Subsidence, Sea Level Rise, and Seismicity in the Sacramento-San Joaquin Delta

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ABSTRACT

Anthropogenic accommodation space, or that space in the Delta that lies below sea level and is filled neither with sediment nor water, serves as a useful measure of the regional consequences of Delta subsidence and sea level rise. Microbial oxidation and compaction of organic-rich soils due to farming activity is the primary cause of Delta subsidence. During the period 1900-2000, subsidence created approximately 2.5 billion cubic meters of anthropogenic accommodation space in the Delta. From 2000-2050, subsidence rates will slow due to depletion of organic material and better land use practices. However, by 2050 the Delta will contain more than 3 billion cubic meters of anthropogenic accommodation space due to continued subsidence and sea level rise. An Accommodation Space Index, which relates subaqueous accommodation space to anthropogenic accommodation space, provides an indicator of past and projected Delta conditions. While subsidence and sea level rise create increasing anthropogenic accommodation space in the Delta, they also lead to a regional increase in the forces that can cause levee failure. Although these forces take many forms, a Levee Force Index can be calculated that is a proxy for the cumulative forces acting on levees. The Levee Force Index increases significantly over the next 50 years demonstrating regional increases in the potential for island flooding. Based on continuing increases in the Levee Force Index and the Accommodation Space Index, and limited support for Delta levee upgrades, there will be a tendency for increases in and impacts of island flooding, with escalating costs for repairs. Additionally, there is a two-in-three chance that 100-year recurrence interval floods or earthquakes will cause catastrophic flooding and significant change in the Delta by 2050. Currently, the California Bay-Delta Authority has no overarching policy that addresses the consequences of, and potential responses to, gradual or abrupt landscape change in the Delta.
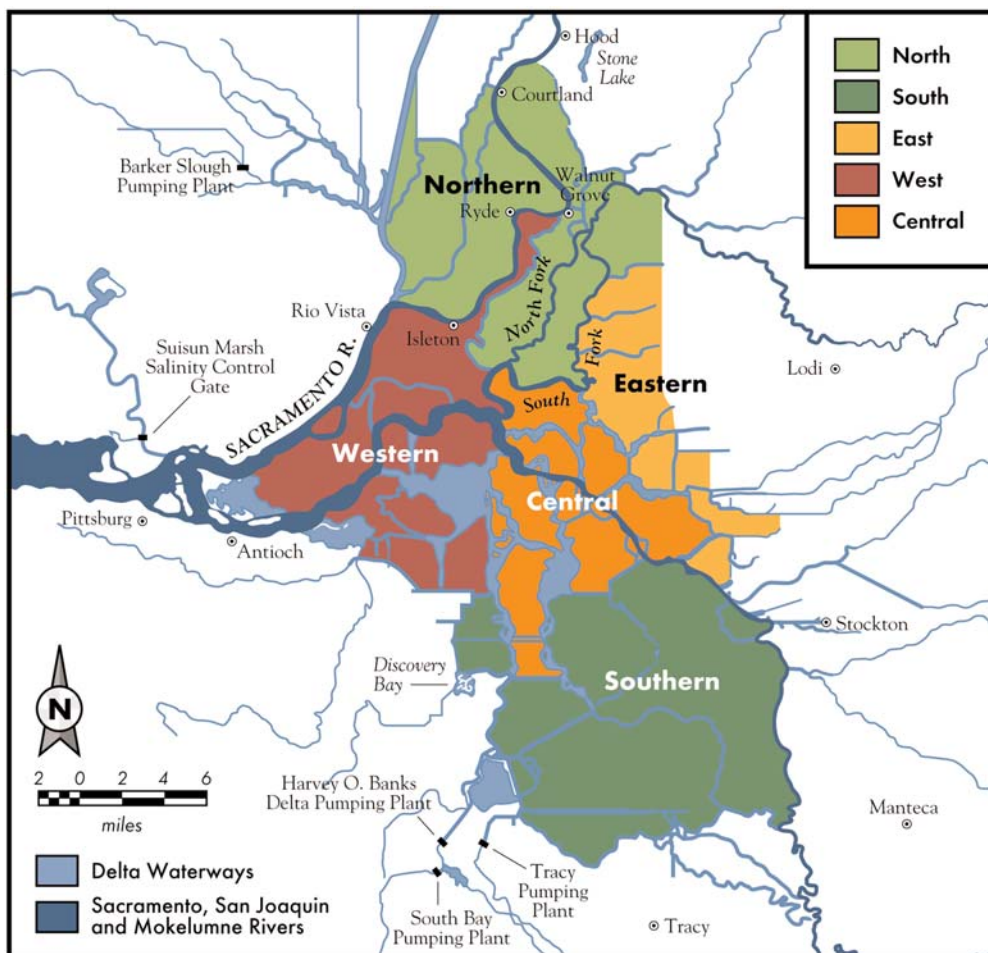
KEYWORDS

SUGGESTED CITATION

INTRODUCTION[1]

The CALFED Bay-Delta Program (CALFED) is an outcome of a 1994 agreement among agencies and environmental and water user stake-holders (the so-called "Delta Accord") that was intended to pro-vide interim environmental guide-lines while CALFED worked with the agencies and stakeholders to develop a long-term solution to environmen-tal and water supply problems in the Sacramento-San Joaquin Delta (Delta). The Delta provides at least a portion of the water supply for about two-thirds of California's pop-ulation, and provides a migratory pathway for four fish that are listed as endangered or threatened pur-suant to the federal Endangered Species Act. Two of the overriding CALFED goals are to maintain the reliability of water supplies from the Delta and to restore the Delta ecosystem and that of its watershed. More information about the CALFED Program can be found at http://calwater.ca.gov/.

Figure 1. Generalized map of subsided portion of the Sacramento-San Joaquin Delta indicating regions discussed in text.

The hydraulic integrity of the Sacramento-San Joaquin Delta is maintained by more than 1700 km of levees, most of which are privately owned and maintained (DWR 1995). Microbial oxida-tion and consolidation of organic-rich soils on Delta islands is causing widespread subsidence (Figure 1), with island elevations in the west and central Delta

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locally more than 8 m below mean sea level (Ingebritsen et al. 2000). Island subsidence has reduced the stability of Delta levees, increasing the risk of failure (DWR 1986, 1989). Embankment and foundation materials for most Delta levees are sub-standard, adding the risk of failure during seismic events (Torres et al. 2000). It is generally acknowl-edged that the current channel network of the Delta and the hydraulic disconnection between islands and surrounding channels is necessary for meeting water quality standards at the south Delta pumping plants that support the Central Valley Project, State Water Project and Contra Costa Water District (NHI 1998; CALFED 2000). CALFED (2000) and the California Department of Water Resources (DWR 1986, 1989, 1995) have noted that failure of the levees and the flooding of subsided islands, particularly during the

spring and summer months, has the potential to significantly degrade Delta water quality by (1) drawing brackish water into the Delta during rapid flooding of Delta islands and (2) changing the dynamics of the tidal prism in the west Delta. Additionally, CALFED's Ecosystem Restoration Program (CALFED 2004) has concluded that subsided islands and deeply flooded islands provide poor quality habitat for native aquatic plant and animal communities, and are generally viewed as undesirable.

With the exception of recognizing the impacts of population growth and increased water demand, federal and state programs that seek to improve water quality, water supply reliability, and ecosystem health in the Delta are predicated upon maintaining the existing levee and channel network. We found no comprehensive CALFED plan or policy that addresses response to gradual or abrupt changes in hydrologic, geomorphic, geotechnical and cultural factors that influence levee integrity. In this report we present low-resolution simulations of potential changes in Delta levee integrity through 2050. These simulations assume business-as-usual approaches to management of the Delta, principally for agriculture. Continued island subsidence, coupled with eustatic rise in sea level, will threaten levee stability significantly by 2050, leading to increased potential for island flooding. Additionally, it is likely that a seismic event or regional flood will impact the levee network of the Delta. Landscape change, whether gradual or abrupt, will affect CALFED programs in the San Francisco Bay, Sacramento-San Joaquin Delta, and the watershed, and should be considered by the California Bay-Delta Authority Independent Science Board.

