Climate change and the Delta

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Abstract:

Anthropogenic climate change amounts to a rapidly approaching, “new” stressor in the Sacramento-San Joaquin Delta system. In response to California’s extreme natural hydroclimatic variability, complex water-management systems have been developed, even as the Delta’s natural ecosystems have been largely devastated. Climate change is projected to challenge these management and ecological systems in different ways characterized by different levels of uncertainty. For example, there is high certainty that climate will warm by about 2°C more (than late 20th century averages) by midcentury and about 4°C by end of century, if greenhouse-gas emissions continue their current rates of acceleration. Future precipitation changes are much less certain, with as many climate models projecting wetter conditions as drier. However, the same projections agree that precipitation will be more intense when storms do arrive, even as more dry days will separate storms. Warmer temperatures will likely enhance evaporative demands and raise water temperatures. Consequently, climate change is projected to yield both more extreme flood risks and greater drought risks. Sea level rise (SLR) during the 20th Century was about 22 cm, and is projected to increase by at least 3 fold this century. SLR together with land subsidence threatens greater vulnerabilities to inundation and salinity intrusion. Impacts traceable to warming include SLR, reduced snowpack, earlier snowmelt and larger storm-driven streamflows, warmer and longer summers, warmer summer water temperatures, and water-quality changes. These changes and their uncertainties will challenge operations of water projects and uses throughout the Delta’s watershed and delivery areas. While impacts of climate change on Delta ecosystems may be profound, the end results are

	difficult to predict, except that native species will fare worse than invaders. Successful preparation for the coming changes will require greater integration of monitoring, modeling, and decision making across time, variables, and space than has been normal historically.

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ABSTRACT

Anthropogenic climate change amounts to a rapidly approaching, "new" stressor in the Sacramento-San Joaquin Delta system. In response to California's extreme natural hydroclimatic variability, complex water-management systems have been developed, even as the Delta's natural ecosystems have been largely devastated. Climate change is projected to challenge these management and ecological systems in different ways characterized by different levels of uncertainty. For example, there is high certainty that climate will warm by about 2°C more (than late 20th century averages) by midcentury and about 4°C by end of century, if greenhouse-gas emissions continue their current rates of acceleration. Future precipitation changes are much less certain, with as many climate models projecting wetter conditions as drier. However, the same projections agree that precipitation will be more intense when storms do arrive, even as more dry days will separate storms. Warmer temperatures will likely enhance evaporative demands and raise water temperatures. Consequently, climate change is projected to yield both more extreme flood risks and greater drought risks. Sea level rise (SLR) during the 20th Century was about 22 cm, and is projected to increase by at least 3 fold this century. SLR together with land subsidence threatens greater vulnerabilities to inundation and salinity intrusion. Impacts traceable to

warming include SLR, reduced snowpack, earlier snowmelt and larger storm-driven streamflows, warmer and longer summers, warmer summer water temperatures, and water-quality changes. These changes and their uncertainties will challenge operations of water projects and uses throughout the Delta's watershed and delivery areas. While impacts of climate change on Delta ecosystems may be profound, the end results are difficult to predict, except that native species will fare worse than invaders. Successful preparation for the coming changes will require greater integration of monitoring, modeling, and decision making across time, variables, and space than has been normal historically.

INTRODUCTION

The Delta is a hub where many flows, natural and artificial (water, nutrients, sediments, energy, and economics) converge and interact in California. And although the Delta has been in this same pivotal position throughout California's history and prehistory, climate change is one stressor among the many that ensure that the Delta of the future will not be the same as the Delta we know today. Nonetheless, the Delta is at the foot of one of the largest, most complex water-management systems in the world with hundreds of reservoir operations, canals and diversions, a predictable if imperfect water-rights system, and vast swaths of managed lands above and contributing to it. That massive upstream machinery can be a source of some optimism in the face of climate change, as can the system's long history of mostly-successful management of the wildest hydroclimatic regime in the country (Dettinger et al. 2011). If we work to understand the challenges and specifics of what climate change will bring, if we begin incorporating this understanding into decisions made today and tomorrow, and if we work to find the most effective adaptations and responses using our many natural and manmade assets, the Delta should be better off overall than many landscapes that will be facing climate-change challenges from much less robust starting points.

That is, the Delta is not a system that needs to be passively waiting for whatever challenges climate change brings. Looking forward, three particularly pressing scientific questions are:

- To what extent does the Delta system have built-in resiliency to future climate changes?
- Will (or when will) climate change push the system beyond its built-in resiliencies, whether physical, biological or socio-economic?
- How will we know, and can we anticipate, when that resiliency has been exhausted?

To answer these questions usefully will require a deeper understanding of the changes to come and of the natural variations that the Delta has historically experienced and that have been managed by society.

This review provides a summary of the current state of climate-change science as it applies to the restoration and sustainability of the Sacramento/San Joaquin Rivers Delta environment, facilities, and ecosystems, as a part of the 2016 State of Bay-Delta Science collection and report. These issues have been near the forefront of much intellectual activity concerning California's water supplies and ecosystems, and often specifically the Delta's ecosystems and water resources. A sampling of some major and recent studies of the potential impacts of, and adaptations to, climate change in the Delta are listed in Table 1.

The challenges that climate change will pose to the Delta and Delta management can only be understood in the context of California's already challenging natural climate and hydrologic variations. Thus we begin this review with a brief synopsis of the State's hydroclimatic variability in its natural state, and follow that with an overview of recent projections of 21st Century climate change. Sea-level rise, droughts and floods will then be discussed, followed by climate-change challenges to the co-equal goals of water-resources reliability and ecosystems restoration and sustainability. We conclude with a discussion of key gaps in knowledge regarding climate change and its likely effects, and future science and monitoring directions to close these gaps.

HISTORICAL CLIMATE VARIABILITY

The climate of the Delta and its watershed is characterized by mildly cool, wet winters under prevailing westerly winds followed by hot, dry summers. This seasonal pattern is shared by the Mediterranean region as well as parts of Chile, South Africa, and southern Australia. This climate regime yields strong seasonal variations in freshwater inflows to the Delta, which in turn is the source of much of the Delta's physical and biological character. In addition to winter floods, spring snowmelts, and summer low flows, the Delta is also influenced, at its seaward end, by tidal inflows and outflows governed by natural daily, monthly and seasonal processes. The coastal ocean also affects the estuary ecosystem and climate with its regular seasonal pattern of strong spring/early summer upwelling of cool, nutrient-rich waters.

On time scales ranging from seasons to decades, the Delta's natural (air) temperature variability is buffered somewhat (relative to much of North America) by California's proximity to the vast Pacific Ocean heat sink (Dettinger et al. 1995). The catchment's seasonal range of temperatures is generally less than seasonal swings in the continental interior, and its year-to-year temperature fluctuations are also less pronounced (in absolute terms) than other parts of the country. Nonetheless the catchment does experience brutal heat waves that can result in warm surface waters, dangerous increases in fire risks in the Delta's upland watersheds, and significant swings in water demand by natural and, especially, human water users.

In contrast to the Delta's comparatively buffered temperature regime, its precipitation and storm regimes are more variable and extreme than almost any other region in the country on storm-by-storm (Ralph and Dettinger 2012) and annual or longer scales (Fig. 1; Dettinger et al. 2011). California's most extreme storms have been a focus of much recent research, which has shown that these storms have historically been the result of landfalling atmospheric rivers (ARs). ARs are naturally occurring, transitory, long (>2000 km), narrow (~ 500 km) streams of intense water-vapor transport through the lower atmosphere (< 2 km above sea level). ARs gather and transport moisture over the North Pacific Ocean, connecting moisture sources from the tropics and extratropics to the West Coast (Ralph and Dettinger 2011). When these ARs encounter California's mountain ranges, they are uplifted, cooled, and produce heavy rain and snow (Guan et al. 2010). The most intense ARs drop massive amounts of precipitation on the state. Among the largest storms in California's history (storms that dropped more than 400 mm of precipitation within 3 days), 92% have been ARs (Ralph and Dettinger 2012).

ARs are the dominant cause of the largest historical floods that have flowed through the Delta, with over 80% of major floods (and levee breaks) since 1950 driven by ARs (Florsheim and Dettinger 2015). The Delta has experienced extremely large floods, including the New Year's 1997 floods of recent memory and the winter 1862 flood (Fig. 2) which may have exceeded the "record breaking" 1997 outflows by as much as 25% (Moftakhari et al. 2013). The 1997 flood and, very likely, 1862 flood were caused by periods with more-or-less continual arrivals of warm AR storms on the central California coast and Sierra Nevada (e.g., Dettinger and Ingram 2013). A notable characteristic of the Delta's historical flood regime is that, although in most years high flows occur during the spring snowmelt season, the largest floods have nearly always occurred during winter months as a result of heavy and warm winter storms that yield rapid runoff and flooding of river channels and the Delta (e.g., Florsheim and Dettinger 2015).

