Appendix 3E
Potential Seismic and Climate Change Risks to SWP/CVP Water Supplies

3E.1 Introduction

This appendix provides an overview of seismic and climate change risks associated with existing levee structures, existing operation, and existing management of the Sacramento-San Joaquin Delta (Delta) and vicinity. This appendix draws on a variety of scientific and technical studies and analysis and peer reviewed literature. These studies look at the Delta in its current physical condition and analyze the potential risks of continuing to operate and manage the Delta as we currently do while seismic risks and climate change impacts increase over time. Throughout this appendix, readers are directed to sections of the EIR/S to find analyses of how the risks and impacts described in this appendix would impact the BDCP alternatives. Appendix 3I, *BDCP Compatibility with Delta Reform Act*, discusses requirements under the Delta Reform Act for incorporation of the BDCP within the Delta Plan. (See Wat. Code, § 85320, subd. (b)(2)(C).).

The Delta is a primary conveyance hub for the SWP and CVP, as well as nearly 500,000 in-Delta residents and 700,000 acres of in-Delta farmland. Most of the water flowing through the Delta originates upstream in the Sacramento and San Joaquin rivers and related tributaries. The watershed draining into the Delta includes about 45 percent of the state's surface area.

The SWP and CVP supply water for around 25 million people and millions of acres of irrigated farmland in California, with water in the related conveyance/storage networks also used for purposes such as augmenting natural flows and generating hydroelectric power. In addition to domestic and agricultural water supplies, the Delta also supports extensive critical wildlife habitat and sensitive species (including many listed as threatened or endangered under federal and state laws), recreational uses, transportation/utility infrastructure, and agricultural activities (including a number of economically important specialty crops). In short, the Delta serves a number of critical functions, and maintaining/enhancing a healthy and productive Delta environment is vital to the interests of both the State of California and the nation as a whole.

SWP/CVP water supplies conveyed through the Delta pass through a maze of channels and islands created by a system of levees. The construction of levees in the Delta began in the early to mid 19th Century and, in combination with channel dredging/modification, has facilitated uses such as flood control, agriculture, human habitation, navigation and recreation. There are currently over 1,100 miles of levees in the Delta, as well as approximately 230 miles of levees in the adjacent Suisun Marsh. Nearly 70 percent of these levees have been constructed, enlarged and maintained by local landowners or reclamation districts, and are largely or entirely non-engineered (i.e., not constructed in conformance with modern engineering and construction industry standards). These levees consist primarily of materials dredged/excavated from adjacent areas, including soils with high organic content (peat or mud/muck), alluvium and other deposits. Most of the Delta levees are also exposed to water 100 percent of the time, as opposed to river levees which are typically only exposed to water during flood conditions. Many of the associated "islands" (i.e., protected areas behind the levees) are currently 25 feet or more below sea level, due to effects including material excavation for levee construction, historic "soil burning" efforts (i.e., in association with agricultural operations), and the previous and ongoing subsidence of organic soils (due to oxidation/ decomposition of organic materials). Based on the described conditions, the existing levee system is subject to failure-related hazards from a number of potential sources, including seismicity and associated effects, high sea stands that will be exacerbated by sea level rise, and changes in inflow hydrology that are likely to become more extreme and more damaging with future climate change.

Delta levees not only act to protect valuable farm land from submersion but also play a critical role in maintaining the hydrodynamics of water flow through the Delta. As explained in more detail in Appendix 1A, *Primer on California Water Delivery Systems and the Delta*, the western Delta islands and levees are critical to restricting the flow of seawater into the interior Delta. The eastern and central Delta levees are critical to routing fresh water from the Sacramento and San Joaquin rivers toward export facilities in the south Delta. Failure of the Delta levee system could lead to an immediate and drastic change in the hydrodynamics of the Delta—allowing saline seawater to surge into the interior Delta—significantly increasing the salinity of interior Delta flows and putting the quantity and quality of SWP/CVP and in Delta water supplies at tremendous risk.

3E.1.1 Purpose of this Appendix

The purpose of this appendix is to describe the potential risks to SWP and CVP water supplies that could result from seismic activity and/or climate change absent changes to the Delta that would improve the reliability of water deliveries to the SWP and CVP. A broad consensus has emerged among scientists that the status quo of the Delta and water delivery system through the Delta is no longer viable (Lund et al. 2008; Delta Vision 2008). The Interim Federal Status Update for the California Bay-Delta: 2011 and Beyond reached this same conclusion. While all of these evaluations cited a myriad of stressors that contribute to the fragility of the Delta, seismic and climate change risks appear to be among the greatest risks for catastrophic interruptions in operation of water supply facilities in the Delta.

Refer to EIR/EIS Appendix 5B, *Responses to Reduced South of Delta Water Supplies*, for a discussion of the potential effects on the human and natural environment that would occur if SWP and CVP water deliveries are disrupted for an extended period of time.

3E.1.2 Organization of this Appendix

Following this Introduction, Section 3E.2 briefly describes the largest SWP and CVP water intake facilities within the Delta—the SWP's Clifton Court Forebay/Banks Pumping Plant and the CVP's Jones Pumping Plant. Section 3E.2 also gives an overview of how the degradation of water quality at the intakes to those facilities could affect the viability of the SWP and CVP to supply water to those systems' users. Section 3E.3 focuses on the potential for seismic activity to cause levee failures that would, in turn, contribute to seawater intrusion and a degradation of water quality in the Delta and at the pumping plants' intakes. Section 3E.4 addresses the potential for climate change-related effects to cause or contribute to levee failures, with similar negative effects on water supply as those described in Section 3E.3. Section 3E.5 summarizes the information provided in Sections 3E.2 through 3E.4 and draws conclusions about the potential risks to the SWP and CVP water supplies. Sections 3E.6 and 3E.7 provide lists of references cited and acronyms/abbreviations used, respectively.

3E.2 Focus of Risk Assessment

This appendix addresses two potential risks to the Delta's ability to convey water to the SWP and CVP export facilities: (1) seismic activity and (2) climate change. These two potential risks would affect the Delta in different ways. For seismic activity, the primary focus is on the potential for levee failures that could alter the hydrology of the Delta, at least temporarily, leading to seawater intrusion into the interior of the Delta and potentially requiring the SWP and CVP to stop pumping. For climate change, the primary focus is on long-term changes in sea level and Delta inflows, which over the next 100 years are projected to change in ways that will put increasing stresses on existing levees and make management of Delta salinity increasingly difficult.

To provide a context for this risk assessment, this section provides a brief description of the largest SWP and CVP water intake facilities in the Delta, followed by a discussion of how the degradation of water quality at those facilities could affect the supply of water delivered by the SWP and CVP.

Climate change is expected to affect precipitation and sea level, and this appendix summarizes analyses of the potential for climate change to contribute to increased salinity and Delta flood risk that would, in turn, affect the viability of the Delta to supply water to the SWP and CVP.

3E.2.1 Water Intake Facilities

As noted above, both the SWP and CVP have water diversion systems in the Delta that are critical to these systems' ability to provide water to their service areas outside the Delta. This appendix focuses on the largest of these in-Delta diversions systems: the SWP's Clifton Court Forebay and Banks Pumping Plant and the CVP's Jones Pumping Plant (see Figure 1-2). Although other SWP and CVP water diversion facilities are located within the Delta, the loss of use of the Banks and Jones Pumping Plants would have the greatest effect on their respective water systems' operations.

The SWP conveys water through the Delta and diverts it to the California Aqueduct via the Clifton Court Forebay, Banks Pumping Plant, and Bethany Reservoir. As indicated on Figure 1-2, Clifton Court Forebay is located in the southwestern edge of the Delta, about 10 miles northwest of the City of Tracy. The Forebay, which is a shallow reservoir that helps moderate inflows to the Banks Pumping Plant, is created by Clifton Court Dam. Water leaves the Forebay via an intake channel and enters the Banks Pumping Plant, where it is lifted to Bethany Reservoir. From Bethany Reservoir, the South Bay Pumping Plant diverts some water into the South Bay Aqueduct, serving Alameda and Santa Clara Counties; however, the majority of the water pumped to Bethany Reservoir flows into the California Aqueduct, the main artery of the SWP south of the Delta.

The CVP's Jones Pumping Plant is also located in the southwestern edge of the Delta, less than two miles east of the SWP's Banks Pumping Plant (see Figure 1-2). This plant raises water into the Delta-Mendota Canal, which travels southward to the Mendota Pool on the San Joaquin River, supplying water along the way to other CVP reservoirs.

3E.2.2 Salinity/Seawater Intrusion

In terms of potential risks to the water supply, this appendix focuses on the potential for increases in salinity and other constituents of concern at the Banks and Jones Pumping Plants, which divert SWP and CVP water from the Delta into the California Aqueduct and Delta Mendota Canal. Increased salinity levels at these pumping plants could require that these plants temporarily stop diverting water to the SWP and/or CVP, respectively, depending on the level and duration of the increased salinity levels. It should be noted that salinity is not the only constituent of concern for water diverted to the SWP and CVP; for example, bromide levels and total organic carbon also are critical to determining whether the water is suitable for export to the SWP and CVP. Salinity, however, is the subject of more modeling and assessment than other constituents of concern. As noted in the DRMS Report (DWR 2009a: 11-1):

Salinity is the obvious marker for tracking the movement and mixing of Delta waters. It is ubiquitous, easily measured, and exhibits strong variations due to the low salinity of freshwater inflow, the high salinity of Bay waters, and the strong tidal hydrodynamic movement and mixing.

Accordingly, except where there are studies available that specifically address other constituents of concern such as bromide or organic carbon, this appendix focuses on salinity as the key factor in determining the suitability of water for export to the SWP and CVP.

Sources of salinity in the Delta include seawater from the San Francisco Bay and salts generated by agricultural activities. Flows from the San Joaquin River also have a relatively high salinity content. At a very general level, the more fresh water that flows into the Delta from upstream sources, the lower the salinity levels within the Delta. Lower freshwater inflows into the Delta generally result in higher salinity levels within the Delta. Reduced precipitation and/or an increase in the sea level could affect the Delta's salinity, by reducing the inflow of fresh water from upstream rivers or increasing the inflow of seawater from the ocean, respectively.

Depending on the hydrologic conditions present within the Delta at the time, levee failures also can have a significant effect on salinity within the Delta. As described in the main body of the EIR/EIS and noted in the Introduction to this appendix, many of the islands in the Delta have subsided to below sea level, some by as much as 25 feet. If a levee failure occurs when there is little freshwater input into the Delta, water rushing through the breached levee can alter flows within the Delta, drawing brackish water from Suisun Marsh and seawater from the San Francisco Bay into the Delta.