BACKGROUND

Historic accommodation space

Sediment core analyses indicate that the Sacramento-San Joaquin Delta has been a tidal freshwater marsh, with a network of channels, sloughs and islands, for more than 6,000 years (Shlemon and Begg 1975; Atwater 1982). The persistence of intertidal conditions reflects a dynamic equilibrium between processes that regulated the influx of sediment into the Delta, the

production of organic sediment within the Delta, and the export of sediment to the San Francisco Bay. A preserved stratigraphic record of intertidal conditions indicates that regional tectonic subsidence and sea level rise were sufficient to allow net accumulation of sediment in the Delta during that time (Atwater et al. 1979; Atwater and Belknap 1980; Orr et al. 2003). This record reflects the long-term formation of accommodation space, or space that is available for the accumulation and preservation of deposited sediment. The concept of accommodation space is well-established within the geologic literature and forms the underpinnings of modern concepts of depositional sequence stratigraphy (Emery and Meyers 1996).

In estuarine settings like the Sacramento-San Joaquin Delta, the formation and destruction of accommodation space controls the distribution and character of sediment deposition and related environmental conditions at large scales. For any given interval of time, accommodation space is created by eustatic (global) sea level rise and subsidence of the bed, typically associated with sediment compaction and tectonic subsidence of the crust. The eustatic rise (or fall) of sea level and the rate of subsidence control the rate at which accommodation space is either created or, in the case of falling sea level or crustal uplift, lost. In intertidal systems, accommodation space is filled with water and sediment.

Where rates of organic and inorganic sediment deposition keep pace with accommodation space formation, intertidal conditions persist; where rates of accommodation space formation exceed sediment deposition, there is a landward shift in sedimentary environments (known as transgression) and subtidal conditions expand. In deltaic or estuarine settings, sediment will tend to move through or bypass areas of low available accommodation space (supratidal or high intertidal) and accumulate in areas with higher accommodation space (low intertidal or subtidal). This process, which is governed in part by tidal energy and wind waves, regulates the movement of sediment through estuarine depositional systems and is responsible for large-scale lateral shifts in sedimentary environments (Pethick 1996; Pethick and Crook 2000; Reed 2002a, 2002b).

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Anthropogenic accommodation space

Prior to the conversion of the Delta to farms, the creation of accommodation space was balanced by sedimentation, maintaining persistent tidal marsh conditions. Sedimentation on marsh platforms consisted of sub-equal mixes of inorganic material, derived from the watershed, and locally-derived organic material from highly-productive tule marshes. Beginning in the late 1800s, there were substantial changes in the balance between the creation of accommodation space and sedimentation patterns. In the 1880s the Delta was impacted by a wave of hydraulic mining sediment (Gilbert 1917). Since accommodation space was limited within the Delta, the bulk of this material by-passed the region, eventually accumulating in San Pablo Bay and other portions of the San Francisco Bay (Jaffe et al. 1998). During and immediately following the arrival of the hydraulic mining sediment, widespread reclamation of Delta tule marsh islands began. By 1930, virtually all of the marshes of the Delta had been reclaimed (Thompson 1957). This reclamation involved construction of more than 1700 km of levees and stabilization of the channel network in the configuration much like that seen today.

Farming of the Delta islands required the construction of extensive drainage ditches to lower water tables below crop root zones. Draining tule marsh soils initiated a sustained period of land subsidence that continues today (Prokopovitch 1985; DWR 1995; Ingebritson et al. 2000). Subsidence of Delta histosols is related to their organic content and farming practices (Figure 2). Draining of organic-rich soils leads to compaction and microbial oxidation of organic matter. Deverel et al. (1998) and Deverel and Rojstaczer (1996) demonstrated that gaseous CO_2 flux associated with microbial oxidation accounts for approximately 75% of
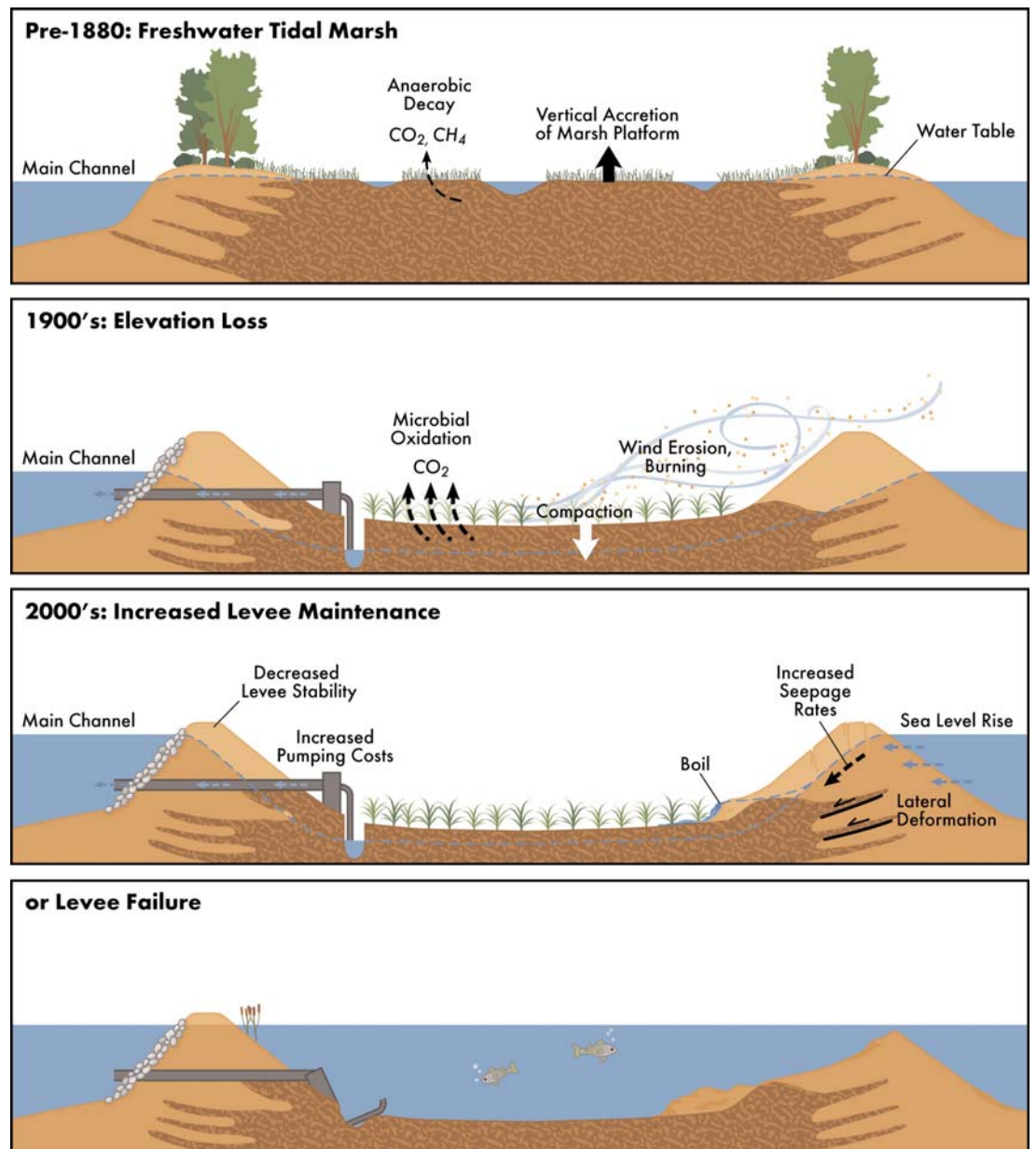
Figure 2. Conceptual diagram illustrating evolution of Delta islands due to levee construction and island subsidence. Modified from Ingebritsen et al. (2000).

current elevation losses, while the remaining 25% is associated with consolidation due to dewatering of the soils and compaction of saturated, underlying soils. Prior to 1950, poor land use practices, including burning of peat soils and wind erosion, exacerbated soil losses due to microbial oxidation (summary in Deverel 1998). Today, the Delta is a mosaic of levee-encased subsided islands with elevations locally reaching more than 8 m below mean sea level.

