatic factors.

14.2.3 North of Delta End-of-September “carryover” Storage

Climate change impacts to North of Delta end-of-September “carryover” storage appear to be remarkably similar to the impacts on Delta exports. This is not unexpected; the ability of the CVS system to meet Delta export delivery targets is strongly driven by the amount of storage derived from snowpack runoff and made available during the irrigation season. Reduction in snowpack translates to reductions in surface storage and strains the system’s ability to “carry” water over to the years ahead. Average annual North of Delta carryover storage is comparatively more sensitive to decreases in interannual precipitation variability than to increases in interannual precipitation variability. Just like Delta exports, increases in interannual precipitation variability exacerbate the sensitivity of North of Delta carryover storage to temperature increases, as indicated by the increasing horizontal slope of the color bands along increases in interannual precipitation variability shown in **Figure 42**(a). **Figure 42**(b) indicates annual standard deviation in North of Delta carryover storage is highly sensitive to both increases and decreases in interannual precipitation variability, with an approximate 8 percent increase in storage variability per 10 percent increase in interannual precipitation variability and 20 percent reduction in storage variability per 10 percent decrease in interannual precipitation variability. This indicates that variability in North of Delta carryover storage has even greater sensitivity to interannual precipitation variability than Delta exports.

The 2050 conditional probability density, shown overlying the response surface in **Figure 42**(a) and (b), indicates a 95 percent confidence that North of Delta carryover storage will be reduced by 2050. There is 68 percent confidence that North of Delta carryover storage will decline by 10 to 25 percent. While there is high confidence that average annual North of Delta carryover storage will decline significantly, there is high uncertainty in how the annual variability in North of Delta carryover storage will change. Within the 68 percent confidence interval, change in annual variability ranges from approximately 18 percent decline to 38 percent increase with the outcome largely a function of the variability of precipitation.

The CDF and PDF of North of Delta carryover storage indicate significant overall annual performance declines at 2050 compared to current conditions, both in terms of variability and expected volumes. As shown in **Figure 43** (a), performance declines of more than 1 MAF occur across all annual carryover storage levels with even larger declines in the driest years (10th percentile and below). The North of Delta carryover storage volume of 1.5 MAF, which represents a lowest storage operational target during the driest year conditions, becomes eight times more likely to occur by 2050. North of Delta carryover storage will become significantly more variable by 2050 as the PDF shows the increased frequency of reduced carryover storage conditions in the thickening of the low storage level tail of the distribution and decline in the mode of 0.83 MAF.

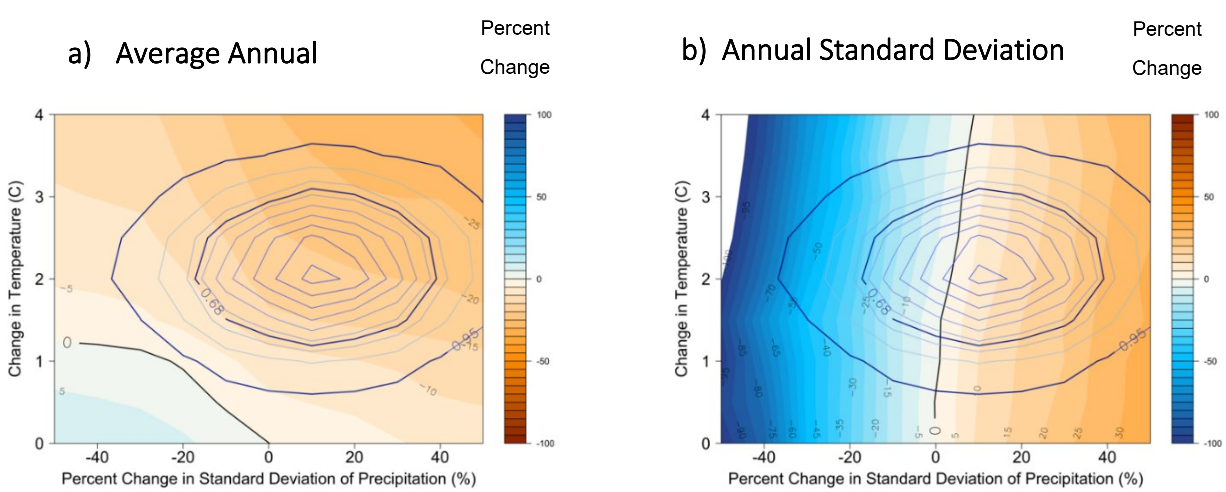
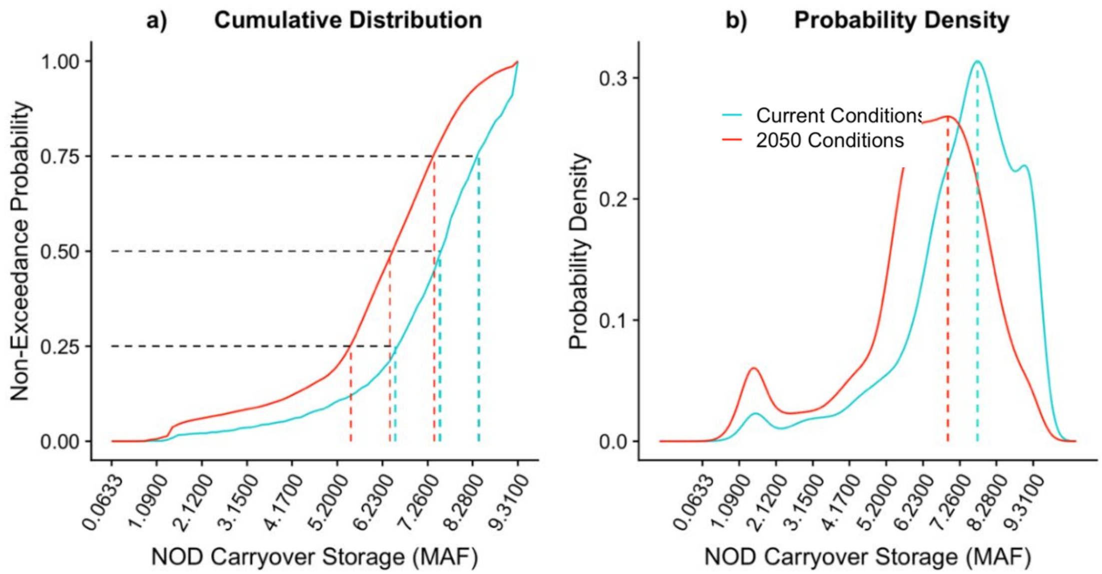


Figure 42a-b: North of Delta September Storage - Sensitivity of Long-term Performance.

Figure 42 includes two response surfaces showing average annual September NOD storage volume and annual standard deviation under a range of scenarios of changes in temperature and precipitation. Vertical black lines show the temperature and precipitation combinations at which no change in performance from historical values would be expected. Areas to the right of the lines indicate performance worse than historical (-100% to 0% change in storage, in orange color scale), and areas to the left indicate performance better than historical (0% to 100% change in storage, in blue color scale). Conditional probability density is shown in concentric circles that indicate confidence intervals.



	P25	P50	P75
Current Conditions	6.52	7.54	8.42
2050 Conditions	5.51	6.4	7.41

	Mode
Current Conditions	7.75
2050 Conditions	6.92

Figure 43 a-b: North of Delta September Storage - Annual Performance at 2050.

