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Factors and Processes Affecting Delta Levee System Vulnerability

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ABSTRACT

We appraised factors and processes related to human activities and high water, subsidence, and seismicity. Farming and drainage of peat soils caused subsidence, which contributed to levee internal failures. Subsidence rates decreased with time, but still contributed to levee instability. Modeling changes in seepage and static slope instability suggests an increased probability of failure with decreasing peat thickness. Additional data is needed to assess the spatial and temporal effects of subsidence from peat thinning and deformation. Large-scale, state investment in levee upgrades (>$700 million since the mid-1970s) has increased conformance with applicable standards; however, accounts conflict about corresponding reductions in the number of failures. Modeling and history suggest that projected increases in high-flow frequency associated with climate change will increase the rate of levee failures. Quantifying this increased threat requires further research. A reappraisal of seismic threats resulted in updated ground motion estimates for multiple faults and earthquake-occurrence frequencies. Estimated ground motions are large enough to induce failure. The immediate seismic threat, liquefaction, is the sudden loss of strength from an increase in the pressure of the pore fluid and the corresponding loss of inter-particle contact forces. However, levees damaged during an earthquake that do not immediately fail may eventually breach. Key sources of uncertainty include occurrence frequencies and magnitudes, localized ground motions, and data for liquefaction potential.

Estimates of the consequences of future levee failure range up to multiple billions of dollars. Analysis of future risks will benefit from improved description of levee upgrades and strength as well as consideration of subsidence, the effects of climate change, and earthquake threats. Levee habitat ecosystem benefits in this highly altered system are few. Better recognition and coordination is needed among the creation of high-value habitat, levee needs, and costs and benefits of levee improvements and breaches.

INTRODUCTION

Since the 1860s, Delta levees have been rebuilt and strengthened in response to failures and threats of failure. Resource availability and subsidence have hampered efforts to repair and reinforce levees. The present-day 1,800-km levee system built largely upon original structures imperfectly protects subsided islands and associated agriculture, homes, urban areas, and infrastructure from the continuous threat of inundation and ensures the movement of water from northern California to areas south of the Delta, including parts of the San Francisco Bay area (Figure 1). Levees provide habitats and protect wetlands on selected Delta islands (e.g., Twitchell, Sherman) (Figure 2). The presence of levees substantially determines Delta land use.

The Delta Risk Management Strategy (DRMS) study concluded that under business as-usual practices, the Delta region is unsustainable because of threats to levee integrity (URS Corporation and Jack R. Benjamin and Associates, Inc. 2009). Levees can be reinforced and augmented to reduce risk but all risk cannot be eliminated (Arcadis 2016). Principal threats to levee stability include earthquakes, seepage, high water, and subsidence (Figure 1). The consequences of levee failure include loss of agricultural production, water supply disruption, habitat loss and species alteration, water quality changes, infrastructural destruction and disruption, and loss of life (Figure 1). Before ongoing mitigation efforts, the DRMS study estimated costs ranging into the billions of dollars would result from losses associated with levee failure and island flooding.

Moore and Shlemon (2008) previously described the modern Delta levee system. The DRMS study provided a comprehensive compilation of data and analysis related to levee risk (URS Corporation and Jack R. Benjamin & Associates, Inc. 2009). Levee science and practice have evolved since Moore and Shlemon (2008) and the DRMS study. Hundreds of millions of dollars have been spent on levee upgrades. Threats to levees and the relation of levees to aquatic and terrestrial habitat have also been further quantified. A reappraisal of key issues is necessary.

Our objective was to assess processes and factors that affect levee-system vulnerability and sustainability through a reappraisal of threats and consequences of levee failure. We also summarized ecosystem effects, and potential benefits and integration of ecosystem function; explored mitigation and monitoring; and defined critical uncertainties and information needs. We focused on three levee threats: high water, earthquakes, and subsidence.

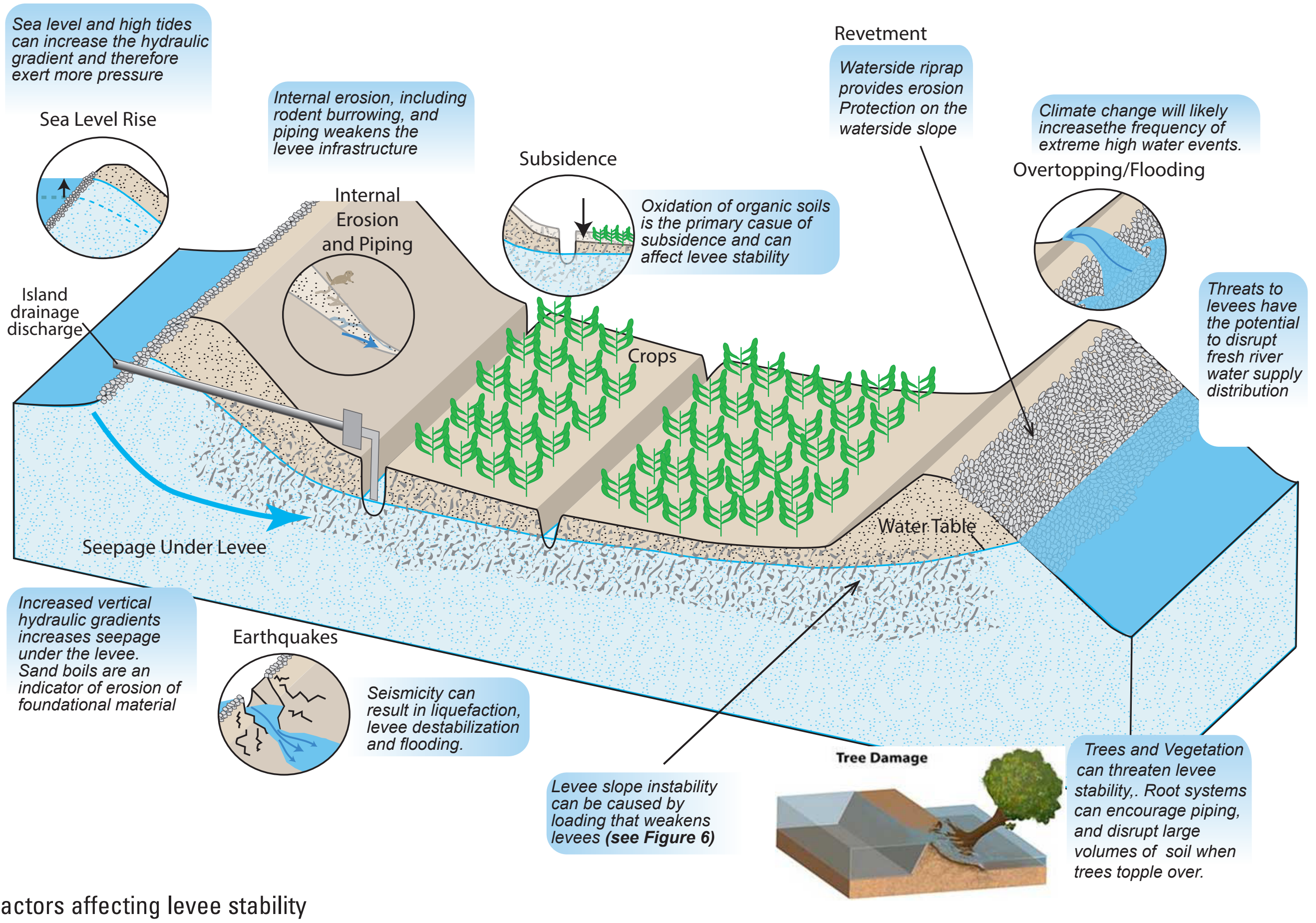
BACKGROUND

Human activities – farming and drainage of peat soils, flood control – and levee upgrades (Figure 3) have affected the stability and failure of levee. After initial levee construction from manually-harvested peat blocks in the 1860s and 1870s, floods in 1878 and 1881 destroyed many levees and sapped much of the previous decade's optimism for reclamation (Thompson 1957, 2006). By the 1890s, peat levees were mostly overlain by stronger and more robust levees built from mineral material extracted from adjacent channels (Figure 3). By the 1940s, reclamation of about 1800 km^2 of Delta land for agricultural use was complete (Thompson 1957).

The legal Delta encompasses about 3,600 km^2 where lowlands are surrounded by levees; about 630 km are "project" levees which are part of the State Plan of Flood Control, and about 1,200 km are "non-project" levees, owned and maintained by local levee-management agencies (Figure 4). Arcadis (2016) identified 125 Delta islands to be included in the Delta Levee Investment Strategy (DLIS) analysis. Because the majority of the land in the Delta is used for agriculture, we focused on levees that surround farmed islands.

Farming and Drainage

Drainage of peat soils for farming resulted in oxidation of organic matter, which is the primary cause of subsidence. Delta peat soils formed from decaying wetland plants and the build-up of below-ground biomass (Atwater 1982; Shlemon and Begg 1975; Drexler et al. 2009a). During the 6,000 to 7,000 years before the 1850s, about 5 billion m^3 of tidal marsh sediment accumulated in the Delta, and, since the 1850s, half of this volume has disappeared (Deverel and Leighton 2010; Mount and Twiss 2005). The present-day area of peat soils is smaller than the area of historic wetlands (Figure 5) that resulted



Sea level and high tides can increase the hydraulic gradient and therefore exert more pressure

Internal erosion, including rodent burrowing, and piping weakens the levee infrastructure

Oxidation of organic soils is the primary casue of subsidence and can affect levee stability

Waterside riprap provides erosion Protection on the waterside slope

Climate change will likely increasethe frequency of extreme high water events.

Threats to levees have the potential to disrupt fresh river water supply distribution

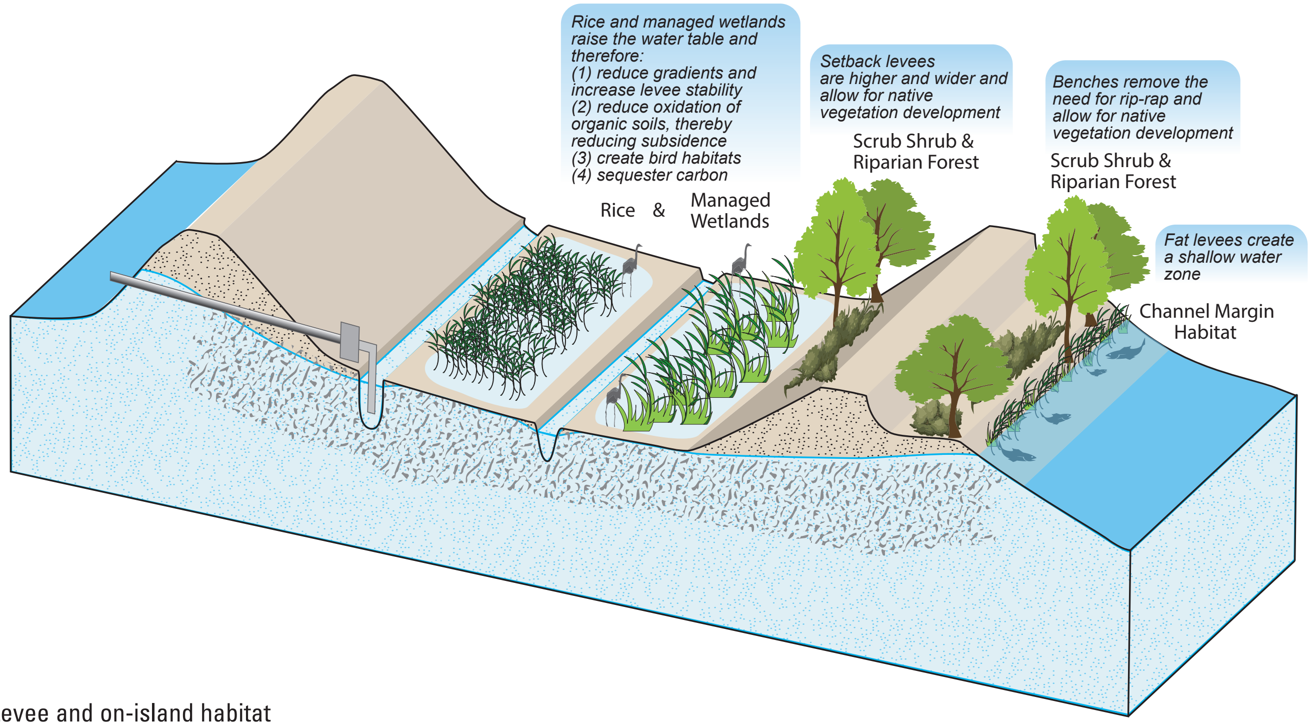
Increased vertical hydraulic gradients increases seepage under the levee. Sand boils are an indicator of erosion of foundational material

Seismicity can result in liquefaction, levee destabilization and flooding.

*Levee slope instability can be caused by loading that weakens levees **(see Figure 6)***

Trees and Vegetation can threaten levee stability,. Root systems can encourage piping, and disrupt large volumes of soil when trees topple over.

Figure 1 Factors affecting levee stability



Rice and managed wetlands raise the water table and therefore:
(1) reduce gradients and increase levee stability
(2) reduce oxidation of organic soils, thereby reducing subsidence
(3) create bird habitats
(4) sequester carbon

Setback levees are higher and wider and allow for native vegetation development

Benches remove the need for rip-rap and allow for native vegetation development

Fat levees create a shallow water zone

Figure 2 Levee and on-island habitat

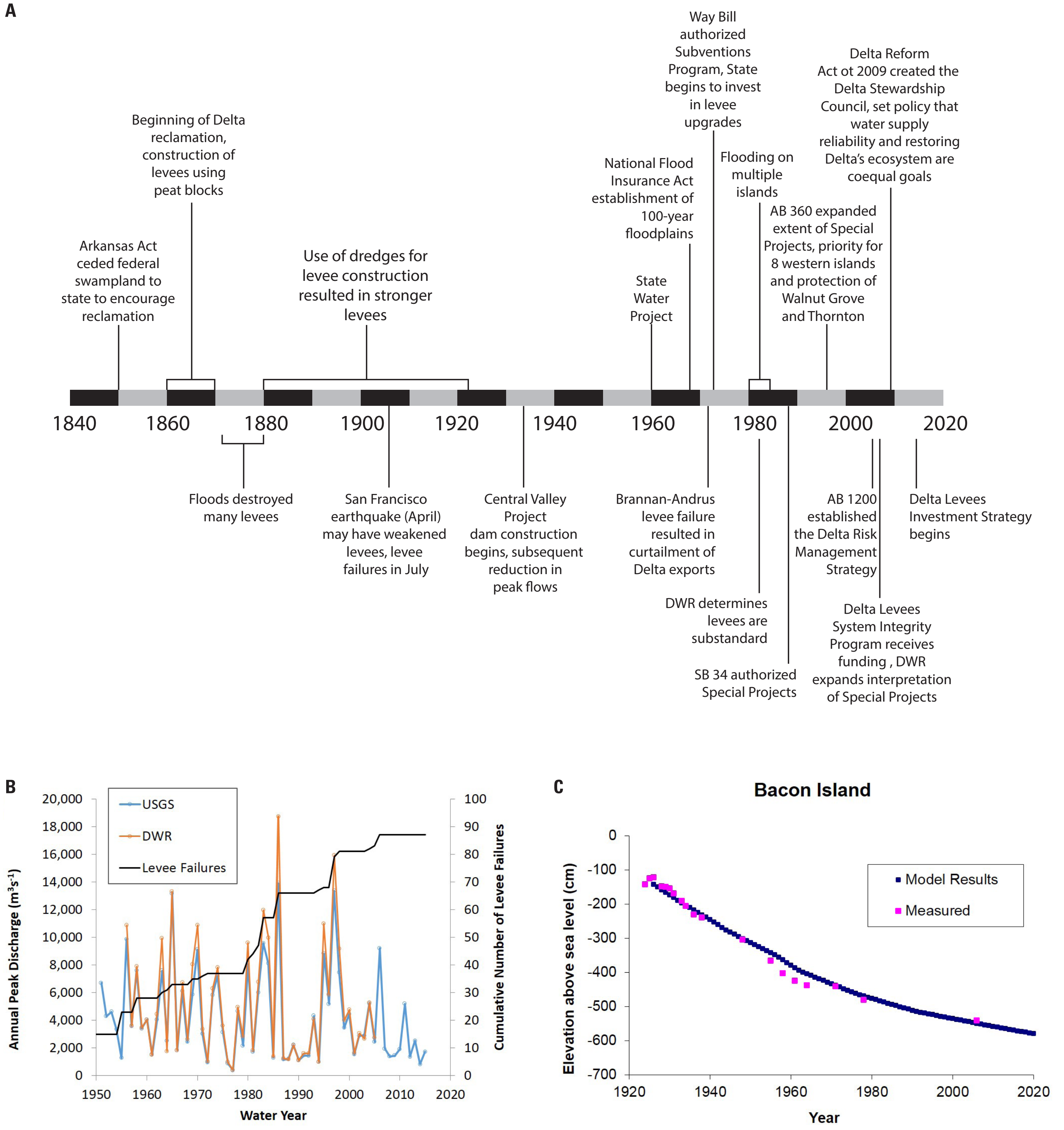


Figure 3 Timeline of Delta levee related events (**A**) failures, (**B**) annual peak discharge and (**C**) subsidence on Bacon Island. Subsidence rates have decreased substantially since the first half of the twentieth century due to cessation of burning, reduced wind erosion and depletion of soil organic carbon as illustrated by the average elevation data from Bacon Island from Deverel and Leighton (2010).

in the formation of Delta peat soils; peat soils have disappeared close to the margins of the Delta. Much of this remnant peat is preserved epidermal parts of rhizomes of bulrush (*Schoenoplectus* spp.) and reeds (*Phragmites* spp.) (Atwater 1982).