At seasonal to multi-year time scales, these large storms are also a key determinant of the Delta's average flows and, especially, its large hydroclimatic variability. ARs bring the Sierra Nevada about 40% of its average precipitation and resulting streamflows (Guan et al. 2010; Dettinger et al. 2011). The arrivals, or not, of large storms—including prominently, ARs—explain about 92% of the year to year and decade to decade variance of water-year precipitation (Dettinger and Cayan 2014; Dettinger 2016), including all the catchment's major droughts during the historical period. Large AR storms also play an important role in ending sustained droughts in the historical period, ending about 40% of Delta droughts since 1950 (Dettinger 2013a). Although these large storms are increasingly being forecasted as much as a week or slightly more in advance (Wick et al. 2013; Lavers et al. 2016), their year-to-year variations remain poorly understood and forecasted. Taken together the central roles that ARs play in California's floods and its droughts strongly suggest their importance to understanding and managing hydrologic variability in the Delta on time scales from days to decades. ARs were first recognized in 1998 (Zhu and Newell 1998) and so our scientific understanding of these features is quite new and still emerging. Their central roles in California's hydroclimate have motivated wide ranging research to improve our ability to track, model and forecast ARs (Ralph and Dettinger 2011), including a major new storm-centered monitoring network led by DWR and NOAA (White et al. 2013), AR- focused modeling and forecasting efforts (Wick et al. 2013, Hughes et al. 2014), and, in recent winters, reconnaissance flights to visit and better characterize ARs several days before their arrival in California (Ralph et al. 2016).

On these longer time scales, some limited forecastability of California's temperature and precipitation derives from observations and forecasts of the state of the climate over the Pacific Ocean. Most attention in the past two decades has focused on the state of the El Niño-Southern Oscillation (ENSO) process in the tropical Pacific (Allan et al. 1996), which is the primary source of climate forecast "skill" (accuracy) almost anywhere in the world. El Niño events reorganize atmospheric circulations in the Tropics in ways that divert and change the normal transports of heat and momentum (and, to an extent, moisture) out of the Tropics towards extratropical regions including the North Pacific and ultimately Western North America. Thus each time an El Niño (a period with anomalously warm sea-surface temperatures across much of the central to eastern equatorial Pacific) begins to form, there is much speculation as to how it will affect winter precipitation over California. Unfortunately, across central to northern California, El Niño years have not yielded consistent precipitation outcomes at seasonal scales (e.g., Redmond and Koch 1991) and in terms of extreme precipitation or streamflow events (Cayan and Webb 1992; Cayan et al. 1999). That is, about as many past El Niño years have yielded dry weather as have yielded wet weather, although there is some evidence that the warmest El Niño years tilt the odds more decidedly towards wet conditions all along the west coast, including in the Delta's catchment (e.g., Hoell et al 2015). ENSO variability is mostly active in time scales from 3 to 7 years, but interacts with the Pacific basin beyond the tropics on longer time scales, most notably in the form of the Pacific Decadal Oscillation (PDO; Mantua et al. 1997), which has historically influenced North American precipitation patterns for periods lasting for 25 years and more. The PDO, like ENSO, has historically led to stronger than normal contrasts in the amounts of precipitation falling in the southwestern US compared to the northwestern US but, also as with ENSO, the PDO's precipitation patterns tend to leave the Delta's catchment with little precipitation certainty from year to year. Nonetheless, although these important global climate modes do not offer much predictability for Delta hydroclimate, they almost certainly are major contributors to the large range of precipitation amounts that the catchment receives from year to year. Arguably, an important but understudied part of the multi-year variation of precipitation over the Delta's catchment occurs on time scales that are between the 3-7 yr ENSO characteristic and the 25-70 year PDO scales; however, this decadal (14-15 yr) variation is not well understood and, although significant during most of the 20th Century, has come and gone in longer term tree-ring records (Meko et al. 2014; St. George and Ault 2011).

In the Delta's widely varying precipitation regime, drought is a fact of life. The catchment has experienced severe short droughts (like 1976-77) and less severe but more sustained droughts (like the 1920s and 1930, or 1987-92) in the historical period. Tree-ring reconstructions of droughts in northern California have documented numerous droughts during the past 2000 years, including strong evidence of much longer and more severe droughts in the past (e.g., Meko et al. 2014; Ault et al. 2014). Precipitation deficits in the current drought (2012-present) have been extreme, although not record-breaking in water-year precipitation aggregates. On longer time scales, though, precipitation deficits during this current drought have been record breaking (e.g., in 14-month, 3-yr, and 4-yr totals) and has been characterized by very wet episodes bracketing the persistent dryness. For example, January 2013 through February 2014 was the driest such “season” since 1895, comprising a string of extremely dry months beginning immediately after strong AR storms in December 2012 and closing with the arrival of major AR storms in March 2014. This character is of special concern because it mimics, to an extent, the way that climate-change projections for the Delta are characterized by occasional very wet conditions separated by longer, drier droughts (see Dettinger 2016, and the next section).

Even more concerning has been the fact that the current drought conditions have been much aggravated by the record-breaking warm conditions that prevailed in 2014 and 2015 (Dettinger and Cayan 2014; Griffin and Anchukaitis 2014). Warmer conditions during droughts exacerbate precipitation deficits with drier soils yielding less runoff and longer periods with much reduced freshwater inflows, more wildfire risk, and warmer streams. Increasingly warm droughts are also a consensus projection for our future climate (see next section).

As a consequence of the large storms and long droughts that California naturally has experienced, the Delta has historically faced great floods and great droughts. These extremes have shaped the land and California’s infrastructure, politics, economy and society (e.g., Kelley 1988) in ways that we will need to mobilize and exploit in order to address the new challenges of climate change.

CLIMATE CHANGE

In the next several sections, the current state of science regarding several aspects of climate change as it will influence the Delta are summarized. Most work to date has begun with consideration of long-term projected changes in temperatures and precipitation, and projected trends in these variables will be the focus of this section. Confidence in the continuation of warming trends, if greenhouse-gas concentrations continue to increase, is high, and as long as global warming continues, sea levels are likewise expected to rise. Thus sea-level rise is considered in the next section. Recent climate-change research around the Delta has increasingly focused on the projected future of hydroclimatic extremes, like major storms, floods, and droughts. Thus the state of science regarding hydroclimatic extremes in the Delta will comprise the third section below, before the water management and ecological implications of findings to date are discussed in subsequent sections.

California has warmed by over 1ºC since the late 19th Century (Hoerling et al. 2013), and all modern climate models indicate that Earth's climate will continue to warm as greenhouse gases accumulate in the atmosphere as a result of fossil fuel combustion and other anthropogenic effects. Warming of the California Delta and its watershed is projected, by another 1°C above late 20th century levels by 2025, between 2-2.5°C by 2055, and 3.5-4°C by 2085 (Fig. 3, depending on how much global greenhouse-gas emissions continue to increase (Cayan et al. 2008b). This warming scales nearly linearly with cumulative carbon emissions into the atmosphere, so that the warming would be significantly less if a lower emissions pathway were achieved globally through aggressive and rapid transitions to economies less reliant on fossil fuels (Maurer 2007; Tebaldi and Arblaster, 2014).

Within the Delta's catchment, local differences are certain to arise. For example, warming is likely to be amplified the farther from the coast one moves, and higher altitudes may warm faster than lower altitudes (Wang et al. 2014). The resulting amplification of warming inland across the Delta's watershed may cause enhanced sea breezes with cooler coastal air penetrating further inland, an effect that has already been detected in California (Lebassi et al. 2009). This effect may also be affected by (and affect) changes in coastal upwelling of deep sea waters (Snyder et al., 2003).

Future changes in precipitation are much less certain than warming and some other changes like sea-level rise and surface-air humidities (Cayan et al. 2008b). Among global climate models, about half project increasing annual precipitation for the Delta's catchment and half project decreasing precipitation (Fig. 4). Within this uncertainty about annual totals, more than half of the models project precipitation increases in winter months and declines in the spring and fall seasons (Pierce et al. 2013b). Also, most projections indicate that there will be fewer days with precipitation by the middle of the 21st century, but increases in the intensity of the largest storms (Pierce et al. 2013a; Polade et al 2013; Dettinger 2016). To date, no strong consensus has emerged among modern projections as to the future prevalence of El Niño or PDO events (Vecchi and Wittenberg 2010), although the range of future ENSO fluctuations may increase (Cai et al. 2015). Thus, even the meager guidance regarding northern California precipitation that knowledge of future El Niño and PDO behavior would provide is not yet available to inform plans for future precipitation variations over the Delta watershed.