Figure 43 shows modeled changes in annual performance of September NOD storage by midcentury in a cumulative distribution (a, left) and probability density (b, right). Current conditions are represented in blue, 2050 conditions are in red. Both figures indicate that September NOD storage will decrease due to climatic factors.

14.2.4 System Shortages

As described earlier in this report, system shortages represent constraint relaxations by the CalLite model to maintain solution feasibility and as such only occur during drier hydrologic conditions. Therefore, change in average annual system shortage is driven predominantly by orders of magnitude increases in shortage volumes during extreme and rare events. The response surface in **Figure 44** indicates that system shortages are sensitive to both interannual precipitation variability and temperature changes. In general, the response shows that average annual shortages rise around 15 percent per 10 percent increase in interannual precipitation variability and around 12 percent per degree (°C) in temperature. Interestingly, system shortages are more sensitive to the first 10-20 percent increase in interannual precipitation variability than the additional 20-50 percent increase in interannual precipitation variability.

The CDF of annual system shortages in **Figure 45** (a) is cropped to the 94th percentile and above to highlight the impacts of climate change during the most severe shortage conditions modeled. In comparing the most severe conditions expected under current climate conditions with the most severe conditions expected under 2050 conditions, system shortages increase by 1200 percent or 0.75 MAF in the driest 2 percent of years, and increase by 178 percent or 3.5 MAF in the driest 0.1 percent of years. The PDF shows a 20 TAF (30 percent) increase in the mode of system shortages and a slight fattening of the tail of the distribution under 2050 conditions. These results suggest that climate change will increasingly lead to rare conditions that result in large and potentially damaging water shortages in which minimum environmental flow targets and other constraints cannot be met.

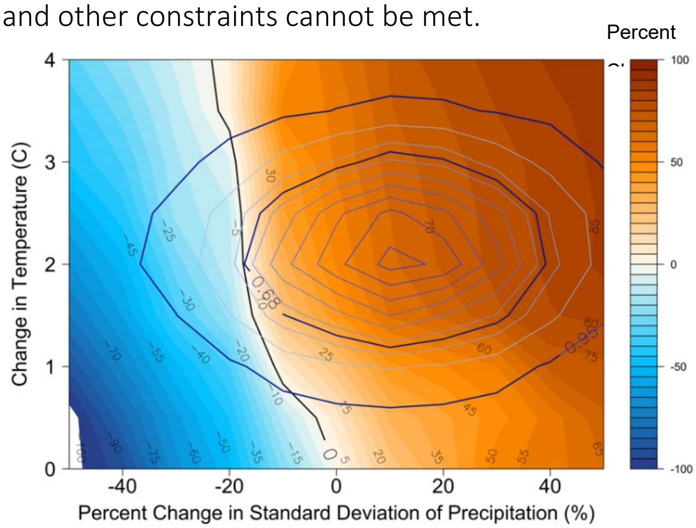
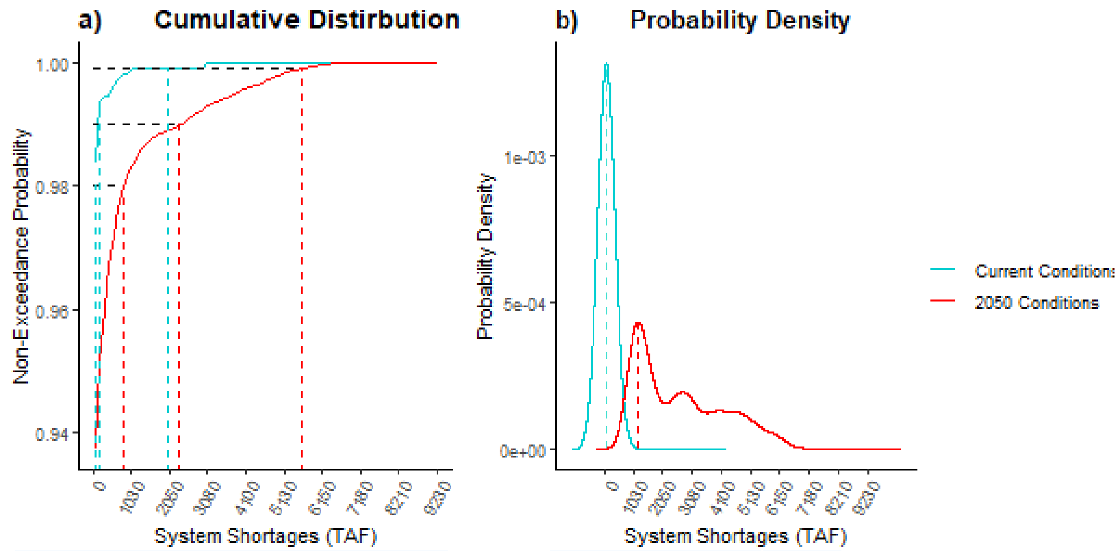


Figure 44: System shortages – average annual sensitivity of long-term performance.

Figure 44 is a response surface showing average annual sensitivity of shortages and annual standard deviation under a range of scenarios of changes in temperature and precipitation. Vertical black line shows the temperature and precipitation combinations at which no change in performance from historical values would be expected. Areas to the right of the lines indicate performance worse than historical (0% to 100% change in shortages, in orange color scale), and areas to the left indicate performance better than historical (0% to -100% change in shortages, in blue color scale). Conditional probability density is shown in concentric circles that indicate confidence intervals.

Figure 45: System Shortages – Annual Performance at 2050.



	P98	P99	P99.9
Current Conditions	62.8	188	2010
2050 Conditions	816	2320	5590

	Mode
Current Conditions	65
2050 Conditions	1180

Figure 45 shows modeled changes in annual performance of system shortages by midcentury in a cumulative distribution (a, left) and probability density (b, right). Current conditions are represented in blue, 2050 conditions are in red. The CDF (a) and PDF (b) indicates that generally shortages will only increase by about 20 TAF per year by 2050, but will increase by millions of acre-feet during the worst droughts (i.e., above the 98 percentile).

Drought conditions

Droughts will become significantly more severe and more frequent as our climate changes. As shown in section 0, changes in precipitation variability disproportionately impact the driest years, resulting in drought impacts being generally worse than impacts to the system in more average and wet years.

Drought Severity

The drought most recently experienced by California between 2012-2016 was one of the driest, warmest, and most damaging in history. By nearly any measure it was a rare event, in terms of soil moisture depletion, the drought registered as a 1 in 1,200-year event (Griffin & Anchukaitis, 2014). Extraordinarily low snowpack levels during the drought were estimated to occur only once in 500 years (Belmecheri et al., 2016). We estimate that under today’s climate conditions and with the water management infrastructure, operations, regulations, and demands of today, conditions as severe as during the 2012-2016 drought would only be experienced twice in 1,100 years (see Figure 26).

While the 2012-2016 drought was rare, it is useful to consider how much more severe a repeat of the meteorological conditions that drove that drought could be if they reoccurred—amplified by the effects of climate change. To evaluate this possibility, we have identified an analogue period of drought within our simulation record of years 900-2000 (as described in section 13.3.1). Section 0 above describes how this historical meteorological record was perturbed to explore potential climate changes. Using these perturbations and the conditional probability estimates of future climate conditions described in section 14.2, we can explore how the conditions during a drought similar to the 2012-2016 drought (as represented by historical years 977-981) change under future climate forcings and how the water supply system would likely respond under such conditions.