While even isolated levee failures can have a large impact on salinity—a 1972 levee break near Isleton increased salinity levels within portions of the Delta, affecting SWP and CVP operations—a greater risk is the potential for multiple, concurrent levee failures. The concurrent failure of multiple levees would mostly likely be associated with a larger event, such as an earthquake or flood. A large earthquake on one of the region's many active faults could cause structural damage to multiple levees throughout the Delta (see Section 3E.3). The above noted effects of climate change, mainly higher sea level and changes in weather patterns, also could contribute to flooding and, ultimately, levee failures.

There is not a specific threshold at which salinity levels, bromide levels, or the presence of other constituents of concern (such as organic carbon) would require the Banks and/or Jones Pumping Plants to cease operations. This reflects that there are a number of factors which affect the SWP's and CVP's customers' ability to accept water from these two systems, including the planned use of that water (e.g., agricultural versus residential), the availability of other water sources to be blended with the SWP/CVP water, the quantity and quality of the other water source(s), and the treatment options available to SWP/CVP customers.

While there is no specific threshold for salinity levels that would require Banks and/or Jones Pumping Plants to cease operations, Water Rights Decision -1641 does set salinity standards based on the geographical position of the 2-parts-per-thousand (ppt) isohale (aka X2, the salinity gradient). The geographical position of the 2-ppt isohale is considered important to the estuary and the resident fishery. D-1641 standards create a systematic approach for SWP/CVP operations to influence the position of the X2 location. Past and continuing sea level rise may require additional fresh water to be used to maintain X2 locations while higher sea levels act to move the X2 position inland.

In terms of drinking water standards, in 1976, California enacted the Safe Drinking Water Act, requiring the California Department of Public Health Services to regulate drinking water, including setting and enforcing federal and state drinking water standards, administering water quality testing programs, and administering permits for public water system operations. The Federal Safe Drinking Water Act allows the state to enforce its own standards in lieu of the federal standards so long as they are at least as protective as the federal standards. Substantial amendments to the California Safe Drinking Water Act in 1989 incorporated the new Federal Safe Drinking Water Act requirements into California law, provided for California to set more stringent standards, and recommended public health levels for contaminants. Currently, California regulates over 90 different potential drinking water contaminants, including inorganics, radionuclides, volatile organic compounds, synthetic organic chemicals, and disinfection byproducts, with the maximum allowable levels for each contaminant established in Title 22 of the California Code of Regulations.

The State Water Resources Control Board and its Regional Water Quality Control Boards also establish water quality standards based on a water resource's designated beneficial use. Along with the concentration value, numerical water quality objectives also typically specify an averaging period to which the concentration value applies to protect the beneficial use of interest. Averaging periods typically depend on the sensitivity of the use, such as a 1-hour averaging period for objectives designed to prevent acute toxicity in aquatic life, to longer averaging periods (e.g., 30 day, annual average) for less sensitive effects (e.g., human health effects, industrial uses, or agricultural crop production).

Irrigation canals are not subject to the same level of regulation as drinking water systems; however, agricultural users are sensitive to water quality, with the level of sensitivity depending in large part on the types of crop being grown, the growth stage of the affected agricultural crop(s), and the type and condition of the soil.

In summary, there are no set thresholds for salinity, bromide, or other contaminants at which the Banks and/or Jones Pumping Plants would cease operations. In general, however, an event that would alter the hydrology of the Delta such that brackish water or seawater is drawn into the southwest portion of the Delta would likely result in these pumps shutting down until freshwater flows can be reestablished and flush the brackish water/seawater from the vicinity of these pumping plants' intakes. In addition, even in the absence of an event that catastrophically alters the hydrology of the Delta, climate change and associated sea level rise will gradually make the operation of the Delta in its current configuration more difficult and require the use of increasing amounts of fresh water just to maintain current salinity standards.

3E.1 Seismic Risks

3E.2.3 Geologic and Seismic Setting of the Delta

3E.2.3.1 Geologic Setting

The Delta and vicinity are located in the Great Valley Geomorphic Province, also referred to as the Central Valley, a 465-mile long and 40- to 60-mile wide region located between the Sierra Nevada to the east and the Coast Ranges to the west (Figure 3E-2). The Central Valley is characterized by a low-lying alluvial plain drained predominantly by the Sacramento and San Joaquin rivers, and ultimately outlets to San Francisco Bay through the Delta and Carquinez Strait.

The Central Valley encompasses a 3- to 6-mile thick sequence of sediments deposited on granitic (Sierra Nevada) and Franciscan Formation (Coast Ranges) bedrock by streams originating in the Sierra Nevada, Coast Ranges and southern Cascade Range. This deposition has been more or less continuous since the late Jurassic Period (Figure 3E-3), with the occurrence, nature, extent and source(s) of this deposition and related drainage patterns influenced by a number of geologic and climatic events. Specifically, such events have included Miocene-age conditions similar to a modern fore-arc basin (a sea floor depression between a subduction zone, an area where one crustal plate descends under another and is subducted into the mantle, and an offshore volcanic arc), which involved extensive deposition of arkosic sediments (exhibiting high quartz and feldspar content and typically derived from granitic rocks) and volcaniclastic materials (sediment derived from volcanic rocks). Additional major events affecting deposition in the Central Valley have included the mid-Pliocene uplift of the Coast Ranges (which, among other effects, separated the Central Valley from the Pacific Ocean), and a number of sea level transgression-regression (advance-retreat) cycles. Since late Quaternary time, the Delta has experienced several cycles of deposition, non-deposition, and erosion, with summary descriptions of the principal surface deposits and underlying bedrock units in the Delta vicinity provided below (refer also to Figure 3E-4).

3E.2.3.1.1 Peat and Organic Soils

These soils consist primarily of mud/muck and peat deposits, with variable sand, silt, clay and carbonate (oyster shell) content. Organic soils are common in much of the central and western Delta, and generally transition into fine-grained alluvial deposits to the north, east and south (Figure 3E-4). The presence of soils with high organic content in the Delta and adjacent areas is attributed to the widespread occurrence of marshland associated with rising sea levels. Specifically, the accumulation of vegetative detritus in thick and widespread marshes results in the formation of organic deposits such as humus or, under anaerobic (oxygen-deficient) conditions, peat. It has been suggested that the organic-rich soils in the Delta began forming as recently as the beginning of Holocene time, in association with the most recent phase of sea level rise (Shlemon and Begg 1975). The previously noted subsidence in the Delta area is partly derived from the creation of aerobic (oxygen-rich) conditions from draining marshlands for agricultural use, and the subsequent decomposition of organic materials.

3E.2.3.1.2 Alluvium

Alluvium consists of sediment deposited by running water from sources including rivers, floodplains, alluvial fans and glacial runoff. Alluvial materials are typically loose and unconsolidated, and encompass variable amounts of silt, clay, sand and gravel size particles. Within the Delta and vicinity, mapped alluvium includes extensive deposits of various ages (i.e., Pleistocene and Holocene) and sources, and is most common in the outer portions of the Delta (with transitions to organic-rich soils in the central and western Delta as previously noted).

3E.2.3.1.3 Levee and Channel Deposits

Levee and channel deposits occurring within the Delta and vicinity include both natural and artificial materials. Specifically, natural levee deposits are associated with low ridges (or natural levees) that form over time along river banks, in association with flooding and the deposition of coarser sediments in proximity to the river channel (with finer-grained floodplain deposits typically deposited further from the channel). As described in Section 3E.1, Introduction, a series of artificial levees has been constructed within the Delta and Suisun Marsh for purposes including flood control, habitation and agriculture. These levees are mostly non-engineered structures comprised of materials dredged/ excavated from adjacent areas (e.g., organic soils and alluvial deposits). Engineered levees (or "project levees") within the Delta were constructed as part of an authorized federal flood control project for the Sacramento and San Joaquin River systems. Such facilities typically consist of engineered fill, which meets associated standards such as proper composition, placement methodology, compaction and drainage, and may be capped (or armored) with material such as appropriately sized riprap. Natural channel (or slough) deposits in the Delta area consist essentially of alluvium (as previously described) deposited within defined drainage channels. Artificial channels in the Delta include stream channels modified for purposes such as flood control, and include unlined channels with alluvial deposits similar to natural channels, as well as concrete-lined reaches. While most individual levee and channel deposits are not mapped, they occur throughout much of the Delta and vicinity.

3E.2.3.1.4 Dune Sand Deposits

Eolian (or wind-deposited) dune sands are mapped primarily in the northern and western portions of the Delta, and consist of very well-sorted (exhibiting uniform grain size), fine- to medium-grained sands. These deposits are generally associated with late-Pleistocene/early-Holocene periods of low sea levels, during which fluvial (river- or stream-derived) and glacial sediments were redeposited as eolian dune sands (Delta Habitat Conservation and Conveyance Program [DHCCP] 2009).

3E.2.3.1.5 Bedrock Units

The Quaternary-age surficial materials described above in the Delta and immediate vicinity overlie Cretaceous- to Tertiary-age sedimentary bedrock. These underlying bedrock units consist primarily of interbedded marine sandstone, shale and conglomerate, although late Tertiary shallow marine, terrestrial and volcaniclastic deposits are also present (DWR 2009c, 2009d). While bedrock deposits in the Delta vicinity generally occur at depths of more than 1,000 feet (Brocher 2005), outcrops of the early-Pleistocene Montezuma Formation are present in the Montezuma Hills, just north of the western Delta area. The Montezuma Formation consists primarily of poorly-sorted and poorly-consolidated clayey-sand, silt, and gravel, apparently of non-marine, fluvial origin. The noted Cretaceous to Tertiary-age rocks are in turn underlain at depth by undifferentiated granitic rocks to the east and the Franciscan Formation to the west as previously described.

3E.2.3.2 Seismic Setting

The Delta and vicinity are within a broad, seismically active region that is potentially subject to substantial hazards associated with moderate to large earthquake events. Specifically, geologic and seismic conditions in the Delta area are controlled primarily by interactions along the boundary between the North American and Pacific crustal (tectonic) plates. This boundary exhibits predominantly strike-slip (lateral) movement in the Delta vicinity, with the Pacific Plate moving in a northwestern direction relative to the North American Plate. In much of California this boundary is marked by the San Andreas Fault System, which incorporates numerous active and potentially active nearby faults including the active San Andreas, Hayward-Rodgers Creek, Calaveras, Concord-Green Valley and Greenville faults (Figure 3E-5). Active faults are defined as those exhibiting historic seismicity or displacement of Holocene-age materials, while potentially active faults have no historic seismicity and displace Pleistocene but not Holocene strata (with pre-Quaternary faults designated as "inactive" and exhibiting a low probability for earthquake activity). Portions of several local active faults are also designated as Earthquake Fault Zones (EFZs) by the California Geological Survey (CGS), including segments of the Cordelia, Concord-Green Valley, Greenville, Calaveras and Hayward-Rodgers Creek faults (Figure 3E-5). The described EFZ designations are generally intended to "[r]egulate development near active faults so as to mitigate the hazard of surface fault rupture" (CGS 2007).