Winter snowfall and spring snow accumulation in the western United States have declined in recent decades, largely in response to warmer temperatures (Knowles et al 2006; Mote et al 2006; Kapnick and Hall 2012). Attendant changes in the timing of snowfed streamflow have already been detected (Fritze et al., 2011). Springtime snowpack will decline significantly in the Sierra Nevada as climate warms, quite likely by at least half of present-day water contents by 2100 (Knowles and Cayan 2002; Maurer et al. 2007; Cayan et al 2008b; Pierce and Cayan 2013). As a result, arrivals of snowmelt-fed inflows to the Delta will be delayed by a month or more by 2100. As snow retreats in a warming climate, the exposed land surface absorbs greater solar radiation, which produces a positive feedback that can accelerate local warming and snow retreat, an effect not well represented in most current projections (Pavelsky et al. 2011). The implication of this is that the rate of snow loss and melt may be even more rapid than has been projected so far.

The details of these influences of warming (and precipitation change) on snowpack and snowfed streamflows in the Delta watershed are strongly modulated by the complex topography of the State's mountain ranges. Because global climate models (GCMs) yield climate projections on coarse spatial grids, with resolutions ranging from about 100-200 km, a process called "downscaling" is applied to re-introduce spatial details of climate differences and variability that drive most of the watersheds, rivers, and systems of California water. The spatial resolutions of GCMs are improving, but the level of spatial detail they will provide is likely to be 50 kilometers or coarser through the next decade.

Two methods have been used in most downscaling efforts to date (CCTAG 2015): Dynamical downscaling is performed by simulating local-to-regional weather responses to coarse GCM outputs. These full-physics (or dynamic) models represent the physics of weather and climate as best we understand them at high resolutions and thus provide a full suite of climate variables (beyond "simply" temperatures and precipitation). But they also have limitations, including their own biases, uncertainties about observations to which the models are calibrated, and high computational storage requirements. The primary alternative has been statistical downscaling whereby historical weather patterns in response to various large-scale climatic conditions are interpolated into the GCM outputs by various statistical means. Statistical downscaling has the advantage that downscaled products are less computationally burdensome to develop and thus can be produced from large numbers of climate-change projections. That said, all statistical downscaling hinges on some assumption of "stationarity," that relationships of historical large-scale to finer-scale variations will apply in the future. The statistical methods inevitably depend on the quality of historical observation data used to develop the statistical relationships.

At present, statistical-downscaled products are most widely used and are probably acceptable to meet immediate needs, as well as for consistency with several iterations of climate assessments in California in the past dozen years. Nonetheless, in years to come, either new statistical methods, new hybrids that apply combinations of both dynamic and statistical tools, or, eventually, dynamical downscaling will be needed to address the full range of issues that may threaten the Delta.

Returning to the issue of how warming will likely impact riverine inflows to the Delta, as winter storms warm and become rainier (less snow), and snowpacks melt earlier, a greater fraction of runoff generated will pass through the Delta earlier in the year. As a result, summer salinity in the upper Bay and Delta is projected to increase (Knowles and Cayan 2004; Cloern et al 2011). The combination of changes in temperature and precipitation, resulting in a much reduced snow regime and occasional more intense storms, is also projected to increase the frequency and magnitude of floods in the river systems feeding the Delta. This was found to produce robust increases, by the end of the 21st century, in floods with return periods from 2–50 years for both the Northern and Southern Sierra Nevada, regardless of whether the climate projections considered were for overall wetter or drier conditions (Das et al. 2013).

Changes have been detected in other aspects of surface climate, including a reduction of wind speed (Vautard et al. 2010), though the driving cause is not primarily large-scale warming. Projections of large-scale wind changes over the Delta have not been much explored and remain quite uncertain even among projections by a single climate model (Dettinger 2013b) although, as noted previously, Delta breezes may intensify. While total atmospheric moisture content is projected to increase, warmer surface-air temperatures offset that effect to produce declines in relative humidity by as much as 14% for California (Pierce et al. 2013c). This decline would result in greater potential for evapotranspiration from soil and vegetation, intensifying hydrologic droughts. However, as CO2 concentrations in the atmosphere increase, plants tend to use water more efficiently (called a 'direct CO2 fertilization effect'), which could offset some of the greater atmospheric evapotranspiration potential, but as temperatures rise, growing seasons will also tend to lengthen, which in turn will contribute to increases in total evapotranspiration (Lee et al. 2011). The net effect of these several countervailing influences on overall evapotranspiration and vegetation water demands remains a topic that needs more research, but the Bureau of Reclamation has concluded that overall agricultural-water demands in the Central Valley will increase (USBR 2015).

On the whole, uncertainties about many of these projections are smaller than they were two decades ago. But, perhaps as importantly, projections today do not differ markedly from projections in past several Intergovernmental Panel on Climate Change assessment cycles. That is, modern climate projections seem to have largely converged toward the values that we currently report. Nonetheless, our ability to predict the future climate over the Bay-Delta's catchment is limited by several sources of uncertainty (Hawkins and Sutton 2009, 2011): 1) uncertainties concerning the rates at which greenhouse gases will be emitted into the atmosphere in the future; 2) uncertainties concerning climate-system responses to the changing greenhouse gas concentrations (essentially climate-model uncertainties and differences); and 3) the limits of long-lead predictability of natural variations of the climate system, for example the fluctuations of ENSO and the Pacific Decadal Oscillation. Natural variability (#3) plays a declining role in terms of projected temperature (and temperature-driven) changes on time scales beyond about two decades. The second source of uncertainty dominates uncertainties by midcentury, and by the end of the 21st century (and beyond) the first uncertainty dominates. Precipitation projections for California, by contrast, vary largely due to natural variability throughout the 21st Century, but with gradually increasing uncertainty deriving from the second source later in the century.

Delta systems, both natural and human-developed, are susceptible to effects of climate change to varying extents and on differing time scales. Effects are likely to include altered water supplies, increased flood and levee-stability risks, and important challenges to the sustainability of species and the Delta ecosystem as we know it (Cloern et al 2011). Decisions about adaptation should accept and, indeed, expect uncertainties in projections

(Mastrandrea and Luers, 2012). The first source of uncertainty can be partially accommodated by considering both ends of the emissions-pathways spectrum, although as a practical matter, it is worth noting that projected climate changes early in the 21st century tend to be similar regardless of the emissions pathway assumed, but then the changes associated with different emissions pathways differ increasingly after mid-century. Because we cannot determine which of the climate models is providing the most accurate projections of the future, standard practice is to consider the statistics (and especially the extent of consensus) of projections from collections or *ensembles* of different models, in hopes that the outcomes upon which the models agree most are the outcomes least subject to the second type of uncertainty. Attempting to characterize likely climate-change effects using too few model projections runs the risk of accidentally over-emphasizing specific natural wetter or drier fluctuations in the various (few) projections, under-representing the full range and consistencies among plausible futures. In the past decade, the numbers of climate models and climate-change projections available for these ensemble analyses has increased and, with them, confidence in many aspects and statistics regarding likely climate changes and effects has improved. Furthermore, detailed outputs from historical simulations by the 30 or more climate models now in use are more readily available than they were a decade ago, so that the models that perform worst in historical simulations (and their projections) can be culled from the ensembles before they contaminate assessments of likely climate-change impacts (CCTAG 2015). Because climate models are not synchronized (for example, as to when El Niño events occur), using an ensemble of century-long projections also reflects the evolving role of natural climate variability more clearly (e.g., Dettinger et al. 2004).

The greater confidence regarding projections of warming and the larger uncertainties concerning how precipitation will change suggest that adaptations that accommodate warming (and its consequences) might be acted on more confidently (deterministically) than adaptations directed at future precipitation changes. The greater uncertainties around precipitation change do not argue for less attention to, nor for less urgency of, adaptations to possible precipitation changes. Rather, they imply that adaptations to changing precipitation and water-supplies should focus on increasing the range of possible water futures that the Delta systems, engineered and natural, can accommodate sustainably.

SEA-LEVEL RISE

Water levels in the Delta are not much higher than coastal sea level, and thus will be affected by sea-level rise (SLR). Astronomical tides are attenuated as they propagate landward through the North Bay and into the Delta, but are still readily detectable. The Delta and its surrounding borders are low-lying, making Delta landscapes and hydrodynamics vulnerable to water level increases and extremes.

During the 20th Century, sea levels along the California coast rose about 20 cm (Cayan et al. 2008a; NRC 2012). Owing to global warming, SLR is projected to continue and very likely will accelerate during the 21st Century (NRC 2012). Satellite altimetry has indicated that global SLR rates increased during the last two decades—from about 2mm/yr to about 3mm/yr (Hay et al. 2015). The rate of SLR along the California coast followed global rates closely during the 20th Century. However there is considerable variability on shorter time scales. For example, the West Coast has experienced little SLR during the last few decades while the western Pacific has exhibited SLR at 3 or more times the global rate (Bromirski et al 2011) because of wind and pressure differences across the Pacific Ocean. Projections of the amplitude of 21^{st} Century SLR remain fairly uncertain, largely reflecting uncertainties about temperature changes and ice-cap loss rates, but most end-of-century estimates are between 0.2 m and 1.7 m of additional rise from the end of 20^{th} Century, with outliers mostly projecting potentially even more rise (Pfeffer et al 2008, NRC 2012, Hansen et al. 2016, DeConto and Pollard 2016).