Figure 46 shows how Delta exports during the drought period would compare under current, 2030, and 2050 conditions. Average exports over the 5-year period decline 11.5 percent below current conditions under 2030 conditions and 18.5 percent under 2050 conditions.

Reductions in exports is not solely due to the years of the drought being warmer and more variable under a future climate, exports are also reduced because of the warmer more variable conditions of the climate in years running up to the drought. In the September of the year prior to the start of the drought, storage in the major North of Delta CVP and SWP reservoirs declined as well. Under current conditions, simulations show over 8 million acre-feet of water being carried over from September of the year before the drought into the first year of the drought. Under 2030 climate conditions, carryover storage going into the first year of the drought is reduced by 400,000 AF (5 percent), and under 2050 conditions carryover storage going into the first year of the drought is reduced by 760,000 AF or nearly 10 percent.

Reductions in carryover storage are pervasive under future climate conditions. These reductions increase the risks and vulnerability of water supplies to any drought conditions and contribute to making the impacts of droughts more severe.

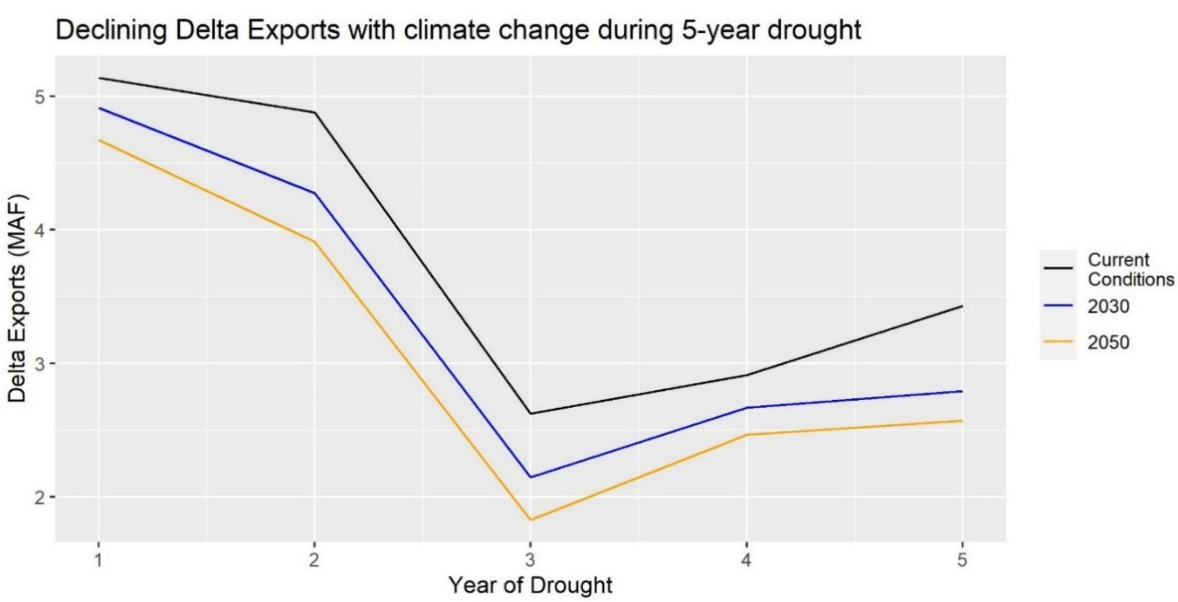


Figure 46: Declining Delta exports with climate change during five-year drought.

Figure 46 shows changes in Delta export volume for three five-year drought periods for current conditions (black), 2030 conditions (blue), and 2050 conditions (yellow).

Drought Frequency

As discussed above, the 2012-2016 drought was by most metrics a rare event. However, warming temperatures, more variable precipitation, and higher sea levels all place additional stress on the water management system and will reduce its ability to provide water supplies as the amounts and reliabilities that have been provided historically. Here we evaluate how much more frequently, under future climate conditions, we might experience severe water supply reductions similar to or worse than those experienced during the 2012-2016 drought.

Applying the two criteria described in section 13.3.2, we find only two previous periods during the last 1,100-years that, under current climate conditions and with current water manage infrastructure, operations, regulations, and demand, match or exceed the severity of the 2012-2016 drought. Those two prior periods were 1843-1847 (5-years) and 1987-1992 (6-years).

Under future climate conditions, the likelihood of experiencing drought conditions like the 2012-2016 drought increase as temperatures increase, sea levels rise, and precipitation becomes more variable as shown in Figure 47.

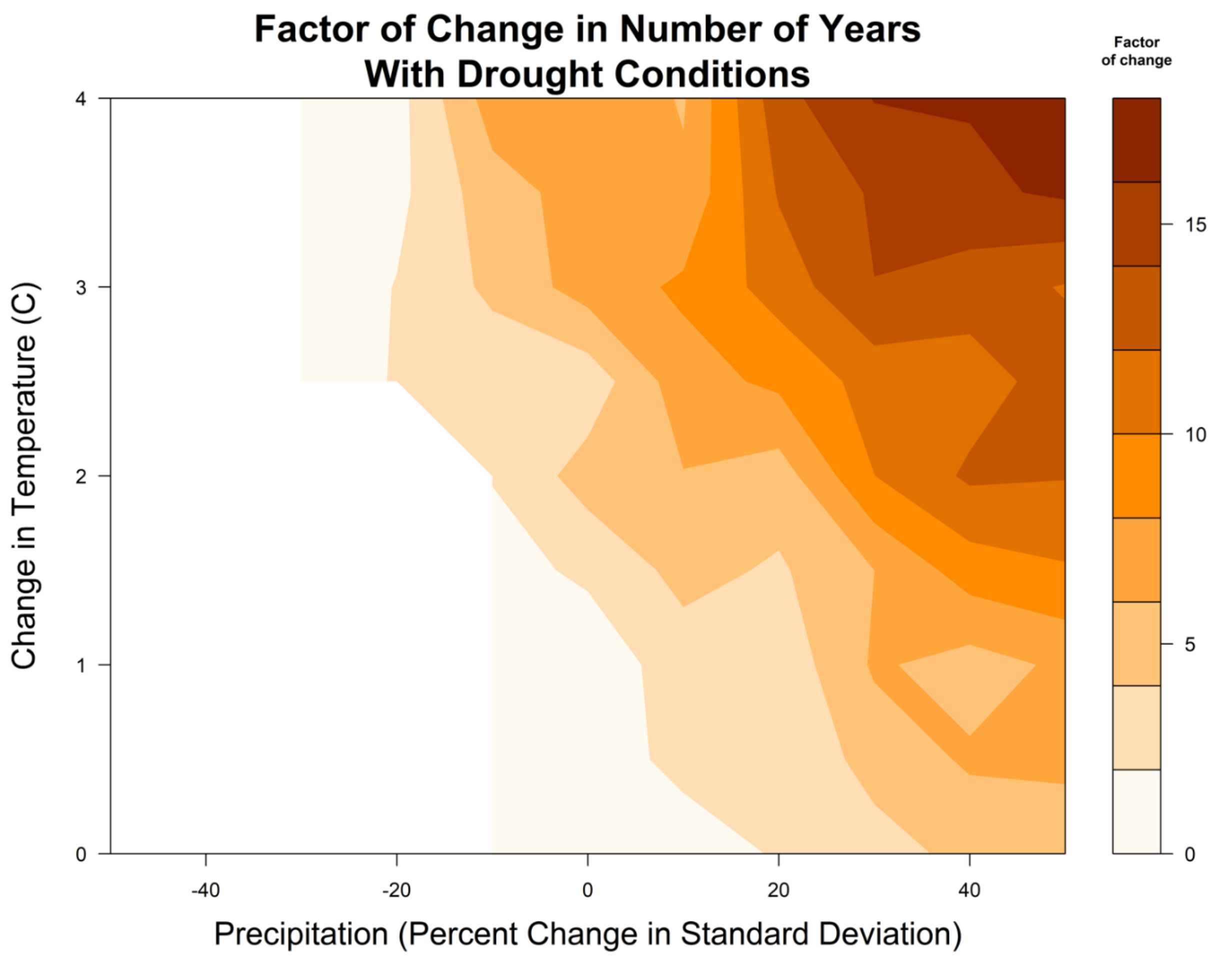


Figure 47: Factor of change in the number years with drought conditions.