A number of additional active seismic sources are located in the Delta and vicinity, including other near-surface crustal faults (i.e., similar in nature to those described for San Andreas Fault System), "blind" thrust faults, seismic zones, and a subduction zone. The primary additional active crustal fault in the Delta vicinity is the Pittsburg-Kirby Hills Fault, which (along with the previously noted Concord-Green Valley and Cordelia faults) extends across portions of the western Delta/Suisan Marsh. A summary of the principal active crustal faults and related seismicity characteristics in the Delta vicinity is provided in Table 3E-1.

Table 3E-1. Principal Active Crustal Fault Locations and Seismicity Characteristics in the Delta Region

Fault	Distance/Direction from the Delta and Suisan Marsh (miles)	Estimated Maximum Slip Rate (inches/year)	Maximum Earthquake Magnitude (M_w)
Concord-Green Valley	0[a]	0.2 ± 0.12	6.7
Pittsburg-Kirby Hills	0[b]	0.02 ± 0.08	6.7
Greenville	6.2/South	0.16 ± 0.08	6.9
Hayward-Rodgers Creek	12.4/West	0.35 ± 0.08	7.3
Calaveras	16.8/South	0.16-0.79	6.9
San Andreas	30/West	0.94 ± 0.12	7.9

[a] Extends north-south across Suisan Bay
[b] Extends north-south across Broad Slough
Mw = Moment Magnitude
Source: DWR 2009c, 2009d

Thrust faults generally consist of structures wherein older rocks (i.e., at lower stratigraphic positions) are pushed up and thrust over younger strata due to compressional forces. Blind thrust (or other) faults do not exhibit any surface expression (e.g., ruptures, offsets, etc.), with known blind thrust faults in the Delta area including the Midland, Montezuma Hills, Thornton Arch, West Tracy, Black Butte, Midway and Vernalis faults. These blind thrust faults, along with other blind faults, are depicted as dashed lines on Figure 3E-5, with a summary of local thrust faults and related seismicity characteristics provided in Table 3E-2.

Two regional seismic zones, the Coast Ranges and Central Valley seismic zones, have been designated to account for seismic activity that is not associated with known fault structures, such as random or “floating” earthquakes. A floating earthquake is an event of some specified maximum magnitude distribution whose rupture length is less than the total length of the fault. These types of events are not associated with a specific fault segment, and are thus allowed to “float” along the length of the fault. The maximum Moment Magnitude assigned to the identified seismic zones is 6.5 ± 0.3.

Subduction zones occur at convergent tectonic plate boundaries as previously described. The closest subduction zone to the Delta is the Cascadia Subduction Zone, where sections of several oceanic plates (including portions of the Pacific Plate) are being subducted beneath the North American Plate. The Cascadia Subduction Zone extends north from Cape Mendocino to Vancouver Island, British Columbia, and is located approximately 200 miles northwest of the Delta at its closest point. Despite this distance, the Cascadia Subduction Zone is included as a possible seismic source for the Delta due to the associated potential to produce very large earthquake events (i.e., Mw of ± 9.0).

Table 3E-2. Principal Thrust Faults and Seismicity Characteristics in the Delta Area[a]

Fault	Maximum Slip Rate (inches/year)	Maximum Earthquake Magnitude (M_w)
Thornton Arch	0.002–0.006	6.0–6.5
Montezuma Hills	0.002–0.02	6.0–6.5
Vernalis	0.003–0.02	6.25–6.75
Southern Midland	0.004–0.04	6.6
West Tracy	0.07–0.5	6.25–6.5
Black Butte and Midway	0.004–0.04	6.25–6.75
Northern Midland	0.004–0.04	6.0–6.5

[a] Refer to Figure 3E-5 for fault locations.
Mw = Moment Magnitude
Source: DWR 2009c, 2009d; Fugro Consultants 2011

3E.2.4 Types of Seismic Risks

Potential seismic risks encompass direct effects, such as ground rupture and ground acceleration (or ground shaking), along with indirect hazards including liquefaction and related effects (e.g., dynamic settlement, lateral spreading, slope failures and lateral pressure), landslides/slope failure, and tsunamis/seiches. These risk categories are described below in the context of geologic/seismic conditions and related general occurrence potential in the Delta area, with associated potential seismic hazards to the existing levee system and SWP/CVP facilities and operations discussed more specifically in Sections 3E.3.3 and 3E.3.4.

3E.2.4.1 Ground Rupture

Seismic ground rupture is the physical surface displacement occurring along the trace of a fault as a result of an earthquake event. Ground rupture can also occur in the form of slow movement along a fault trace that is unaccompanied by a specific earthquake event, with this phenomenon termed fault creep. For major earthquakes along larger faults, ground rupture can extend for considerable distances (hundreds or thousands of feet), with associated risks for surface and subsurface structures such as buildings, dams (or levees), power plants, and utilities (e.g., gas or water pipelines). Known surficial fault structures in the Delta and immediate vicinity include portions of the Pittsburg-Kirby Hills, Concord-Green Valley and Cordelia faults, as described in Section 3E.3.1 (refer also to Figure 3E 5). Segments of the Concord-Green Valley and Cordelia faults also encompass EFZ designations (as defined in Section 3E.3.1), while no EFZs have been designated for the Pittsburg-Kirby Hills Fault. Based on empirical relationships (per Wells and Coppersmith 1994) and fault parameters, the following estimated fault offsets (displacements) are identified along the Pittsburg-Kirby Hills and Concord-Green Valley faults: (1) average offsets ranging between approximately 10.6 and 38.6 inches; and (2) maximum offsets ranging between approximately 13.4 and 63 inches.

As previously noted, a number of active or potentially active blind thrust faults are also located within the Delta area. Such structures are potentially capable of producing ground manifestations during offsets (e.g., subsurface shear zones and/or surface bulging), with the previously described Midland Fault, for example, exhibiting an anomalous relief feature of between 6.6 and 9.8 feet along the trace of this fault near the base of an associated peat layer (DWR 2009c, 2009d). Despite this anomaly and the fact that associated geologic data are limited, however, blind thrust faults in the Delta area are generally considered to have a low potential for surface rupture due to their depth.

3E.2.4.2 Ground Acceleration (Ground Shaking)

Seismic ground shaking is the result of vibratory waves emanating from the focus of an earthquake (i.e., the hypocenter, or point within the earth where seismic activity initiates), and traveling through the surrounding bedrock and soil strata. Seismic waves typically affect large areas encompassing several square miles or more, and generally constitute the most significant hazard from earthquake events. The severity of ground shaking can vary with a number of factors, including earthquake magnitude/acceleration levels, soil and geologic characteristics, and earthquake/shaking duration. Seismic ground shaking can result in direct effects to surface and subsurface structures (e.g., collapse, rupture or slope failures), as well as indirect effects including liquefaction (discussed separately below in this section). Potential seismic ground shaking in the Delta area has been evaluated using standard and modified Probabilistic Seismic Hazard Analyses (PSHAs). The basic principles of the standard and modified PSHAs are summarized below, followed by a discussion of the resulting potential ground shaking hazards in the Delta area.

The standard PSHA assumes a Poisson (probability) process for earthquake occurrences, or a time-independent earthquake recurrence model. Specifically, the application of a Poisson process in PSHAs includes a stochastic (or randomness) process, in which the probability that any one seismic event will result in ground motions at a site in excess of a specified level is independent of the occurrence of other (previous) seismic events. The results of a standard PSHA are expressed in terms of the percent probability that a certain level of ground shaking will be exceeded in a given time interval. The modified PSHA includes calculation of time-dependent hazards associated with several major Bay Area fault structures. That is, the time-dependent model uses the time of the last earthquake to estimate the recurrence interval (or frequency) for earthquake events along individual faults. Based on the availability of historic seismic data, the time-dependent analysis was conducted for seven major Bay Area faults, including the San Andreas, Hayward-Rodgers Creek, Calaveras, Concord-Green Valley, San Gregorio, Greenville and Mt. Diablo Thrust faults.

From the described analyses, it was determined that the seismic sources expected to dominate ground motions (and related ground shaking hazards) in the Delta are associated with the nearby (time-independent) Delta seismic sources. The time-dependent major seismic sources in the region, however, become a more important factor over longer time periods as, for example, the probability of a 1906-type earthquake along the San Andreas System increases. Ground motions in the Delta associated with time-independent nearby seismic sources were calculated for a number of return periods ranging from 72 to 2,475 years. A summary of calculated ground motions for return periods of 475 years (10 percent probability of being exceeded in a 50-year period) and 2,475 years (2 percent probability of being exceeded in a 50-year period) are provided in Table 3E-3, along with similar data from estimates prepared by the U.S. Geological Survey (USGS; 2009). The data in Table 3E-3 include ranges of mean peak ground acceleration (PGA) and Spectral Acceleration (SA; i.e., ground motion of buildings or structures), with both figures given in "g" or the acceleration due to gravity.

Table 3E-3. Summary Comparison of Ground Motions in the Delta Area

Ground Motion Return Period	Range of Mean Peak Ground Acceleration (g)		Range of Mean 1.0-second Spectral Acceleration (g)	
	Project Analysis[a]	USGS Estimate[b]	Project Analysis[a]	USGS Estimate[b]
475 Years	0.20-0.46	0.20-0.40	0.26-0.53	0.14-0.30
2,475 Years	0.29-0.74	0.30-0.70	0.42-0.89	0.25-0.50

[a] Mean ground motion ranges for six sites in the Delta area, including Clifton Court, Delta Cross Channel, Montezuma Slough, Sacramento, Sherman Island, and Stockton.

[b] Mean ground motion ranges over the Delta.

g = acceleration equal to that of gravity

Source: DWR 2009c, 2009d; USGS 2009

The project analysis and USGS estimates noted above are not directly comparable due to differences in average shear-wave velocities associated with assumed subsurface conditions. That is, the USGS model assumes firm rock conditions, while the project model assumes stiff (or firm) soil. Accordingly, the noted differences in acceleration levels can be attributed to site amplification of the soil versus the USGS firm rock ground motions. Both sets of data, however, identify PGA/SA values that could potentially generate moderate to severe hazards in the Delta area.

