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Delta Subsidence Reversal, Levee Failure, and Aquatic Habitat—A Cautionary Tale

Matthew E. Bates[1, 2,†] **and Jay R. Lund**[1]

ABSTRACT

Various schemes are often suggested to reverse the subsidence of lands below sea level in California's Sacramento–San Joaquin Delta, an area protected by levees (dikes) that have significant probabilities of failure. Elementary modeling is used to estimate the probability distribution of land elevations at time of failure for 36 of these subsided islands, assuming a reasonable potential subsidence reversal rate. Given estimated annual probabilities of levee failure, elevation gains at this rate are not expected to exceed 1 to 2 m before flooding, which would be insufficient to restore most subsided islands to mean sea level (msl). However, under some circumstances 1- to 2-m gains are significant. A framework is introduced for evaluating islands as promising candidates for subsidence reversal based on elevation goals other than msl, as demonstrated though a hypothetical aquatic habitat example. Here, we recommend relevant subsidence reversal strategies by comparing an elevation goal with each island's anticipated flooded depth, and we prioritize islands for investment based on trade-offs between anticipated outcome and lost agricultural revenues. This approach might help integrate subsidence-reversal activities into long-term Delta planning under a range of flooding, land use, and habitat management scenarios.

KEYWORDS

Subsidence reversal, levee failure, Sacramento–San Joaquin Delta, flooded islands, aquatic habitat, agricultural revenue.

INTRODUCTION

Like many coastal and inland lowlands, California's Sacramento–San Joaquin Delta (Delta) is an often unstable landscape whose fate is commonly debated. Far from the dynamic tidal estuary of pre-European times, today's Delta is a fixed system of islands and levees (dikes) built by various groups and individuals, adhering to no uniform standard (Thompson 1957; Jackson and Paterson 1977; Hundley 2001; Lund and others 2010). Though levee dependability is crucial for local agriculture, local flood protection, and statewide water supply, the possibility of levee failure is ever-present (Matthew 1931; Houston and Duncan 1978; Duncan and Houston 1983; Finch 1985;

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Prokopovich 1985; CDWR 1995; Kelly 1998; Torres and others 2000; USGS 2003; URS and J.R. Benjamin & Assoc. 2009a).

Unplanned levee breaches are costly, with dewatering and repair costs ranging from $43 million to $240 million per island (URS and J.R. Benjamin & Assoc. 2009a), yet frequently occur (Florsheim and Dettinger 2007)—approximately 160 Delta levees breached and flooded during the 1900s (URS and J.R. Benjamin & Assoc. 2009c). If breached islands are sufficiently subsided, repair is often uneconomical (Weir 1950; Logan 1989, 1990a, 1990b; Suddeth and others 2008, 2010). Flooded islands such as Clifton Court Tract (1907), Lower Sherman Island (1925), Big Break (1927), Donlon Island (1937), Franks Tract (1938), Mildred Island (1983), Little Franks Tract (1983), Little Mandeville Island (1994), and Liberty Island (1998), were abandoned completely when their owners faced repair costs that exceeded land values (CALFED 1998; URS and J.R. Benjamin & Assoc. 2009c). Furthermore, rates of levee failure persist (Florsheim and Dettinger 2007), and continued island subsidence and sea level rise, increasing seismic tension, and the effects of climate change are expected to increase the frequency and consequences of levee failure (URS and J.R. Benjamin & Assoc. 2009a; Lund and others 2010). Annual risks of levee failure have recently been calculated for most islands in the Delta (URS and J.R. Benjamin & Assoc. 2009a).