Figure 47 shows how the factor of change in the number of years with drought conditions is affected by shifts in precipitation and temperature. Factor of change ranges from 0 (light yellow) to 18 (dark red). Increases to the percent change in standard deviation of precipitation and increases in temperature result in a higher factor of change, or more years with drought conditions expected.

By 2050, temperatures are expected to be about 2 degrees C warmer than today, precipitation about 12% more variable, and sea levels about a 1 foot higher; combined, those conditions would result in drought conditions like 2012-2016 becoming 5-7 times more common.

14.2.5 In-Delta Water Supplies

In-Delta water users' are also likely to face reductions and reduced reliability of their diversions as the climate changes. However, impacts to in-Delta water users are likely to occur specifically in years in which the water delivery system as a whole is stressed and water supplies are extremely limited.

In-Delta users diverting more than 10,000-acre feet per year must report their diversions. However, the primary limit on diversions is due to salinity levels that would negatively impact agricultural crops. Such salinity intrusion was historically an issue in the Delta prior to operation of the State and Federal water projects, especially during droughts and in the fall. More recently, in-Delta water quality regulations aim to protect in-Delta beneficial water use through the Bay-Delta Water Quality Control Plan and Decision D-1641 (D-1641). However, during low Delta inflow conditions it may not be possible to meet these requirements while balancing other beneficial uses. Between 2014 and 2016, because of extremely low flow conditions and low reservoir storage levels, the SWRCB granted Temporary Urgency Change Petitions to temporarily waive portions of flow or water quality requirements. During these temporary conditions, salinity in the Delta increased and in-Delta water diversions were curtailed, impacting in-Delta water users. The modeling and analysis provided above in section 0 related to system shortages is a proxy for these types of extreme conditions occurring under current and future conditions. Historically, these conditions have been rare, occurring only during the driest parts of the year during years with extremely dry conditions. Our analyses indicate that shortages will become slightly more common in the future and that when they occur the shortages will be significantly larger, requiring more substantial trade-offs between beneficial uses and potentially longer periods during which normal regulations and requirements are relaxed. These conditions appear likely to cause increased limitations and disruptions to in-Delta diversions in the future, assuming flow objectives and other factors remain similar.

14.3 Water Supply System Adaptive Capacity

Water supply facilities and operations are human constructed and managed systems and therefore do not have the capacity to passively adapt without human intervention. However, these systems can be adapted through investments to infrastructure, changes in operations, and restoration of watershed and floodplain areas to ameliorate losses in performance. Several structural improvements, such as conveyance infrastructure in the Delta, non-structural improvements, such as upper meadow restoration and forest management in the upper watersheds of the Delta, and operational improvements, such as forecast-based operations of reservoirs have been proposed as potential adaptation strategies for Delta water supplies. Adaptation strategies, such as those evaluated in the California Water Plan Update 2013 and USBR Sacramento-San Joaquin Basin Study, range in cost from a few million dollars to billions of dollars and range in social acceptability from highly acceptable to highly contentious.

14.4 Other Water Supply System Risks and Potential Vulnerabilities

Modeling conducted for this vulnerability assessment identifies higher temperatures and increased precipitation amount and variability as key drivers affecting future water supply. In contrast, sea level rise is projected to have a more nominal effect in all but the most extremely dry years, at least up to 1-2 feet. In addition to primary drivers, several other factors that are not represented in the results of section 0 are relevant to water supply.

One such factor is a potential decrease in ability to predict dry or drought conditions due to loss of snowpack and a larger corresponding percentage of precipitation and runoff coming from rainfall. In this case, decreased snowpack could result in rainfall and runoff early in the year being stored in reservoirs, but with lesser ability to predict water supply conditions later in the year since it will be more dependent on rainfall and reservoir levels throughout the wet season.

A second factor is a potential reduction in allowable storage in order to maintain a flood control buffer. The amount of the buffer is currently described by rule curves. Increased precipitation variability could require a larger buffer – and decreased reservoir storage – in order to accommodate larger, less predictable flows. However, this could also be mitigated or even improved by more accurate short-term forecasting, known as Forecast-Informed Reservoir Operations (FIRO) which allow reservoir operators to adjust storage levels based on watershed conditions and meteorological forecasts.

Third, infrastructure may be more vulnerable to flooding or other risks. Increased precipitation variability, compressed runoff seasons, and aging infrastructure could require more conservative infrastructure operations as noted above, or could result in damage to or failure of infrastructure. For example, dam reservoir failure or flooding of Delta islands could have large impacts to water supply.

These additional factors may have water supply impacts beyond those described in section 0 and would require a scenario-based modeling approach to assess quantitatively.

CHAPTER 15. KEY FINDINGS

This analysis focused on three primary policy and management questions:

1. What are the impacts to the water supply system of sea level rise greater than 1.5 feet (45 cm)?
2. How sensitive is the Delta water supply system to projected changes in the interannual variability of California precipitation?
3. Of the key climate stressors to the water supply system, which drive system vulnerability and which might be most important to monitor to identify observable changes?

These questions guided our analysis of which stressors are likely to affect water supply, and to what degree. Climate stressors considered include temperature, interannual variability of precipitation, amount of precipitation, and sea level rise. Key findings for each stressor are highlighted below, as are expected overall impacts and drought specific impacts. All key findings are summarized in **Table 5**.