3E.2.4.3 Liquefaction and Related Effects

Liquefaction is a phenomenon in which loose, saturated and granular (generally sandy) soils lose shear strength, develop high pore water pressure and exhibit fluid-like behavior after the occurrence of earthquakes or other sources of ground shaking. Liquefaction can result in the loss of structural bearing support or failure (e.g., slumping) of surface facilities, and can also generate related effects such as dynamic (or seismically induced) settlement of liquefied soils, lateral spreading (i.e., horizontal displacement on gently sloping surfaces as a result of underlying liquefaction), slope failures or increased lateral earth pressures (due to the fluid-like nature of liquefied soils). Liquefaction and related effects are influenced by ground motion intensity and shaking duration. While earthquake magnitude, as previously noted, measures the energy released at the source of the earthquake, intensity is a measure of the strength of shaking produced by the earthquake at a certain location (and is associated with effects to people, structures, and the natural environment, refer to Figure 3E-6). Longer periods of ground shaking, even at lower intensities, can result in liquefaction as the soil is subject to repeated cycles of seismic loading. Longer duration ground shaking is most typically associated with larger magnitude earthquakes occurring on major regional faults. The identified potential for liquefaction and related effects in the Delta area ranges from low to high, with alluvial soils typically exhibiting higher potential and peat/organic soils generally exhibiting lower potential.

3E.2.4.4 Landslide/Slope Instability

Landslides and related slope movements, such as soil creep and slumping, can be associated with factors including seismic activity, gravity, precipitation and fires (i.e., from the loss of stabilizing vegetation). As previously noted, strong seismic ground shaking can trigger landslides or other slope failures, particularly in areas with existing susceptibility for slope instability (e.g., saturated slopes). The Delta area does not include any designated State or local landslide hazard zones, and due to its level topography associated landslide hazards are considered generally low. An exception to this conclusion involves the associated levee structures, however, many of which are non-engineered and may encompass saturated materials (due to their constant exposure to water and related seepage) as previously described.

3E.2.4.5 Tsunami/Seiche

Tsunamis (sometimes referred to as tidal waves) are large ocean waves produced by events such as submarine earthquakes or volcanic eruptions, and can generate impacts related to inundation of coastal areas. While no known maps of tsunami hazards are available for the Delta area, potential inundation risks in the Delta area are expected to be minimal, based on the following considerations: (1) mapped tsunami hazards west of the Delta area (west of Benicia Bridge) identify maximum inundation levels of three feet above sea level (California Department of Conservation 2009); and (2) tsunami effects east of the Benicia Bridge would likely be further attenuated in Suisun and Grizzly bays prior to reaching the Delta area.

Seiches are wave-like oscillatory movements in enclosed or semi-enclosed bodies of water such as lakes, reservoirs, or bays, and are associated with seismic ground shaking. This phenomenon can result in flooding damage and related effects (e.g., erosion) in surrounding areas from spilled or sloshing water, as well as increasing pressure on containment structures. The potential for seiche-related hazards in the Delta area is generally considered low, based primarily on the shallow nature of local enclosed water bodies.

3E.2.5 Potential for Seismic-related Levee Failure

As described in Sections 3E.3.1 and 3E.3.2, the Delta area is subject to a number of potential hazards related to geologic and seismic conditions. Based on these analyses, ground shaking and related effects (e.g., liquefaction) represent the most significant potential seismic hazards in the Delta area. These potential hazards are particularly applicable to the existing levee system, due to the previously described composition and non-engineered nature of many of these structures. The occurrence of levee failures, or breaches, results in flooding of the associated islands located behind the levee structures, with related implications for issues including damage to homes and agricultural activities, as well as water quality conditions (i.e., from the influx of seawater). A summary discussion of levee failure/seismic history is provided below, followed by discussion of seismic-related hazard potential.

3E.2.5.1 Historical Context

Historically, there have been at least 166 Delta and Suisun Marsh levee failures leading to island inundations since 1900 (Fleenor et al. 2008). None of these failures is attributable to seismic events, but Delta levees have not experienced the greatest potential seismic shaking at their current size and configuration. The largest earthquakes experienced in the Delta region over the last century include the 1906 Great San Francisco Earthquake and the 1989 Loma Prieta Earthquake. (The locations, magnitudes and intensities of the principal historical earthquake events in the Delta vicinity are depicted on Figure 3E-5) The epicenter of the 1906 Great San Francisco Earthquake (magnitude 7.8) was approximately 60 miles from the center of the Delta, and the earthquake occurred early in the era of Delta island reclamation, when the levees were in their early stages of construction and were much smaller and less extensive than today. The epicenter of the 1989 Loma Prieta earthquake (magnitude 6.9) occurred approximately 80 miles from the center of the Delta. Although the levee system was similar to existing conditions at that time, the smaller magnitude and more distant Loma Prieta earthquake did not cause perceptible damage to the levees. Because of the geologically recent reclamation of Delta islands, combined with the sporadic nature of major seismic events, the historical response of Delta levees to major earthquakes lacks predictive value. Seismologists predict that large seismic events will affect the Delta area in the future (as outlined below) and such events would be expected to represent more substantial hazards to the levee system than observed in the noted historical earthquakes.

3E.2.5.1.1 Seismic Hazard Potential to the Delta Area Levee System

As previously described, the Delta area is within a highly active seismic area and is predicted to experience the effects of moderate to strong earthquake events along nearby faults in the future. Specifically, a related assessment conducted for the Delta area in 2002 concluded that the likelihood of large earthquakes (Moment Magnitude ≥ 6.7) in the region is increasing (and will continue to increase) over time, with the probability of such an earthquake in the next 30 years given as 62 percent (the Working Group on California Earthquake Probabilities [WGCEP]; 2003). As discussed above, the principal seismic hazards for the Delta levee system are ground shaking and liquefaction (Section 3E.3.2). Accordingly, the following assessment is focused on these potential hazards, with seismic ground rupture addressed briefly (due to the presence of several active crustal faults and the related potential for surface displacement), and hazards from tsunami/seiche and landslide events (except in the context of ground shaking effects to levee structures) not discussed further.

3E.2.5.1.2 Ground Rupture

Seismic ground rupture is not considered a major hazard in the Delta area (see Section 3E.3.2). The potential for ground rupture hazards is greatest in the western Delta/Suisan Marsh area due to the presence of active crustal faults. Specifically, portions of the Pittsburg-Kirby Hills, Concord-Green Valley and Cordelia faults are located within the western Delta/Suisan Marsh, with maximum estimated ground rupture offsets identified for the Pittsburg-Kirby Hills and Concord-Green Valley faults ranging from approximately 13.4 to 63 inches. This level of offset could potentially result in substantial breaching and/or failure of associated levee structures, and is considered a significant potential hazard in the associated locations. The potential for seismic ground rupture in other portions of the Delta area is much lower due to the absence of known active crustal faults and the depth to known blind thrust faults. Accordingly, associated potential ground rupture hazards in these areas are considered less than significant, although as previously noted the descriptions of local thrust faults and related conclusions regarding the potential for seismic ground rupture are based on limited geologic data.

3E.2.5.1.3 Ground Shaking/Liquefaction and Related Effects

The Delta area is subject to potential PGA/SA values that could generate moderate to severe hazards, including structural deformation and related effects to the existing levee system (Section 3E.3.2, refer to Table 3E-3). Earthquake-generated levee deformations can result in liquefaction-induced flow slides, inertia-induced seismic deformation in non-liquefiable cases, or a combination of the two. Other potential seismically induced modes of failure include overtopping as a result of crest slumping and settlement, internal piping and erosion caused by earthquake-induced differential deformations (varying degrees of deformation occurring over relatively short distances), sliding blocks and lateral spreading resulting in transverse cracking, and exacerbation of existing seepage problems due to deformations and cracking (with existing seepage associated with the fact that Delta levees are mostly non-engineered and in contact with water 100 percent of the time, as previously described). Unlike flood-related (or other conventional-type) breaches, which typically affect a few hundred feet, seismically induced levee failures often extend for thousands of feet or more (DWR 2009a). In addition, levees damaged or weakened, but not physically breached, during a major earthquake event may be subject to failure during subsequent wet seasons if not repaired. These conclusions are based on evaluation of historical levee failures associated with major seismic events, including the 1995 Kobe, 1940 Imperial Valley, 1989 Loma Prieta, and 1971 San Fernando earthquakes (DWR 2009a).

As part of the DRMS analyses, a series of “vulnerability classes” (VCs) were identified to reflect zones with similar levee failure potential, based on documented historical events and site-specific data for the Delta area including subsurface profile (e.g., the presence and thickness of peat/organic soils), levee fill conditions and geometry, past performance, and maintenance history (DWR 2009a). A total of 22 VCs were identified in the Delta (along with two additional VCs specific to Suisan Marsh), to reflect the following categories/considerations (refer to Figure 3E-7):

- Liquefiable Material in the Levee Fill – Four VCs (VC I to VC 4) were identified for levees containing liquefiable fill material. These designations were independent of levee geometry and whether or not the levee foundation contained liquefiable material. That is, the seismic behavior of the associated levees was determined to be controlled by the liquefiable nature of the levee itself, rather than the other noted factors.
- Liquefiable Material in the Levee Foundation but not in the Levee Fill – Ten VCs were identified in this category (VC 5 to VC 14), in which seismic behavior is controlled by the liquefiable nature of the levee foundation, and the levee fill and geometry are not controlling factors.
- No Liquefiable Material in the Levee Fill or Foundation – This category includes 8 VCs (VC 15 to VC 22), with levee geometry (steep or non-steep slopes) and the presence/thickness of peat representing the controlling factors (with thicker peat deposits resulting in higher failure vulnerability).
- Suisan Marsh VCs – The two VCs identified for Suisan Marsh (VC 23 and VC24) were based primarily on the presence or absence of liquefiable material in the levee fill and foundations.

All 24 of the identified VCs were then evaluated to reflect a number of additional variables/ considerations, including ground motions (PGA and SA), seismic deformation characteristics (e.g., acceleration levels of a seismically induced "sliding mass"), material properties (e.g., shear strength properties of levee and foundation materials), and randomness (e.g., in relation to slough/river water levels at any given time, and peat thickness at any given location). The results were calibrated with conditions at the following two existing sites in the west-central Delta area that exhibit known geotechnical issues: (1) Bradford Island, which is experiencing tension crack and vertical offset at the levee crest; and (2) Holland Tract, which is experiencing erosion resulting in an over-steepened waterside slope.

Computer model simulations were also conducted to evaluate existing levee system responses to three historical seismic events, including the following: (1) a 5.8-magnitude earthquake in 1980 near Livermore (approximately 11 miles south of the Delta); (2) a 6.19-magnitude earthquake in 1984 along the Calaveras Fault (about 50 miles south of the Delta); and (3) the 1906 Great San Francisco Earthquake (magnitude 8.0). No damage to Delta levees was reported for any of these events (although the levee system was substantially smaller in 1906 as previously noted), and no damage was calculated in the Delta from the 1980 and 1984 event simulations. Under the 1906 earthquake model, calculated deformation of the current levee system ranges from 0 to 3 feet, with a conditional probability of levee failure ranging from 0 to 23 percent (DWR 2009a).