Subsidence rates have decreased substantially since the first half of the twentieth century because of the cessation of burning, reduced wind erosion resulting from the planting of alternative crops, and depletion of soil organic carbon (Figure 3). Present-day rates range from a few mm yr^{-1} to over 1.8 cm yr^{-1} where elevations are −2 m or less (Deverel et al. 2016). Based on data from extensometers, greenhouse-gas emission measurements, and modeling, subsidence is occurring primarily where organic soils are at elevations at or below −2 m (Figure 6) (Deverel et al. 2016), which represents about 24% of the legal Delta or about 70,700 ha.

In his review of the history, causes, and costs of the flooding of Delta islands from the early 1900s to the 1980s, Prokopovitch (1985) concluded that levee foundation instability resulting at least partially from subsidence became an important factor in island flooding after the 1940s. Duncan and Houston (1983), CDWR (1982), and the U.S. Army Corps of Engineers (1982) generally agreed. For example, foundation failure caused 12 of 18 failures that occurred from 1950 to the early 1980s (Prokopovitch 1985). Subsidence lowered island interiors and created height differences between island surfaces and adjacent surface-water levels (Figure 3), which contributed levee internal failures. Mount and Twiss (2005) stated that during the 1950s and beyond, the percentages of failures from levee structural problems increased because of the subsidence of organic soils, which augmented hydraulic forces against levees.

Flood Control

The benefit for Delta levees of flood control resulting from dam construction on California's major rivers, which began in the 1930s, is uncertain. Prokopovitch (1985) stated that before dam construction, greater numbers of levees failed from overtopping, relative to after the 1940s. The decrease in levee failure from overtopping may have been lessened because of reduced Delta inflow. McDonald et al. (2008) speculated that reservoirs increased flood protection somewhat by reducing flows. However, some of the flood attenuation reservoirs provided may have occurred anyway because of floodplain storage. Numbers of Central Valley levee breaks were not significantly different during the first half of the twentieth century (before major dam construction) compared to the last half of the twentieth century (after major dam construction) (Florsheim and Dettinger 2007).

The National Flood Insurance Act of 1968 and establishment of 100-year floodplain elevations likely provided a solid basis for levee upgrades. Before the establishment of 100-year floodplain elevations, land-owners used approximate elevations of previous floods to attempt to increase levee heights. Establishment of flood control and flood insurance thus provided benchmarks for levee upgrades and maintenance, and likely reduced levee overtopping.

Investment in Levee Upgrades

Large-scale state investment in levee upgrades began after the June 1972 Brannan–Andrus levee failure and the authorization of Subventions[1] funding (Figure 3). The Brannan–Andrus failure resulted in curtailment of Delta exports because of increased salinity, and additional reservoir releases were required to re-establish Delta exports (Cook and Coleman 1973). Along with recognition that structural disintegration[2] caused increasing numbers of failures, the California Department of Water Resources (CDWR) (1982) reported the generally substandard levee conditions.[3] Subsequently, additional funds were authorized for Special Projects which widened the sphere of levee improvements, and thus began the current epoch of upgrading Delta levees to meet applicable standards.[4, 5]

Assembly Bill 360 (1996) expanded Special Projects to require aquatic habitat enhancement, with the stated goal of preserving the 1996 Delta. Priority went to eight western Delta islands[6] and protection of Thornton and Walnut Grove. After 2006, CDWR expanded the interpretation of Special Projects, which included a reduction in local cost share for levee improvements throughout the Delta. Assembly Bill 1200 mandated the completion of DRMS study to assess major risks to Delta resources and to develop measures to reduce risk (URS Corporation

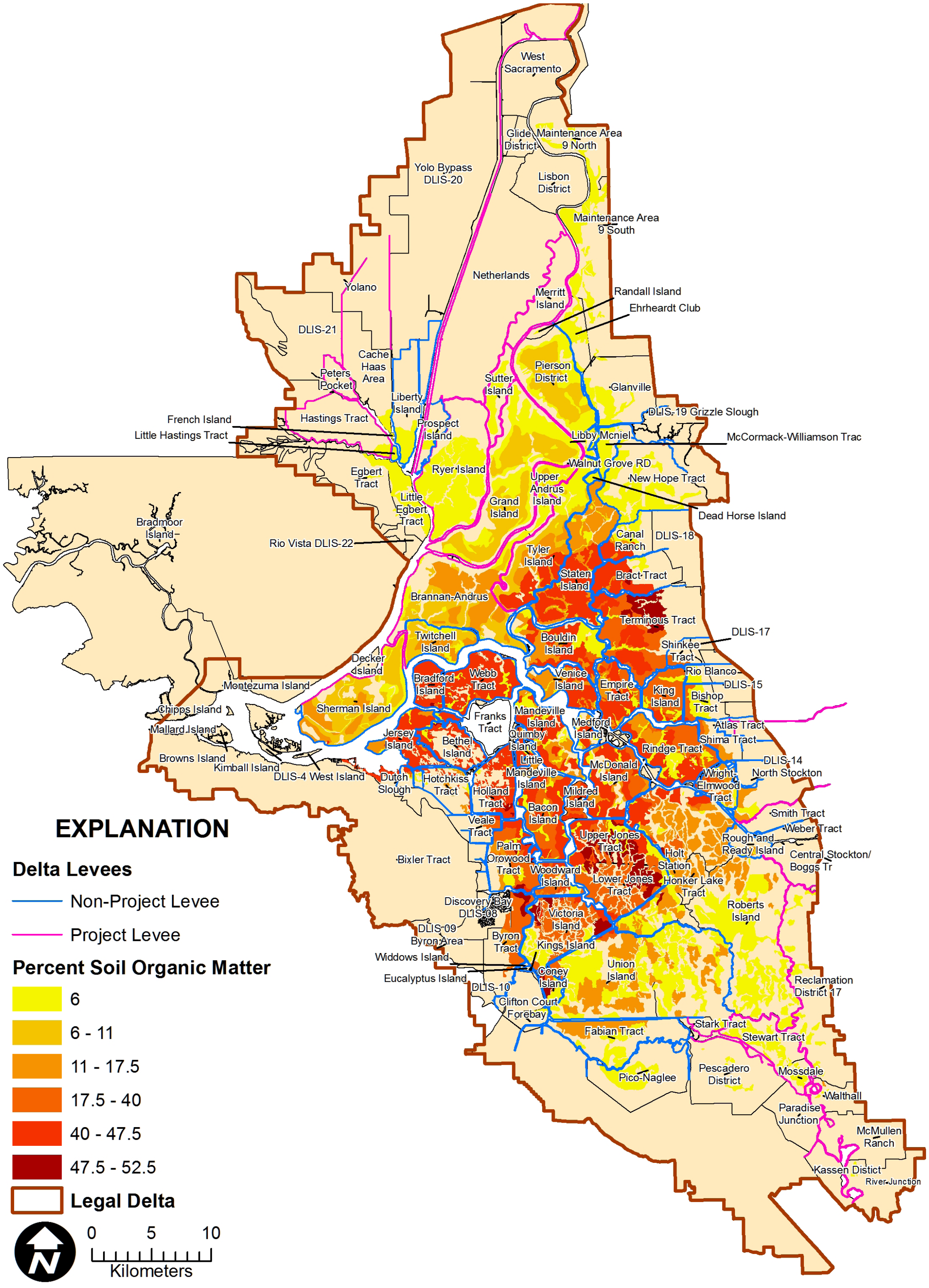


Figure 4 Levees and islands, project and non-project islands and legal Delta, soil organic matter content from Deverel et al. (2016)

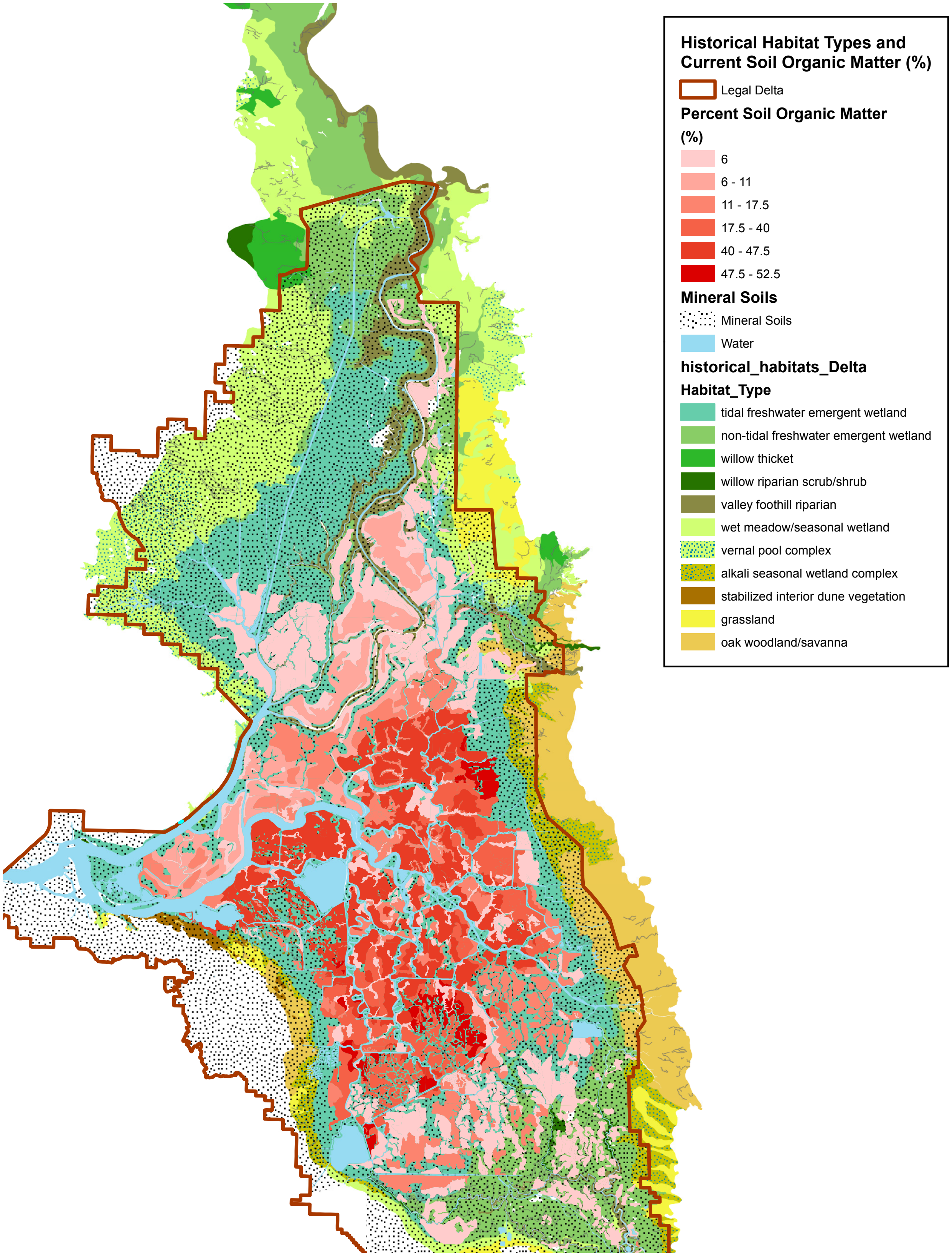


Figure 5 Overlay of organic soils from Deverel and Leighton (2010) on former historical habitats from Whipple et al. (2012)

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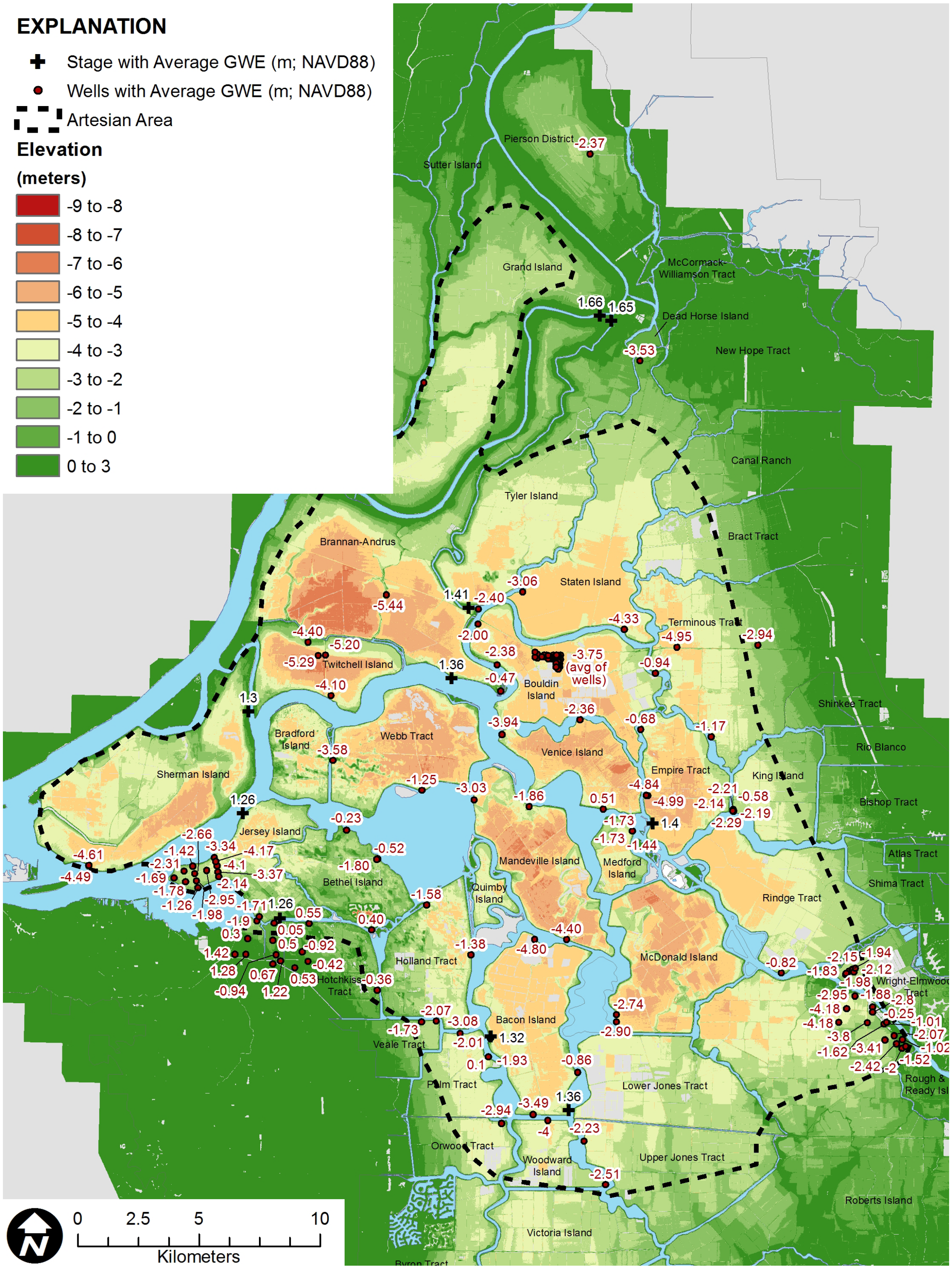

Figure 6 Land surface elevations where organic soils predominate (based on LiDAR data (CDWR 2007), and approximate delineation of artesian areas from Deverel et al. (2015)

and Jack R. Benjamin & Associates, Inc. 2008b). The Delta Reform Act requires the Delta Stewardship Council to develop risk-based priorities for state spending on Delta levees (Arcadis 2016): the Delta Levee Investment Strategy (DLIS).[7] A continuation of the original Levee Subventions and Delta Flood Protection Program, the Delta Levees System Integrity Program received funding from both the Disaster Preparedness and Flood Prevention Bond Act of 2006 (Proposition 1E) and the Safe Drinking Water, Water Quality and Supply, Flood Control, River and Coastal Protection Bond Act of 2006 (Proposition 84). Over $700 million of state funds have been invested in Delta levee maintenance and improvement since the mid-1970s. After the 1970s, the state's cost share for levee improvements generally increased, and ranged from 50% to 100%.