Condition	Effect
Higher temperatures *…likely[†] ~2°C by 2050*	• Higher temperatures alone will likely diminish Delta exports by 350,000-500,000 AF/year by 2050 (about 6-9 percent of average annual historical Delta exports).
Higher interannual variability of precipitation *…likely[†] ~15% increase by 2050*	• Higher interannual variability alone will likely diminish Delta exports by 125,000 acre-feet per year (about 2 percent of average annual historical exports) for years at the 25th percentile of exports and by 325,000 acre-feet per year (about 6 percent of average annual historical exports) for years at the 10th percentile of exports.
Higher sea levels *…likely[†] ~1 foot by 2050*	• Sea level rise will have a nominal effect on water supply performance through mid-century, diminishing Delta exports by approximately 34,000 acre-feet per year for each 10 cm of sea level increase but could have a disproportionately substantial impact later in the century under higher sea level conditions.
Consensus of GCM projections suggests both higher temperatures	• Increased occurrence of lower North of Delta end-of-September carryover storage conditions driven primarily by higher temperatures and lower snowpack

and increased interannual variability of precipitation by 2050	will exacerbate the vulnerability of the system to increased precipitation variability. • Average annual Delta exports decline in all year types, with declines most significant in below average years. Years in which Delta exports are below 4 million acre-feet double to 25 percent of years. • Rare years in which there is not enough water to meet all minimum water quality and environmental flow requirements will remain rare, but when they occur, will be more severe causing wider and deeper impacts. • Average annual Delta exports are expected to decrease by approximately 130,000 AF per decade and average annual carryover storage in North of Delta reservoirs are expected to decrease by approximately 220,000 AF per decade, though actual annual decreases of both are expected to be significantly greater in drought years.
California (and the SW US) are prone to high variation in hydrologic conditions independent of climate change, evidenced by multiple medieval "mega" droughts lasting 20 years or more	• Climate changes resulting in greater variability of precipitation and warmer temperatures will make these "naturally occurring" droughts worse in the future.
Drought conditions similar to 2012-2016[††] *Frequency*	• 2050 likely climate conditions make water supply droughts similar to 2012-2016 five to seven times more likely to occur (still a fairly rare event).
Drought conditions similar to 2012-2016[††] *Severity*	• The same 2012-2016 drought, if it were to reoccur with likely 2030 climate conditions, would result in water supply impacts 12% worse, in 2050 impacts would be 19% worse.

† "Likely" refers to the approximate center of the probability distribution function of the global climate model projections at the given time frame, representing the consensus of the models.

†† A drought is defined here as one that is expected to recur once every 500 years and lasting 5-6 years under current climate, infrastructure, and regulatory conditions.

15.1 System Sensitivity to Climate Stressors

15.1.1 Precipitation

We find that the Delta water supply system is most sensitive to changes in the amount of precipitation, with performance across all metrics considered here improving significantly as precipitation goes up and decreasing significantly as precipitation goes down. However, change in the amount of precipitation in the future is the most uncertain aspect of climate change. As stated above, global climate models are approximately evenly split between those that project wetter future conditions for California and those that project drier future conditions. In addition, California and the southwest United States in general are prone to extended dry periods (even without climate change), long periods, in some cases lasting decades, of dry conditions can be considered a stressor independent of climate change.

15.1.2 Interannual precipitation variability

California's climate is characterized by a highly variable Mediterranean climate. While past studies have evaluated impacts to the water supply system of changes in the amount of precipitation or the amount and variability of precipitation, in this study, we have evaluated the impacts to water supply based on changes in interannual variability in precipitation independent of any change in the average amount of precipitation. This analysis is important and informative because global climate model projections of future conditions in California show a wide range of potential changes in the average amount of precipitation- with models about evenly split between models showing drying conditions and wetting conditions. Conversely, our analysis shows that there is more consistency and agreement across global climate model projections of future conditions in California for changes to the interannual variability of precipitation. For this metric, the consensus of the models indicate that future conditions will likely be more variable than historical precipitation conditions by about 15 percent by mid-century. Our analysis further shows that this shift in the interannual variability of precipitation would lead to unique challenges for the Delta water supply system.

For all performance metrics evaluated for this study, changes in interannual variability appear to have the most significant impact in drier years, and only have a marginal impact, if any, in wetter years. Our simulations of Delta exports indicate that under current climate conditions, Delta exports average about 5.46 MAF per year. An increase in interannual variability of precipitation of 15 percent (i.e., the amount of increase projected by the consensus of the models) with no change in any other stressor, would reduce Delta exports by approximately 125,000 acre-feet per year (about 2 percent of average annual historical exports) for years at the 25th percentile of exports and by 325,000 acre-feet per year (about 6 percent of average annual historical exports) for years at the 10th percentile of exports. This means that in those years that already place the most stress on water users because of low Delta export levels, this aspect of a changing climate will disproportionally degrade Delta exports, with the most severe changes occurring in what are already the most stressful years.

Further, increases in the variability of precipitation would lead to increases in the variability of Delta exports, we find that a 10-20 percent increase in the variability of Delta exports is likely by 2050, thus increasing the stress on users of Delta water to manage ever greater swings between high and low export conditions than they have historically experienced. These types of changes would likely require substantial planning and investment in conveyance and storage infrastructure both north and south of the Delta to take advantage of additional water available in wet years (i.e., fewer wet years but wetter conditions in years that are wet) so that the water can be drawn on during dry years—which will become even drier and more frequent.

15.1.3 Temperature

The second most significant stressor, after the amount of precipitation, was found to be temperature. Because of the system's high sensitivity to temperature change and the higher certainty that temperatures will increase in the future (as opposed to high uncertainty about how amount of precipitation will change), the temperature impact of climate change on the Delta water supply system should be of special concern to water managers and climate adaptation decision makers. All global climate model projections agree that temperatures will increase with the consensus of models indicating that temperatures will increase by around 2 degrees Celsius by mid-century over the Delta watershed.

Unlike precipitation amount, increases in temperature do not impact all performance metrics in the same way. End of September or carryover storage at the three major North of Delta reservoirs (Shasta, Oroville, Folsom) is strongly impacted by increasing temperature. But increasing temperature has almost no impact on storage values earlier in the year (April) at the end of the rainfall season. September storage values diminish as temperature increases because winter snowpack is diminished as temperature increases; with less snowpack, there is less spring and summer runoff to replenish reservoir storage as summertime water deliveries are made. Conversely, April storage values see minimal impact because warmer temperatures actually result in more winter precipitation falling as rain instead of snow—and a greater percentage of winter precipitation arriving at the reservoir by April. However, because all three reservoirs are managed for flood protection benefits until April, the additional water often can't be stored and ends up flowing out of the reservoir leaving reservoir storage levels nearly unchanged from historical conditions. This behavior is important to understand as media and public information sources often report on reservoir storage values as a way of communicating to the public the State's water supply picture. This analysis shows that we would not expect to see lower reservoir storage values at the critical April observations. However, while we may often see April storage observations that are at or near historical average values, the impact of a warming climate on storage is likely to manifest later in the season when storage quantities are more critical for ecosystem heath, water supply, and drought hedging.

Delta exports, similar to end of September North of Delta reservoir storage, shows high sensitivity to increases in temperature. Our analysis indicates that for each 1-degree Celsius increase in temperature, average annual Delta exports would decrease by approximately 200,000 acre-feet. By mid-century projected temperature increases of around 2 degrees Celsius will likely decrease Delta exports by 400,000 acre-feet per year or about 7 percent. This impact alone (without considering the impacts of sea level rise or precipitation changes) would significantly alter water supply reliability south of Delta.

15.1.4 Sea Level Rise

We find that the water supply is relatively insensitive to sea level rise in all but the most extremely dry years, at least up to the 60 cm (2 foot) threshold analyzed for this study. This finding reflects current management practices and regulations that establish ranges for salinity and flows within the Delta. The analysis finds that up to this level of sea level rise, water managers can maintain required conditions in the vast majority of years. However, sea level rise may have a substantial impact at higher levels and/or when combined with changes in Delta geometry, such as from island flooding. The relatively smaller near- and medium-term impact of sea level rise should be considered with a view toward longer-term potentially large impacts.