Subsidence of Delta islands created a new form of accommodation space. This *anthropogenic accommodation space* is distinguished by the fact that it is filled with neither sediment nor water, yet lies below mean sea level. The current levee system imperfectly isolates this space from processes that seek to fill it throughout the Delta. We suggest here that the amount of anthropogenic accommodation space is a 3-dimensional, landscape-scale measure of potential consequence of subsidence within the Delta. When levee breaches occur on deeply-subsided islands, rapid filling draws brackish water into the Delta, temporarily degrading water quality over a large region (DWR 2002). Known colloquially as the "Big Gulp," the water quality impact of island filling is principally a function of the magnitude and location of anthropogenic accommodation space. Island flooding directly affects tidal prism dynamics within the Delta (DWR 2002), with the potential for long-term degradation of water quality. The magnitude of the impact depends upon the location of flooded islands, the volume of water within the island, and the geometry of breach openings.

Levee instability

While regional increases in anthropogenic accommodation space in the Delta increase the consequence of island flooding, there is increase in the concomitant force that acts to destabilize levees and introduce water and sediment into available accommodation space. At the local scale, the processes that cause levee failure are diverse and commonly exacerbated by island subsidence. The increase in head difference between the water surface of the Delta channels and the interior of the islands increases hydrostatic forces on levees and seepage rates through and beneath levees. Depending upon location and magnitude, subsidence increases levee foundation problems by reducing

lateral support and shear resistance, promoting settling or deformation of underlying peat layers (Foote and Sisson 1992; Enright 2004). This leads to lateral spreading, slumping and cracking of levees, which increases the likelihood of their failure due to seepage erosion or overtopping.

Susceptibility of Delta levees to failure is highly variable and, to date, poorly-documented (Torres et al. 2000; CALFED 2004). This variability and poor understanding make it difficult to address precisely the level of risk associated with island subsidence at the landscape scale. However, generalizing over the regional scale, the forces that are acting on Delta levees derive, in some form, from the differences in elevation between the water surface of the channels and the interior of the subsided island. For this reason, hydrostatic force for any length of levee can be used as a proxy for the potential to destabilize that levee. In order to apply this as a landscape-scale measure that can capture regional differences at various scales, hydrostatic force needs to be summed over the length of levees. The potential for levee failure on an island, or group of islands, is therefore a function of the magnitude of subsidence and the length of levee that the hydrostatic forces are acting on. Although not precisely recording the processes that cause levee failures at the local scale, we suggest that *cumulative hydrostatic force* provides a useful landscape-scale measure of levee failure potential in the Delta.

ACCOMMODATION SPACE AND LEVEE FORCE INDICES

To evaluate historic, current and projected landscape changes in the Delta, we developed two indices: the Accommodation Space Index, an index that captures the consequence of island subsidence and flooding, and the Levee Force Index, an index that is a proxy for the potential for levee failure and island flooding.

For any given time the Accommodation Space Index (ASI) is calculated as:

$$ASI = (A_s + A_a)/(A_s) \qquad (1)$$

where A_s = subaqueous accommodation space, or the volume of the Delta that is filled with water and lies

below mean sea level, and A_a = anthropogenic accommodation space, or the subaerial volume of the Delta that lies below mean sea level. Up until the late 1800s, all accommodation space that was generated by sea level rise or regional subsidence in the Delta was filled with water and sediment. Thus, the ASI in the late 1800s, prior to the construction of high levees and the initiation of widespread subsidence, was approximately 1. As discussed below, by the early 1900s island subsidence created rapid increases in anthropogenic accommodation space, dramatically increasing the ASI. This rate of increase in the ASI has been slowed somewhat by the abandonment of some islands within the Delta, such as Franks Tract and Mildred Island, since these flooded islands are counted as subaqueous accommodation space.

The Levee Force Index (LFI), a concept and method suggested by Jack Keller of the CALFED Independent Science Board, records the cumulative hydrostatic force acting on the levees of the Delta, indexed to an estimated force in 1900, immediately prior to widespread subsidence of the Delta. To simplify the calculation of this index, each levee is considered as a wall, with the difference between the average elevation of water in the channel and the average elevation of the adjacent island as the control on the magnitude of hydrostatic force. Based on this simplification, the cumulative hydrostatic force (CF) for an island is represented by

$$CF = P \times A \times L \qquad (2)$$

Where P is average hydrostatic pressure on the island levee, A is area of the unit length of levee (1 m x H), and L is levee length of the island. Since

$$P = 0.5 \rho g H \qquad (3)$$

where ρ is the density of water, g is gravitational acceleration and H is the difference between the average channel water surface elevation and the average elevation of the island, then

$$CF = 0.5 \rho g H^2 L \qquad (4)$$

The cumulative hydrostatic force acting on an island's levee is therefore a function of the square of the depth of subsidence in the island. In contrast to arithmetic increases in accommodation space, hydrostatic forces due to subsidence increase with the square of subsidence depth.

Cumulative hydrostatic force, as defined here, captures two general processes that influence the regional stability of levees. Islands that are deeply subsided are more prone to levee failure due to greater force acting on the levees. Additionally, when coupled with deep subsidence, islands with relatively long levee lengths are more prone to levee failure because hydrostatic forces are acting over a greater levee surface, increasing the likelihood of exposing weaknesses in levee construction, maintenance and foundation.

Based on these calculations, the LFI for the Delta is

$$LFI = CF_t/CF_{1900} \qquad (5)$$

where CF_t and CF_{1900} are the sum of the estimated cumulative hydrostatic force throughout the Delta at time t and 1900, respectively. The two islands that are filled, Mildred Island and Franks Tract, are not counted in these totals since their cumulative force is effectively zero. In addition, islands with mean elevations at or above MSL are not included in this calculation since their LFI = 0.

METHODS

For the purposes of this report, we used a simplified approach for reconstructing historic and projected changes in the ASI and LFI. An elevation model of the Delta was constructed from the Shuttle Radar Topography Mission (SRTM) data obtained from the Global Land Cover Facility (USGS 2004). This dataset was collected in February 2000 at approximately 1:100,000 scale, with reported +/-1 meter vertical resolution and 1 arc-second/30-meter horizontal resolution. Delta island maps were acquired from the Research Program in Environmental Planning and GIS (REGIS), at the University of California, Berkeley, http://www.regis.berkeley.edu/, which digitized the island-forming levees from the DWR Delta Atlas and USGS maps. Zonal statistics for each island were then used to calculate mean island elevations in the year 2000. Based on area/elevation relationships, the average elevation and accommodation space was estimated for each island in year 2000.

It is important to note that the resolution of the SRTM data within the Delta has not been established. Efforts at the Global Land Cover Facility are testing the reso-

lution of SRTM data. We conducted a first-order assessment of the SRTM data through comparison with multiple data sources. Recent, unpublished surveys have been performed on Bacon Island by private consultants (personal communication, Delta Wetlands, December 2004). These surveys re-established historic transects across the island and were used to calculate average elevation losses due to subsidence. Based on these surveys, conducted in the summer of 2000, the average elevation of the island was estimated to be -5.06 m; calculated mean elevation based on SRTM data is -4.82 m. Given the different methods used to estimate average elevation (transect versus zonal statistics) these results are surprisingly comparable. In addition, we compared SRTM data with local high-resolution LIDAR surveys supplied to us by DWR. These surveys covered Staten Island and McCormick-Williamson Tract in the north Delta (flown in February/March 2002). For all datasets we used zonal statistics to calculate average island elevation. The mean difference in average elevation between LIDAR and SRTM data is +0.31 m, with a maximum difference of +0.49 m on Staten Island and a minimum difference of +0.13 m on McCormack-Williamson Tract. This cursory analysis of SRTM data indicates that areal averaging of elevations on islands provides a reasonable method for estimating accommodation space and total subsidence.