Estimates for necessary future standards-based Delta levee improvements range from $3.8 billion to $4.28 billion (DSC 2015). Suddeth et al. (2010) estimated from half a million dollars per kilometer to over $2.48 million per kilometer to meet PL 84–99 standards.[8] As part of the CALFED Levee Integrity Program Plan, Murray, Burns and Kleinlen, and Kjelson, Sinnock, and Neudeck (2000) estimated from $0.2 to $0.6 million per km to meet PL 84–99 standards.

Investments since the mid-1970s augmented levee structure and resulted in improved conformance to levee standards, but data are inconsistent about corresponding reductions in numbers of failures. The DRMS study estimated that mean annual frequency of island failures was 1.39 for the period between 1980 and 2006, compared to 0.80 during 1950 to 1979 (URS Corporation and Jack R. Benjamin & Associates, Inc. 2008).[9] They attributed the increased rate of island flooding to cumulative effects of subsidence, sea level rise, and higher peak storm inflows. Delta peak inflows were higher during 1980–2006. Extending the DRMS study analysis to 2015, we estimated an annual frequency of 1.2. Hopf (2011) re-assessed Delta levee failures and concluded that levee performance was better than indicated by DRMS. By separating out some levee failures, Hopf (2011) reported an annual failure rate of 0.75 since 1972.[10] Storm events associated with the high Delta in-flows since 1980 correspond to simultaneous flooding of multiple islands and tracts: 6 in1980, 11 in 1983, 9 in 1986, and 11 in1997 (Figure 3).

Recent levee upgrades increased compliance with relevant levee standards. About one-third of Sacramento–San Joaquin Delta levees ("project levees") complied with federally-authorized flood-control projects (Figure 4). Local reclamation districts own and maintain on behalf of private land-owners or the State of California the remainder of "non-project levees." The CDWR used Light Detection and Ranging (LiDAR) survey and reclamation district-engineer-supplied survey data[12] to estimate that 84% of the total levee length complied with the Water Code's Hazard Mitigation Plan (HMP) standards, and 61% complied with the higher PL84-99 standards[11]. At least 80% of levee lengths on 72% of individual islands complied with the HMP, and 39% of levee lengths on 80% of individual island complied with PL84–99. Most of the non-compliant islands were concentrated in the central Delta. However, there was some uncertainty in the mapping because of gaps in the LiDAR data.

Although HMP compliance numbers generally appear encouraging, individual island flood protection requires 100% compliance. Moreover, standards specify geometric requirements and are not performance-based, nor do they account for the probability of floods larger than those prescribed by their water-surface metric. Ongoing consolidation of underlying peat and levee creep can contribute to future non-compliance and the need for ongoing upgrades to meet guidelines, which include provisions for overtopping, but not necessarily for other levee failure causes such as earthquakes and under-seepage. Additional data analysis is needed to confirm that levee upgrades since 2007 have increased compliance with standards.

Levee upgrades may have resulted in reduced estimated failure probabilities. The DRMS study estimated the range of mean annual probability of failure from combined flooding, dry-weather, and seismic threats for 2005 conditions from greater than 7% (for Sherman, Tyler, Venice, and New Hope) to less than 1% for islands on the periphery of the Delta (URS Corporation and Jack R. Benjamin and Associates, Inc. 2008a). A 5% annual probability of failure translates to a 72% probability of failure

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during a 25-year period. For most of the central and western Delta, estimated mean annual probability of failure generally ranged from 3% to 7% (53% to 84% probability of failure in 25 years).

For 2012 conditions, Arcadis (2016) estimated similar annual probabilities of failures for hydraulic- and earthquake-related failures ranging from 1% to 5% for most of the Delta. Probabilities in the central and western Delta generally ranged from 2% to 5%. Earlier studies (CDWR 1982; USACE 1982) estimated annual failure frequencies from overtopping and stability failure for 1974 levee conditions to be generally higher than the DRMS estimates for much of the central Delta, where land-surface elevations are below −2 m (Figure 6). The DRMS estimated annual failure frequencies were lower than the CDWR (1982) estimates for 13 of the 27 islands. These reductions in failure probability may have resulted from investments in levee upgrades and different analytical methods, but the extent to which DRMS study and the DLIS considered upgrades when estimating probabilities is unclear.

HOW LEVEES FAIL

Levees fail in multiple ways from external and internal processes. Moss and Eller (2007) listed six failure modes: destabilizing inertial loading, sliding along a preferred failure plane, slumping or spreading, seepage, erosion, and overtopping during extreme high-water events. URS Corporation and Jack R. Benjamin & Associates, Inc. (2008a) summarized stressing events: floods, earthquakes, animal burrowing, and wind waves, which correspond to failure modes of under- and through-seepage, overtopping, seismic deformation, and erosion (Figure 7). A normal-condition "sunny day" failure stressing event was also listed and associated with failure modes of through- or under-seepage, slope instability, erosion, animal burrowing, and falling trees. Levee construction inconsistencies exacerbate failure mechanisms where, for example, crest heights of two adjoining levee sections differ. These create potential locations for seepage, overtopping, and erosion (Seed et al. 2006). Duncan and Houston (1983) and Foott et al. (1992) suggested that differential settlement and deformation of peat soils resulted in cracks in levees and greater susceptibility to failure during high-water events. Seepage is a common failure mechanism in fluvial depositional environments such as the Delta (Moss and Eller 2007). Coarse-grained materials allow for flow underneath levees, which can erode foundation materials. The thickness of marsh deposits affects the magnitude of under-seepage (URS Corporation and Jack R. Benjamin & Associates, Inc. 2008a). Flooding may also increase seepage onto adjacent islands, and the need for increased drainage and pumping requirements (Arcadis 2016).

Biogenic agents (e.g., rodent holes, tree roots, or other biological activity that create conduits) can also lead to destabilizing seepage and erosion of levee fill materials (Figure 2). The magnitude of vertical exit gradients[12] indicates the potential for under-seepage to erode levee foundational materials. Exit gradients greater than the critical gradient (the point where seepage forces approximately equal soil resistance) can result in piping or "boils," as water moves with sufficient force to transport soil particles and levee foundation materials. Based on observations and theoretical considerations, the critical exit gradient is about 1.0, and is proportional to peat thickness (URS Corporation and Jack R. Benjamin & Associates, Inc. 2008a).

The CDWR's Northern Non-Urban Levee Evaluations (NULE) generally classified the under-seepage susceptibility adjacent to Delta project levees as high to very high for levees in the western Delta (URS Corporation and Lettis Fugro–William & Associates 2011). The Southern NULE analysis included project levees in the southern Delta adjacent to Roberts Island and Union Island where levees were also classified mostly as having high or very high under-seepage susceptibility (Kleinfelder et al. 2011). The DRMS study also mapped most of the central Delta as highly to moderately vulnerable (URS Corporation and Jack R. Benjamin & Associates, Inc. 2008a).

THREATS TO LEVEE STABILITY

Delta levees do not conform to the traditional definition. Unlike Central Valley levees, which are designed to prevent flooding only during high water, Delta levees withhold water continuously. Functionally, Delta levees are similar to dikes: embankments built to prevent flooding from the sea similar to those protecting Dutch polders

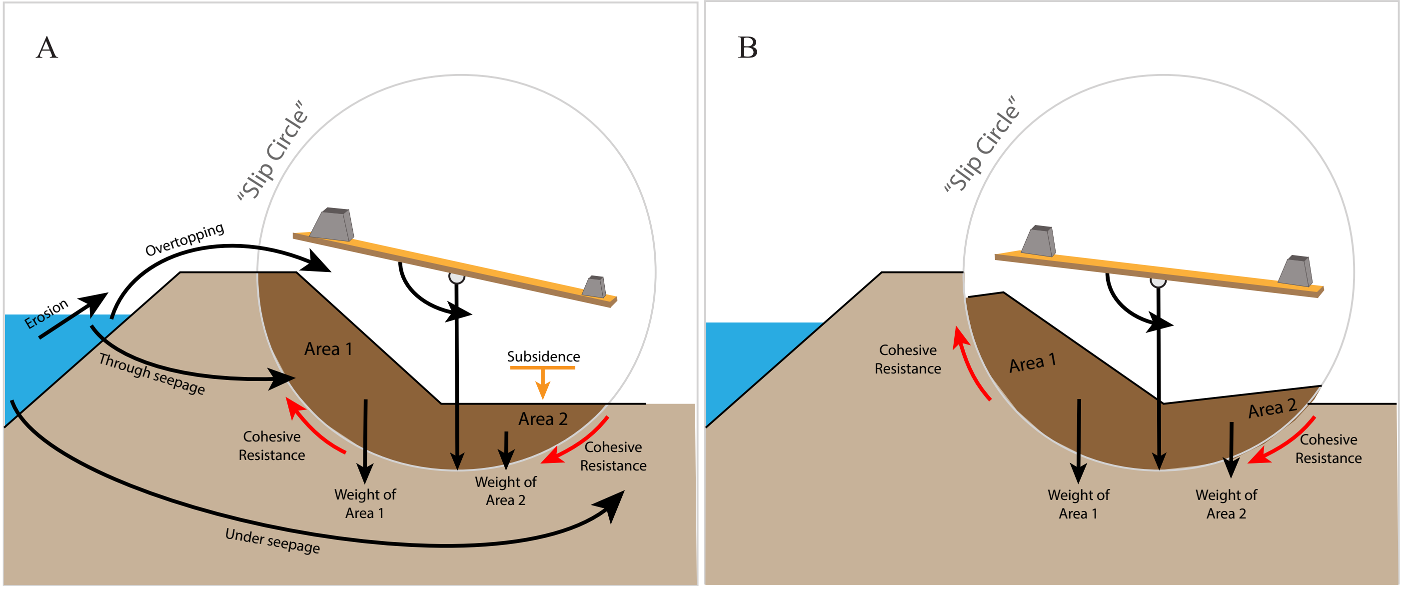

Figure 7 Levee modes of failure. Levees fail when external forces upset the levee internal cohesive forces holding the embankment in place against forces that would cause it to move towards equilibrium (like a teeter-totter) (**A, B**). Through seepage reduces levee cohesive forces. Under-seepage can erode levee foundation materials and also upset the ability of cohesive forces to keep the embankment in place.

(which are dams without spillways). The ability of levees to effectively withhold water from subsided islands depends on the strength of the levee and its foundation relative to external threats (e.g., subsidence, seepage, animal burrows, hydraulic pressure gradients, seismic shaking, high water). When external forces cause internal stresses that exceed the cohesive and frictional strength of the levee or its foundational materials, levee failure can occur. We appraised three threats to levee vulnerability: seismic shaking, high water, and subsidence.

Seismic Shaking

Historic Observations

What can past observations of earthquake effects in the Delta tell us about present levels of seismic risk?

As we explore this subject it is important to recognize that large earthquakes are rare events with recurrence intervals often spanning hundreds to thousands of years; therefore, observations made over relatively short time intervals (tens to hundreds of years) inadequately predict future performance. For example, the 2010 Haiti earthquake that killed over 100,000 people was the first large event in the region since 1860 (DesRoches et al. 2011), and the tsunami created by the 2011 Tohoku earthquake in Japan was the largest in the region since the Jogan earthquake in 869 AD (Sawai et al. 2012). Past observations and personal experience of earthquake effects are, therefore, clearly inadequate to assess the risk to the 150-year-old Delta levee system. Nevertheless, such observations are present in the literature, and offer some clues about Delta seismic vulnerabilities.

An oft-repeated perception among some Delta interests is echoed by CALFED: “historical information indicates that there has been little damage to Delta levees caused by earthquakes.” The literature indicates otherwise. Although Delta levees were relatively new in 1906 and low in height, Finch (1985) and Youd and Hoose (1978) reported that the 1906 earthquake caused the foundation of a railroad bridge on the Middle River to drop about a meter and become misaligned, and the pier supporting the bridge over the main San Joaquin River sank ”several inches.” The embankments associated with those structures were similar in composition to the present Delta levees (Finch 1985). Hopf (2011) investigated evidence that might link the earthquake (which occurred in April 1906) to subsequent levee failures. He discovered that six islands flooded in

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June and July of 1906 (Hopf 2011). Although these floods could be earthquake-related, high-water events that spring and summer were also documented. For example, The San Francisco Call on July 6, 1906 described "alarming high conditions on the San Joaquin River due to warm weather."[13] Prokopovitch (1985) stated that the 1906 earthquake may have weakened levees, resulting in the 1907 flooding of 53 major Delta Islands. Indeed, the largest numbers of failures on record occurred during the winter of 1906–1907. The record also contains evidence of damage to levees in their essentially contemporary state. Finch (1985) reported 15 instances of observed Delta levee damage from relatively modest earthquakes from 1979 to 1984 with epicenters in Livermore, Coalinga, Pittsburg, and Morgan Hill. Reported damages included lateral and vertical levee displacements, rotational slip (see Figure 7), and cracks.

We lack recordings of strong ground motion in the Delta region, because local seismicity has been low since seismographic instruments were installed (URS Corporation and Jack R. Benjamin & Associates, Inc. 2008). This lack of strong shaking should be interpreted as a fortuitous outcome of a random process rather than evidence of a lack of seismic risk.