In addition, we find that sea level rise appears to have a stronger correlation and influence on system shortages, i.e., conditions under which there is not enough water to meet all needs and regulations and choices and trade-offs need to be made over which priorities to meet. Sea level rise appears to be an important factor in conditions that lead to especially large system shortages that would cause the greatest impacts to in-Delta water users and ecological resources in the Delta and Delta watershed. While current water management and operations may effectively manage increases in sea level rise generally, the chronic impacts of higher sea levels create greater vulnerability to severe impacts, for example in the form of system shortages when extremely dry conditions occur.

15.1.5 Summary of Sensitivity of Water Supply Performance to Climate Stressors

Table 3 below provides summary metrics for the change in performance metric volume as a function of changes in each climate stressor. This table provides a simplified statistic (linear fit) that can be used to understand how much each performance metric would be expected to change for each increment of climate change that occurs. (We have attempted to present the climate stressor units in a way that normalizes the unit of change to be consistent across all stressors so that each unit represents about 1 fourth to 1 sixth of the uncertainty range for the stressor.)

Table 3. Summary of performance metric sensitivity to climate stressors.

	Volumetric change in performance metric by unit of stress (AF)			
Climate stressor unit	Delta Exports	NOD April	NOD Carryover	System Shortages >50k
10 cm sea level rise	-34,060[1]	-18,223[1,2]	-44,220[1]	18,133[1,2]
1° C temp increase	-210,556	-40,840	-291,024	149[2]
10% precip increase	487,826	461,550[1]	659,520[1]	-24,740
20% increase in precip variability	-168,538	-330,874	-272,904	59,140

1 standard error > 0.01

2 p-value > 0.01.

15.2 Expected Climate Change Impacts to the Delta Water Supply System

Climate change will place greater stress on the water supply system. Loss of snowpack due to rising temperatures will reduce the amount of streamflow entering reservoirs in spring and summer reducing reservoir storage levels. Precipitation in California is expected to get even more variable, resulting in more extreme wet and extreme dry years. In the extreme wet years, storage and conveyance infrastructure will be unable to capture and deliver the extra water—thus these additional wet years will provide little benefit to water supply given current infrastructure and operations. When dry years do occur, our carryover storage going into these years will, on average, be lower than historical levels exposing water users and the environment to greater vulnerability and impacts.

Section 0, discusses how sensitive the Delta water supply system is to each of the climate stressors we evaluated. These evaluations looked at each climate stressor in isolation i.e., no other climate changes occurring. However, climate change is already and will likely continue to drive multiple simultaneous changes to each of the stressors. In this section we highlight key findings about the likely impacts to Delta water supplies resulting from the combined impacts of all stressors. For the results below, conclusions are drawn from simulations of the system with changes in temperature, precipitation, and sea level rise all occurring. The estimates of climate impact reported here provide our best estimate of the likely impacts by 2030 and 2050, as with all estimates of future conditions, actual conditions may end up being better or worse. These estimates are developed by estimating climate impacts across a very wide range of potential climate conditions and then calculating the likely level of impacts by weighting each impact by its relative likelihood of occurrence (as described above).

Based on the CMIP5 GCM ensemble, there is a very high likelihood (95 percent confidence) that annual Delta exports will be reduced by 2050. The most likely range of Delta export outcomes by 2050 will be between a 10 and 20 percent reduction for annual exports and a similar increase in annual export variability. Overall, we find a significant performance decline at 2050 compared with current conditions across the entire range of year types. However, reductions to exports are most severe during drier years (lowest quartile) with a decline of nearly a million acre-feet (20 percent) in the driest years as compared to the driest years under current conditions. We find that the percentage of years in which Delta exports fall below 4 million acre-feet will increase from about 12 percent under current climate conditions, to nearly 25 percent under 2050 conditions. There is high confidence that these reductions will be significant and will require substantial adaptation to maintain resilience.

For North of Delta storage, climate impacts are expected to affect end-of-September or carryover storage much more severely than storage at the end April. April storage in reservoirs is expected to remain largely unchanged at 2050 when compared to historical conditions, except in the driest quartile of years. In these years, storage volumes are expected to decrease by about 5 percent. Conversely, North of Delta carryover storage volumes at 2050 are expected to decrease by about 15 percent in all year types—a loss of approximately 1 million acre-feet of water storage that represents one of California's most important hedges against dry winter conditions and extended droughts. This shift would increase the vulnerability of resources throughout California that depend on Delta watershed water supplies.

Lower carryover storage conditions and higher likelihood of extreme hot and dry conditions combined with higher sea levels in the future are also highly likely to lead to situations in which there is not enough water in the system to meet all regulatory requirements—necessitating some type of extraordinary management. Historically, these conditions have occurred but have been rare. During the 2012-2016 drought, the SWRCB relaxed Delta water quality requirements after requests from the State and federal water project operators indicated that relaxations were needed to avoid more damaging water shortages later in the year. We estimate that while shortage conditions, like those experienced during the 2012-2016 drought, are not expected to become much more frequent, when they do occur under future conditions, they are likely to be much more severe—meaning the gap between the amount of water needed to meet all water quality and flow requirements and the amount available will be much larger. This would lead to the need for greater deviations from regulations and consequently greater impacts to resources and likely in-Delta water users.

As described above, the impacts of climate change on the water supply system will occur differently in different water year types and in different ways to different parts of the system. Table 4 below show a simplified representation of how climate impacts will unfold on Delta water supplies indicating that losses in performance (water supply reliability and volume) will continue to mount overtime, accumulating with each decade and increasing the necessity and difficulty of adaptation.

Table 4: Summary of performance metric change by decade based on current GCM projections of changes in temperature, precipitation variability, and sea level; and current system operations, and regulations. Volume change per decade indicates how much each performance metric can be expected to change with each successive decade over the period 2000-2060. Linear trends are presented as a simplified metric of change, these changes will occur differentially in different year types, as explained in previous sections.

Performance Metric	Volume change per decade (AF)[1]
Delta Exports	-132,000
North of Delta April Storage	-62,000
North of Delta Carryover Storage	-217,000
System Shortages (>50kaf)	16,000
[1] Standard error for all metrics was less than 0.0022 and P-value was less than 2e-16	

15.3 Drought Impacts

The 2012-2016 drought caused significant economic, social, and environmental impacts throughout California. If a similar drought were to reoccur under future climate conditions—with warmer temperatures, higher sea levels, and more variable precipitation, it would likely be much more severe. In addition, those extreme meteorological conditions that created the drought would hit a system that had significantly less water in storage going into the drought. Reductions in carryover storage are pervasive under future climate conditions. These reductions increase the risks and vulnerability of water supplies to any drought conditions and contribute to making the impacts of droughts more severe.

Average Delta exports during the 2012-2016 drought, if it were to reoccur under 2030 climate conditions would be 11.5 percent lower than those experienced during the actual 2012-2016 drought and under 2050 climate conditions would be 18.5 percent lower.

Drought conditions are not only likely to become more severe, but also more common. It is estimated that under today's climate conditions and with the existing water management infrastructure, operations, regulations, and demands of today, conditions as severe as during the 2012-2016 drought would only be experienced twice in 1,100 years. However, warming temperatures, more variable precipitation, and higher sea levels all place additional stress on the water management system and will reduce its ability to provide water supplies at the amounts and reliabilities that have been provided historically.

By 2050, temperatures are expected to be about 2 degrees C warmer than today, precipitation about 12% more variable, and sea levels about a 1 foot higher; combined, those conditions would result in drought conditions like 2012-2016 becoming 5-7 times more common.