Within the Delta, subsidence of Delta islands increases risks from SLR (Mount and Twiss 2005; Brooks et al. 2012). Increased water levels in the Bay/Delta are projected to change the tidal regime in the estuary (Holleman and Stacey 2014). Depending on how the estuary's shorelines change in coming decades—e.g., with hardened seawalls and levees vs. restored wetlands--the tidal regime could become more amplified or more dissipated, yielding wider tidal ranges, with even local shoreline changes affecting tidal ranges in parts of the estuary both near and far. Many problems associated with SLR will be amplified or hastened when large storms coincide with high astronomical tides (Cayan et al. 2008a). Strong storm winds and wind waves compound the impacts of flooding along the Delta's land-water boundaries. Storm-generated freshwater flood flows may dwarf the high sea levels; flood stages in the Delta's upper reaches stand several feet above normal levels. The resulting high waters increase risk that Delta lands and surroundings will be inundated and levees breached.

Although short-term water-level extremes are of early and pressing concern, even the most gradual expressions of SLR will eventually transport more ocean salinity into the Bay-Delta (Knowles and Cayan 2004; Cloern et al 2011). Increased salinities will affect brackish and freshwater habitats and, unless managed very skillfully, threaten water supplies (more in a later section).

DROUGHTS AND FLOODS (CLIMATE EXTREMES)

As temperatures rise, the character of California's climatic and hydroclimatic extremes are almost unanimously projected to change. Some extremes are extreme because of their size relative to historical climate distributions while other events are extreme because they comprise never before seen combinations of events. Both types of extremes will likely increase in frequency and magnitude, ultimately crossing thresholds that require reassessment and adaptation of management and restoration strategies. Understanding the underlying processes is key to understanding how to adapt to these "new" events. The current drought (2012-present) highlights these considerations: Over the past four years, temperatures have reached new highs, snowpack has declined to record lows while precipitation deficits have been challenging but not record breaking. Thus, this drought has provided both record-breaking extremes (in isolation) and a historically new set of hydrologic challenges for water management. In the Delta, new water-quality challenges and greater vulnerability to salinity intrusion have resulted. Outcomes such as these are expected to become more frequent in the coming decades.

At the other extreme, Central California's largest floods have historically been driven by winter storms with heavy rains that reach higher up into the mountain watersheds than most. When these storms and floods have coincided with extreme winter tides, storm surges and high wind waves, they have formed a dual threat (high river flows and water levels) for Delta levee failures and flooding within the Delta. Warmer storms yield higher flood flows because more of the watershed receives rainfall, and contributing runoff that immediately runs off, rather than snow which accumulates in snowpacks. Warmer temperatures also can support greater atmospheric moisture influxes that may lead to higher precipitation rates and thus higher flows. At the same time, a large majority of climate models project that the numbers and (less so) intensities of ARs making landfall in California will increase significantly in the 21st Century if greenhouse-gas emissions continue to increase (Dettinger 2011, Warner et al. 2015, Gao et al. 2016). Together these changes are projected to result in larger peak flows and flood risks in the warming future (Fig. 5).

In current climate-change projections, both droughts and floods increase as the climate warms, with storms becoming more intense, and intervening periods drier, longer, and warmer. Although changes in these extremes have not been detected with any confidence to date, these projections offer a vision of the future in which more severe droughts tempt us to store more (increasingly, cool-season) runoff even as more severe floods motivate us to release more water in pursuit of greater flood-mitigation capacity behind our primary dams. Unique new management balances between flood-control and water-supply management imperatives will likely be needed. Water year 1997 might provide an inkling of the problems involved. Following the record-breaking floods of New Year's 1997, the late winter and spring of 1997 was one of the driest on record, so that water released in coping with the winter floods was sorely missed later in the year. Although these conditions are disruptive to the human built system, flood and drought are natural conditions that the Delta's ecosystems have evolved to accommodate and, in some cases, even benefit from (e.g., Opperman et al. 2009; Moyle et al. 2010; Opperman 2012) .

Two important "climate change" problems that Delta science will need to resolve (or see resolved) are better understanding and prediction of future extreme events and their implications for ecosystem conservation and water supply, and identifying and anticipating thresholds beyond which these extreme events will result in substantially new adverse impacts on management and adaptation.

WATER RESOURCES IMPACTS

Water management in and for the Delta is an ever evolving process of addressing competing needs for a reliable supply of high quality water, protecting and restoring ecosystems, controlling floods, and satisfying legal and regulatory requirements in the face of highly variable climatic and hydrologic conditions (DWR 2008; Lund 2016). Climate change will almost certainly exacerbate the challenges inherent in that process.

The many effects of climate change on the Delta outlined earlier will very likely affect operation of all water projects and uses that rely on freshwater transports through the Delta. Along with the climate uncertainties, changes in land cover and use in response to climate-change and other stresses will exacerbate the challenges to water-resources and flood-risk management even more, and should be an important focus of future assessments.

Trends toward declining late winter and spring flows are already evident on both the Sacramento and San Joaquin Rivers (Fig. 6). Since the upper reaches of the Sacramento watershed are at lower elevation than those of the San Joaquin watershed, the Sacramento watershed is more sensitive to the modest temperature increases, and the attendant shifts of precipitation from snow to rain and earlier melting of snow packs, experienced thus far. In the second half of the 21st Century, however, warming will have long since driven precipitation-form changes and earlier snowmelt to their practical limits in the Sacramento catchments but will continue to cause ever larger increases in peak flows and more dramatic shifts in seasonal timing from the San Joaquin basin (Das et al. 2013; Maurer et al. 2007). Since the Sacramento River provides nearly 80% of the freshwater inflow into the Delta (DWR 2014b), losing the natural reservoir of snowpack in that basin will be a major challenge to the State's water resources management (Dettinger and Anderson 2015). On the other hand, the snowfields of the San Joaquin basin have more capacity to change in the face of continuing warming trends, so that by the end of this century some of the largest proportional challenges will likely arise from this tributary.

Water managers have recently been confronted with present-day examples of what these future changes might look like. During the current drought, each year's state-average April 1 snowpack water content has been among the bottom 10 values in the record dating back to 1950. Prior to 2015, the previous low snow pack was 25% in water years 1977 (due to lack of precipitation) and 2014 (due to the combination of a moderate lack of precipitation and record-breaking warm winter-spring temperatures). Then, in 2015, the April 1 snow pack was an unprecedented 5% of historical average, reflecting moderate lack of precipitation again and even higher winter temperatures. Recent climate-change projections do not yield snowpacks this low more than 10% of the time until after about 2070 (Fig. 7). But, as climate change proceeds, such low snowpacks will become progressively more common, so that 2015 can be viewed an early warning of challenges to come.

These changes in temperature, snowpack, and runoff timing result in a greater fraction of annual-flow volumes passing through the Delta during the time of year historically managed (by mandate) for flood control, that is, prior to April 1. This timing shift is expected to cause a cascade of changes in the watershed and Delta systems. For example, it has been estimated that, by the end of the 21st century, one or more of the major reservoirs feeding the Delta will be unable to release water during critical warm-season months due to low reservoir levels as often as once every 3-8 years (DWR 2009); reservoir levels this low have not yet been experienced. Future declines in the amounts of water in storage at the end of the water year in upstream reservoirs (DWR 2009) are analogous to a shrinking saving account, which reduces the ability to draw from those savings later, in times of need and shortfall. Reductions in upstream reservoir releases can be expected to result in increased groundwater pumping downstream (DWR 2009, 2014a; Hanak and Lund 2012).

Projected SLR will increase pressure on over 1000 km of levees that surround Delta islands and protect the river channels that constitute a water supply conveyance corridor (DWR 2014b). Many of these levees were not designed or built to modern engineering standards (Deverel et al. 2016). Salinity intrusion from SLR will require increased releases of freshwater from upstream reservoirs to repel that salinity (DWR 2009). Careful evaluations of California's water operations have indicated that Delta inflows can be managed to maintain the position of the X2 (position with a bottom-water salinity concentration of 2 ppt) under many such futures (DWR 2009). However, maintenance of salinity levels at other locations (e.g., Vernalis on the San Joaquin River) poses its own challenges (Vicuna et al. 2007). Reservoir releases to repel salinity reduce the amount of water available for other purposes (DWR 2009). This tradeoff has been projected to reduce the amount of water available for export from the Delta by about 10% under mid-century climate projections and about 25% by end of century, with current operating rules (DWR

2009). Current operations are governed by complex water rights, contracts, water quality standards, biological opinions, flood control rules, agricultural and economic forces and demands, and human health and safety requirements. However, the actual impacts of climate change will depend on future operating rules and future decisions including responses to climate change itself, and the California Water Plan states that “The water management community has invested in, and depends on, a system based on historical hydrology, but managing to historical trends will no longer work because historical hydrology no longer provides an accurate picture of future conditions” (DWR 2014a).