The DRMS study assessed the stability of levees under a range of earthquake scenarios (URS Corporation and Jack R. Benjamin & Associates, Inc. 2008b) using simplified numerical models. Several factors allow these hazards to now be more reliably characterized, including improved regional seismic source and ground motion models, as well as improved insights from physical model studies and investigations of levee failures in similar geologic conditions elsewhere in the world. The three essential components for assessing levee seismic vulnerability are seismic source characterization, ground motion modeling, and fragility assessment for levee sections and systems. The first two are often combined in a probabilistic seismic hazard analysis (PSHA) (McGuire 2004); PSHA maps show ground motion levels with specified probabilities of exceedance within a particular time-period. A common reference value is 10% probability of exceedance in 50 years, which is the ground motion level expected to be exceeded, on average, every 475 years. Larger probabilistic ground motion levels correspond to a higher seismic risk. We attempted to address the following questions:

1. What does recent data indicate about seismic ground motion in the Delta region?
2. What are the threats to levees from earthquakes?

Seismic Ground Motions

Seismic Sources

Several faults are present in and near the Delta: Pittsburgh–Kirby Hills, Orestimba, Los Medanos, Clayton–Greenville, and others (Figure 8). The Midland Fault underlies portions of the western Delta (Harwood and Helley 1987; Johnson 1990; Unruh et al. 2007; Unruh and Hitchcock 2009; Weber–Band 1998; Unruh et al. 2016) (Figure 8). Additionally, more distant larger faults, such as the Hayward and San Andreas, also contribute to the Delta's seismic hazard. These faults are included in the Uniform California Earthquake Rupture Forecast Model Version 3 (or UCERF3; Field et al. 2013, 2014), which considers the potential for future earthquakes on unknown and known sources. The characteristics of unknown sources are linked to the locations and rate of small earthquakes in the region ($M<6$);[14] this aspect of UCERF3 is referred to as the background (or gridded) seismicity model.

Based on geological evidence, UCERF3 documentation indicates deformation rates across the Coast Range faults ranging from 0.1 to 4 mm yr^{-1} based on geological evidence and earthquakes rates with moment magnitude $M>6$ ranging from 7×10^{-5} to 5×10^{-3} events per year (approximate return periods of 200 to 14,000 years). UCERF3 represents the slip rates for the Midland Fault that underlies the west Delta as 0.4 mm yr^{-1} and a $M>6$ earthquake rate of 7×10^{-4} events per year (return period of 1,400 years). Unruh et al. (2016) suggests lower levels of activity, with an estimated slip rate range of 0.03–0.13 mm yr^{-1}; this would reduce the earthquake rates cited above on this fault by a factor of three to ten.

Earthquake rates for local faults can be difficult to conceptualize in the abstract, but in 2014 nature provided a tangible reminder of the capacity of similar fault systems to produce damage with the M 6.0 South Napa Event. That event occurred on

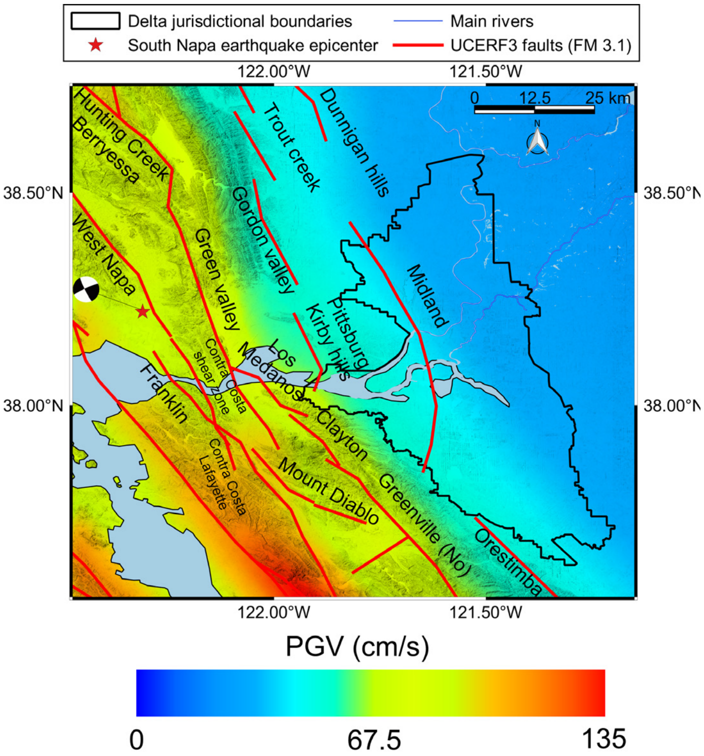

Figure 8 Map of Sacramento–San Joaquin Delta and adjacent San Francisco Bay region showing Coast Range (and other) faults that control seismic hazard and distribution of peak ground velocities (PGVs) at the 10% probability of exceedance hazard level. The source model used in the calculations is UCERF3 (Field et al. 2014); the fault geometries shown here are from Fault Model 3.1 (FM3.1) although both FM3.1 and FM3.2 were used in hazard calculations. Ground motion hazard at all grid points was computed for a common firm-soil site condition encountered in the Delta beneath surficial soft peats and fluvial soils represented by 30-m time-averaged shear wave velocity $VS30 = 300 \text{ m s}^{-1}$.

the West Napa Fault (Figure 8) (Brocher et al. 2015), which is one of a series of Coast Range faults that have slip and event rates within the aforementioned ranges. The event produced ground motions in the Delta region, but was too distant to produce damage. Ground motions during the Napa earthquake were observed to attenuate more quickly with distance than predicted by the ground motion models used in the DRMS study (Erdem et al. 2016). Currently, it is unclear whether the rapid attenuation was a specific characteristic of the Napa event, or whether it is a more general characteristic of ground motions in the region. Future research is needed to clarify if this could potentially result in regional modifications to ground motion models for the Delta.

Ground Motion

Figure 8 depicts the spatial distribution of peak ground velocity in the Delta region based on analyses performed by the USGS seismic hazards mapping team in collaboration with the authors (Zimmaro et al. (2016). We used the UCERF3 source model (time-independent, branch-averaged model, known as Mean UCERF3). We applied ground motion models developed in the Next Generation Attenuation (NGA)-West2 project (Bozorgnia et al. 2014). The results apply for a 10% probability of exceedance in 50 years and for site conditions that correspond to relatively firm soil conditions that are present at depth below surficial soils in the Delta (peats, fluvial deposits). The mapped ground motions range from 70 cm s^{-1} in the west Delta to 30 cm s^{-1} near the eastern margin of the Delta in West Sacramento. The most proximate Coast Range faults, background seismicity, and the Midland Fault are the principle contributors to the hazard (Figure 8). Distant (but more active) sources near the plate boundary (San Andreas and Hayward faults) make minor contributions. Ground motions provided by separate hazard runs using updated parameters for the Midland Fault (with reduction of the Midland Fault earthquake rate by a factor of 4.7) are reduced on average by ~2% within 20 km of the surface projection of the fault, with a maximum discrepancy of about 6% in the immediate vicinity of the central segment of the fault relative to those shown in Figure 8.

Local variations in thickness and stiffness of relatively soft, shallow soil layers may alter mapped motions. For example, Tokimatsu and Sekiguchi (2007) described ground motions during an earthquake in Nigata, Japan on organic soils that were appreciably stronger (exceeding 1g) than those on nearby inorganic soils, indicating that organic soils can amplify strong ground motions. These results are consistent with the results of simulations of amplification (even at high amplitude) for conditions consistent with those in the Delta (Kishida et al. 2009a). Even in the absence of strong site amplification, motions presented in Figure 8 are sufficient to induce ground failure in levee fills and underlying foundation soils.

Seismic Threats to Levees

A substantial seismic threat to levees during and immediately after an earthquake is liquefaction: the sudden loss of strength in granular (cohesionless) soils resulting from an increase in the pressure of the pore fluid and corresponding loss of inter-particle contact forces. Liquefaction occurs in loose, saturated cohesionless soils such as sands, non-plastic silts, and, in some cases, gravel. Delta levees can be comprised of liquefiable soils and founded on liquefiable soils. Liquefaction can cause levees to slump, spread, and crack as a result of shear strains, which result in shape changes (Figure 9), and volumetric strains that lead to settlement as pore water is expelled from liquefied sand. Liquefied sand may also flow out through cracks, resulting in additional volume loss and settlement. In some cases, the strength of the liquefied soil is too low to support the levee, resulting in a levee collapse.

The size and spatial continuity of the liquefiable stratum is an important consideration. Small liquefiable lenses surrounded by non-liquefiable soils may result in negligible deformations, whereas large, spatially-continuous liquefiable zones will likely cause significant deformations. Earthquake-induced liquefaction has caused levee deformations during past earthquakes in various locations around the world (though not in the Delta) (Miller and Roycroft 2004; Sasaki 2009; Green et al. 2011; Sasaki et al. 2012; Kwak et al. 2016a).

Liquefaction analysis begins with evaluating a soil's susceptibility to liquefaction. The liquefaction resistance of susceptible soils is then computed using semi-empirical correlations that consider the density or stiffness of the soil (e.g., Idriss and Boulanger 2008; Kayen et al. 2013). The seismic load imposed on the soil (i.e., the demand) is computed based on earthquake ground motion, and the factor of safety against liquefaction is computed as the resistance divided by demand. Liquefaction-triggering procedures are formulated for level-ground conditions, and corrected to account for the influence of static shear stress on liquefaction resistance (Boulanger 2003) and demand (Athanasopoulos–Zekkos and Seed 2013). Once liquefaction triggering is predicted, settlements and lateral deformations are estimated using semi-empirical engineering evaluation procedures that have been calibrated with case history data (Zhang et al. 2004; Faris et al. 2006), or using dynamic numerical simulations.

Levees not subject to liquefaction may be susceptible to earthquake-induced deformations (Figure 10). Earthquake shaking may weaken clays and plastic silts. However, the strength loss is not as significant as for liquefiable soils (Bray and Sancio 2006; Boulanger and Idriss 2007). This weakening combined with inertial loading from seismic shaking may result in levee slope deformations.

Because of uncertainties, levees seismic response is commonly treated probabilistically. Fragility functions define the probability of a levee exceeding a damage level; this probability depends on ground shaking, geologic conditions, groundwater levels, and other predictive variables. Fragility functions have historically been derived based on a combination of engineering evaluation procedures and expert opinion. More recently, Kwak et al. (2016a) developed empirical fragility functions based on observations of damage to Japanese levees shaken by earthquakes in 2004 and 2007. A key finding was that high groundwater and soft geologic conditions increased levee fragility. The Japanese levees are infrequently loaded flood-control levees, and the groundwater table was either beneath the levee base or near the levee toe during the earthquake. In contrast, Delta levees are continuously loaded (i.e., groundwater levels are above the base of the levee) and are therefore more fragile than the Japanese levees because saturated levee fill can liquefy. The fragility functions of Kwak et al. (2016a) indicate high probabilities of levee damage using the ground motion levels shown in Figure 8, despite the relatively favorable (compared to the Delta) hydrological and geotechnical conditions. This suggests that damage to the Delta levees is highly likely at the 475-year ground-motion return period.

Although fragility functions quantify the probability that any particular levee segment or reach will be damaged by shaking, the probability that a levee system will survive equals the probability that all segments survive the earthquake. Levees comprise a series system in which failure of any single component constitutes system failure, especially when they are constantly loaded, as

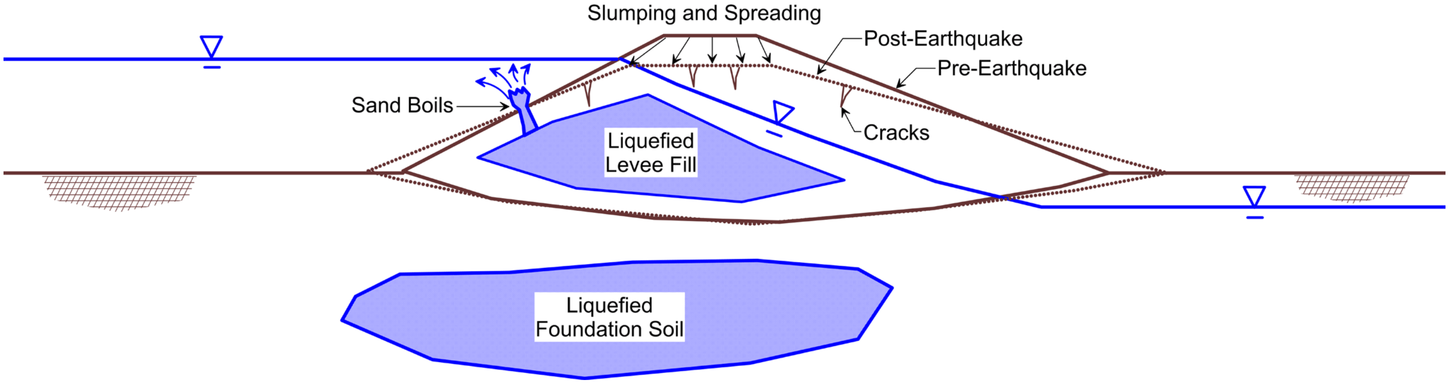

Figure 9 Levee deformation mechanisms due to liquefaction. Liquefaction occurs in loose saturated cohesionless soils such as sands, non-plastic silts, and in some cases, gravels. Delta levees often contain liquefiable soils and/or are founded upon foundation material containing liquefiable soils.

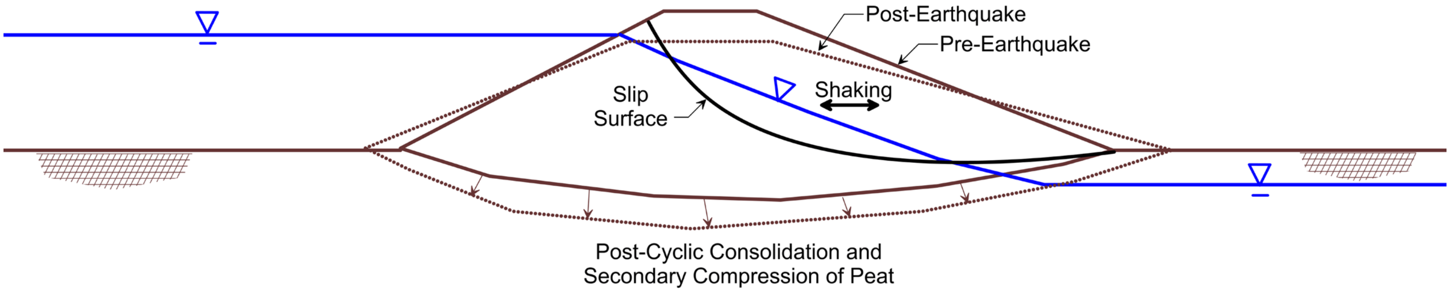

Figure 10 Levee deformation mechanisms in non-liquefiable soils

in the Delta. The probability of system failure depends significantly on correlation of seismic demands and seismic resistances among levee segments. Various approaches have been adopted to compute the probability of system failure, given spatially correlated demands and capacities (Wolff 2008; URS Corporation and Jack R. Benjamin & Associates, Inc. 2009; Kwak et al. 2016b). Kwak et al. quantified these spatial correlations for the Japanese levee system and explicitly accounted for spatial distribution and correlation. Other researchers selected a "characteristic length" where the levee system is divided into reaches that are considered uncorrelated (e.g., Wolff 2008; Jongejan and Maaskant 2015; VNK 2015).

Aside from the immediate threat to levees that liquefaction and related phenomena present, other longer term threats may also affect levees. Levees that are damaged but do not immediately release water may eventually breach because of several mechanisms. Cracks that form as a result of earthquake shaking may alter the flow of water through the levee by providing seepage channels. Also, earthquake-induced cyclic loading may increase settlement rates of levees founded on peat after an earthquake (Shafiee et al. 2015). This mechanism could result in a loss of freeboard, or formation of cracks in the days and months after an earthquake. Existing methods of analysis, and fragility relationships, do not consider these longer-term threats to levees.