3E.2.5.1.4 Summary of Seismic Hazard Potential for Delta Levees

The Delta and vicinity is within a highly active seismic area, with a generally high potential for major future earthquake events along nearby and/or regional faults, and with the probability for such events increasing over time. Based on the location, extent and non-engineered nature of many existing levee structures in the Delta area, the potential for significant damage to, or failure of, these structures during a major local seismic event is generally moderate to high. General site- and/or analysis-specific observations and conclusions regarding seismic performance and hazards in the Delta area are summarized below.

3E.2.5.1.5 General Seismic Performance Observations/Conclusions

- Seismic site response in the Delta area is complex, due to the highly variable younger alluvial deposits, organic marsh deposits, and levee fill condition.
- The potential for earthquake induced ground rupture is generally high for levees in Suisan Marsh located along or across the Pittsburg-Kirby Hills, Concord-Green Valley or Cordelia faults.
- At Suisun Marsh, the earthquake-induced deformations under strong shaking are large due to the presence of deep, very soft clay deposits at the levee foundations.
- The areas most prone to liquefaction potential are in the northern and southeastern regions of the Delta. The central and western regions of the Delta and Suisun Marsh show discontinuous areas of moderate to low liquefaction potential.
- Levees composed of liquefiable fill are likely to undergo extensive damage as a result of a moderate to large earthquake in the region.

Levees founded on liquefiable foundations are expected to experience large deformations (in excess of 10 feet) under a moderate to large earthquake in the region.

3E.2.5.1.6 Site- and Analysis-Specific Seismic Performance Observations/Conclusions

- VCs 1 to 4 represent the levees most vulnerable to seismic loading. These include structures with liquefiable levee fill, and peat/organic soils and potentially liquefiable sand deposits in the foundation. Numerous islands are associated with the VC 1 to 4 levees, including (but not limited to) Sherman, Brannan-Andrus, Twitchel, Webb, Venice and Bouldin islands.
- The majority of islands within the Delta have at least one levee reach in VCs 1 to 4.
- The weakest vulnerability class within an island levee generally controls the performance of that levee, per the "weakest link" principle.
- Assuming 2 feet of levee freeboard: (1) The median probabilities of failure for VCs 1 to 4 range from 5 to 28 percent at a reference PGA of 0.10g, and from 70 to 90 percent for a reference PGA of 0.5g; (2) the median probabilities of failure for VCs with no liquefiable foundation sand and no liquefiable levee fill increase with peat thickness under the levee for a PGA of 0.5g, with smaller probabilities of failure (less than 22 percent) when peat is absent, and larger probabilities of failure (30 percent to 60 percent) when peat is more than 25 feet thick; and (3) where waterside slopes are steeper than 1.5:1 (horizontal to vertical), the assessed probabilities of failure tend to be larger for the same vulnerability classes.

3E.2.6 Potential Effects on SWP and CVP Water Supply

The probabilities of moderate to large earthquake events and related damage to or failure of Delta area levees are generally high and increasing over time. Many of the related Delta islands are currently below sea level due to factors including subsidence of underlying organic soils, with this subsidence expected to continue at a generalized rate of approximately 0.9 inch per year until the organic content is largely depleted (with subsidence in Suisan Marsh substantially lower due to associated management practices). Based on the noted conditions, seismically induced levee breaches would result in the influx of seawater into the associated islands, with a number of resultant issues including water quality and related water supply concerns. A summary overview of Delta area hydrologic conditions is provided below, followed by an assessment of potential impacts to associated water quality/supply conditions from seismically induced levee failure.

3E.2.6.1 Sacramento-San Joaquin Delta Hydrology

The Sacramento-San Joaquin Delta is an inverted river delta, wherein the narrow end of the delta emerges on the seafront and the wide end is located further inland. Freshwater flows from the Sacramento and San Joaquin rivers enter the eastern Delta, and ultimately move through the narrow Carquinez Strait into San Francisco Bay. Conversely, seawater flows east via tidal action, with a resulting complex series of interactions and mixing of fresh and seawater. Suisan Marsh and adjoining bays comprise brackish water "transition areas" between these fresh and seawater movements. The natural "balance" of fresh and seawater interactions in the Delta system has been altered by a number of human interventions, including water diversions that can remove 40 percent of the freshwater flowing into the Delta. Accordingly, the existing Delta system incorporates a complicated and delicate balance to maintain fresh and saline water flows/conditions, while accommodating a myriad of dependent uses including water supplies, agricultural operations and ecological concerns (e.g., native habitats and fisheries).

3E.2.6.2 Potential Impacts to Water Quality/Supplies from Seismic Levee Failure

3E.2.6.2.1 Water Quality Concerns

A major earthquake event could result in breaching/failure of existing levees within the Delta area, with a substantial number of these structures exhibiting moderate to high failure probabilities. The most immediate and significant effect to water quality under such a scenario would be the influx of large volumes of seawater and/or brackish water into the Delta, which would alter the "normal" balance of freshwater/seawater flows and result in flooding of the associated islands. The corresponding shift in Delta water quality conditions would be characterized by an increase in salinity levels, including specific associated constituents such as bromide (which affects total dissolved solids concentrations and can contribute to the formation of undesirable chemical byproducts in treated drinking water). Additional water quality concerns in a large-scale levee failure/scenario would include soil- and agricultural-related pollutants such as organic material, and hydrocarbons associated with local oil and gas exploration/production activities. The described water quality concerns, particularly the influx of seawater/brackish water and associated salinity increase, would continue for an extended period of time. In general, the process following levee breaches would be to (1) repair the levees, (2) dewater the flooded islands using pumps, and then (3) flush brackish water from the Delta. Specifically, for a seismic event in which 20 islands are breached, associated repairs would require 25 months on average, with a range of 20 to 30 months from the date of the earthquake. Dewatering of all the associated islands would be completed approximately 29 months after the earthquake on average, with a range of 25 to 34 months. Repair times for a scenario in which 30 islands are flooded would likely double these estimated repair times (DWR 2009).

Note that the time required to repair levees and dewater affected islands would probably not be the same as the duration of time that SWP/CVP water exports from the Delta are curtailed. The DWR Delta Flood Emergency Preparedness, Response and Recovery plan studies suggest that several years would be required, at about a five percent exceedance probability, to restore salinity concentrations necessary for municipal water quality needs at the export pumps from a catastrophic failure of twenty or more islands.

For the purposes of this appendix, it is assumed that in some instances, restoration of the export of Delta water supplies after a major seismic (or flood) event could be longer than the approximate one year period variously attributed to the DRMS, Phase 1 Risk Report. Because of the potential extent of levee slumping and liquefaction, the possible competition for repair materials and labor, the time required to pump saline water from all (or most) flooded islands, and the time needed to flush saline water from the south and central Delta, restoration of water exports from Jones and Banks Pumping Plants could require up to three years.

3E.2.6.2.2 Water Supply Concerns

The described seismic levee failure scenario and resultant water quality issues could generate both direct and indirect effects to water supply sources and facilities associated with the SWP and CVP. Direct impacts to SWP and CVP operations would result from the potential increase of salinity (or other adverse water quality conditions) at the associated Banks and Jones Pumping Plants' intakes near the southwestern edge of the Delta. If salinity (and/or other pollutant) levels exceed related thresholds at these intakes, pumping would be appropriately curtailed or terminated, with corresponding effects to the viability of the Delta to convey water for the SWP and CVP over a substantial time period (as outlined above under the discussion of Water Quality Concerns). While it is difficult to project the level of direct effects to SWP/CVP water supplies due to the complex nature of the described earthquake/levee failure scenario (with several additional complicating variables outlined below), it is conceivable that the Banks and Jones Pumping Plants' intakes would be largely or completely out of service for a period of months to years, as described above. Under such conditions, the availability of water for agricultural and domestic consumption in much of central and southern California would be severely curtailed, with associated potential catastrophic economic losses and lifestyle changes (such as water shortages and rationing) affecting millions of people. Even in a scenario in which water supplies to the SWP and CVP are maintained at reduced levels, the effects would likely be pronounced, and additional factors may further reduce the amount of SWP/CVP water that can be diverted from the Delta. Specifically, these may include the following considerations:

- Overall water supplies in the Delta are finite, with future supplies potentially subject to reductions due to projected shifts in global climate conditions and related decreases in Delta water sources such as precipitation and snowpack runoff (see Section 3E.4, below).
- Depending on the severity of the levee breach scenario, the management of up- and downstream Delta reservoirs may also be substantially altered. As noted previously, multiple levee breaches would require (1) levee repairs, (2) dewatering the flooded islands, and (3) flushing the brackish water from the Delta. Specifically, in a larger levee failure event, a prolonged period may occur with reduced or no pumping and an associated need to ration water supplies and/or release water from reservoirs south of the Delta due intrusion of higher salinity seawater in the Delta. Managed Delta inflows and outflows to San Francisco Bay would also be needed to provide flushing and restore water quality. After adequate flushing is achieved, the quantity of inflow required to maintain water quality would exceed the "normal" Delta outflow based on increased tidal flows into and out of the unrepaired levees and flooded islands. Finally, when limited export pumping is reestablished, additional Delta inflow would be needed to provide adequate water for pumping, as well as for increased flows to maintain water quality as noted. All of these potential management shifts could reduce the amount of water allocated for pumping by the SWP and CVP.
- Allocations for Delta water supplies are established by long-standing legal and regulatory mandates, and could affect the ability to pump water for the SWP and CVP under reduced water supply conditions associated with a major earthquake/levee failure scenario. The response to emergency orders by in-Delta water users is therefore not predictable, and no plan exists to issue and enforce such orders. Accordingly, continued withdrawals by in-Delta users under the described scenario could further reduce the ability of the SWP and CVP to obtain water from an already diminished supply.
- In addition to the allocated consumptive uses noted above, water supplies in the Delta are subject to regulatory and judicial requirements intended to protect the Delta ecosystem and associated floral and faunal species. Under the Federal Endangered Species Act, for example, protection of a species listed as threatened or endangered may require reductions in consumptive withdrawals in order to protect associated habitat(s). Due to the extensive occurrence of critical wildlife habitat and species in the Delta area, these types of restrictions could limit the ability to pump water for the SWP and CVP, especially under the scenario of reduced water supply conditions related to a major earthquake event and associated levee failures.

3E.3 Climate Change Risks

This section addresses the potential for climate change to affect the viability of the Delta as a water supply source for the SWP and CVP.