In addition to these salinity-management challenges, projected changes in the amount and timing of fresh water inflows combined with sea level rise have the potential to change water quality in other ways. For example, Ficklin et al. (2013) simulated water quality in the Sacramento and San Joaquin system and found that water-temperature increases of 2-2.5°C could result in 10% declines in dissolved oxygen (DO) in the rivers, with high potential for detrimental impacts on water quality and aquatic species. Rising sea levels and more frequent flooding of the Yolo Bypass may inundate previously dry areas, and if conditions are right these could become new areas for the occurrence of mercury methylation (Fong et al. 2016). Increased bromide concentrations from sea-water intrusion might threaten drinking-water uses (Fong et al. 2016). Much additional research is needed if we are to understand and predict the effects of climate-change on water-supply quality.

Another complication in evaluating the effects of climate-change is that the geometry of the Delta will likely change due to planned structural modifications, natural forces, and combinations of the two (Lund et al. 2008). The currently proposed Water Fix and Eco Restore programs (formerly known as the Bay Delta Conservation Plan) include plans to add water conveyance tunnels under the Delta to move high-quality water from the Sacramento River safely to the export pumps in the South Delta (CNRA 2015), resulting in a hydrodynamically very different Delta. Delta islands could become flooded by levee failures (e.g., the 2004 Jones Tract levee failure) due to an earthquake or major flood or by planned breaching of levees to flood islands (PPIC 2008; Florsheim and Dettinger 2015). How changes in the geometry of the Delta might exacerbate or mitigate challenges from climate change is another area needing more study.

The >200 federal, state, regional and local agencies responsible for managing various components of the Delta system (DWR 2014b) have a long history of coping with the region's highly variable climate and hydrology. As noted earlier, this is a cause for some limited optimism. However, although many future conditions will fall within the range of historically-observed conditions, even more extreme events are expected to occur in the future. For example, increases in heavy precipitation are projected with high confidence and are already being observed (Kunkel et al. 2013; Pierce et al. 2013a; Dettinger 2016). At the other extreme, future droughts are projected to become more frequent with, under the influence of warmer temperatures, higher evaporative demands and increased numbers of dry days overall (Cayan et al. 2010; Polades et al. 2014; Cook et al. 2015). Notably, the persistent high pressure over the northeastern Pacific that has steered storms away from California causing most of the precipitation shortfall in the ongoing 2013-2015 California drought has been projected to be 3-4 times more likely in today's already-changed climate than under pre-industrial conditions (Swain et al. 2014). The combined effects of precipitation deficits and record breaking warm temperatures have resulted in the current drought being even more intense than the 1977 drought, with an estimated 200-year recurrence interval (Aghakouchek et al. 2014). In fact, extremely dry soil-moisture conditions during 2014 and 2015 may be without precedent in a 1200-year tree-ring record for the region (Griffin and Anchukaitis 2014).

The current drought offers numerous examples of what climate-change responses may look like. In February 2014, for the first time, the state and federal water projects set water allocations to zero due to low water supplies (DWR 2014a). In 2015, drought measures for the first time included curtailments of pre-1914 water rights (SWRCB 2015a). In 2015, the state of California and the US Bureau of Reclamation jointly petitioned the State Water Quality Control Board to temporarily modify Delta water quality standards (SWRCB 2015b). The US Bureau of Reclamation drafted a Shasta Temperature Management Plan to guide use of the limited cold-water pool available in Shasta Reservoir to protect temperature-sensitive Chinook salmon eggs during late summer. The California Department of Water Resources built a $28 million emergency temporary barrier in West False River to try to protect the interior Delta from encroaching ocean salinity due to low freshwater outflows (http://www.water.ca.gov/news/newsreleases/2015/052915.pdf). These are all examples of how the Delta's operational and infrastructure frameworks may be modified in response to conditions caused by, or exacerbated by, climate change in the future, with increasing frequency and increasing desperation. It is imperative that plans for protecting the Delta evaluate all tradeoffs and opportunities, with the aim of being sufficient to meet the coming challenges and robust enough to accommodate large uncertainties that will not disappear.

FISHERIES, HABITATS AND ECOSYSTEM IMPACTS

While the effects of climate change on the Delta ecosystem are expected to be profound, their exact nature is difficult to predict. This is partly because ecosystems are made up of many species, each of which will respond to changes in the physical environment in its own way, affecting feedbacks in the food web (Brown et al. 2016a) and other ecological processes. It is also because ecosystem responses to climate change will depend on decisions about restoration and management that are being made now and that will be made in the future. That is, climate change will have very different effects on a future Delta with massive tunnels to protect export water qualities vs a future Delta with freshwater throughflows aggressively managed to repel salt. Both futures would have winners and losers, but not the same winners and losers.

Generally, however, gradual changes in average environmental conditions are unlikely to be the largest challenges to the Delta's organisms until those averages exceed organismic tolerances. It is much more likely that extreme events attending those gradually deteriorating baselines will be the most challenging for biological systems for a long time to come. For example, a heat wave associated with a drought occurred in 2014, and 95% of naturally spawned winter-run Chinook salmon eggs and fry died because the temperatures of releases from Shasta Reservoir exceeded their tolerance (NMFS 2015). A similar event also occurred in 2015 (http://www.sacbee.com/news/state/california/water-and-drought/article41684160.html).

Here we consider several of the expected effects of climate change on Delta species from a factor by factor perspective. We also consider some upstream ecological effects. Just as upstream processes affect what occurs in the Delta hydrologically, upstream processes also have important effects on in-Delta species.

In a natural system, the most obvious effects of SLR on ecosystems would be at the land-water interface, particularly in tidal marshes. As sea-level rises, tidal marshes can respond in two ways. A tidal marsh might respond to SLR with increased sediment trapping and accumulation of organic material (peat building), allowing the elevation of the marsh plain to follow along with SLR, maintaining a marsh-open water elevations differential similar to the historical difference. However, importantly, tidal marshes also might encroach on terrestrial habitat as the water level rises. Essentially the marsh might extend landward with the deeper portions “drowning” and converting to other habitat types, such as a mudflat or subtidal habitat. Effects on the aquatic organisms could be minimal since they would be able to find suitable habitat conditions by moving short distances landward. However, in today’s landscape, few tidal wetlands remain and many of those that remain cannot move landward due to the presence of levees and other hard infrastructures. Under these circumstances, accommodation of SLR must occur primarily by accumulation of sediment and organic material that raises the marsh levels in place. A number of models have been applied to this problem with results that are dependent on the models and assumptions used (Stralberg et al. 2011; Swanson et al. 2013). Some modeled marshes keep pace with SLR while others cannot, depending on assumed rates of SLR, amounts of sediments in the water column, and rates of organic detritus accummulation. More research is needed.

A spatially and temporally varying salinity gradient is a defining feature of the estuary’s waters. Estuarine organisms are adapted to geographically variable salinity fields that change on tidal, seasonal, annual, and longer time scales. The most mobile organisms can simply move to remain within their preferred salinity ranges. Less mobile organisms, such as benthic invertebrates (e.g., clams), can adapt to fluctuating salinity through dispersal of eggs and larvae that can colonize new areas of appropriate habitat. In the SFE, Feyrer et al. (2015) identified 5 salinity guilds of fishes, ranging from freshwater to saltwater guilds. Salinity intrusion can also affect terrestrial, emergent, submerged, and floating vegetation and other organisms.

Under natural conditions, these various species communities might respond to changing salinity conditions by simply moving by colonization of appropriate habitats within a new salinity regime. However, salinity changes affect spatial extents, locations, and abundances of species. Moyle and Bennett (2008) have argued that management-induced reductions of variability in the Delta's salinity fields have contributed to declines in native species, changing the Delta from a naturally variable estuarine system supportive of native fishes to a reservoir-like freshwater system that favors invasive submerged aquatic plants (i.e., *Egeria densa*) and fishes such as largemouth bass and other centrarchids. Freshwater releases to prevent saltwater intrusion in the summer and fall now result in salinity gradients that historically would have been typical of extreme drought in all but the wettest years. Climate-change induced reductions in late-season water availability will make such salinity conditions even more common (Brown et al. 2013, 2014; Feyrer et al. 2010).