To derive the time-averaged subsidence, we made the assumption that the average elevation of the interior of Delta islands prior to reclamation was approximately current mean sea level (MSL). This is based on the distribution of topographic features, including tidal channels and tule marsh, which make up the marsh platform, and the limited change in sea level over the past century. Based on this information, we calculated an average annual subsidence rate for each island for the period 1900-2000. Because detailed information about individual islands is relatively sparse, the year 1900 was chosen as an average year for the initiation of subsidence throughout the Delta, recognizing that subsidence may have begun as early as 1880 on some islands (e.g. Jersey Island) and as late as 1930 on some smaller islands (Thompson 1957).

Rojstaczer and Deverel (1993, 1995), Deverel and Rojstaczer (1996), Deverel et al. (1998) and Deverel

(1998) conducted detailed studies of the rates of subsidence on several Delta islands. Based on field experiments and analysis of historic survey data, they suggest that rates of subsidence have been declining since the 1950s due to improved land use practices and decreasing organic content of island soils. For this reason, projecting average 1900-2000 subsidence rates into the future will result in significant overestimation of future subsidence. To address this issue, we reanalyzed elevational data summarized by Deverel et al. (1998) for Mildred Island, Bacon Island and Lower Jones Tract. Survey transects on these islands were reoccupied 18 times between 1925 and 1981, with average island depth estimated for each survey. We used linear regression analysis to establish average subsidence rates for each island during the survey period. To estimate the decline in subsidence rates associated with better land use practices, we regressed post-1950 island elevations separately (Figure 3). The post-1950 subsidence rates range from 20% to 40% less than the averaged rate of subsidence for the period 1925-1981. To simulate subsidence of Delta islands from 2000-2050, we applied the more conservative rate of 40% reduction in subsidence rates to the calculated 1900-2000 subsidence rates based on the SRTM data.

Future subsidence in the Delta is constrained by the thickness of organic-rich sediments, deposited since the mid-Holocene. Using 500 m grid point data provided by DWR, spline interpolation was used to derive a surface representing the base of the organic-rich sediments. Subsequently, we were able to use this surface in conjunction with subsiding land surface elevations to calculate depth to the base of the peat layer through time. Average interior island subsidence and anthropogenic accommodation space were simulated in annual time steps. Annual subsidence at 40% less than the 1900-2000 average for each island was held constant for each time step until depth of subsidence equaled the depth of organic-rich soils, at which point subsidence ceased for the remaining time steps.

Subaqueous accommodation space and average channel depth were calculated from bathymetry maps supplied by the California Department of Fish and Game (DFG 2004) using ArcGIS 3D Analyst. With the exception of space added by flooding of Franks Tract and Mildred Island, subaqueous accommodation space was

assumed to be constant since the late 1800s. This volume may overestimate the subaqueous accommodation space during the late 1800s and early 1900s, since channel dredging and re-alignment may have increased the total channel volume. With local exceptions, channel depth is typically greater than the elevation difference between the water surface and the average elevation of the subsided island.
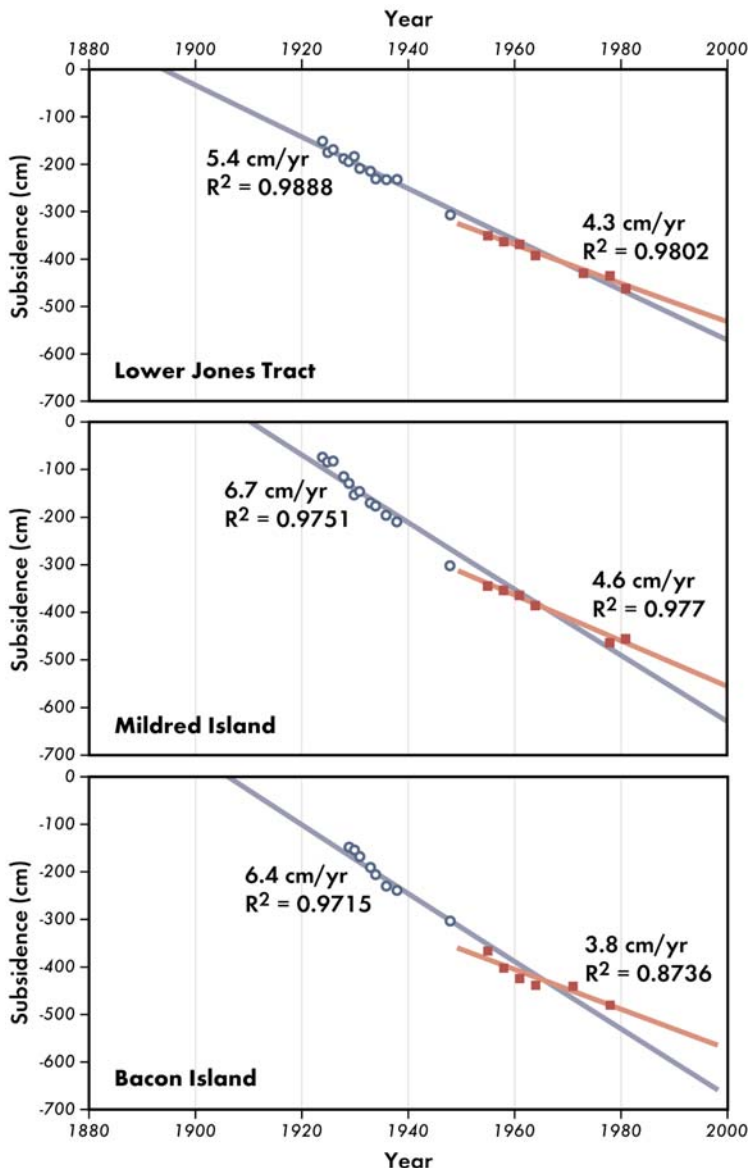
Figure 3. Linear regression of elevation data from three Delta islands to assess changes in rates of subsidence. Blue line depicts best fit for subsidence data from 1925-1981: red line represents post-1950 data. See text for discussion. Data from Deverel (1998; personal communication, S. Deverel, 2004).

Since accommodation space and difference in elevation between the channel and the island is a function of subsidence and sea level change, we adjusted our simulations for sea level rise over the period 2001-2050. Eustatic sea level rise in the latter parts of the 20th century and the present is being driven by a combination of thermal expansion of the oceans due to global warming and increases in ocean mass associated with melting of continental ice. A recent discussion (Miller and Douglas 2004) notes significant disparity among current estimates of sea level rise. Most estimates range from 1.5 to 2.0 mm/yr, based on analysis of historic gage and dynamic ocean height data, to approximately 2.5 mm/yr based on satellite altimetric estimates from the 1990s. We used an average of the range of reported sea level rise values of 2 mm/yr for this study. Modeling efforts summarized by the IPCC (2001) indicate variable rates of projected sea level rise, ranging from as little as 1 mm/year to as much as 5.1 mm/yr by 2050. For the purposes of this simulation, we assumed a conservative linear increase in sea level rise from 2 mm/yr in 2001 to 3 mm/yr in 2050. This reflects an approximate average of six different global climate models (IPCC 2001) and may underestimate total sea level rise.

The results of this modeling effort are summarized in the maps shown in Figure 4, depicting the current elevations within the Delta and simulated elevations in 2050. The 2050 map elevations reflect a systematic lowering of relative inner island elevations by an average rate of subsidence and an increase in sea level.

This simplified approach to estimation of the ASI and LFI makes multiple assumptions that should be taken into account in interpreting the results of this study. First, projections to 2050 assume business-as-usual approaches to management of the Delta. That is, Delta islands will continue to be farmed using current best management practices and levees will continue to be maintained in their current configuration.