15.4 Summary of Key Findings

Table 5: Summary of key findings. This table summarizes the findings of the analysis conducted above. All findings and likelihood projections are based on currently available global climate models. Some of the findings in this table have been simplified, which often necessitated the loss of nuances in how impacts may occur, readers should review the full results section for a deeper understanding of these nuances.

Condition	Effect
Higher temperatures *...likely*† *~2°C by 2050*	• Higher temperatures alone will likely diminish Delta exports by 350,000-500,000 AF/year by 2050 (about 6-9 percent of average annual historical Delta exports).
Higher interannual variability of precipitation *...likely*† *~15% increase by 2050*	• Higher interannual variability alone will likely diminish Delta exports by 125,000 acre-feet per year (about 2 percent of average annual historical exports) for years at the 25th percentile of exports and by 325,000 acre-feet per year (about 6 percent of average annual historical exports) for years at the 10th percentile of exports.
Higher sea levels *...likely*† *~1 foot by 2050*	• Sea level rise will have a nominal effect on water supply performance through mid-century, diminishing Delta exports by approximately 34,000 acre-feet per year for each 10 cm of sea level increase but could have a disproportionately substantial impact later in the century under higher sea level conditions.
Consensus of GCM projections suggests both higher temperatures and increased interannual variability of precipitation by 2050	• Increased occurrence of lower North of Delta end-of-September carryover storage conditions driven primarily by higher temperatures and lower snowpack will exacerbate the vulnerability of the system to increased precipitation variability. • Average annual Delta exports decline in all year types, with declines most significant in below average years.

	Years in which Delta exports are below 4 million acre-feet double to 25 percent of years. • Rare years in which there is not enough water to meet all minimum water quality and environmental flow requirements will remain rare, but when they occur, will be more severe causing wider and deeper impacts. • Average annual Delta exports are expected to decrease by approximately 130,000 AF per decade and average annual carryover storage in North of Delta reservoirs are expected to decrease by approximately 220,000 AF per decade, though actual annual decreases of both are expected to be significantly greater in drought years.
California (and the SW US) are prone to high variation in hydrologic conditions independent of climate change, evidenced by multiple medieval “mega” droughts lasting 20 years or more	• Climate changes resulting in greater variability of precipitation and warmer temperatures will make these “naturally occurring” droughts worse in the future.
Drought conditions similar to 2012-2016[††] *Frequency*	• 2050 likely climate conditions make water supply droughts similar to 2012-2016 five to seven times more likely to occur (still a fairly rare event).
Drought conditions similar to 2012-2016[††] *Severity*	• The same 2012-2016 drought, if it were to reoccur with likely 2030 climate conditions, would result in water supply impacts 12% worse, in 2050 impacts would be 19% worse.
† “Likely” refers to the approximate center of the probability distribution function of the global climate model projections at the given time frame, representing the consensus of the models. †† A drought is defined here as one that is expected to recur once every 500 years and lasting 5-6 years under current climate, infrastructure, and regulatory conditions.	

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CHAPTER 17. SUPPORTING APPENDICES

Appendix A

Supplemental Tables

Table S1 Modelling Groups and CMIP5 Models and Used in this Assessment

Modeling center (or group)	Institute ID	Model name
Commonwealth Scientific and Industrial Research Organization (CSIRO) and Bureau of Meteorology (BOM), Australia	CSIRO-BOM	ACCESS1.0 ACCESS1.3
Beijing Climate Center, China Meteorological Administration	BCC	BCC-CSM1.1 BCC-CSM1.1(m)
Canadian Centre for Climate Modelling and Analysis	CCCMA	CanESM2
National Center for Atmospheric Research	NCAR	CCSM4
Community Earth System Model Contributors	NSF-DOE-NCAR	CESM1(BGC) CESM1(CAM5)
Euro-Mediterranean Center on Climate Change	CMCC	CMCC-CM
Centre National de Recherches Meteorologiques / Centre Europeen de Recherche et Formation Avancees en Calcul Scientifique	CNRM-CERFACS	CNRM-CM5
Commonwealth Scientific and Industrial Research Organization in collaboration with Queensland Climate Change Centre of Excellence	CSIRO-QCCCE	CSIRO-Mk3.6.0
EC-Earth consortium with Swedish Meteorological and Hydrological Institute (SMHI)	EC-EARTH	EC-EARTH
LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences and CESS, Tsinghua University	LASG-CESS	FGOALS-G2
The First Institute of Oceanography, SOA, China	FIO	FIO-ESM
NOAA Geophysical Fluid Dynamics Laboratory	NOAA GFDL	GFDL-CM3 GFDL-ESM 2G GFDL-ESM 2M

Modeling center (or group)	Institute ID	Model name
National Institute of Meteorological Research/Korea Meteorological Administration	NIMR/KMA	HadGEM2-AO
Met Office Hadley Centre	MOHC	HadGEM2-CC HadGEM2-ES
Institute for Numerical Mathematics	INM	INM-CM4
Institute Pierre-Simon Laplace	IPSL	IPSL-CM5A-MR IPSL-CM5A-LR IPSL-CM5B-LR
Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies	MIROC	MIROC-ESM MIROC-ESM-CHEM
Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	MIROC	MIROC5
Max Planck Institute for Meteorology	MPI-M	MPI-ESM-MR MPI-ESM-LR
Meteorological Research Institute	MRI	MRI-CGCM3
Norwegian Climate Centre	NCC	NorESM1-M NorESM1-ME

Table S2 Change in standard deviation and average of annual precipitation and average annual temperature at 2050 for 32 CMIP5 models (RCP 4.5)

Model	RCP	Standard Deviation of Precipitation Change (%)	Average Annual Precipitation Change (%)	Average Annual Temperature Change (°C)
ACCESS1-0	RCP4.5	8	3	1.97
ACCESS1-3	RCP4.5	30	2	1.84
BCC-CSM1-1	RCP4.5	15	1	1.54
BCC-CSM1-1-M	RCP4.5	-11	0	1.26
CANESM2	RCP4.5	-2	13	2.42
CCSM4	RCP4.5	1	3	1.56
CESM1-BGC	RCP4.5	-2	4	1.45
CESM1-CAM5	RCP4.5	15	-4	1.96
CMCC-CM	RCP4.5	2	-8	1.87
CNRM-CM5	RCP4.5	57	19	1.62
CSIRO-MK3-6-0	RCP4.5	-7	1	2.42
FGOALS-G2	RCP4.5	5	-5	1.95
FIO-ESM	RCP4.5	-14	-2	0.67
GFDL-CM3	RCP4.5	15	-3	2.65
GFDL-ESM2G	RCP4.5	77	-3	1.68
GFDL-ESM2M	RCP4.5	10	6	1.22
HADGEM2-AO	RCP4.5	31	-1	2.52
HADGEM2-CC	RCP4.5	9	8	2.12
HADGEM2-ES	RCP4.5	4	0	2.28
INMCM4	RCP4.5	-14	-4	0.89