Hopf (2011) and Prokopovitch (1985) noted an increased rate of levee failures after the 1906 earthquake. We can only speculate on whether earthquake-induced embankment cracking, perhaps combined with accelerated settlements, may have contributed to these failures. The levees are now significantly taller and under more hydraulic load than they were in 1906, and are thus more susceptible to earthquake damage. Furthermore, the

1906 earthquake was on the San Andreas Fault, which is approximately 80 km from the Delta. Seismic hazard is controlled by smaller and much more proximate faults (Figure 8), which threaten the Delta levees in a manner that has not yet been experienced.

When the factors that affect seismic risk in the Delta are considered, it is important to recognize key sources of uncertainty:

1. Source models are uncertain about earthquake rates and the M range of events that can be produced. The use of background seismicity models also indicates a lack of completeness relative to observed events.
2. Ground motion models estimate the mean and variability of ground motion parameters using global data for active crustal regions, but the local applicability of such models for the Delta is uncertain (Erdem et al. 2016).
3. Ground failure potential, and associated seismic fragilities, lack spatial certainty primarily because of the lack of data on the soil materials comprising levees fills and their foundations, which in turn controls liquefaction susceptibility.

The current DLIS uses seismic fragility models developed during the DRMS study. We recommend re-visiting this approach given more recent knowledge in source modeling, ground motion modeling, potential levee failure mechanisms, and system risk assessment. Such an analysis should consider the aforementioned uncertainties inherent to each component.

High Water

What are future threats to levees from high water? High water is the primary external force that resulted in 200 to 300 levee breaches in the Delta and associated rivers since the mid-1800s (Florsheim and Dettinger 2005, 2007). Arcadis (2016) consistently identified hydrologic failures as the primary Delta failure mechanism. Since 1951, 81% of Central Valley levee breaks occurred during floods generated by wintertime atmospheric river (AR) storms (Florsheim and Dettinger 2015), which are projected to increase in number and frequency in the warming future (Dettinger et al. 2016). These winter storms with heavy rains that reach higher up into the mountain watersheds than most have historically driven central California's largest floods. When these storms and floods coincided with extreme winter tides, storm surges and high wind waves have caused levee failure and flooding in the Delta. These processes, part of El Niño Southern Oscillations, represent significant Delta hazards (Cayan et al. 2006; Bromirski and Flick 2008). As an example, the day Mildred Island flooded (January 27, 1983), West Coast sea levels were elevated by an El Niño, and high tides reached record levels in San Diego and Seattle (CSLRCOW 2012). Field experience indicates consistently that these low-pressure storms are associated with high water levels in the Delta such as those that occurred in 1982–1983, 1998, and 2006). Increased seepage onto islands has been observed during these events.

The reported linkage of levee failures to high-river flows (URS Corporation and Jack R. Benjamin & Associates, Inc. 2008a), suggests that projected increases in high-flow frequency associated with climate change will increase levee failure rates. In this case, overtopping (i.e., water flowing over the crown of the levee), is the primary failure mode (Figure 7). Overtopping failure results from the erosion and scour of levee materials during high-water-stage events during which there is insufficient time to complete flood barriers[15] or during which the barriers settle (USACE 2000).

Climate change undermines the assumption of stationary processes upon which most water resource and levee management paradigms and tools are grounded (Dettinger et al. 2016) by forcing changes in water-resource behavior that exceed the underpinning probability functions. Cloern et al. (2011) concluded that there is a strong link between California's warming climate and coastal flooding and storms, and the rate of global warming will increase with higher greenhouse gas emissions (Dettinger et al. 2016). Global circulation models described in Cayan et al. (2008) and hydrologic models trained with data to predict Sea level rise (Cloern et al. 2011) indicate an increased incidence of extreme flooding events and the risk of coastal flooding: increased frequency of extreme water heights above the 99.99th percentile of water elevation over the historical rate. This translates to increases of 1,200 to 2,000 hours per decade by mid-century, and 15,000 to 30,000 hours per decade by the end of the century (Cloern et al. 2011). Water levels in the Delta are influenced by the tide level at Golden Gate and variable Delta inflow. An increase in the average sea level at the Golden Gate will affect water levels in the Delta, and thus likely increase hydraulic stress on the levees and contribute to an increase in the annual likelihood of levee failure.[16] Quantification of this increased threat requires further research and data collection.

Historic hydrologic and levee failure data and climate-change modeling provide evidence for increased potential future levee failure associated with high water. For example, Arcadis (2016) indicated that the expected number of flooded islands for a 100-year flood event is approximately 16 of 109 leveed Delta islands and tracts (14.6% of the islands), with one standard deviation ranging from approximately 8 to 24 flooded islands. URS Corporation and Jack R. Benjamin & Associates, Inc. (2008b) estimated a unit probability for exceeding 10 island failures at 100 years. Suddeth et al. (2010) stated that, based on current flood and seismic failure probabilities, the median Delta island has a 95% probability of failure by 2050, and a 99% probability of failure by 2100. These estimates were based on likelihoods of failure without major investments in levees.

How do earthquake and high-water threats compare? High-water threats and a large earthquake will likely result in multiple levee failures. High-water events, which we conclude will increase in frequency with time, are more probable in any year than major earthquake threats, although the damage will generally be less. Earthquakes will result in larger numbers of island failures, more extensive damaged levee reaches, and more widespread repair. The likelihood of a large earthquake is rare in any given year, but the potential economic consequences are much larger than high-water events, which are expected to occur more regularly.

Subsidence

How does subsidence affect levee probability of failure? Bachand et al. (submitted) investigated the effect of subsidence on current and future failure risk, and the potential benefit of strategic placement of shallow aquatic systems such as rice fields and wetlands. They did this by modeling changes in seepage and static slope instability relative to horizontal sliding failure typical of Delta levees (Duncan and Houston 1983) (Figure 7). They used 13 simplified scenarios in which levees met or exceeded the HMP requirements with varying levee heights and marsh deposit thicknesses relevant for the entire Delta. The simplified geology consisted of marsh deposits (peat, soft clay, and silt) underlain by sand. They used median soil property values for the analyses, and explored via a sensitivity analysis the effects of varying values within the ranges of the most critical variables.

Mechanistic models (Geo-slope 2012a, 2012b) (Figure 11) were used to calculate factors of safety against static and seepage failures, and to assess the sensitivity of the calculations to variability in soil-property values. Bachand et al. (submitted) used modeling results to calculate relative probabilities of failure (*RPF*) as a function of levee height (H) and marsh deposit thickness (T). Equations describing *RPF* for seepage and static slope stability were fit to the modeled results for H and T in meters:

$$RPF_{Seep} = \frac{1.114}{\left(1 + e^{1.945\left(T - 0.3602\right)}\right)\frac{1}{0.8919H}}$$

$$R^2 = 0.998$$

$$RPF_{Slope} = -1.3543 + .009152\left(T\right) + .04816H$$

$$R^2 = 0.992$$

RPF_{Seep} is greater than RPF_{Slope} when marsh deposits are thinner than about 6 m. The two failure modes were combined into a total *RPF* using the following equation (Hubel et al. 1990; URS Corporation and Jack Benjamin & Associates, Inc. 2008a):

$$RPF_{total} = 1 - \left(\left(1 - RPF_{Seep}\right) \times \left(1 - RPF_{Slope}\right)\right)$$

Calculated RPF_{total} varied as a function of levee height and marsh deposit thickness (Figure 12); predicted failures became more likely as marsh deposits thinned to less than 3 or 4 meters, and risk was exacerbated where levees were higher. The increasing probability of failure with thinning peat

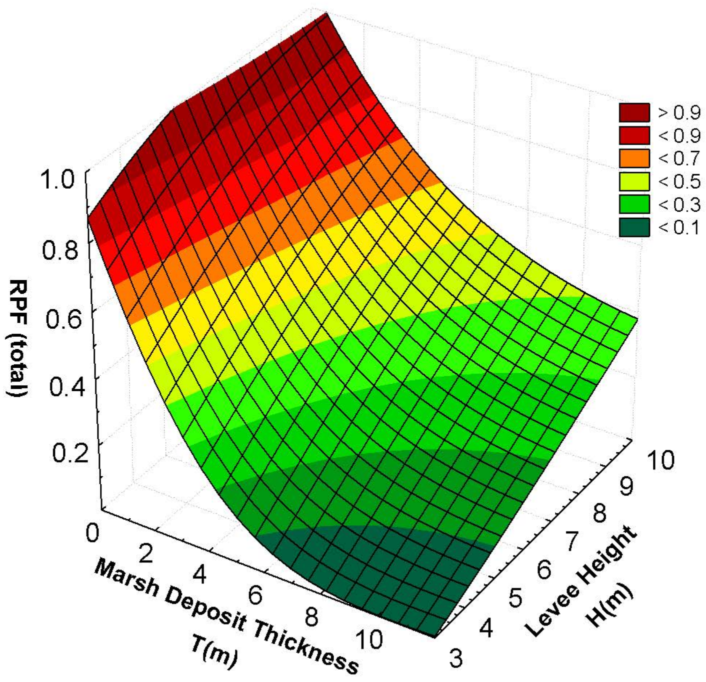

Figure 11 Relative Probability of Failure (RPF) as a function of marsh deposit thickness (T) and levee height (H)

results from increasing seepage forces, and increasing risk with levee height is from increasing static loads. The *RPF* results were applied to the subset of levees likely to be affected by subsidence over time: levees underlain by marsh deposits and associated with islands greater than 60 hectares.

Levee height (H) and marsh deposit thickness (T) were calculated based on LiDAR elevation maps and a marsh deposit base elevation grid (Deverel et al. 2015). Deverel and Leighton (2010) also constructed a Delta-wide grid of an estimated 2050 ground surface elevations and estimated subsidence rates, which were used to estimate changes in ground surface elevations, and values of *H* and *T*, over time. *H* was also increased as a function of sea level rise, estimated to be 0.33 m by 2050 (Deverel and Leighton 2010). Levees were divided into segments of about 4 m and elevation, subsidence, and sea level rise data were used to calculate *RPF* for each segment over time. To calculate a failure occurrence rate, Bachand et al. (submitted) reviewed levee failures and determined that 9 of 15 failures since the mid-1970s were likely related to seepage or slope stability issues. Based on this information, they calculated an instability failure rate of 0.22 failures per year for 1994, the mid-year of the observed failure period. Bachand et al. (submitted) estimated a failure rate of 0.25 failures per year in 2016, and 0.32 failures per year by 2066 from subsidence and Sea level rise without change in land use or levee structure. Growing rice or wetlands adjacent to 600 km of levees is projected to stop subsidence (Deverel et al. 2016) and thus reduce the failure rate; Bachand et al. (submitted) estimated the failure rate to be 17% lower than if subsidence were allowed to continue.

To achieve 50% of the risk reduction, rice or wetlands would be required adjacent to 190 km of the levees where the greatest risk increase is expected, i.e., levees where marsh deposit thickness is less than 3 m and that have estimated subsidence of about 1.4 m or more during 50 years (Bachand et al., submitted). This magnitude of subsidence would occur in highly organic (> 25% organic matter content) soils at least 1.4 m thick (Deverel and Leighton 2010). Bachand et al. (submitted) suggested that guidance for seepage berm width be used to estimate effective rice field width. The primary uncertainty in this analysis is the distance from the levee where subsidence affects levee stability for current and future conditions.

The seepage model results indicated that subsidence will increase seepage rates and *RPF*. For model runs with levees more than 4.5 m high and peat less than 3.5 m thick, 1.5 m of subsidence increased seepage flow by about 67%. This is consistent with data presented in Deverel et al. (2015), which indicates that subsidence resulted in increased seepage-affected marginally or non-farmable areas 10-fold from 1984 to 2012 – a key factor was the presence of artesian conditions, which were delineated in most of the areas where there are organic soils (Figure 6).

Delta levee practical experience indicates that failure occurs typically at the interface of the marsh deposits and levee fill where there can be through-seepage and internal erosion. A potential solution is a vertically-placed cut-off slurry wall[17] that extends through the center of the levee to prevent seepage. However, a cut-off slurry wall is expensive, and is likely impractical on a wide scale in the Delta.

Bachand et al. (submitted) used traditional equilibrium factor-of-safety calculations related to slope stability and seepage to estimate RPF.

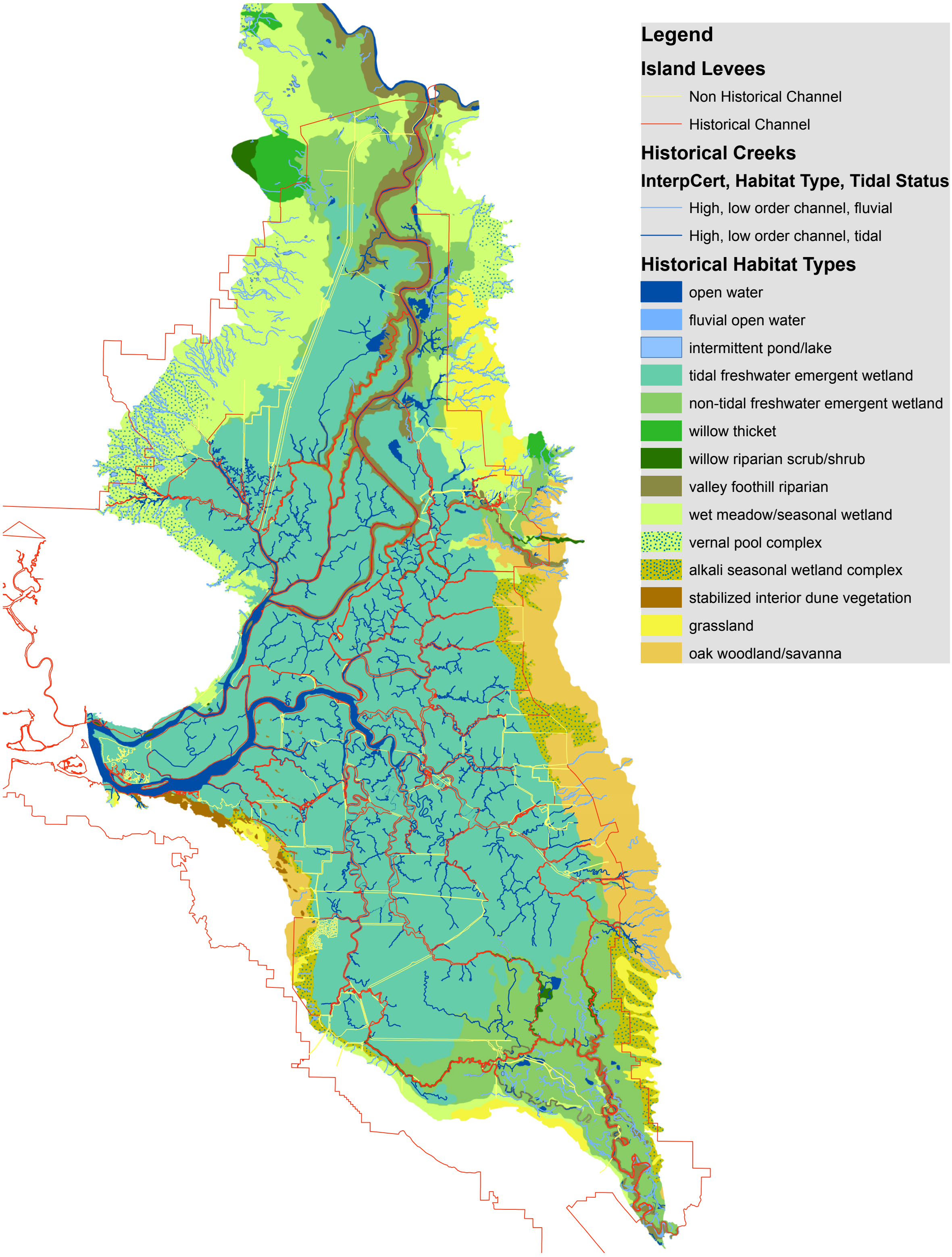

Figure 12 Overlay of current island boundaries on historic channels (red). Non-historic channels are indicated in yellow and were excavated in areas where there were not historic channels as mapped by Whipple et al. (2012).