Second, this approach does not accurately model anticipated asymptotic declines in rates of subsidence that should occur as the inorganic fraction of some island soils increases over time. For that reason, the estimates of accommodation space given here should be viewed as conservative maxima. However, it is

important to note that if farming continues to be the dominant land use in the Delta, subsidence will continue and accommodation space will increase. There is no known or anticipated technologically feasible method to eliminate or reverse subsidence in land that is being farmed. As the regression analyses of subsidence data from Bacon and Mildred islands and Jones Tract show, improved land use practices have only slowed subsidence rates by 40% or less (Figure 3). Additionally, the impact of increased concentration of inorganic content of the soils appears to only impact subsidence once the organic-matter content of the soils is less than 20% (Deverel 1998). In many central and west Delta islands the organic matter content of the soils is unlikely to reach concentrations below 20% during the next 50 years.

Finally, it is important to note that the methods used here cannot resolve local-scale complexities of historic or projected subsidence in the Delta. Detailed studies by Rojstaczer and Deverel (1995) and Deverel and Rojstaczer (1996), showed order-of-magnitude variation in subsidence within individual islands. Areas near the margins of the islands tend to be organic-poor, recording the influence of natural levee deposition prior to reclamation. Conversely, the center of the islands, which were covered by marsh plain and were most isolated from channel influences, tend to be most organic rich. Differential rates of subsidence occur on every island, with generally less subsidence near the margins and higher
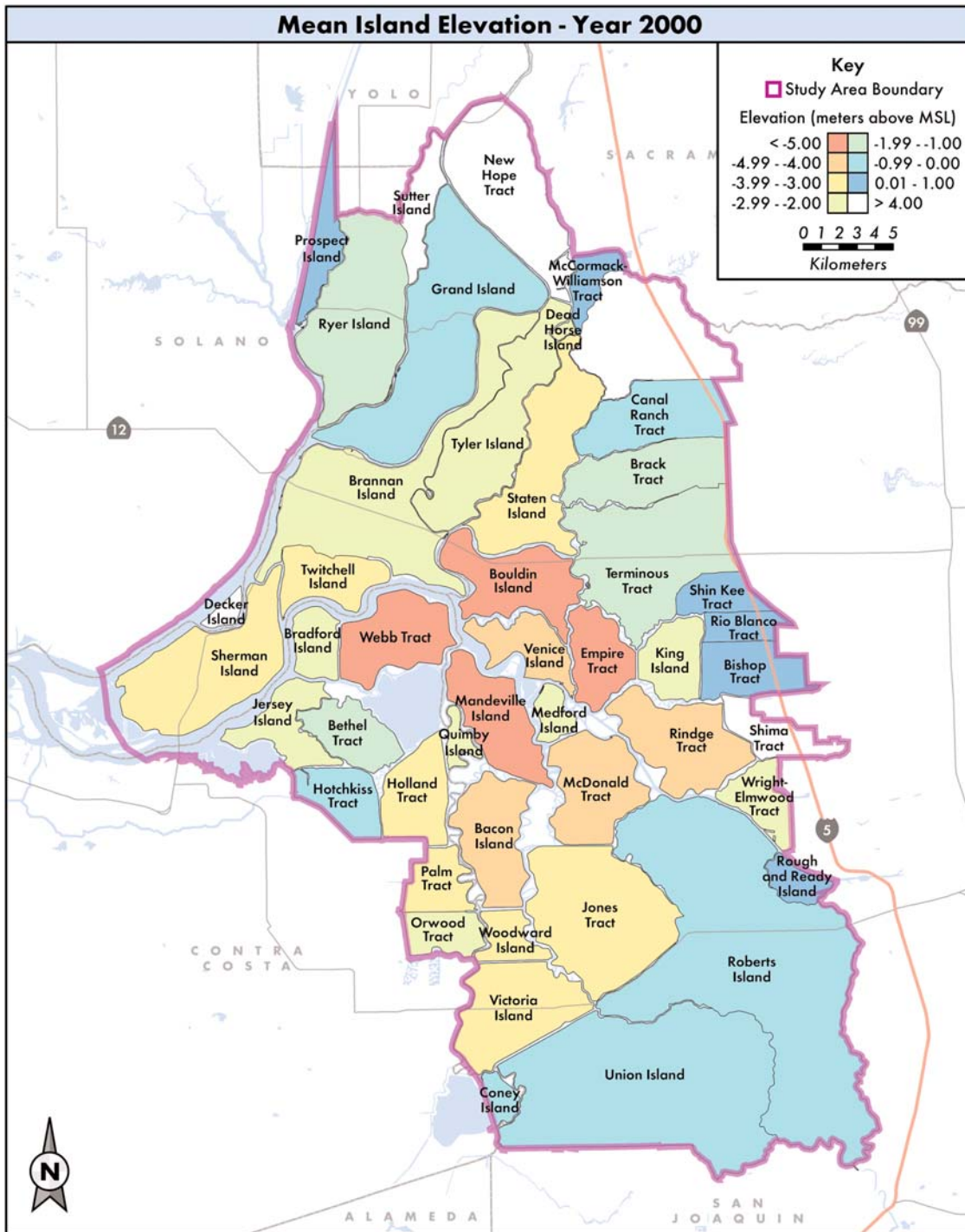

Figure 4A. Calculated average island elevations for 2000. Methods described in text.

subsidence near the center. Acknowledging the limits of resolution of SRTM data described above, the approach taken here averages subsidence for the entire island and should not be used to interpret processes within a specific island. This approach may also overstate the cumulative levee force on some islands since the LFI is based on the average elevation, rather than elevations immediately adjacent to the levee.