Overall, many of the invasive species present in the Delta are better adapted to warm temperatures and low inflows than are native species (Kiernan et al. 2012, Moyle et al. 2013, Moyle et al. 2016). Rising water temperature will be one of the most significant climate-change stressors in the Delta. Ficklin et al. (2013) examined the effects of climate change on Sierra Nevada streams and found that spring and summer water temperatures are likely to increase from 1°C to 5.5°C, depending on location. Biota in subbasins with the greatest warming are more likely to be adversely impacted. Within the Delta, statistical modeling of water temperatures by Wagner et al (2011) has projected that water temperature will likely become stressful for delta smelt through much of their range during the summer and will likely change the timing of important events in their life history, such as spawning time (Brown et al. 2013). Warmer temperatures in the fall combined with earlier spawning would severely limit the time available for adult delta smelt to mature, with unknown consequences for the reproductive success (Brown et al. 2016b) of this bellwether species that is already on the verge of extinction (Moyle et al. 2016).

Water management actions taken to support upstream fisheries will also alter conditions in the Delta. Warmer inflows and enhanced floods and droughts are likely to adversely affect the cold-water pools of large reservoirs that support downstream Chinook salmon, steelhead, and sturgeon fisheries. Several modeling studies have indicated that management of salmonids below dams and diversions will become more difficult as climate change proceeds (Yates et al. 2008, Cloern et al. 2011, Thompson et al. 2012, Null et al. 2013). These challenges are real and serious as demonstrated by the recent mortality of federally listed winter-run Chinook salmon below Shasta Dam (described above).

Although potentially disastrous in many ways, future levee failures might ultimately be of some benefit for some aquatic organisms because more aquatic habitat would be created. Many Delta "islands" are completely surrounded by levees that hold Delta waters away from their interiors wherein land surfaces are well below the water levels outside the levees (Deverel et al. 2016). Once levees are breached and the interiors flooded, the flooding of these low-lying islands is often permanent. The benefits or damages from this flooding will vary with the species being considered, the location and specifics of the levee failure, and the type and physical attributes of habitat created. For example, Liberty Island, flooded in 1998, provides habitat for delta smelt because it has not been extensively invaded by *Egeria densa* or *Corbicula* to date, the water remains turbid, and the habitat is accessible to native species (Lehman 2010, 2015). In contrast, the flooded Mildred Island of the southern Delta has been extensively invaded by *Egeria densa* around its perimeter, supporting mainly invasive fish species (Grimaldo et al. 2012). The interior of the flooded island is too deep for *Egeria densa* and pelagic production is relatively high; however, dense *Corbicula* in the outflow channels rapidly deplete exported chlorophyll-*a*, greatly reducing the benefit of primary production there to adjacent habitats (Lucas et al 2002, Lopez et al. 2006). Flooded islands in warmer areas might well be ideal habitat for harmful algal blooms (see Fong et al. 2016). Depending on the size and location of newly flooded areas, there may be largely unexpected effects on the hydrodynamics of the entire Delta with unknown effects on the ecosystem.

Flooding in the late winter and early spring tends to benefit native fishes, particularly splittail and Chinook salmon (Perry et al. 2016), if floodplains remain inundated for a sufficient time (Sommer et al. 2004, Moyle et al. 2007, Jeffres et al. 2008; Moyle et al. 2016). This early flooding is important because native species tend to reproduce at cooler temperatures than many invasive species (Moyle et al. 2013). If inundations recede before water temperature increases much, reproduction of exotic species will be less successful. Conversely, droughts tend to favor exotic species because they yield fewer floodplain inundations and thus less opportunity for natives to reproduce in isolation from exotic species.

All of the above factors will be changing at the same time, and all of the communities and species will be responding each as best as it can throughout their respective life cycles with their respective individual strengths and vulnerabilities. Given all the moving parts, our ability to predict in advance how climate change will affect Delta ecosystems and interact with human efforts to maintain desired ecosystem services is extremely limited. There will most assuredly be many surprises requiring flexibility in our management systems. However, some changes we can expect. Success of habitat protection and restoration projects will require them to be designed to accommodate SLR or to evolve gracefully into other desired habitat types as SLR proceeds. The entire life cycles of organisms of interest will need to be considered if we are to anticipate ecological effects of climate changes and attendant salinity and water-temperature responses. Specifically, management that increases salinity and hydrodynamic variability in the Delta is likely to be an important tool for improving conditions for native fishes, but we need to understand which variations are beneficial and how all the moving parts will interact far better than we do now if we are to use this tool successfully.

THE WAY FORWARD

Many specific gaps in knowledge have been called out above. More generally, global climate change is a "new" stressor that will influence many different climate, hydrologic and ecosystem variables in the Delta system. Climate change will influence variables everywhere in the Delta's catchment but not in the same way everywhere. Initially, this century, impacts will arise mostly through enhanced extreme events. In response to this intermeshed complex of challenges, making use of the assets we have to avoid dire outcomes will require integrated monitoring systems, integrated modeling approaches, integrated assessments of vulnerabilities and options, and adaptive and adaptable decision making processes. Models of the many complex and interacting subsystems that comprise the Delta will need to be better developed to provide more realistic and reliable guidance for planning and management of the overall Delta system. The longstanding Delta Science Program-funded Computational Assessments of Scenarios of Change in the Delta Ecosystem (CASCaDE) program is one example of how such a modeling integration across scientific fields might look (e.g., Cloern et al. 2011). Greater life-cycle and end-to-end understanding of processes and responses, whether biological or technological, are needed. That is, such integrations and attention to the extremes have not always been the norm in the past.

Three questions concerning "how important is this event or change" were posed in the Introduction to this paper. Answering these questions in the Delta, and anticipating cascading and potentially unexpected consequences of climatic events and of our responses to those events, will require a new generation of models and observations that cut across the scientific disciplines that connect as many of the parts of the Delta system, from mountain ridges to coastal ocean with all the varied landscapes in between. Meeting this requirement will depend on sustained research and observations (Dettinger and Culbertson 2008), as well as considerable investment in developing the best reconstructions (through all means available) of past climates and climate impacts as a baseline for the challenges and changes to come. These actions can reduce many uncertainties and help to avoid some unintended and unanticipated consequences of managing the Delta in a time of climate change. However, the uncertainties associated with climate change in the Delta will not disappear in time to allow precise outcomes to be predicted or planned for. Instead we will know most precisely what the climate changes and effects will be as they emerge (or afterwards), and management of the Delta needs to accommodate this limitation with an urgency commensurate with what we do know or expect, and with flexibility borne of a humble recognition of what we won't know until later.

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Table 1. Selected recent planning efforts that consider climate change and the Delta.

Study Name and Reference	Year	Key Topics
CASCaDE: Computational Assessments of Scenarios of Change for the Delta Ecosystem USGS http://cascade.wr.usgs.gov/	ongoing	Ecosystems Sea Level Rise
Sea Level Rise Policy Guidance California Coastal Commission http://documents.coastal.ca.gov/assets/slr/guidance/May2015_PublicReviewDraft.pdf	ongoing	Sea Level Rise
Water Fix and EcoRestore (formerly the Bay-Delta Conservation Plan) CA Dept. of Water Resources and US Bureau of Reclamation http://www.californiawaterfix.com/ https://s3.amazonaws.com/californiawater/pdfs/ECO_FS_Overview.pdf http://baydeltaconservationplan.com/Home.aspx	ongoing	Water supply Ecosystems
Central Valley Flood Protection Plan's Basin Wide Feasibility Study CA Dept. of Water Resources http://www.water.ca.gov/cvfmp/bwfs/	ongoing	Flood Control Ecosystems
Delta Levee Investment Strategy Delta Stewardship Council http://deltacouncil.ca.gov/delta-levees-investment-strategy	ongoing	Levees
Safeguarding California: Reducing Climate Risk CA Natural Resources Agency http://resources.ca.gov/docs/climate/Final_Safeguarding_CA_Plan_July_31_2014.pdf	2014	Agriculture Ecosystems Water, etc
West-wide Climate Change Risk Assessments: Sacramento and San Joaquin Basins US Bureau of Reclamation http://www.usbr.gov/WaterSMART/wcra/	2014	Water Supply Water Quality Groundwater
California Water Plan Update 2013 CA Dept of Water Resources http://www.waterplan.water.ca.gov/cwpu2013/final/index.cfm http://www.waterplan.water.ca.gov/docs/cwpu2013/Final/Vol2_DeltaRR.pdf	2013-14	Water Supply Water Quality Flood Management
Sea-Level Rise for the Coasts of California, Oregon, and Washington National Academy of Sciences http://www.nap.edu/catalog/13389/sea-level-rise-for-the-coasts-of-california-oregon-and-washington	2012	Sea Level Rise
Sustainable Water and Environmental Management in the California Bay-Delta National Academy of Sciences http://www.nap.edu/catalog/13394/sustainable-water-and-environmental-management-in-the-california-bay-delta	2012	Ecosystems Water
Delta Risk Management Strategy Dept of Water Resources http://www.water.ca.gov/floodsafe/fessro/levees/drms/ http://www.water.ca.gov/floodsafe/fessro/levees/drms/docs/Climate_Change_TM.pdf http://www.water.ca.gov/floodsafe/fessro/levees/drms/docs/Water_Analysis_Module_TM.pdf (see appendix F and appendix H)	2011	Levees Flow Water Level Water Quality
Delta Vision http://deltavision.ca.gov/index.shtml	2008	Ecosystems Water