3E.3.1 Overview of Climate Change Effects on the Delta

3E.3.1.1 Climate Change Fundamentals

Climate is commonly defined as the weather averaged over a long period of time. Although the climate has changed, in the past in response to natural drivers, recent changes in climate appear to be occurring at a faster rate than historical changes have occurred, appear to be accelerating, and have been unequivocally linked to human activities (Intergovernmental Panel on Climate Change [IPCC] 2007). Climate change has already increased temperatures around the world, raised sea levels, and changed snowpack and runoff patterns in mountainous regions like the Sierra Nevada. These changes have already had an impact on water management in the Delta and are projected to make management of the Delta even more challenging in the future. This section of this appendix focuses on how climate change could affect future management of the Delta for water supply purposes due to hydrologic changes to flows coming into the Delta and sea level rise. Other portions of this EIR/EIS, such as Chapter 29, *Climate Change,* and various resource chapters provide additional information on the historical and projected impacts of climate change on the project area.

3E.3.2 Projected Climate-Change Related Effects to the Delta

Hydrologic conditions in the Delta are largely determined by precipitation (amount, form, and timing) in the Sierra Nevada and in other watersheds that supply the Delta, water management upstream of the Delta (reservoir releases, diversions, operation of weirs, etc.), and tidal influences. The amount and timing of rainfall directly in the Delta typically has a minor effect on flow conditions. Climate change-related effects on the Delta include:

- changes in precipitation within and upstream of the Delta,
- increased sea levels with a corresponding increase in seawater and brackish water entering the Delta from the west, and
- changes in weather patterns that could affect the frequency and magnitude of storms and storm-related flooding.

Climate change impacts to the Delta due to shifts in hydrology and rising sea levels are discussed in more detail in the following sections.

3E.3.2.1 Hydrology

Delta inflows are mainly driven by precipitation and runoff in the vast watershed that drains into the Delta (not by precipitation falling on the Delta itself). The watershed that drains into the Delta is the largest in California, encompassing roughly 45 percent of the state's surface area and stretching from the eastern slopes of the Coastal Range to the western slopes of the Sierra Nevada (Lund et al. 2007). The Delta watershed encompasses high mountain areas up to 14,000 feet of elevation and the vast Central Valley of California. Areas of the watershed above 5,000 feet typically accumulate snow between October and March. The snow typically remains frozen high in the watershed until March when it begins to melt. Snowmelt runoff usually continues into July.

Snowpack accumulation and storage are important components of Delta inflow hydrology. Snowpack accumulation during winter storm events reduces the amount of precipitation that runs off directly during the storm, reducing peak stream flow volumes. Snowpack storage keeps water high in the watershed during winter when reservoirs are at their maximum storage levels and releases it in the spring and summer when the water can be stored in reservoirs or released downstream for use.

Increased temperatures in the upper watershed due to climate change threaten to disrupt this delicate balance. Warmer temperatures mean higher snowlines and more precipitation falling as rain instead of snow, which then contributes to direct runoff, increases peak stream flows and raises the risk of levee failures and flooding. Warmer temperatures also mean that the remaining snow will melt earlier, releasing more of the water during winter when it cannot be stored because reservoirs are operated for flood control and leaving less to melt in spring and summer when it is needed for water supply. (Huang et al. 2012)

These changes are already being observed. Over the course of the 20th Century, warming has been prevalent over the Sacramento and San Joaquin River basins. In both the Sacramento and San Joaquin basins, the overall 20th Century warming has been about 3°F. In the Sacramento basin, the warming trend has also been accompanied by a gradual trend, starting in the 1930s, toward a slight increase in precipitation. However, a similar precipitation trend is not evident in the San Joaquin basin (U.S. Department of the Interior, Bureau of Reclamation 2011). Even with the increased precipitation in the Sacramento River basin, increases in temperature have resulted in the average early spring snowpack in the Sierra Nevada decreasing by about 10 percent during the last century, a loss of 1.5 million acre-feet of annual snowpack storage (DWR 2008). Figures 3E-1 and 3E-2 below show how overall unimpaired runoff in both the Sacramento and San Joaquin River basins has generally remained constant over the last 100 years. But spring and summer unimpaired runoff between April and July has decreased significantly. (Corresponding increases in December to March unimpaired runoff have been observed but are not shown below.)

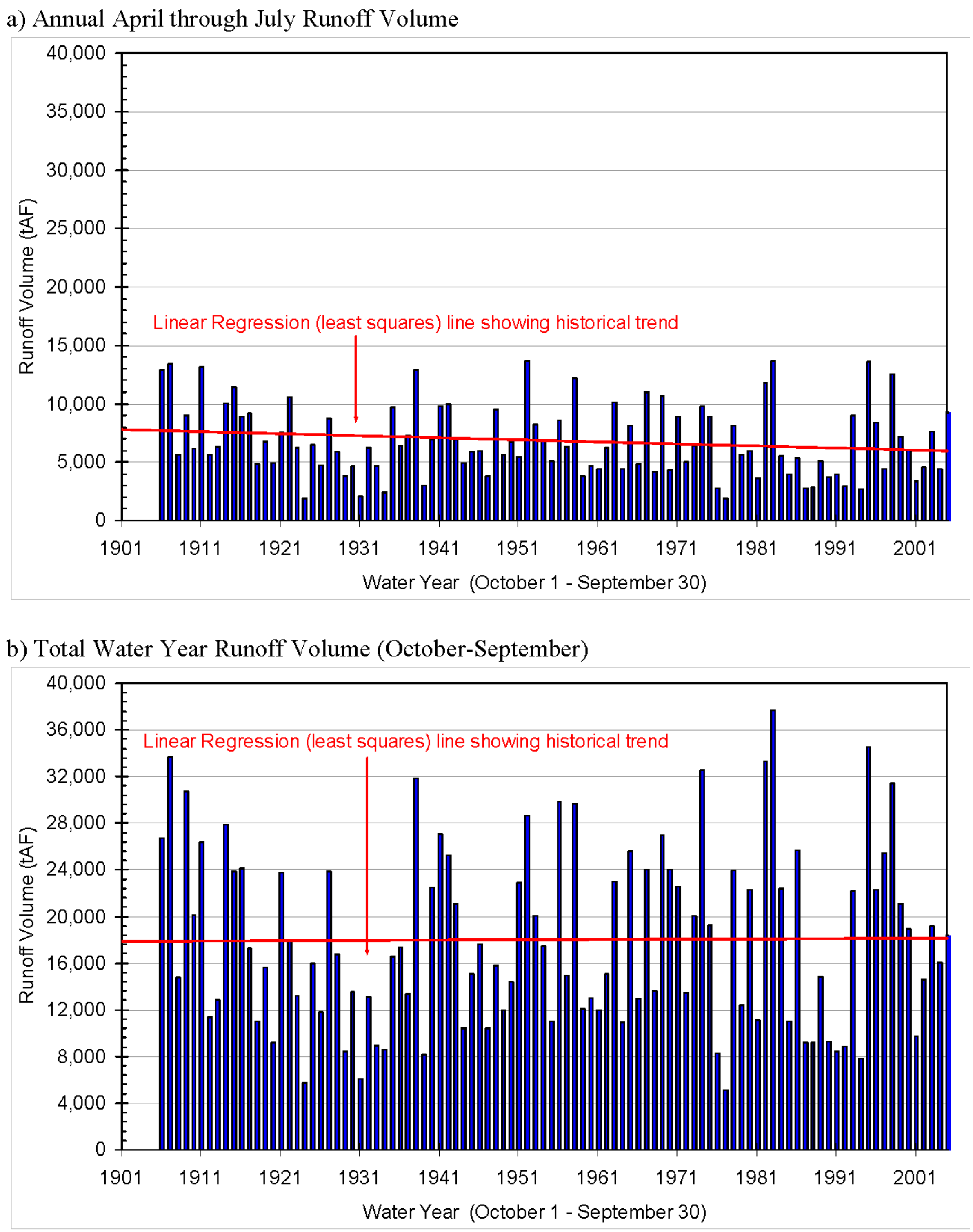
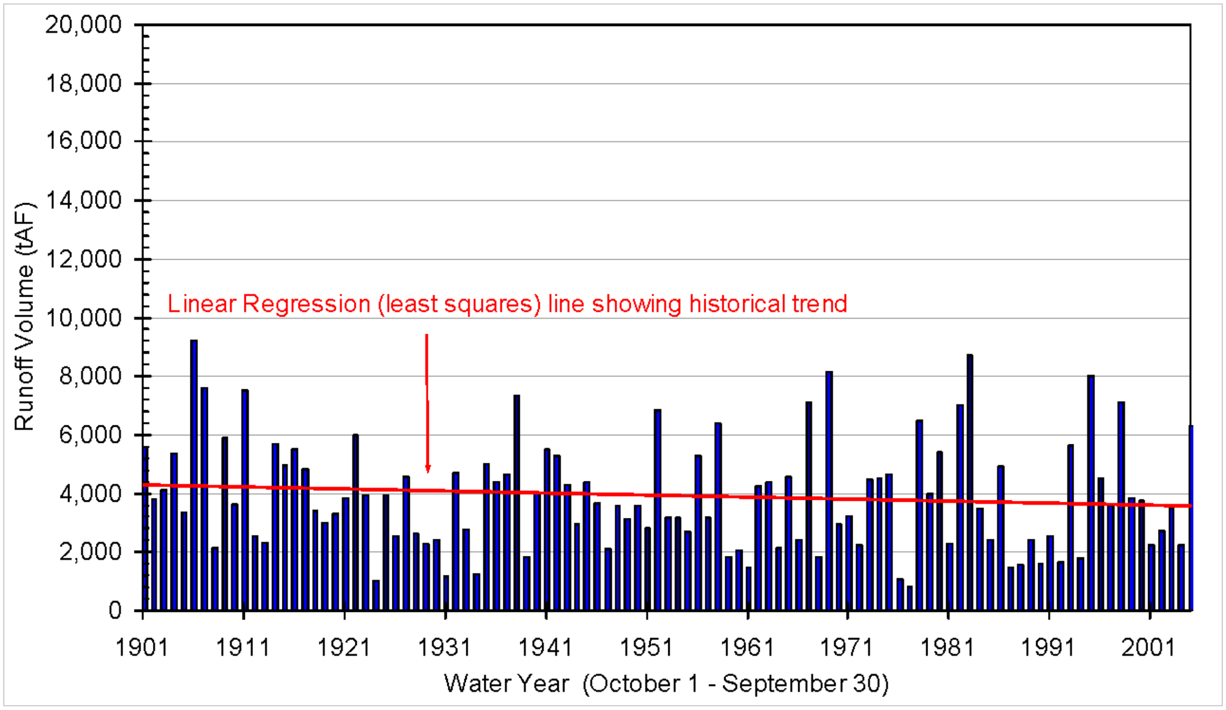