Figure 4B. Simulated elevations for 2050. Methods described in text.
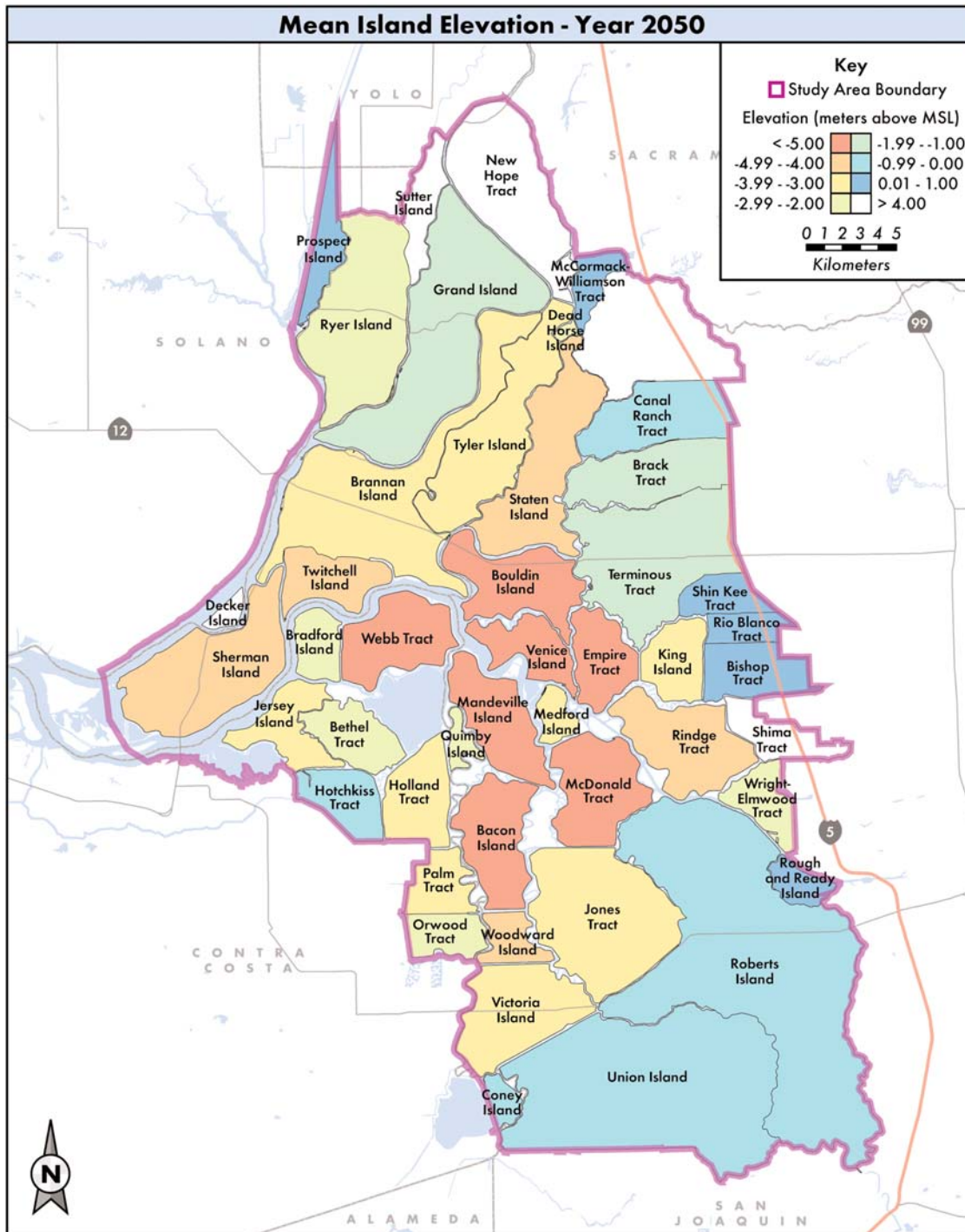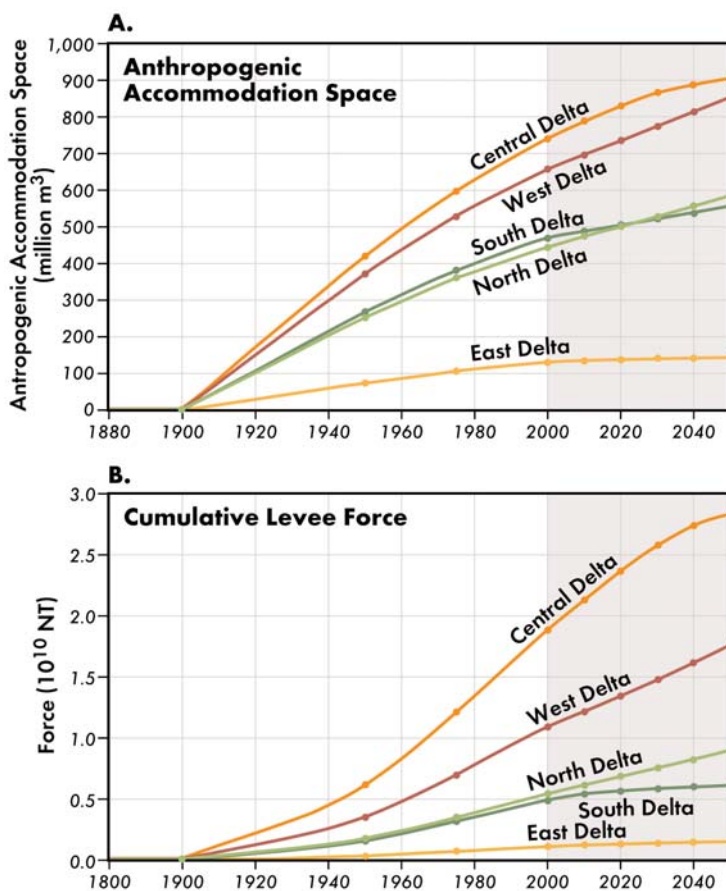
RESULTS

Wherever there are organic-rich soils in the Delta that have been farmed, there has been significant subsidence and the formation of anthropogenic accommodation space. The magnitude of anthropogenic accommodation space generation varies in space and time (Figure 5A). As noted above, rates of subsidence are a function of organic content of the soils and land use practices. The organic-rich soils of the central and west Delta, for example, exhibit the highest historic average rates of subsidence, 3.2 and 4.8 cm/yr respectively. More than half the total 2.5 billion cubic meters of anthropogenic accommodation space formed during the past century occurs in the central and west Delta. Simulations of future accommodation space generation also reflect the distribution and thickness of organic-rich soils. In the east and south Delta, historic subsidence has reduced or eliminated

the organic-rich soils. In these areas, anthropogenic accommodation space formation will be dominated by the effects of eustatic sea level rise, rather than continued subsidence. In contrast, the central and west Delta, which contains thick organic-rich soils, will continue to subside. Although the north Delta retains the thickest organic-rich soils of the Delta, the lower subsidence rate reflects the lower total organic content.

Similar to changes in anthropogenic accommodation space, historic and future cumulative levee force varies substantially in the Delta (Figure 5B). The lowest cumulative levee forces are in the east Delta, where relatively high island elevations and correspondingly smaller levees predominate. The Central Delta dominates cumulative levee force, approximately equaling all other regions of the Delta combined. The dispropor-

tionate cumulative levee force of the Central Delta is a function of both the high regional rates of subsidence and the large levee lengths relative to total island area. Unlike anthropogenic accommodation space, future cumulative levee force in the central, west and north Delta increases substantially in the period 2000-2050.

To establish anthropogenic accommodation space and cumulative levee force for the 1950 and 1975 data points we adjusted individual island subsidence rates for the periods 1900-1950 and 1951-1975 based on an average of relative rate changes noted on Lower Jones Tract and Mildred and Bacon islands, as shown in Figure 3.
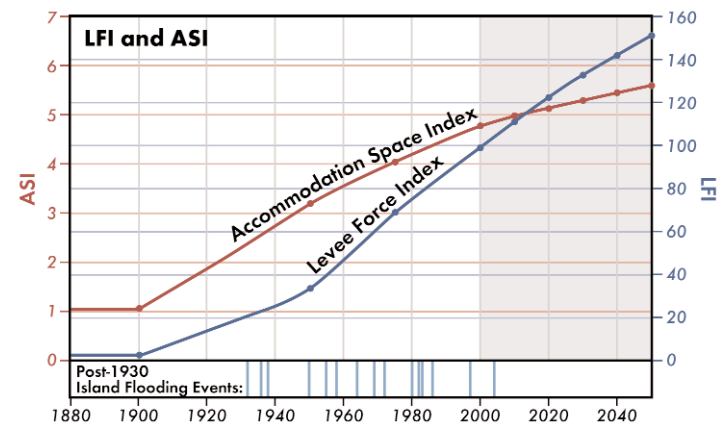
Figure 6. Accommodation Space Index (ASI) and Levee Force Index (LFI) for the subsided portion of the Delta. See text for discussion.

The ASI and the LFI for the Delta are depicted in Figure 6. These indices provide a landscape-scale proxy for current and future consequence of levee failure in the Delta (ASI) and the relative risk of island flooding (LFI). As noted above, these indices are dominated by the impacts of central and west Delta subsidence and, in the case of the LFI, relative levee lengths. Both indices show substantial increases in the future, due to continued subsidence and sea level rise.

LANDSCAPE CHANGE IN CONTEXT

During the past 100 years, farming activity in the Delta has resulted in the loss of approximately 2.5 billion cubic meters of soil—an average of 25 million cubic meters per year. The amount of anthropogenic

Figure 5. Calculated and simulated Anthropogenic Accommodation Space and Cumulative Hydrostatic Force for regions of the Delta shown in Figure 1.

accommodation space generated from subsidence and sea level rise is projected to increase to more than three billion cubic meters in 2050, an annual average of approximately 10 million cubic meters per year. Sea level rise accounts for approximately 30% of the increase in the anthropogenic accommodation space during this period.

It is important to place the amount of anthropogenic accommodation space into historic perspective. The volume of organic-rich sediment that accumulated within the Delta during the mid- to late Holocene can be approximated by summing the volume of anthropogenic accommodation space and the volume of organic-rich soils that underlie the islands. This underestimates the total volume because it does not account for material that underlies the current channel network. Based on this approach, we estimate that approximately 5.1 billion cubic meters of tidal marsh sediment filled accommodation space within the Delta during the past 6000 years. This represents an average annual rate of accumulation of approximately 850,000 cubic meters. During the past 100 years, oxidation, compaction, erosion and burning have reduced the volume of accumulated sediment by almost one half—an annual rate of loss almost 30 times the rate of historic accretion. Over the next 50 years rates of anthropogenic accommodation space generation will decline, but will remain more than an order of magnitude greater than historic rates of accretion, substantially increasing the forces acting on the Delta levee systems.