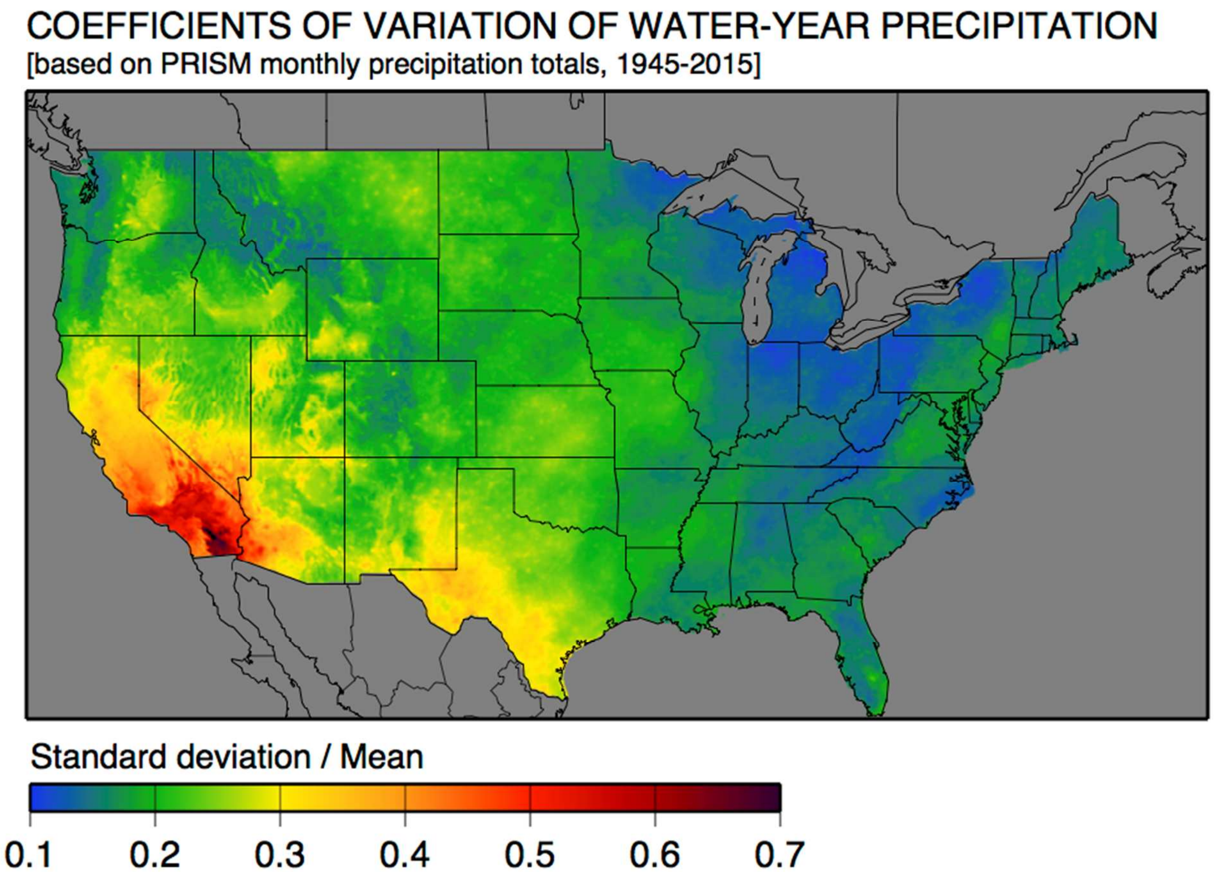

Fig. 1– Coefficients of variation (standard deviation divided by mean) of water-year precipitation totals across the conterminous US, 1945-2015.

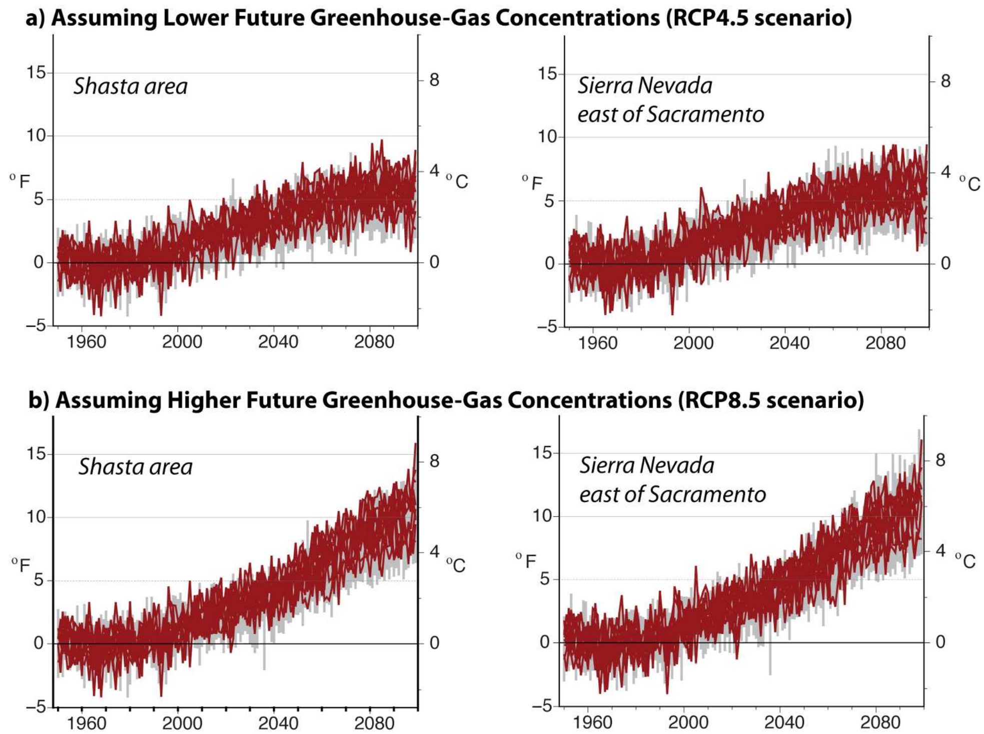

Fig. 2—Projected annual changes in air temperature, relative to 1961-90 averages, in 10 selected global climate models (bright curves, 5-yr moving averaged) and in 31 models (grey, unsmoothed), under low and high future greenhouse-gas emissions; from DWR Climate Change Technical Advisory Group (2015).

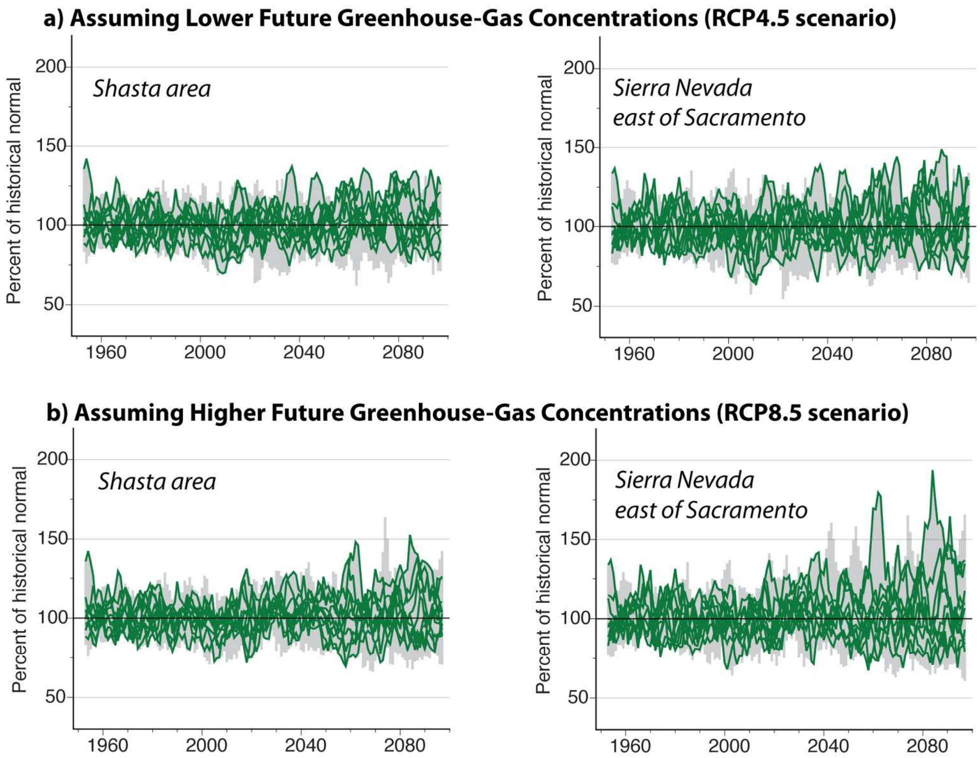

Fig. 3—Same as Fig. 2, except for precipitation projections.