However, relying solely on traditional calculations for highly-deformable peat soils is uncertain because deformations may affect levee stability before critical factor-of-safety values are reached (Foott et al. 1992). Tension-induced differential consolidation from peat deformation outside of the radius of a typical slip circle led to levee crack formation, which Foott et al. (1992) attributed to dewatering of the peat. Subsidence that results in drainage ditch deepening beyond the radius of the typical slip circle (see Figure 7) may affect levee failure, and merits further investigation.

Consequences and Risk

Consequences of Levee Failure and Maintaining the Status Quo

Delta levee failure and island flooding effects may include loss of life, residential and commercial buildings and their contents, machinery, and crop production; interrupted highway and railway travel, emergency services, and water supply; and ecosystem effects. Economic consequences may extend well beyond the Delta, especially for curtailments in exported water. When island levees fail, island repair and recovery costs can be substantial, and, as exemplified by the Jones Tract failure in June 2004, the financial effects and repair costs can exceed the value of the land. Costs associated with 11 of the 28 islands that flooded from 1969 to 1983 were about $177 million (Prokopovitch 1985). Estimated costs to repair the 2004 Jones Tract failure totaled $90 million (Suddeth et al. 2008), but the actual levee breach repair cost was $30 to $40 million; additional costs were from property damage. URS Corporation and J. R. Benjamin & Associates, Inc. (2009) estimated the cost of repairing a levee breach to range from $20 million to $40 million. URS Corporation and Jack R. Benjamin & Associates, Inc. (2009) indicated that a seismic event during 2005–2030 is the single greatest risk to levee integrity, resulting in multiple island failures and in economic costs of over $10 billion resulting from water supply and utilities service disruption, emergency repairs, and infrastructure replacement. High water failures were also estimated to be in the billions of dollars (CDWR 2009).

Costs of repairing a levee failure depend on the size of the breach, the materials, engineering and construction costs of fixing and reinforcing breached levees, armoring and repairing the suddenly-inundated unrocked landside slopes that experience erosion damage when winds arise, pumping out the island, and the lost profits from agricultural production on the island (assuming annual crops) (Suddeth et al. 2010). These costs, which reoccur each time the island fails, should be considered in the present net value for the island and in the average cost of failure repair. The cost of not repairing an island when it fails is the sum of the cost of rebuilding or re-locating existing infrastructure (such as highways and railways). Suddeth et al. (2010) suggested that comparing the estimated cost of repair and no repair will lead to identifying the least expensive or most profitable choice. Using estimated property and asset values, levee upgrade costs, and probabilities of failure from the DRMS study, Suddeth et al. (2010) developed a list of islands to be repaired if they failed. Of the 34 subsided islands analyzed, between 11 and 25 islands economically justified repair after a levee breach.

Water Supply Consequences

The Delta provides a portion of the drinking water for more than 27 million Californians—nearly two-thirds of the state's population. The primary elements of state-wide costs as a result of levee failure are agricultural losses, urban user losses from water supply disruption, and the lost use of major infrastructure (e.g., state highways that cross the Delta). However, not all islands that provide conveyance or salinity barriers, or that contain essential infrastructure are essential to ensuring water supply. The current Arcadis (2016) island water supply risk metric is based on counts of water supply functions (conveyance, salinity barrier, water user groups served, and infrastructure), relative water quantity used, and number of water user groups served.

Based on a survey of urban water suppliers, DRMS estimated urban user loss costs with a 50% reduction in supply at $1 to $1.5 billion. Over 60% of the estimated cost was for southern California suppliers. The DRMS study assumed that reductions in agricultural water supply would result in additional groundwater use and reduced crop acreage. With implementation of the Sustainable Groundwater Management Act, additional groundwater pumping may not be a viable option in most of the San Joaquin Valley. URS Corporation and Jack R. Benjamin & Associates, Inc. (2008b) estimated the statewide costs for water supply reduction and infrastructural damage to range from tens of millions of dollars to multiple billions of dollars, for one to multiple flooded islands resulting from hydrologic events.

Maintaining the Status Quo

Ongoing system operation results in relatively high costs for municipal water treatment because of the presence of bromide and dissolved organic carbon (Chen et al. 2010). Dissolved organic carbon (DOC) concentrations in Delta export waters consistently exceed the 3 mg L^{-1} water-quality objective. Formation of disinfection byproducts (DBPs) such as trihalomethanes (THMs) can result from high DOC concentrations, which has required utilities to increase treatment costs.

Amy et al. (1990) estimated that agricultural drainage from Delta island organic soils contributes 20% of the THM formation potential (THMFP) at Delta export pumps. Recent U.S. Geological Survey (USGS) analysis of historic data indicates percentages that range from 13% to 49% from in-Delta sources (Kraus et al. 2008). Higher percentages are associated with winter drainage. Deverel et al. (2007) demonstrated that oxidation of soil organic matter and subsequent mobilization of DOC to drainage ditches are the primary mechanisms that lead to DOC export from subsided Delta islands. Oxidation of soil organic matter in drained agriculture also results in losses of carbon dioxide that range from 15 to 20 tons carbon dioxide per ha (e.g., Knox et al. 2015), which could be stopped or greatly reduced if islands are converted to rice and permanently-flooded carbon sequestration wetlands (Knox et al. 2015) or tidal wetlands.

Documented increased wet and non-farmable and marginally-farmable acreage resulting from subsidence and consequent seepage from the 1980s to 2012 (Deverel et al. 2015) brings into question long-term sustainability of the status quo. As differences in elevation between surface water and island surfaces have increased because of subsidence, seepage rates onto islands have increased, and are predicted to increase in the future. Wet, non-farmable, and marginally-farmable acreage affects the future of farming and property values, and should be considered when levee investments are prioritized.

Ecosystem Consequences

Achieving the coequal goals of protecting, restoring, and enhancing the Delta ecosystem requires successfully establishing a resilient, functioning estuary and surrounding terrestrial landscape that can support viable populations of native resident and migratory species with diverse and biologically appropriate habitats, functional corridors, and ecosystem processes (DSC 2013). High-value habitat types include those that are important to recovering species (e.g., Herbold et al. 2014), those that replace historic habitat losses (e.g., Whipple et al. 2012), and those that emphasize priorities from conservation plans (DSC 2013): tidal marsh, non-tidal marsh, managed wetlands, riparian forest and scrub, seasonal floodplain, alkaline seasonal wetland, and vernal pools. Location and number of levee failures, time of year, and water conditions influence the effects on the ecosystem. When multiple islands flood, the DRMS study team estimated vegetation losses of up to 39%. Moreover, large-scale habitat losses were predicted, with consequent displacement of birds and other species. However, if levees fail, ecosystem and water-quality benefits could also result from increases in tidal habitat.

Potential high-value, non-tidal habitat that could result from restoration or levee failure has been quantified as the maximum of known proposed restoration (tidal or leveed non-tidal) and elevation-based mapping of habitat potential (Arcadis 2016). Arcadis (2016) calculated expected flooding of high-value non-tidal habitat as the sum of the product of the annual probability of flooding with the area of existing and potential non-tidal habitat.

Risk

Risk analysis combines the hazards, the estimated frequency of the different magnitudes of these

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hazards, and the consequences of failures in a probabilistic approach. Arcadis (2016) estimated the expected annual damage (risk) for varying flood levels on infrastructure and assets as the sum of the product of the probability of annual flooding for estimating economic losses. Through the DRMS Phase I study, the URS Corporation and Jack R. Benjamin & Associates, Inc. (2008, 2009) implemented a multi-step process to develop conditional probabilities of levee failure under seismic, high water, and sunny-day stresses. They used geotechnical modeling and professional judgement to develop probability-of-failure curves to analyze how levees responded to loading from a stressing event for different combinations of loading parameters and levee characteristics.

The DRMS study estimated mean annual number of failures for Delta islands and Suisun March that ranged from less than 0.01 to over 0.07. Most Delta island annual mean failure estimates ranged from 0.03 to 0.05. Sherman, Tyler, Venice, Sargent Bernhard, and New Hope were assigned values over 0.07. The DRMS study estimated probabilities of multiple island failures that ranged from over 70% to less than 20% for 10 to 30 simultaneous levee failures associated with high-water conditions between 2005 and 2030. Higher probabilities were estimated for a major earthquake: 40% from 2005 to 2030. The frequency of levee failure and flooding for single and multiple islands, and the generation of levee failure sequencing, were used to perform both levee emergency response and repair as well as hydrodynamic analyses, which in turn provided input into cost estimates.

The DRMS study results have been challenged because of their alleged failure to fully and accurately account for substantial recent levee upgrade investments, the extent of subsidence, analysis of uncertainty and error, and misrepresentation of failure risks from Sea level rise, flooding, and seismic hazards (e.g., Brandenberg and Stewart 2008; California Central Valley Flood Control Association 2011; Hultgren–Tillis Engineers 2015;). The way in which risk for individual levee segments has been used to evaluate levee system risk was not sufficiently robust to properly consider spatial variability and correlation of demand and capacity (Kwak et al. 2016). Moreover, independent scientific review (CALFED Science Program Independent Review Panel 2008) concluded that although DRMS study is acceptable as a tool for informing policy-makers and others about potential resource allocations and strategies to address risk, important caveats relate to prediction uncertainty and ecosystem consequences. Specifically, the CALFED panel considered future economic consequences to be over-estimated, and recommended additional sensitivity analyses.

The DLIS seeks to improve upon the DRMS study results, specifically relating to inclusion of additional levee structural information to develop non-seismic fragility curves. To reduce risks and further advance the coequal goals of water supply reliability and Delta ecosystem restoration, the DLIS objectives include development of a methodology that decision-makers can use to evaluate and recommend priorities for investments in Delta levees. Seismic levee risk is treated separately from hydrologic and hydraulic risk. Current planning is for seismic risk to be based on USGS ground motions (similar to Figure 8) and fragility curves developed by the DRMS study, despite the known problems with those fragility curves, as discussed previously. For this reason, we recommend that fragility models be redeveloped in consideration of changes in levee configuration, updated site amplification models, and improved knowledge of the mechanisms (including earthquake damage) that threaten levee stability, as described in the previous section.

Risk reduction analysis in the DLIS support tool relies on representing levees using non-seismic fragility curves. Baseline risks have been estimated using fragility curves that reflect the current data set. To update fragility curves, geotechnical data can be added as it becomes available,. To develop fragility curves, reclamation district engineers (Gilbert Cosio, Chris Nuedeck, and Gil LeBrie) provide ongoing review of the process to provide the most recently available input. Fragility curves require updating in response to ongoing subsidence and settlement of the levee system, because of improvements funded with state and reclamation district investments, and would require updating because of the potential change in levee geometry resulting from a seismic event.

The DLIS risk methodology (Arcadis 2016) will estimate expected annual damages (EAD), which is an average annual monetary value of current and future losses from flooded Delta infrastructure and other assets based on the probability of flooding. Among the future hazard changes, the DLIS is considering only potential sea level changes in the risk analyses. Arcadis (2016) used revised hydrologic and hydraulic levee fragility curves generated since the completion of the DRMS study (e.g., CDWR 2012). The other future hazard changes (i.e., subsidence, earthquakes) are considered to be too unpredictable to provide a meaningful estimate of levee response to changed conditions (Arcadis 2016).

How would a single-island levee affect levee vulnerability and associated costs on other islands? For example, flooding of an island may impede access to other islands. Seepage may also increase on islands adjacent to flooded islands. Concern has been expressed about an increase in wind fetch that would result in greater water-side erosion on nearby islands. URS Corporation and Jack R. Benjamin & Associates, Inc. (2008a) concluded that this domino effect was not supported by the long-term survival of remnant levees of flooded and abandoned islands. Twenty-three years after Mildred Island flooded, the entire levee—except the breach area—is still visible. Similar observations were made for Little Franks Tract as well as Little Mandeville and Rhode islands, which flooded 23, 12, and 35 years ago, respectively. These observations indicated that the remaining levees did not erode extensively after they were breached.

What lessons from the DRMS study apply to the ongoing DLIS? The DRMS study used a coordinated multi-discipline scientific effort that included a wealth of data and analyses prepared by topical experts (who responded to rigorous and substantial technical review) in various subject areas; geomorphology; subsidence, seismology, climate change, flood hazard, wind-wave hazard, emergency response, levee vulnerability, hydrodynamics, water quality, water management and operations. The DRMS study channeled information into comprehensive estimates of failure probability, consequences, and risk, which resulted in highly useful products. The science and approach remain valid and applicable.

Within the DLIS, we recommend integration of the best available science into analysis of future risk for all potential hazards. Interdisciplinary discussion and dialogue among scientists, engineers, and practitioners would be optimal. The flexible risk-analysis tool may serve as a technical consensus-building platform in which different options and approaches could be tested, and uncertainty assessed and discussed by experts from various related scientific disciplines. In this way, future inclusion of the risk from future subsidence and earthquakes could be assessed.

This approach could also lend itself to the following factors for prioritization of levee investments being considered: sustainability as discussed previously relative to the Deverel et al. (2015) results; accommodation space below sea level (which increases with ongoing subsidence) that can fill with flood water when levees fail (see Deverel and Leighton 2010); and effects of levee failure on habitat and water quality. Hydrodynamic modeling suggests reductions in central Delta salinity from flooding of Liberty Island and other Delta islands that results from modifications to the distribution of the tidal prism (URS Corporation and Jack R. Benjamin & Associates, Inc. 2011; 2016 phone conversation with J. DeGeorge, unreferenced, see "Notes"). Hydrodynamic modeling of island flooding in Suisun Marsh also indicated benefits to Delta salinity (U.S. Bureau of Reclamation et al. 2011).

Delta Levees and the Ecosystem

The Delta once supported abundant diversity and large wildlife populations. Since reclamation, agriculture and urban areas replaced the large expanse of approximately 365,000 acres of tidal freshwater emergent wetlands and over 1,600 km of associated tidal channels (Whipple et al. 2012; Brown et al. 2016, Figure 12). Interrelated changes included loss of ecological function; reduction in habitat extent and heterogeneity; loss of connectivity within and among habitat types; degradation of habitat quality; disconnection of habitats from sustaining physical processes; and invasive species (SFEI–ASC 2014). SFEI–ASC (2014) identified historical ecological functions: processes and characteristics that supported the life histories of resident and migratory fish, marsh wildlife, water birds, riparian wildlife, and marsh–terrestrial transition zone wildlife. Modern channels are wider, straighter, deeper, and simpler, and generally lack the fine-scale structure and micro-topography that provided abundant aquatic habitat. There is also evidence for reduced organic matter to food webs that existed in the pre-reclamation freshwater Delta (Brown et al. 2016).

The California Water Code specifies inclusion of habitat restoration in levee projects[18] and directs the CDWR to create "net long-term habitat improvement." Moreover, levee-improvement projects authorized under Assembly Bill 360 "shall include provision for the protection of fish and wildlife as determined to be necessary by the California Department of Fish and Game have a net aquatic habitat enhancement." The CDFG (now called the California Department of Fish and Wildlife, CDFW) is also required to determine that the proposed expenditures are consistent with a net long-term habitat improvement program and have a net benefit for aquatic species in the Delta. There is little publicly-available evidence for compliance with these provisions of the Water Code (Davenport et al. 2016).