In his seminal study of the impacts of 19th century hydraulic mining on the Bay-Delta watershed, G.K. Gilbert (1917) estimated that mining introduced 1.2 billion cubic meters of sediment into the Sacramento River system. As noted above, when the hydraulic mining sediment waves entered the Delta in the late 1800s, there was little accommodation space and the material by-passed the Delta. The volume of sediment created by hydraulic mining, considered one of the most destructive land use practices in the history of the Bay-Delta watershed (Mount 1995), is less than half of the volume of accommodation space created by subsidence to date, and approximately one-third of the projected total volume in 2050.

Alternatively, levee and dam construction throughout the Bay-Delta watershed limits the current sediment inputs into the Delta. Wright and Schoellhamer (2004) estimate that approximately 6.6 million metric tons of sediment enter the Delta annually, with 2.2 million metric tons leaving the Delta and 4.4 metric tons deposited within the Delta. Assuming a bulk density of 850 kg/m^3, annual deposition in the Delta is approximately 1.7 million cubic meters. This volume is less than 7% of the rate of historic anthropogenic accommodation space generation and only 17% of future rates. If sea level remained unchanged, subsidence in the Delta were stopped, and current rates of inorganic deposition in the Delta were maintained, it would take 1470 years to restore elevations to mean sea level. However, projected annual accommodation space created by sea level rise alone is roughly twice the amount that could be filled by inorganic sedimentation.

The goal of these comparisons is to illustrate that subsidence and associated anthropogenic accommodation space generation is the dominant landscape-forming process in the Delta during the past 100 years and will remain so for the indefinite future. All CALFED programs that relate to the Delta are being affected in some manner by this process, yet, with the exception of the Levee System Integrity Program (CALFED 2004), no programs appear to fully recognize the potential impacts and implications.

PUNCTUATED LANDSCAPE CHANGE

The above discussion illustrates that the landscapes of the Delta are dynamic, with change occurring incrementally. However, change in the Delta is not limited to gradual shifts. Punctuated, or sudden landscape change has a high probability of occurring within the Delta during the period simulated here, posing a considerable policy challenge for the CBDA and its member agencies. Punctuated change can be derived from two sources: seismicity and extreme flood events.

The levees of the Delta are at significant risk of failure due to seismicity. This stems from poor foundation soils prone to settling or liquefaction, or poor-quality engineering and construction materials (DWR 1995). Although there have been no significant quakes in or closely adjacent to the Delta since high levees were

originally constructed, there are at least five major faults within the vicinity of the Delta capable of generating peak ground acceleration values that would likely lead to levee failures. A preliminary analysis of the risk of levee failure due to seismicity was prepared for the CALFED Levee System Integrity Program (Torres et al. 2000). Based on standard methods and local expertise, Torres et al. (2000) estimated the magnitude and recurrence intervals of peak ground accelerations throughout the Delta. Two competing fault models were evaluated for this study, producing a wide range of potential accelerations. Then, based on local knowledge and limited geotechnical information, Damage Potential Zones were established for the Delta (Figure 7). The zones of highest risk lie in the central and west Delta where tall levees are constructed on unstable soils that are at high risk of settling or liquefaction during an earthquake. This also coincides with areas of the Delta that have the highest cumulative hydrostatic force and anthropogenic accommodation space.

Torres et al. (2000) estimated recurrence intervals for ground accelerations and the number of potential levee failures in each Damage Potential Zone. It is useful to examine their estimates of the number of failures that might occur during a 100-year event, or an event with a 0.01 probability of being equaled or exceeded in any given year (Figure 8). As in any probabilistic analysis of this sort, the range of potential responses to this kind of earthquake are broad and difficult to predict with precision. Based on their estimates, it is a roughly 50-50 chance that 5 to 20 levee segments (equal to one standard deviation around a mean of seven) will fail during a 100-year event in the Delta. This does not imply that 5 to 20 islands will flood, but just that 5 to 20 levee segments will fail. The loss of 5 to 20 levee segments in the Delta con-
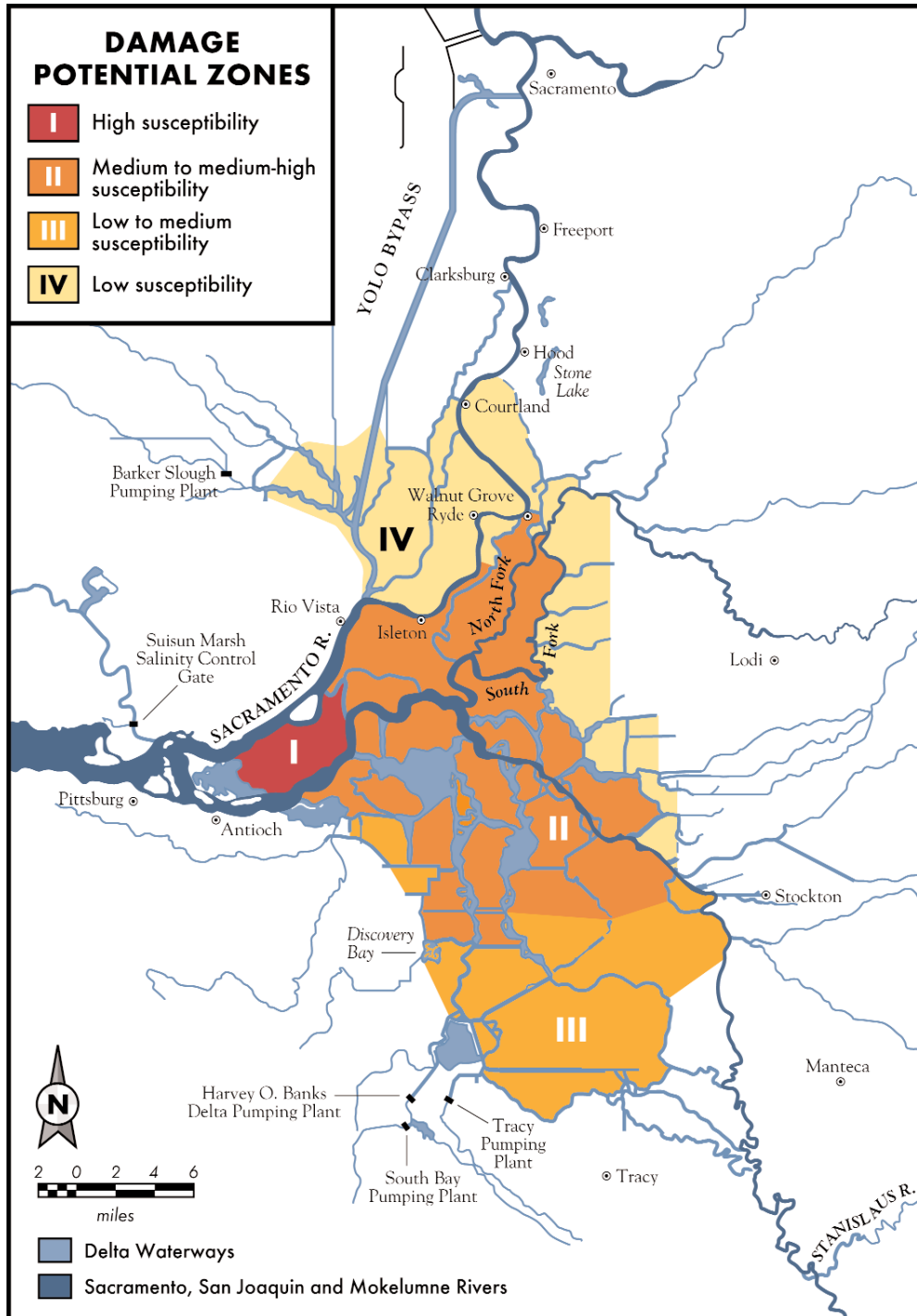
Figure 7. Zones of varying potential damage due to seismically-induced liquefaction and levee collapse. Modified from Torres et al. (2000).
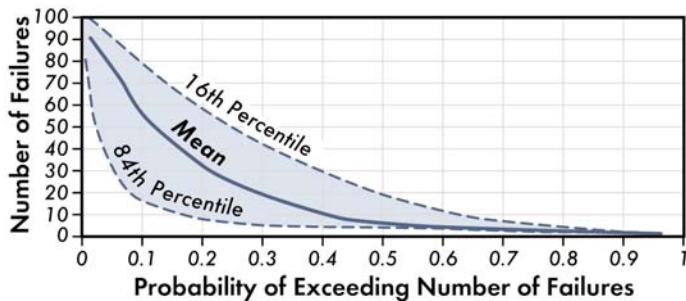
Figure 8. Figure 8. Probabilities of number of levee failures expected in 100-year recurrence interval event impacting Delta. Modified from Torres (2000).

stitutes considerable and abrupt landscape change, since island flooding is likely to be widespread and, as discussed below, persistent for a long period of time.