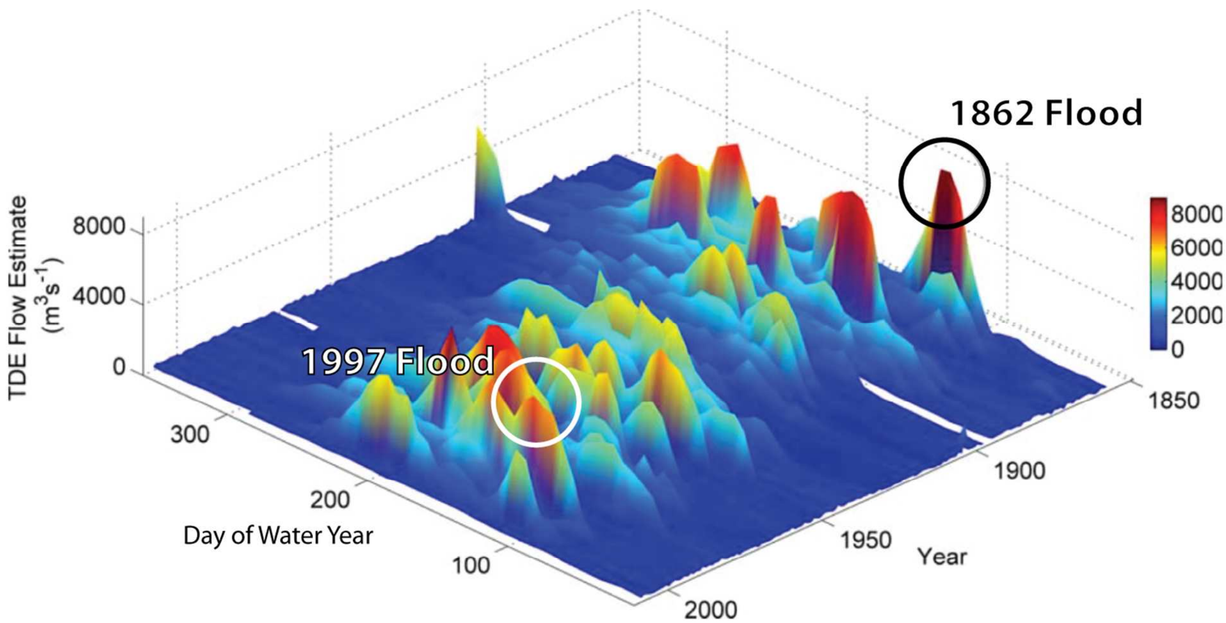

Fig. 4–Freshwater outflows from the San Francisco Estuary, as tidal-discharge estimates (TDE) based on tidal gages in San Francisco Bay at the Presidio, as a function of years in the past and time of year, illustrating the high flood flows in winter 1862 and many subsequent occasions (modified from Moftakhari et al. 2013).

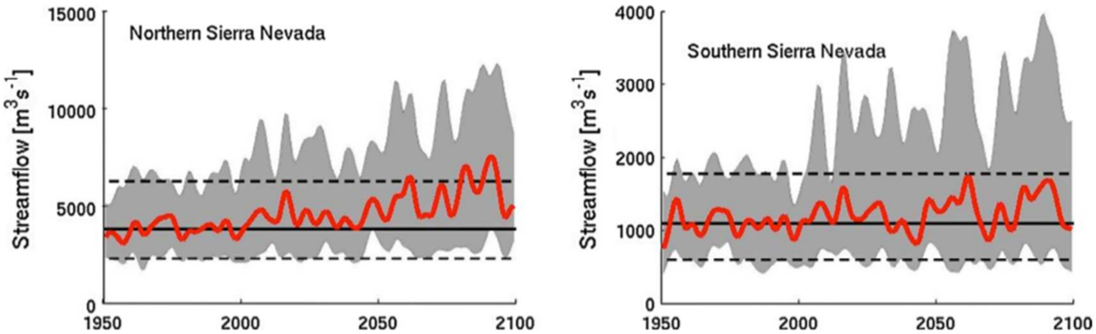

Fig. 5-- VIC simulated 3-days annual maximum streamflows as driven by downscaled meteorologies from 16 global climate models. The median (red line) and 25th and 75th percentiles (gray shading) are shown from the simulated streamflows distribution among the 16 models. Black horizontal lines represent median (solid black line), 25th and 75th percentiles (dotted black lines) computed over the climate model simulated historical time period 1951–1999. Results are smoothed using low pass filter shown from high emission scenario (SRES A2); from Das et al. (2013).

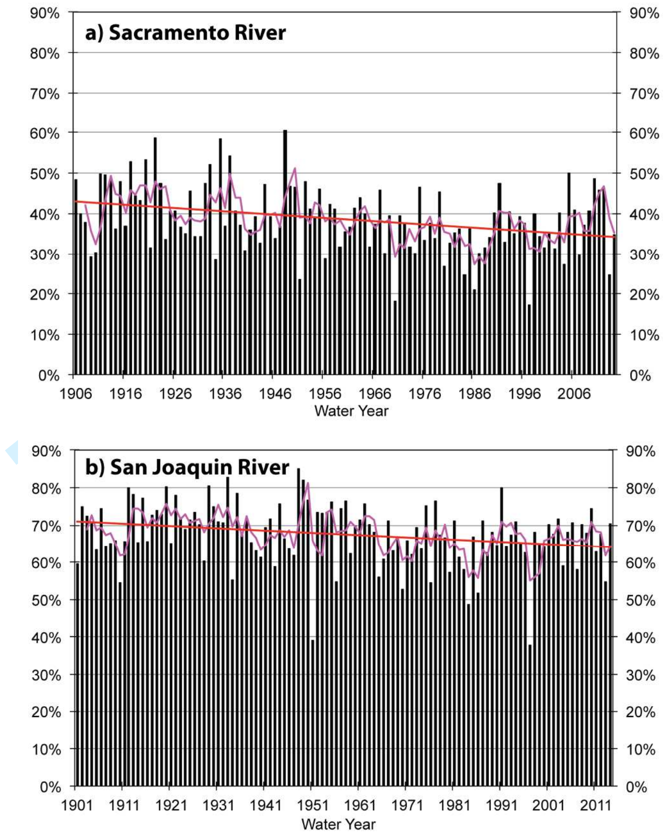

Fig. 6—Full-natural (reconstructed natural) April-July streamflows in the a) Sacramento and b) San Joaquin Rivers, as fractions of water year totals, since early 20th Century (from California DWR); red line is a least-squares trend and pink curve is a 3-yr moving average. The variance captured (r^2) by the fitted trends are (a) 9.5% and (b) 6.1%, respectively, with $p<0.05$ in both cases.

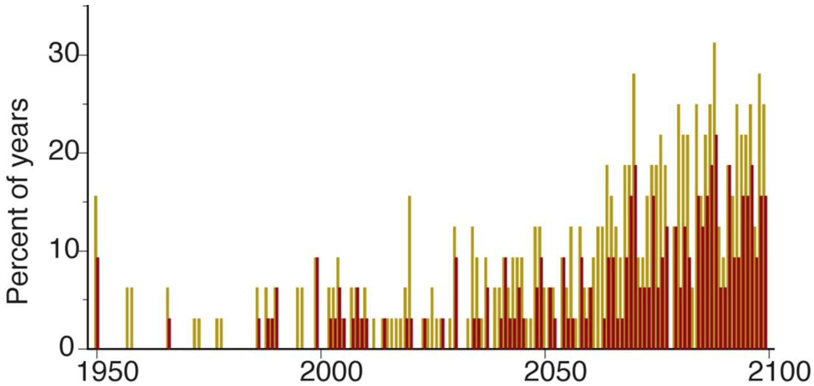

Fig. 7– Odds that a year yields less than 5% (red) or 10% (orange) of 1961-1990 average April 1 snow-water equivalent across the mountains of California, in an ensemble of simulations and projections by the VIC macrohydrologic model (Liang et al. 1994) as forced by BCSD-downscaled (Wood et al. 2004) outputs from 16 global-climate models under high- (A2) and low- (B1) emissions scenarios (updates to results in Cayan et al. 2008b).