In addition, the Delta Reform Act of 2009 required the Delta Stewardship Council to promote expansion of floodplains and riparian habitats in levee projects, and established objectives that include interconnected habitats; establishment of migratory corridors for fish, birds, and other animals; and the restoration of habitat necessary to avoid a net loss of migratory bird habitat. The Delta Plan promotes the expansion of riparian habitat on levee projects and requires evaluation of levee habitat within the Delta.

Monitoring and Mitigation

Assessment of Levee Structure

Levee subsurface investigations provide essential information about the ability of levees to withstand external stresses. Without knowledge of internal composition and structural integrity, assessment of levee response to earthquakes or high water, and prioritizations of maintenance and upgrades, are uncertain. Delta levee artificial fills contain a spatially-variable heterogeneous mixture of geologic materials of varying strength and compressibility that include silt, sand, clay and peat. Levees are founded upon peats and mineral soils that range from clays to sands that may be poorly consolidated and loose. Quantification of levee inner layering and structural integrity are required to realistically assess how levees will respond to external forces, and for maintenance planning. Traditionally, borehole logs, blow counts, and cone penetrometer testing (CPT) have been used to assess the internal structure of levees and the potential for liquefaction. The lateral extent of a liquefiable stratum is an important issue to determine earthquake vulnerability. Liquefaction of a sand layer that extends hundreds of meters along a levee (and is similarly present along other levees) is more likely to yield a multiple-island earthquake catastrophe.

Delta levees have been investigated extensively (URS Corporation and Jack R. Benjamin & Associates, Inc. 2008), and CDWR maintains an extensive borehole–CPT database that includes data collected since the DRMS study. Although substantial geotechnical information can be often gained from borehole and CPT logs and sampling, the heterogeneous inter-layering of materials can make it difficult to stratigraphically correlate from one borehole or CPT to another. Moreover, soil sampling and laboratory characterization of soil materials often involves disturbed samples that may not represent in situ conditions, and which, from a holistic, island levees-as-a system perspective, may be too widely spaced to enable engineering properties (e.g., shear strength, volume change characteristics, and seismic properties) that critically influence levee risk to be adequately assessed. Estimation of peat thicknesses can provide useful information for levee upgrades that compensate for post-earthquake peat consolidation and potentially increased settlement rates . The presence of loose, saturated sand or low-plasticity silts (as indicated by low blow counts) can indicate liquefaction potential. Recommended geotechnical practice includes drilling boreholes at regular intervals; in situ sampling (in addition to CPT) and shear strength testing; visual soil textural and depth-to-groundwater evaluation; and laboratory testing for moisture content, density, particle size, and Atterberg limits (USACE 2000). Professional judgment should be used to configure a site investigation for existing levees, including assessment of the spatial variability of geologic strata on which the levees rest.

Most levees in the area of organic soils appear to contain, or be underlain to some degree by, organic materials (Atwater 1982; URS Corporation and Jack R. Benjamin & Associates, Inc. 2008; Deverel and Leighton 2010; Kleinfelder 2011; URS Corporation and Fugro–Lettis & Associates 2011; Deverel et al. 2015). However, because the present-day artificial levees were mostly constructed on the overflow banks of the river and distributary sloughs, most rest on natural levee deposits (Figure 12) or on peat and mud deposits that interfinger in the subsurface, creating vertical interbeds of silt and sand with organic-rich material. URS Corporation and Jack R. Benjamin & Associates, Inc. (2008a) revealed that the foundation materials for Delta levees varies greatly, even between neighboring islands, because of a history of channel migration and river meandering.[19]

Beyond the DRMS study efforts, more recent studies to characterize geologic materials within and underneath levees and associated vulnerability have been conducted or are ongoing. For example, the CDWR's Non-Urban Levee Evaluations (NULE) Project evaluates over 2100 km of non-urban state and federal project levees and over 660 km of appurtenant non-urban non-project levees.[20]

Geophysical Methods and Remote Sensing

Moore and Shlemon (2008) suggested that geophysical and remote sensing techniques were for developing a more comprehensive and systematic picture of levee internal structure. These techniques may provide continuous soil data along survey paths for less cost than traditional borehole logging. Surface-based geophysical techniques have since been more widely tested. Methods included electromagnetic (EM) induction, electrical resistivity, capacitively-coupled resistivity (CCR),[21] ground penetrating radar (GPR), and seismic (multi-channel analysis of surface waves) methods to rapidly interrogate subsurface conditions. In general, geophysical techniques have not, thus far, proved useful for widespread use in the Delta.

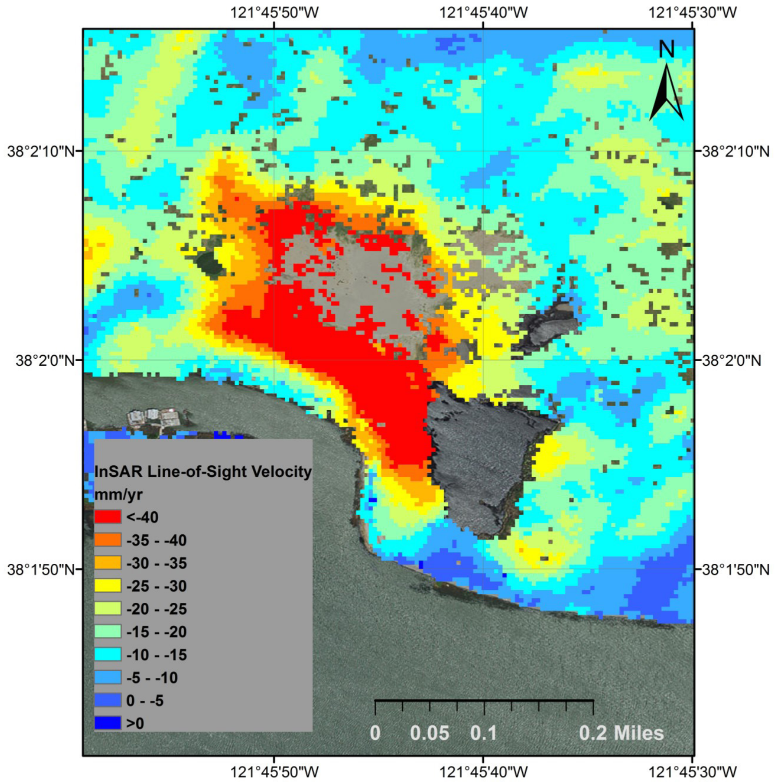

Figure 13 InSAR-derived map showing rate of ground movement at a site on Sherman Island that underwent relatively rapid deformation during 2009–2015. InSAR can only measure displacement in the line-of-sight direction, which in this case is a combination of vertical movement and horizontal movement in the north-south direction. It is likely that this area is experiencing both subsidence and horizontal movement on the levee slopes, and InSAR data from at least three different look directions would be needed to determine the 3-D velocity field. However, even from a single line-of-sight direction it is possible to identify areas along the levees experiencing the most movement. InSAR-derived displacements are relative, i.e., not in a geodetic frame, and require tie points of known movement within the scene as a reference. The data used to generate the map were acquired with the NASA/UAVSAR instrument (*https://uavsar.jpl.nasa.gov/*, accessed 2016 December 28).

To map subsurface variations in subsurface electrical-conductivity conditions and to identify excessively permeable zones, EM and CCR surveys were conducted along levees on the Feather River, Bear River, American River, Sutter Bypass, Yolo Bypass, Sacramento River, Stanislaus River, San Joaquin River, and tributaries, and proved useful to assess foundation conditions and potential underseepage areas (USACE 2015). Also, the CDWR has used airborne EM to survey urban levees.[22] However, where there is extensive borehole data in the Delta, EM technology results have not compared well with borehole data (2016 in-person conversation with G. Cosio, unreferenced, see “Notes”).

The multi-channel analysis of surface waves method (Park et al. 1999; Miller et al. 2000) uses low-frequency surface waves (e.g., 4 to 100 Hz), which propagate within several tens of meters of land surface, to estimate shear-wave velocity variations with depth. Shear-wave velocity[23] can be correlated with soil stiffness and compaction. Ferriz (2016) recently tested this technique on Sherman Island, where shear wave variations were evident with depth. Ground-penetrating radar transmits high-frequency electromagnetic pulses into the subsurface. Leclerc and McDaniel (2006) attempted to use GPR to detect peat/mineral layering in Delta peat soils, and reported a lack of radar reflections below depths of about 1.5 m, indicating rapid signal attenuation, and thus indicating that where there is saturated peat GPR cannot be used effectively to assess levee stratigraphy.

Remote Sensing

Two remote sensing techniques provide important information about levee deformation, movement, and conditions: synthetic aperture radar (SAR) and light detection and ranging (LiDAR). Previous SAR satellite studies (Cohen et al. 1998; Brooks et al. 2012) faced obstacles related to small-scale changes in land–surface elevation and levee deformation. Longer wavelengths for SAR imagery combined with regular acquisitions, high spatial resolution, and novel data-processing techniques have been effectively used to monitor subsidence and levee deformation, and to identify areas where seepage may be occurring (Jones et al. 2016).

Interferometric SAR (InSAR) measures surface deformation directly through radar remote sensing via high-altitude aircraft or space craft (Bamler et al. 1998). Measurements simultaneously cover large areas at one time in imaged swaths that are tens to hundreds of kilometers wide. It is possible to achieve measurement accuracies of aproximately 5- to 10-mm surface deformation when earthen levees are imaged in a single pair of measurements, and significantly higher accuracy, as fine as 1–2 mm yr^{-1}, when using a time-series of multiple images (e.g., Sharma et al. 2016). InSAR also differs from traditional survey methods and LiDAR because it can see through clouds, smoke, haze, and image surfaces without solar illumination.

To determine the cumulative deformation that occurred between data collections, the InSAR technique involves acquiring an initial image that serves as a baseline reference, relative to which movement is quantified by subsequent imaging and processing. Earthen levee and farm field monitoring is particularly challenging because surface disturbance (temporal de-correlation) caused by grazing and agricultural (e.g., cultivation) activities corrupts the deformation signal. Nonetheless, single pairs of images, and a time-series of images collected at intervals of roughly 2 months, have successfully been used to identify deformation on or near levees (Jones et al. 2012, 2016; Sharma et al. 2016).

InSAR is particularly useful to identify areas of localized levee deformation, and will be valuable in determining the extent of movement after major floods, breaks, or seismic events. For example, Jones et al. (2012) investigated the levee on the north side of Bradford Island where a barge caused levee damage that necessitated repair between InSAR data collections in July and September 2009. The method has been used to identify rapidly-subsiding areas in the Delta, including an area on Sherman Island where movement is occurring on a levee and extending a significant distance inland from the levee (Figure 13). Regularly collected and processed airborne InSAR can, therefore, detect levee deformation remotely, and could potentially help identify areas that require attention. InSAR may also provide reasonable estimates for soil subsidence on Delta islands. InSAR-derived subsidence rates for Sherman Island during 2009–2014 averaged 1.3 ± 0.2 cm yr^{-1} (Sharma et al. 2016), generally consistent with rates reported in Rojstaczer and Deverel (1995) and Deverel et al. (2016).

A second LiDAR survey (the first was conducted in 2007) may improve our knowledge of the spatial distribution of oxidative subsidence rates, and would certainly provide useful information about how levees conform to the Pl 84–99 and HMP standards. However, in light of the uncertainty in the LiDAR data conducted in 2007 (15 cm at the 90th percent confidence interval), for a return LiDAR flight in the Delta during the next few years, uncertainty needs to be accounted for in the delineation of Delta-wide estimates of subsidence that are occurring at rates of about 1 to 3 cm yr^{-1} or less. Periodic InSAR data collection with sub-centimeter accuracy is a tool of substantial potential value, but ground truthing is needed to verify subsidence rates and to serve as reference points for the InSAR-derived rates. This could be supplied by continuous GPS stations and extensometers (Deverel and Rojstaczer 1996). Extensometer data on Sherman Island (Deverel et al. 2016) was useful to validate the Sharma et al. (2016) estimates.

Bawden et al. (2014) reported the use of terrestrial LiDAR (T-LiDAR) to topographically map 3-D surface elevation displacements with exceptionally high resolution. These were used to calculate levee-surface changes during and after a seepage test on Twitchell Island. The high density of measurement points allowed sub-centimeter-scale changes in the levee surface (cracks and consolidation) to be accurately determined. This first-of-kind assessment in the Delta provided substantial insight about how to optimally detect, measure, and characterize dynamic deformation and surface changes. T-LiDAR may prove useful if set-up and data acquisition can prove economical. The USGS Water Science Center in Sacramento recently invested in a high-resolution bathymetric and LiDAR system that may help map levee geometry for a reasonable cost (2016 phone conversation with J. Howle, unreferenced, see “Notes”).

Assessment of Seismic Effects

A key data gap for improved assessment of seismic vulnerability is the characterization of levee materials and the extent of liquefiable materials. Figure 14 shows the extent of available borehole and CPT data in the Delta. A key area for future investigation is improved geotechnical characterization of these earth materials, and consideration within the risk assessment process of the full range of ground failure mechanisms that may develop from local soil conditions, especially as related to the potential for liquefaction of levee foundation and fill materials, and the deformations of levees founded on peat. This work would provide a clearer picture of overall seismic vulnerability.

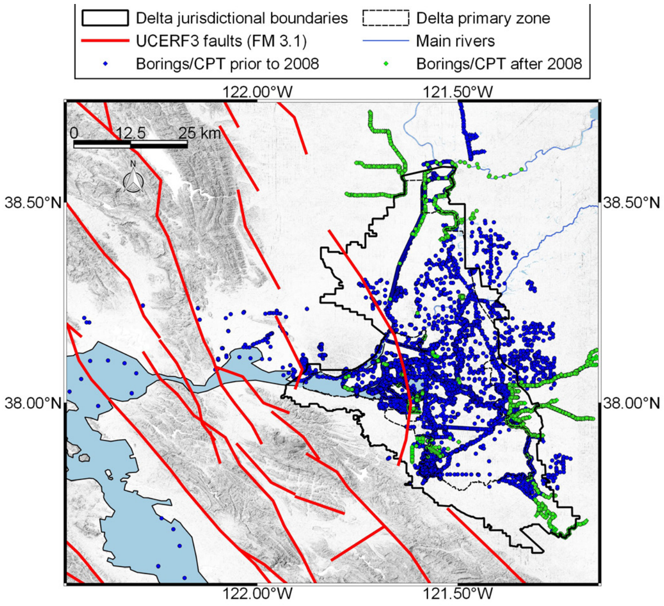

Figure 14 Delta region jurisdictional boundary, coast range faults, and borings that have been conducted in the Delta

Mitigation and Restoration

Mitigation of Delta Levee Vulnerabilities

During Phase II, the DRMS steering committee and consultants, and the CDWR identified improvements in the forms of building blocks or individual improvements and scenarios, ensembles, or combinations of building blocks that could mitigate levee vulnerability, with the objective of achieving multiple risk-reduction objectives (URS Corporation and Jack R. Benjamin & Associates, Inc. 2011). For example, levee upgrades were proposed to reduce the risk of levee failures, isolated and non-isolated Delta conveyance mechanisms were intended to preserve and protect water-export capabilities if levees fail, and ecological restoration solutions were chosen to increase and diversify the habitat in the Delta and Suisun Marsh and mitigate the potential effects of levee failures.

Some scenarios and building blocks have been implemented, or progress has been made toward implementation. These include preparedness improvements such as acquisition of easements; development of capabilities to rapidly assess levee stability, repair, design, and construction; emergency planning (CDWR 2014); and acquisition of flood fight materials and supplies and training.[24] The Middle River earthquake recovery strategy establishes a freshwater pathway from the Sacramento River to the export pumps in the south Delta, generally along Middle River (CDWR 2014), which will apply if many islands flood after an earthquake. Repair of levees and construction of channel barriers along this corridor can help restore Delta water exports during extreme events. Land-use changes to stop and reduce island subsidence include wetland construction and rice cultivation on Twitchell and Sherman islands.