The high likelihood of abrupt change during seismic events is compounded by the potential for change during and immediately following major winter runoff events. Following the 1986 flood event, the State legislature developed target elevations and cross sections for levees throughout the Delta. Under Senate Bill 34, the State established the Subventions Program to support maintenance and levee upgrades. Under this program, the elevation of the levee crowns were to be upgraded to one foot above the U.S. Army Corps of Engineers' estimated 100-year flood stage (DWR 1995). Although this target elevation is tied to the 100-year flood stage, it does not imply that there is 100-year flood protection for Delta levees. There is insufficient freeboard or levee cross section to withstand sustained flows of this stage. The National Flood Insurance Program maps of the Delta reflect this vulnerability, indicating that all the major islands have less than 100-year flood protection. It is reasonable to assume, therefore, that a flood of 100-year recurrence interval will produce substantial, widespread, and as discussed below, possibly permanent flooding of islands in the Delta comparable to that associated with seismic events.

The risk of abrupt change in the Delta during the 50-year simulation period can be evaluated probabilistically using standard methods (review in Mount 1995). In any year, the probability that a flood with a 100-year recurrence interval will occur is 0.01. However, the probability that such a 100-year event will occur sometime in the next 50 years is 0.40, or a two-in-five

chance. Since either a 100-year flood or 100-year seismic event can produce significant change in the Delta, it is more appropriate to estimate the probability that either event would occur in the 50-year time interval. When evaluated this way, the odds of either event occurring is 0.64: a roughly two-in-three chance. This discussion is meant to highlight the fact that punctuated landscape change in the Delta is not a remote, hypothetical possibility, but is highly likely during the simulated period of 50 years. This is especially pertinent to the risk of seismicity where continued accumulation of strain on local fault zones may increase the risk of an earthquake with time.

DISCUSSION: FUTURE TENDENCIES

The approach used here to assess historic and projected changes in the Delta does not offer the resolution necessary for island-by-island assessments or prediction of future levee failure. Thus, this paper is not intended to be used as a planning tool. Rather, this approach offers a landscape-scale assessment of processes that are increasing the overall consequences of, and potential for island flooding in the Delta over the next 50 years. However, given the relative magnitude of increases in the ASI and LFI and the high probability of seismic or flood events that will result in levee failure, it is reasonable to assume that there will be an increasing tendency for island flooding events, with the consequences of any flooding event also increasing.

Local island flooding events are a relatively common occurrence in the Delta (Figure 5). Since the 1930s there have been more than 15 such flooding events (DWR 1995). Several State and federal programs, including the Subventions and Special Projects Programs (DWR) and the Base Level Protection and Special Improvements Programs (ACOE) have improved maintenance of many private levees within the Delta and have upgraded multiple at-risk levee segments. Although improvements have been made within the Delta and reduced the risk of flooding, the current level of risk is largely unknown. Levee programs are focused principally on maintaining current levels of protection, set in 1986, rather than assessing and planning for future conditions. The Levee System Integrity Program Plan (CALFED 2000) notes that

885 km of levees will require upgrading to meet Federal PL 84-99 standards at a cost of more than $1 billion in today's dollars. Recently signed federal legislation authorizing the CALFED Bay-Delta Program includes $90 million for levee projects in the Delta for the next five years. However, this represents less than 10% of the current backlog and is unlikely to address future needs. Levee upgrades to meet existing standards typically cost $1.0 to 1.7 million/km, with costs rising to near $3.4 million/km where extensive reconstruction is required (DWR staff, personal communication, 2004). Given the high costs and historic trends in funding, the Delta levee system, which is already well behind in maintenance, repairs and upgrades, will continue to fall behind under future, business-as-usual landscape change scenarios.

Although maintenance and upgrade of levees represents a significant, on-going cost in the Delta, island flooding events have the potential to dramatically impact local and government resources. The June 3, 2004, flooding of Jones Tract in the south Delta created substantial costs for repair, flood fighting, emergency services, and island pumping. According to DWR staff, costs to government alone for this break exceeded $44 million. This does not account for crop losses, job losses, farm infrastructure repair or carriage water releases to maintain water quality. Estimates of total costs of the Jones Tract failure reported in the *Sacramento Bee* and *Contra Costa Times* approach $90 million (quoted from California Office of Emergency Services sources): a figure equal to the total amount allocated for levees in the 2004 federal authorization of CALFED.

Limited funding for levee maintenance and upgrades, high costs of emergency levee repairs, and projected increasing instability of the Delta indicate that local island flooding will impact the Delta significantly during the next 50 years. Climate change and changes in runoff conditions (which are, for the most part, beyond the scope of this report) may exacerbate these conditions. There are multiple potential policy responses to this projected trend. However, to date, there has been no comprehensive assessment of the effects of increased island flooding on CALFED programs. Rather, current policies appear to be predicated upon the unlikely prospect of maintaining fixed hydraulic conditions.

The impact of regional flooding associated with seismic events or large floods poses an additional challenge to CALFED programs. These events have the capability to significantly and permanently change conditions within the Delta over a very short period of time. To illustrate, currently there is one contractor, Dutra Corporation, with the equipment necessary for repairing levee breaks in the Delta. According to DWR staff, this contractor is capable of restoring two to three levee breaches in a single season. If regional island flooding results in numerous levee breaches, it is unlikely that levee integrity can be restored for many years, with protracted disruption of water supply and loss of farm income. Moreover, if a seismic event leads to levee failures in the Delta, it is likely to be associated with significant damage to infrastructure in the San Francisco Bay Area, creating competition for resources necessary for restoring levee integrity.

To our knowledge, the California Bay-Delta Authority and its member agencies have not articulated a policy regarding regional flooding in the Delta and the possibility of permanent, abrupt change. It is important to note, however, that the Levee System Integrity Program has initiated a comprehensive, multi-year study of the risks due to seismicity in the Delta (CALFED 2003). This program, which is being run by DWR, is in its nascent stage, but will address some of the key issues raised here and provide more precision on estimates of risk.

CONCLUSIONS

The results of the simulations conducted for this report indicate that microbial oxidation and compaction of organic-rich soils in the Delta have led to significant regional subsidence in the Delta. Although slowing substantially, subsidence is likely to continue into the indefinite future, particularly in the central and west Delta. When coupled with rising sea level over the next 50 years, continued subsidence will magnify the instability of the Delta levee network, leading to increased potential for and consequence of island flooding. Additionally, there is significant likelihood of regional flooding in the Delta during the next 50 years due to earthquake-induced levee failures or sustained large floods. These events are likely to result in dramatic change in the Delta.

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The implication of future Delta landscape change is, at present, largely unknown and speculative. Outside of initial efforts by the Levee System Integrity Program, there are no systematic assessments of risk to CALFED program elements. There have been efforts to assess methods of subsidence reversal in the Delta, but these have been stalled by on-going contract issues at DWR. In our view, there is no comprehensive scientific effort to address this issue and to provide the necessary information to inform policymakers.

ACKNOWLEDGMENTS

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