Figure 3E-1. Total Unimpaired Runoff Volume for Four Sacramento Valley Rivers (Source: DWR 2006)

a) Annual April through July Runoff Volume



b) Water Year Runoff Volume

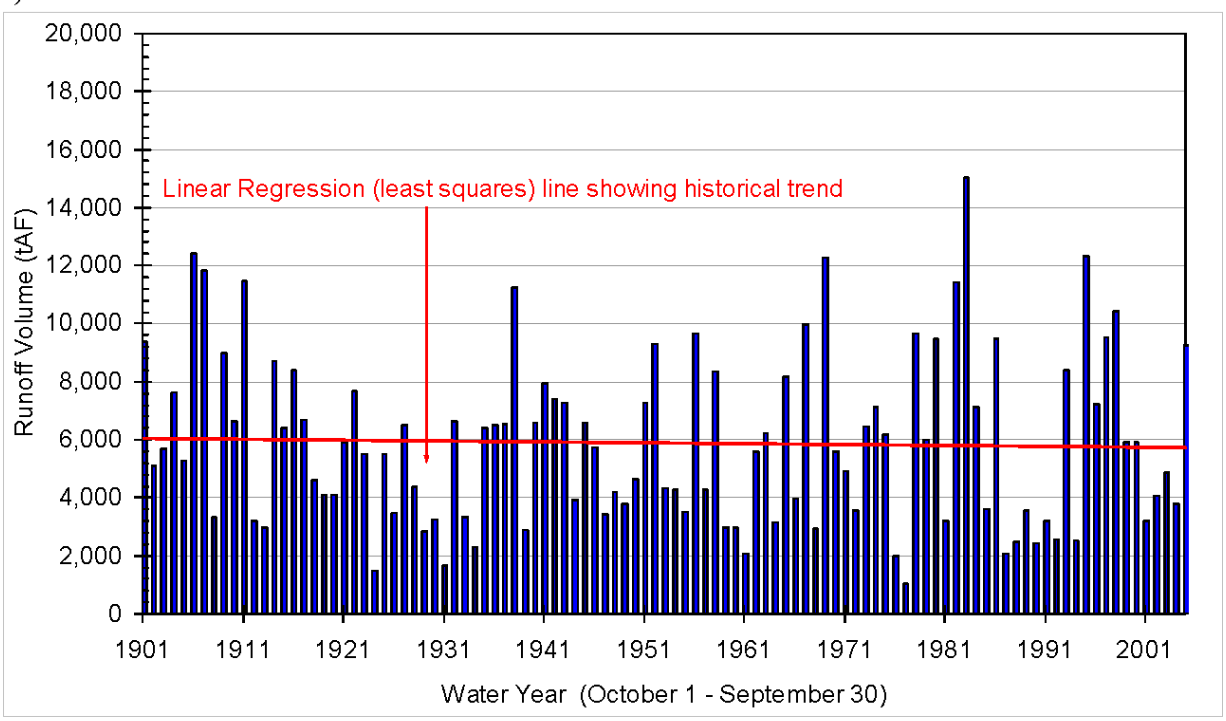


Figure 3E-2. Total Unimpaired Runoff Volume for Four San Joaquin Valley Rivers (Source: DWR 2006)

Climate change may also result in changes in the amount, timing, and intensity of precipitation and storm events in the Delta watershed. Projections of future precipitation conditions for the Delta watershed vary from significant increases in annual precipitation to significant decreases with the models more or less evenly split between wetter conditions and dryer conditions. Other research looking at extreme precipitation events indicates that the Delta watershed will likely see increasing numbers and intensity of large storm events in the future, particularly those associated with the Atmospheric River phenomenon (the “pineapple express” is one well known manifestation of an Atmospheric River), (Dettinger 2011).

As described in other sections of this EIR/EIS, projections of future climate change indicate that warming in the Delta watershed is highly likely to continue and changes in precipitation patterns, while less certain, are also likely. These changes will increase the risk of Delta water supply degradation including reduced water quality and water supply reliability and increase the risk of interruptions in the ability to export water through the Delta and divert water from within the Delta. Reductions in snowpack accumulation and storage will result in reduced spring and summer Delta inflows and reduced operational flexibility. These reduced inflows combined with sea level rise (described in the following section) will result in increasing operational challenges and decreasing ability to export water from the Delta. Increases in extreme precipitation events, combined with increasing temperatures that raise the snow line causing more of the precipitation to fall as rain instead of snow, will result in larger peak inflows into the Delta. Larger peak inflows will increase the risks of levee failures within the Delta. Flooding of Delta islands due to a levee breach could cause seawater to be drawn into the Delta severely reducing water quality and potentially causing Delta export operations to be halted for extended periods of time.

There is limited quantitative analysis of upstream hydrological changes on Delta conditions where only the hydrological changes are considered without also considering the effects of sea level rise. Sea level rise is discussed in more detail in the next section, and quantitative analysis of the combined impacts of upstream hydrological changes and sea level rise on SWP and CVP operations are described in section 3E.4.3.3 below. Information on how changes in hydrology due to climate change were modeled and used to analyze the impacts of the BDCP alternatives are in Appendix 5A, *BDCP EIR/EIS Modeling Technical Appendix*.

3E.3.2.2 Sea Level Rise

Rising mean sea level is expected as a result of global warming. As much as 167 cm (66 inches) of sea level rise is projected for the California coast and Delta region by 2100 (NRC 2012). Sea level is neither constant nor uniform everywhere, but changes continually as a result of interacting processes that operate on timescales ranging from hours (e.g., tides) to millions of years (e.g., tectonics). Processes that affect ocean mass, the volume of ocean water, or sea-floor topography cause sea level to change on global scales. A warming climate causes sea level to rise by warming the oceans, which causes seawater to expand and increases ocean volume. Warmer temperatures also accelerate melting of land ice, which transfers water to the ocean. Human activities also affect sea level, albeit to a much more limited degree. Withdrawing water from aquifers, which eventually reaches the ocean, causes sea level to rise. Conversely, storing water behind dams that would have otherwise reached the ocean results in reductions in sea-level (NRC 2012). At more localized scales, apparent or relative changes in sea level can occur from vertical motion of land (e.g., subsidence, isostatic rebound [the rise of land masses previously depressed by the huge weight of ice sheets, and tectonic uplift]). Short-term localized conditions can also result in large variations in sea levels.

Astronomical tides, variations in atmospheric pressure, variations in the local density of seawater due to short term climate fluctuations (such as El Niño) and changing winds (URS/JBA 2008a) can all result in substantial changes in short-term localized sea level.

In 2012, the National Research Council (NRC) conducted an exhaustive review of existing global sea level rise science and projections and produced a definitive study of sea level rise projections for the west coast of the United States. While several other reports and journal articles have been issued which provide projections of global sea level rise (IPCC 2007; Vermeer and Rahmstorf 2009; Pfeffer et al. 2008; Rahmstorf 2007; and others) this is the first comprehensive study for the west coast of the United States which accounts for local land surface movements and ocean current effects that may result in sea level rise values that deviate from global values. Table 3E.4 below provides NRC (2012) projections for sea level rise values for the California coast in the Delta region. Projections of sea level rise used in the analysis of BDCP alternatives (Appendix 5A, *BDCP EIR/EIS Modeling Technical Appendix*) are within the range of potential sea level rise projected by NRC (2012).

Table 3E.4 Sea Level Rise Projections for San Francisco and Delta Region 2030, 2050, and 2100

		2030		2050		2100	
		Projection	Range	Projection	Range	Projection	Range
Projected Sea Level Rise at San Francisco	cm	14.4 ± 5.0	4.3–29.7	28.0 ± 9.2	12.3–60.8	91.9 ± 25.5	42.4–166.4
	in	5.7±2	1.7-11.7	11±3.6	4.84-23.9	36.2±10	16.7-65.5

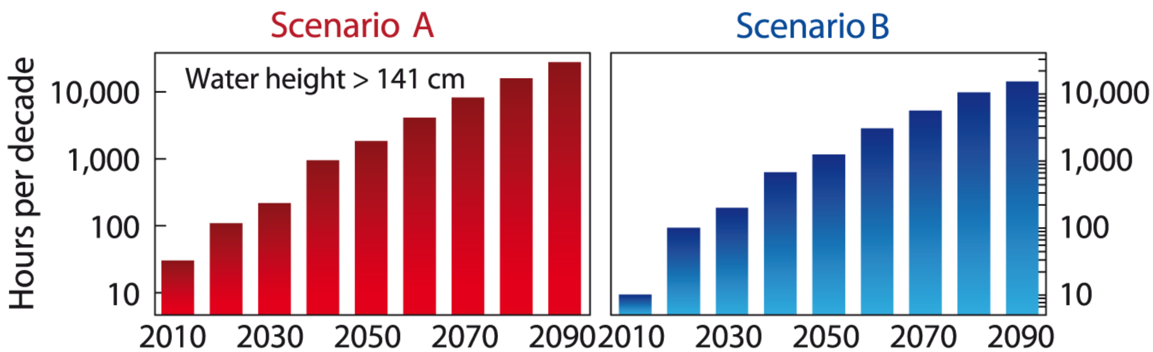
Source: NRC 2012, projected sea levels are increases from values for the year 2000

A rising sea level will impact the Delta in two important ways: 1) increase the risk of overtopping and other forms of levee failure and 2) increased saline/brackish tidal pressure, which if not counteracted by increases in freshwater outflows will lead to increased salinity intrusion and higher salinity levels in the Delta.

Higher sea levels increase the risk of levee failure by producing higher hydrostatic loads against levees and by increasing internal seepage gradients. Most of the land in the Delta is below sea level as a consequence of ongoing subsidence. Rising sea levels would place more pressure on the Delta's already fragile levee system, and as a consequence could increase the risk of levee breeches. High water events such as storm surges and seasonal high tides could further increase the risks of levee failure. Since sea level rise increases the mean sea level, it raises not just the level of the highest sea stands but also increases the amount of time that levees are exposed to higher sea stands as described below.

Cloern et al. (2011) in *Projected Evolution of California's San Francisco Bay-Delta-River System in a Century of Climate Change* evaluated the extent to which extreme water levels might increase in the future by looking at two different scenarios for climate change: one representing a higher degree of change (scenario A) and one representing a lower degree of change (scenario B). Both scenarios included impacts on upstream hydrology as well as sea level rise. As indicated in Figure 3E 8, both scenarios result in marked increases in the frequency of extreme water heights 1.41 m or above mean sea level. Historically, sea levels have only exceeded 1.4 m for approximately 8 hours per decade in San Francisco Bay, Cloern et al. (2011) project that sea levels in 2050 will exceed 1.41 m 1,200 to 2,000 hours per decade and by the end of century will exceed 1.41 m 15,000 to 30,000 hours per decade (note that the "Hours per decade" scale in Figure 3E-8 is logarithmic). Although the projected increase in water heights addressed in the cited study was modeled for the San

Francisco Bay, it correlates to increased, though somewhat attenuated, water heights within the hydrologically connected Delta.