To mitigate the effects of earthquakes on levees, many possible mechanisms of deformation that could result in a breach must be considered. Possible mitigation options include ground improvement (especially when liquefaction contributes to ground deformation), construction of setback levees, increasing levee height, or placement of buttress fill (e.g., Hultgren–Tillis Engineers 2009). Uncertainties in soil properties and seismic demands should be considered when mitigation measures are designed and implemented, so the reliability of the levee system – pre- and post-mitigation – can be evaluated holistically. Levee mitigation should be based on analysis of systems that comprise many reaches. Failure at any particular point along a levee system results in inundation of the protected island; target failure probabilities from cross-section analysis would need to be low (and factors of safety would need to be high) to provide an acceptable level of system reliability.

Levee- Habitat Projects

The DLIS intends to guide habitat enhancement that will mitigate adverse environmental effects of levee projects, help ensure compliance with relevant legislation and co-equal goals, and benefit aquatic species. Although levee-related habitat improvements will provide a small part of all ecosystem benefits needed by native species, levee habitat projects need to occur within the larger context of Delta restoration, and ensure that state levee investments contribute to achieving co-equal goals and providing net benefit for aquatic species.

The Ecosystem Restoration Program (ERP 2014) vision advocated setting back or flattening levees to enhance river meanders and restoration of erosion and deposition processes, as well as providing fish and wildlife with access to floodplains. Restored habitats will re-establish a greater land–water connection and facilitate transport and exchange of sediment, nutrients, and organic materials that contribute to ecosystem productivity. Challenges to implementation include: U.S. Army Corps of Engineers-required removal of trees and most shrubs on and around levees under their jurisdiction, lack of information about the effectiveness of existing and potential levee–habitat projects, and local resistance to allocating land for restoration. Four key structural modifications—and related habitats, setback levees, adjacent levees, extra-wide levees, and planting benches—have been assessed (Davenport et al. 2016). Levee-related habitat types include channel-margin habitat, freshwater marsh (tidal and non-tidal), shaded riverine aquatic, and riparian habitat. Extra-wide levees (Figure 2) (sometimes referred to as habitat levees) provide a gradual waterside slope on which riparian, shaded riverine aquatic, and channel margin habitat can be established.[25] Benefits to salmonids have been a primary focus, but benefits to native and non-native species requires evaluation. These structural modifications provide overhanging riparian vegetation, (i.e., shaded riverine aquatic) slower water velocities, and soft bank substrates, which may offer important protective and feeding habitat for migrating juvenile salmon (Murphy and Meehan 1991; Smokorowski and Pratt 2007). Overhanging vegetation also protects small fish from predation by birds. In contrast, levee revetment at the channel margin is generally unsuitable habitat for juvenile salmon because predators in the gaps of the riprap can ambush smaller fish (McLain and Castillo 2009). Greenberg et al. (2012) presented evidence that Delta shaded aquatic riverine habitat provides cooler microclimate during the summer months when native fish can be temperature-impaired in open channels. Levees that are set back a substantial distance from channels can facilitate restoration of natural riverine processes and provide broad areas of floodplain habitat that benefit aquatic and terrestrial target species (Golet et al. 2013).

Davenport et al. (2016) assessed 15 Delta levee-related habitat improvement projects. Appropriate fish and wildlife monitoring data were lacking for most projects, data were inconsistent across projects, and monitoring of wildlife response was rarely implemented. A few of the projects demonstrated through subsequent wildlife monitoring that target species occupy restored areas. Determining net benefit to targeted species will require evidence of increased occupancy and of a relationship between increased habitat availability and population growth.

Recommendations include improved consideration for and monitoring of effects on all wildlife, in particular fish and birds. Block et al. (2001) advocated using measures of population dynamics. Additionally, future habitat improvement projects should be strategically located and planned in the light of conceptual models for target species and future changes in sea level, sediment input, and infrastructure, and then managed adaptively. Larger spatial scales and complex landscapes that mimic the pre-development habitats (Figure 12; Whipple et al. 2012) are preferable and will benefit a wider array of wildlife (Brown 2003; Herbold et al. 2014). The Delta Plan calls for the Delta Science Program to develop landscape-scale conceptual models in collaboration with other agencies, academic institutions, and stakeholders.

Levee policy has focused on habitat associated with levees. However, tidal wetlands in the Delta such as those on Liberty Island, Little Holland Tract, and Lower Sherman Island Lake, will likely benefit native pelagic fishes (Brown et al. 2016). In light of the pelagic organism decline; the potential water-quality benefits of flooded islands; the economics of levee failure, repair, and upgrades; and island flooding, levee investments and development of tidal wetlands in appropriate areas of the Delta merit consideration in tandem. Current policy emphasizes levee improvement. We suggest that improved recognition, evaluation, and coordination are needed between the creation of high-value tidal ecosystems and the needs of levees. The DSC (2015) advocates for future restoration opportunities, but the mechanisms to optimize future restoration are unclear.

CONCLUSIONS

Delta levee science and practice have evolved substantially during the last decade, and hundreds of millions of dollars have been spent on levee upgrades. In the light of newly-available data and information, we attempted a reappraisal of key factors and processes that affect levee vulnerability.

We appraised key sources of levee vulnerability, external forces and processes that influence future Delta levee failures are seismic shaking, high water and subsidence. We attempted to answer questions about implications of recent data for seismic ground motion and earthquake threats.

Estimated ground motions are large enough to induce failure but local applicability is uncertain. Sources of seismicity include multiple local faults and background seismicity as a result of larger but more distant faults. Source models are uncertain with respect to earthquake rates and magnitudes. The use of background seismicity models also indicates a lack of completeness relative to observed events. Moreover, seismic threats lack spatial certainty primarily due to data for liquefaction potential of levee and levee-foundation materials.

A key seismic threat is liquefaction-induced strength loss of levee fill and foundation materials. Liquefaction threats to levees lack spatial certainty primarily due to data for liquefaction potential of levee and levee-foundation materials. Even if levees remain standing following an earthquake, secondary failure mechanisms can threaten the long-term stability of levees and may have contributed to a large number of observed levee failures within approximately a year following the 1906 San Francisco earthquake. These secondary mechanisms include earthquake-induced levee cracks causing

http://dx.doi.org/10.15447/sfews.2016v14iss4art3

accelerated and potentially destabilizing seepage, as well as accelerated rates of settlement for levees founded on peat. These are particularly important processes for Delta levees because they hold back water continuously. These failure mechanisms are not considered in current risk assessments for Delta levees and merit consideration in future work.

While fragility functions quantify the probability that any particular levee segment or reach will be damaged by shaking, the probability of survival of a levee system equals the probability that all of the segments survive the earthquake. Levees comprise a series system in which failure of any single component constitutes system failure especially since they constantly restrain water as in the Delta.

We also attempted to address questions about threats of high water. There is a strong link between climate change to coastal flooding and storms. Global circulation and hydrologic models indicate increased frequency of extreme flooding events, risk of coastal flooding and extreme water heights. An increase in the average sea level at Golden Gate will affect water levels in the Delta and thus increase hydraulic stress on Delta levees and contribute to an increase the annual likelihood of levee failure. Quantification of these effects merits further investigation.

We addressed the question about how subsidence affects levee probability of failure. The results of mechanistic modeling for varying levee geometry and marsh thicknesses indicate thinning of peat soils will increase probability of failure due to increased seepage forces. The spatial extent to which subsidence affects present-day and future levee failure probability is uncertain and requires further investigation. This is related to uncertainty in the extent of subsidence rates in organic soils. Additional uncertainty stems from tension-induced differential consolidation due to peat deformation.

Monetary consequences for historic and future levee failure and island flooding range from hundreds of millions to billions of dollars. Ongoing analysis of future risks focus on high-water failure and rely on revised hydrologic and hydraulic levee fragility curves. The DRMS study used a coordinated multi-discipline scientific effort to arrive at risk estimates. While the risk estimates have been challenged, the science and approach remain valid and applicable. Integration of the best available science into analysis of future risk (including seismic and subsidence effects) for all potential hazards is recommended. Interdisciplinary discussion and dialog among scientists, engineers and practitioners will be optimal.

Levee policy has focused on habitat associated with levees which will benefit from more coordinated and systematic monitoring of target species. However, levee habitat represents a small portion of potential Delta habitat restoration. In light of the pelagic organism decline and the economics of levee failure, repair and upgrades and negative and positive consequences of island flooding, prioritization of levee investments and development of tidal wetlands in appropriate areas of the Delta merits consideration and cost/benefit analysis. Better recognition and coordination is needed between the creation of high value tidal habitat and levee needs.

Improved description of levee upgrades and strength can likely result from analysis of the extensive database of borehole data and integration of these data to develop improved fragility analysis. Assessment of potential levee failure in general and seismic failure in particular, depend on a holistic and systematic assessment of island levees.

To address uncertainty in key areas, we suggest:

1. Improved description of levee upgrades and strength and improved probability of failure estimates based on recent information.
2. Improved potential estimates for seismic failure throughout the Delta.
3. Improved assessment of the effects of subsidence on levee stability and the spatial distribution of subsidence rates.
4. Improved understanding of levee habitat and the potential for integrating levee investments and prioritization with development of tidal habitat.
5. Improved assessment of effects of projected increased height and duration of Delta surface-water stages that account for water-supply scenarios and corresponding risks and benefits.

6. Additional hydrodynamic modeling to simulate a wide range of scenarios and corresponding risks and benefits to water supply and quality.

The March 2011 tsunami taught the Japanese that they must be ready for "Soteigai" (pronounced *sew-ty-guy*)—that which is outside our imagination.

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END NOTES

1. The Delta Levees Maintenance Subventions Program is a cost share program that provides technical and financial assistance to local levee-maintaining agencies in the Delta to maintain and rehabilitate non-Project and eligible project levees. Since the inception of the Subventions program in 1973, the California Department of Water Resources (CDWR) has reimbursed more than $175 million of eligible levee maintenance and rehabilitation work.

2. After 1950, incidents of levee failure from foundation or levee instability had doubled. Structural failures are often preceded by a localized partial failure involving 200 to 1,000 feet of levee. Partial failure includes settlement of the levee and the formation of cracks and sinkholes in the landward levee slope.

3. The CDWR inspected non-project levees around 52 islands and tracts, and concluded that the majority of the Delta levees did not meet Corps of Engineers maintenance standards; of the 52, 4 were rated “very poor,”, 28 were rated “poor,” and 20 were rated “fair.” The CDWR identified more than 500 potential problem sites. The CDWR (1982) also examined the problems and feasibility of upgrading 537 miles of non-project levees surrounding 56 islands. The estimated cost for proposed levee-improvement plan implementation was $3.7 billion. Although the CDWR stated that the proposed levee improvement project would substantially reduce the frequency of levee failures, future levee failures are recognized to be inevitable.

4. As outlined in Section 12311 of the California Water Code.

5. *http://www.water.ca.gov/floodsafe/fessro/deltalevees/special_projects/docs/special_guidelines14_final.pdf* (accessed 2016 December 28).

6. Bradford, Bethel, Holland, Hotchkiss, Jersey, Sherman, Twitchell, and Webb islands.

7. *http://deltacouncil.ca.gov/delta-levees-investment-strategy* (accessed 2016 December 28).

8. These figures were based on evaluation of a range of PL 84-99 upgrade costs taken from multiple islands, including Twitchell, Sherman, Bouldin, and King, based on conversations with levee and CDWR engineers.

9. The data cutoff at 1950 was intentionally selected to remove the older historical events during which the levee configurations were dissimilar to the current levees.

10. Hopf (2011) separated out failures that occurred directly on levees designed to fail, on the “height-restricted” levees, and incidents on the smaller (less than 200 hectares) island levees as well as those in the Suisun Marsh and those not designed to protect the agricultural, residential, and other economic activities of the main Delta agricultural islands.

11. Three standards specify minimum freeboard above the 100-year of 300-year flood frequency elevations, crown width, access, and waterside and landslide slope steepness: the short-term HMP, according to Water Code section 12984(a); the PL 84–99 of the U.S. Army Corps of Engineers (1988); and the Bulletin 192–82 standard (CDWR 1982).

12. Exit gradient = $(WLE_{ua} - WLE_{td}) / D$ where WLE_{td} and WLE_{ua} are the water level elevations in toe drain and underlying aquifer, respectively, and D is the vertical distance from the drainage ditch bottom to the bottom elevation of the organic soil.

13. On July 9, 1906: “Flood Conditions are Critical—Twitchell Island is inundated and Venice Island is filling. The levee that keeps the water off of the big Levi tract broke this morning. Unconfirmed report states that Sherman Island is filling with water due to a big levee break. Fears that the cross levee near the Levi tract on the lower division of Roberts Island may break.”

14. The moment magnitude scale denoted as M_W or M) is used by seismologists to measure the size of earthquakes in terms of the energy released. The scale was developed in the 1970s to succeed the 1930s-era Richter magnitude scale (M_L). Even though the formulations are different, the new scale retains a similar continuum of magnitude values to that defined by the older one and is officially used by the USGS (Hanks and Kanamori 1979).

15. Generally, flood barriers are constructed above the crest stage prediction. Capping is usually accomplished with earth fill and plastic.

16. We estimated the 99.9th-percentile stage values for selected stations in the Delta and compared them with nearby levee heights, 100-year stages, and HMP and PL 84–99 elevations. The nearby levee crown elevations (based on the LiDAR data) ranged from 0.19 to 3.4 m above the 99.99th-percentile values. HMP and PL 84–99 elevations ranged from 0.4 to 2.4 m above the 99.99th-percentile values. The lowest differences were associated with the San Joaquin River at Andreas Landing and the San Joaquin River at Venice Island. Stations where there were sufficient data available from CDWR were: Sacramento River at Georgiana Slough; Sacramento River below Georgiana Slough; San Joaquin River at Andreas Landing; San Joaquin River at Venice Island; Mokelumne River at the San Joaquin River; Threemile Slough; and Old River at Bacon Island.

17. Slurry cut-off walls consist of a cement–bentonite soil mix placed in a trench about 1 foot wide from the crown to the base of the levee. The trench extends along the length of the levee.

18. Water Code sections 12311 through 12318.

19. For example, URS Corporation and Jack R. Benjamin and Associates, Inc. (2008) found that on southern Sherman Island, levee materials consisted of dredged loose to medium sand and silt. Beneath the levee is a thick layer of consolidated peat that is underlain by an approximately 25-foot-thick layer of silty clay, under which is a dense sand stratum. In contrast, on nearby western Webb Tract, levee materials consisted of peat, silty–clayey sand, and silt underlain by organic foundational materials that are in turn underlain by loose to dense silty sand and silty clay.

20. *http://www.dwr-lep.com* (accessed 2016 December 28).

21. Electrical resistivity uses current in electrodes driven into the subsurface to measure subsurface resistivity, which can be correlated with lithology. Capacitively-coupled resistivity (CCR) is similar to electrical resistivity, except that resistivity measurements are made by using a set of cables or capacitive plates instead of metal stakes in the ground, as is the case with the EM technology.

22. *http://www.water.ca.gov/levees/evaluation/docs/factsheet-EM-Survey.pdf* (accessed 2016 December 28).

23. Shear-wave velocity is directly proportional to the square root of the shear modulus and inversely proportional to the square root of the bulk density.

24. *http://www.water.ca.gov/floodmgmt/hafoo/fob/dfeprrp/* (accessed 2016 December 28).

25. In lieu of or in combination with an extra-wide levee or an adjacent levee, a planting bench on the waterside levee slope may be installed to provide the appropriate depths and elevations for establishing channel–margin habitat. These benches may be stabilized with riprap (broken rock) covered with a mixture of soil and rocks that can support tidal marsh or riparian vegetation.