IPSL-CM5A-LR	RCP4.5	14	-3	2.24
IPSL-CM5A-MR	RCP4.5	38	5	2.11
IPSL-CM5B-LR	RCP4.5	3	2	1.47
MIROC-ESM	RCP4.5	8	-10	3.01
MIROC-ESM-CHEM	RCP4.5	2	-2	2.83
MIROC5	RCP4.5	5	-6	1.83
MPI-ESM-LR	RCP4.5	54	1	1.69
MPI-ESM-MR	RCP4.5	57	9	1.89
MRI-CGCM3	RCP4.5	8	2	1.06
NORESM1-M	RCP4.5	19	4	2.01
NORESM1-ME	RCP4.5	0	-2	1.72

Table S3 Change in standard deviation and average of annual precipitation and average annual temperature at 2050 for 32 CMIP5 models (RCP 8.5)

Model	RCP	Standard Deviation of Precipitation Change (%)	Average Annual Precipitation Change (%)	Average Annual Temperature Change (°C)
ACCESS1-0	RCP8.5	3	-13	2.69
ACCESS1-3	RCP8.5	25	6	2.42
BCC-CSM1-1	RCP8.5	58	10	2.34
BCC-CSM1-1-M	RCP8.5	6	9	1.87
CANESM2	RCP8.5	19	25	3.10
CCSM4	RCP8.5	-11	-4	1.89
CESM1-BGC	RCP8.5	0	2	2.10
CESM1-CAM5	RCP8.5	30	12	2.70
CMCC-CM	RCP8.5	-35	-2	2.50
CNRM-CM5	RCP8.5	45	12	2.32
CSIRO-MK3-6-0	RCP8.5	19	2	2.75
FGOALS-G2	RCP8.5	-23	-3	2.43
FIO-ESM	RCP8.5	-9	6	1.33
GFDL-CM3	RCP8.5	2	-1	3.19
GFDL-ESM2G	RCP8.5	30	7	2.00
GFDL-ESM2M	RCP8.5	45	-1	2.06
HADGEM2-AO	RCP8.5	14	5	3.00
HADGEM2-CC	RCP8.5	7	13	3.13
HADGEM2-ES	RCP8.5	0	-2	3.11
INMCM4	RCP8.5	-13	-11	1.49

IPSL-CM5A-LR	RCP8.5	10	2	2.87
IPSL-CM5A-MR	RCP8.5	5	4	3.17
IPSL-CM5B-LR	RCP8.5	15	6	2.09
MIROC-ESM	RCP8.5	-15	-11	3.88
MIROC-ESM-CHEM	RCP8.5	-6	-11	3.41
MIROC5	RCP8.5	-9	-11	2.48
MPI-ESM-LR	RCP8.5	1	-5	2.49
MPI-ESM-MR	RCP8.5	91	5	2.30
MRI-CGCM3	RCP8.5	-6	21	1.45
NORESM1-M	RCP8.5	18	-5	2.57
NORESM1-ME	RCP8.5	1	-1	2.15

Appendix B

CLIMATE CHANGE AND WATER SYSTEM VULNERABILITY ASSESSMENT TOOLS AND APPROACHES

1.1 Global Climate Models

Global Climate Models (GCMs) help simulate impacts to precipitation and temperature, which in turn affect water supply. For state-specific studies, GCM data is generally downscaled to a finer spatial resolution. There are multiple different downscaling methods, such as bias correction (quantile mapping), Bias Correction and Constructed Analogues (BCCA), Multivariate Adapted Constructed Analogues (MACA), Regional Climate Model (RCM) evaluation, dynamical downscaling, and Localized Constructed Analogs (LOCA). Each of these have different strengths and weakness. Limitations include not preserving model-projected changes, muting extremes, and potentially missing the impacts of atmospheric rivers. LOCA has emerged as a commonly used tool, especially in California, in recent years due to its high resolution (1/16th degree spatial resolution, or around 6 km / 3.7 mi) while maintaining both extremes and seasonal means fairly well. The output of these downscaled GCMs can then be input into rainfall-runoff models including VIC, SAC-SMA, HEC-HMS, and others to predict runoff and reservoir inflows.

1.2 Rainfall-Runoff Models

The Variable Infiltration Capacity (VIC) model is a rainfall-runoff model. VIC is a largescale, semi-distributed hydrological model that solves water and energy (i.e. solar flux) balances (Liang et al., 1994). VIC provides a way to couple GCMs with a land-surface model and to simulate water balance and inflow to reservoirs and the Delta under various climate scenarios. Streamflow routing may be performed using a separate model, which ultimately provides flow at a given location, such as a dam or inflow into the Delta. These daily flows can then be integrated with monthly operational models such as CalSim, and analyzed for water supply impacts. This is an important step, because modeled VIC flows can vary greatly from managed flows, given the large reservoirs and complex water management system in California.

1.3 Operational Models

Operational models that have been used in past analyses of California's integrated Central Valley water system include CalSim2 and 3, CalLite, SACWAM, and WEAP. For water supply assessments, there are two broad approaches that are generally used: Level of Development and transient. These are described below. CalSim3 remains a beta product and is not recommended for production work at this time (H. Yin, personal communication, September 13, 2019).

1.4 Modeling Development Approaches

Level of Development studies include those conducted for California's Fourth Assessment, background for the Water Quality, Supply, and Infrastructure Improvement Act of 2014

(Proposition 1), and the 2014 Sustainable Groundwater Management Act (SGMA). These studies broadly assess water supply impacts by selecting a projected level of development, or physical characteristics of the land surface for a future year, in this case 2030. Land surface characteristics in turn are modeled for how they would affect evapotranspiration, runoff, and other variables. The values from this single year, 2030, are then used to statistically adjust runoff and water management operations for a historic period (1922-2003 for CalSim2, 1922-2015 for CalSim3) and to project managed flows in the future. This approach has an advantage in that it uses observed hydrology as a foundation. This means that the inputs are known to be possible to occur in California, and therefore the outputs are likely possible as well. However, this also constrains outputs to the observed record, whereas future climate conditions could result in conditions that have not been observed in the historic record. For this study the historic period will be extended for the period 900-2010 AD, similar to work by Schwarz et al. 2018. This 1,100-year stream flow record will help encompass a greater range of climatic conditions.

Transient modeling studies include those conducted under the Water Evaluation and Planning model (WEAP) (used by the 2013 California Water Plan and the Sacramento Water Allocation Model, SacWAM), the U.S. Bureau of Reclamation Basin West-Wide Climate Risk Assessment (Tansey et al., 2014), and other studies analyzing water supply and related issues (N. Knowles et al., 2018; Noah Knowles & Cronkite-Ratcliff, 2018). Cal-Adapt data is another example of transient modeling, providing precipitation and temperature, prior to operational modeling. A transient modeling approach uses the output of GCMs to simulate precipitation, runoff, and Delta inflows. Similar to level of development studies, this approach can also use operational models such as CALSIM to simulate managed flows. However, transient modeling differs in that future projections are not statistically adjusted based on the observed historical record. This allows modeled precipitation and temperature data to include ranges beyond those observed, but means that it is less certain if such values are likely to occur in the future.

1.5 Regulatory and Other Assumptions

Almost all climate change and water supply studies for California use existing water quality or flow regulatory requirements (e.g., D-1641). Similarly, most quantitative studies to date have used a maximum sea level rise projection equal to or less than 45 cm (1.5 feet) at the Golden Gate Bridge. This has implications for compliance with D-1641 because higher sea level rise projections released in recent years could make compliance with current regulations difficult or unfeasible in light of water demand and Delta exports to other regions of the state. In addition, some studies do not include sea level rise (N. Knowles et al., 2018).