Source: Cloern et al., Scenario A reflects higher climate change and scenario B reflects less climate change

Figure 3E-8. Increases in Duration of High Water in the Bay-Delta System

Higher sea levels also increase the hydrostatic pressure of seawater flowing in from the Pacific Ocean and San Francisco Bay. This higher pressure can increase salinity in the Delta's inland waterways if not counteracted by increased outflows of freshwater. Greater inflows to the Delta of freshwater would likely be achieved by releasing greater amounts of water from upstream reservoirs. This would reduce the amount of water available for other uses as this additional water would end up as Delta outflow to the ocean. However, even if freshwater inflows to the Delta were increased to counteract the effect of sea level rise, increased salinity intrusion could still occur in deeper more stratified channels by increasing density driven-flows (Fleenor et al. 2008). Conversely, if freshwater inflows were not increased to counteract higher hydrostatic pressures applied by increased sea level, additional saline water would flow deeper into the Delta and would increase the salinity in areas of the Delta that are already brackish. The X2 position would move east and water quality for in Delta water uses and south Delta exports would be diminished (DWR 2009b).

Chen et al. (2010) evaluated the effect of a 1 to 3 foot increase in sea level rise (with no change in Delta inflow hydrology) on Delta water quality and drinking water treatment by modeling salinity (and other water quality metrics) at multiple Delta intake locations. Table 3E-5, shows that for Banks Pumping Plant, a 1-foot increase in sea level (about the level of increase projected for 2050) has a minimal impact on salinity at the low end of the impact range. Salinity increased by about 30% for average impacts, and at the high end of impacts salinity nearly doubled. A 3-foot increase in sea level (about the level of increase projected for 2100) would significantly diminish water quality with conductance and Bromide concentrations increasing by two to three times baseline sea level conditions. Another study, Fleenor et al. (2008) found similar results, predicting that a one-foot sea level rise would increase the annual average salinity concentration at the Clifton Court Forebay (which supplies the Banks Pumping Plant) by approximately 4 to 26 percent, with even higher concentrations associated with a three-foot rise.

Table 3E-5. Salinity Levels at the Banks Pumping Plant Associated with Sea Level Rise

	Conductance (μS cm^{-1})			Bromide (mg L^{-1})		
Condition	Low	Average	High	Low	Average	High
Current (2003-2007)	125	355	671	0.03	0.15	0.41
1-foot Sea Level Rise	126	455	1,166	0.03	0.16	0.85
3-foot Sea Level Rise	126	741	2,120	0.03	0.50	1.64

mS cm-1 = microsiemens per centimeter
mg L-1 = milligrams per liter
Source: Chen et al. 2010

Quantitative analysis of the combined impacts of upstream hydrological changes and sea level rise on SWP and CVP operations are described in section 3E.4 below.

3E.3.3 Potential Long-term Progressive Effects of Climate Change and Sea Level Rise on SWP and CVP Water Supply

The hydrological changes and sea level increases described above will likely occur concurrently, thus most quantitative analyses of future Delta conditions and potential effects on SWP and CVP water supplies evaluate the effect of combined hydrological and sea level rise changes. Below is a summary of DWR's 2009 study *Using Future Climate Projections to Support Water Resources Decision Making in California,* which quantitatively evaluated these impacts (DWR 2009b).

Possible climate change impacts to SWP and CVP operations were assessed using 12 future climate projections which included 6 different Global Climate Models and 2 different GHG emissions scenarios. Sea level rise was modeled as 1-ft in 2050 and 3-ft in 2100 for this study. No changes were made to the existing SWP and CVP infrastructure in the future. Future system operations used State Water Resources Control Board Decision 1641 (SWRCB D1641) regulations (SWRCB 2000). Operations guidelines that are subject to change, such as reductions in Delta exports resulting from Endangered Species Act biological opinions, were not included in these studies due to the high uncertainty of how such reductions in exports may be applied 50 or 100 years from now, thus actual impacts on Delta exports could be significantly larger if current reductions continue to be implemented or become more restrictive in the future. (See Appendix 5B, *Responses to Reduced South of Delta Water Supplies*; additionally, for more information about assumptions used in modeling for the BDCP EIR/EIS, see Appendix 5A, *BDCP EIR/EIS Modeling Technical Appendix*).

Median results for the 6 projections under each of the GHG emissions scenarios are presented in Table 3E.6. In general, DWR (2009b) shows that the reliability of the SWP and CVP water supply systems will be reduced under future climate and sea level rise conditions. Delta exports would be reduced by as much as 25% by the end of the century. In addition, 30% reductions in reservoir carryover storage would reduce the systems' flexibility during water shortages. And, in the Sacramento Valley, water users would be expected to make up for reduced surface water supplies by increasing their use of groundwater, which could exacerbate existing overdraft and have other environmental impacts. Both power generation and power use by the SWP and CVP are anticipated to decrease under climate change due to the expected reductions in available water and water deliveries.

Most concerning is that these projections of future conditions indicate that in some future years water levels in the main supply reservoirs (Shasta, Oroville, Folsom, and Trinity) could fall below the lowest release outlets—making the system vulnerable to operational interruption. In those years, additional water would be needed to meet current regulatory requirements and to maintain minimum system operations. This water could be obtained through additional water supplies, reductions in water demands, or a combination of the two.

Table 3E.6 Summary of Projected Changes Due to Climate Change as Reported in DWR's 2009 study "Using Future Climate Projections to Support Water Resources Decision Making in California"

	Mid-Century: Some Uncertainty		End of Century: More Uncertainty	
	Average of 6 Higher GHG Emissions Scenarios	Average of 6 Lower GHG Emissions Scenarios	Average of 6 Higher GHG Emissions Scenarios	Average of 6 Lower GHG Emissions Scenarios
Delta Exports	-10%	-7%	-25%	-21%
Reservoir Carryover Storage	-19%	-15%	-38%	-33%
Sacramento Valley Groundwater Pumping	9%	5%	17%	13%
Power Supply				
CVP Generation	-11%	-4%	-13%	-12%
CVP Use	-14%	-9%	-28%	-24%
SWP Generation	-12%	-5%	-16%	-15%
SWP Use	-10%	-5%	-16%	-16%
X2 Delta Salinity Standard	Expected to be Met	Expected to be Met	Expected to be Met	Expected to be Met
System Vulnerability to Interruption*	1 in 6 years	1 in 8 years	1 in 3 years	1 in 4 years
Additional Water Needed to Meet Regulations and Maintain Operations**	750 TAF/yr	575 TAF/yr	750 TAF/yr	850 TAF/yr

Source: DWR 2009b

* The SWP-CVP system is considered vulnerable to operational interruption during a year if the water level in one or more of the major supply reservoirs (Shasta, Oroville, Folsom, and Trinity) is too low to release water from the reservoir. For current conditions, the SWP-CVP system is not considered vulnerable to operational interruption.

3E.4 Conclusions

The Delta currently faces significant risks from catastrophic levee failure and potential water export and in-Delta water supply interruptions. In addition, the Delta faces long-term progressive risks of levee failures and diminishing operational efficiency and supply reliability from sea level rise and changes in Delta inflow hydrology driven by climate change. Continuation of existing management and operation of the Delta will increasingly expose Delta water users and those that depend on water exported from the Delta to risks of water supply interruption and diminishing water supply reliability over time.

As described above, many of the Delta's 1,100 miles of levees have not been geotechnically engineered and lack the strength to resist increasing hydrostatic pressures or potential seismic loads. These deficiencies expose the Delta to risks of failure that increase with the passage of time. The Delta area is within or near several active seismic areas and is likely to experience the effects of moderate to strong earthquake events along nearby faults in the future. Based on the location and design of existing levee structures, the potential for significant damage to, or failure of, these levees during a major local seismic event is moderate to high. Climate change may further increase the potential for levee failure by altering the factors that contribute to flooding within the Delta. Most notably, more precipitation in the Sierra Nevada will fall as rain instead of snow and sea levels will rise, increasing the frequency, duration, and magnitude of high water levels within the Delta. Levee failures in the Delta resulting from a seismic event or high Delta inflows could result in the influx of salt and/or brackish water that could substantially affect water quality conditions (e.g., salinity) in the Delta, with corresponding effects to in-Delta water users and SWP and CVP water supplies which could last months or even years and result in expensive remediation efforts.

While levee failures resulting from a seismic event or very high inflow could cause catastrophic effects, sea level rise and long-term hydrologic trends are likely to increasingly diminish water supply reliability and operational flexibility placing both in-Delta water users and Delta export users at increasing risk. Multiple studies incorporating the impacts of sea level rise and using a number of different projections of future climate change impacts on hydrology indicate that current management and operation of the Delta is unsustainable and some effects are already reducing system reliability and performance. Continued operation and management of the Delta with current practices would yield an increasingly unstable system with supply interruptions and the inability to meet regulatory requirements occurring multiple times per decade. All of these projections exclude current and potential future regulatory actions designed to protect endangered species in the Delta or anadromous fish species that use the Delta and upstream waterways to complete their life cycles. Biological opinions issued in 2008 and 2009 to protect endangered Delta Smelt and salmon respectively have added additional constraints to management and operation of the Delta which combined with climate change and sea level rise will result in even greater reductions in water supply reliability and operational flexibility then has been quantitatively modeled.

These analyses show that continued operation and management of the Delta using current procedures will not yield a continuation of current environmental conditions, water supply reliability, or water quality. Instead, continued operation and management using current procedures will yield continuously declining water supply reliability and quality and ever changing ecological conditions. In addition, the likelihood of catastrophic levee failures due to a seismic or hydrological event increases each year.

3E.5 References

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3E.6 Acronyms and Abbreviations

µS cm-1	microsiemens per centimeter
mg L-1	milligrams per liter
°	degrees
C	Centrigrade
CGS	California Geological Survey
CVP	Central Valley Project
Delta	Sacramento-San Joaquin Delta
DHCCP	Delta Habitat Conservation and Conveyance Program
DRMS	Delta Risk Management Strategy
DWR	California Department of Water Resources
EIR/EIS	Environmental Impact Report/Environmental Impact Statement
EFZs	Earthquake Fault Zones
F	Fahrenheit
G	acceleration equal to that of gravity
IPCC	International Panel on Climate Change
M	meter(s)
Mm	millimeter(s)
Mw	moment of magnitude
PGA	peak ground acceleration
Central Valley	Great Valley Geomorphic Province
PSHAs	Probabilistic Seismic Hazard Analyses
SA	Spectral Acceleration
SWP	State Water Project
USGS	U.S. Geological Survey
VCs	vulnerability classes
WGCEP	Working Group on California Earthquake Probabilities