Land subsidence worsens the consequences of island failure, and is primarily caused by the aerobic microbial oxidization of soil carbon, and the shrinking and compaction of peat soils drained of their natural water content. Other factors—including the historical burning of peat to remove weeds and pests and to prepare the soil for planting, wind erosion, compaction from heavy farm equipment, and the general geologic subsidence of the area—also are relevant (Weir 1950; Broadbent 1960; Atwater and others 1977; Prokopovich 1985; Rojstaczer and others 1991; Rojstaczer and Deverel 1995; Ingebritsen and others 1999; Drexler and others 2009b). Farming and other soil disturbances continue to transfer Delta topsoil into the atmosphere, leaving island elevations farther below mean sea level (msl) (Mount and Twiss 2005; Deverel and Rojstaczer 1996; Drexler and others 2009b). Changes in land use or shallow flooding can halt subsidence from soil oxidation and compaction (Tate 1979; Ingebritsen and others 1999). Island subsidence can be reversed through land-management practices that foster the accumulation of sediments and organic material (e.g., Miller and others 2008).

Natural subsidence reversal (accretion) often occurs in marshes and wetlands as mild flow rates and vegetation encourage sediments and plant litter to collect. Thick layers of organic soils, like those found throughout the Delta, form when these deposits accumulate faster than they decompose (Gorham 1957; Boelter and Verry 1977). Many studies have analyzed natural accretion under various settings, finding elevation-gain rates that range from a few millimeters to a few centimeters per year, depending on location and management (e.g., Patrick and DeLaune 1990; Callaway and others 1996; Goman and Wells 2000; Lane and others 2006; Drexler and others 2009a; Deverel and Leighton 2010). In engineered subsidence reversal, the natural accretion of organic matter and sediments is expedited in protected and managed marshes (Ingebritsen and others 1999; Miller and others 2008). Earth-moving, controlled levee breaches, deposition of dredged sediments, and similar techniques may also be plausible for raising elevations or augmenting natural accretion (Ford and others 1999; Ingebritsen and others 1999; Ray 2007).

Subsidence reversal has implications for aquatic habitat. Much of the Sacramento–San Joaquin Delta is now inhabited primarily by non-native aquatic plants and animals, which complicates Delta management. Limiting and mitigating the effects of non-native plant species has become a major concern for Delta ecologists (e.g., Moyle and others 2010) and the California Department of Boating and Waterways (2001), which has a legislative directive to manage specific aquatic weeds in the Delta. Even if subsidence reversal cannot restore islands to mean sea level, it may be suitable for tailoring flooded-island habitats that favor or discourage particular native or invasive species. Other purposes (e.g., recreation, water quality) also may benefit from depth-dependent, subsidence-reversal activities.

This study examines subsidence reversal's potential role in the Delta by (1) modeling each island's expected elevation over time with a reasonable subsidence-reversal rate and probability of levee failure, (2) estimating the likely extent that subsidence reversal can restore Delta islands to mean sea level before flooding, and (3) introducing a framework for evaluating expected outcomes in terms of elevations other than mean sea level. This approach is demonstrated through a hypothetical application to avoid depths dominated by a submerged invasive waterweed. Islands are then ranked based on cost and probability of achieving this outcome. The results are analyzed for sensitivity to alternative subsidence reversal rates. In modeling subsidence reversal, we examine ambitious engineering projects with rates of elevation gain that surpass natural accretion and sedimentation. The most promising methods will be those that produce the greatest elevation gains with lower costs, and without excessive social or ecological harm.

METHODS

By combining initial island elevations with a generalized subsidence reversal rate, we project plausible changes in elevation for 36 Delta islands over time. These elevation gains, when associated with island-specific probabilities of levee failure, produce a probability distribution of mean elevations at time of failure for the subsided islands. In addition to analytical elevation and probability evaluations, we simulate 10,000 Monte Carlo scenarios of Delta flooding to show the potential variability in flooding. Expecting applied subsidence reversal to be used to achieve specific elevation goals, we demonstrate analysis with a land-elevation criterion below mean sea level (msl). This section describes the data sources and methods.

Probabilities of Failure

Current annual probabilities of levee failure have been estimated for most Delta islands as part of the Delta Risk Management Strategy (DRMS) study commissioned by the California Department of Water Resources (CDWR). These failure probabilities include the effects of earthquakes, floods, and other causes (URS and J.R. Benjamin & Assoc. 2009a), with the methods, models, assumptions, and background data for these calculations described by URS and J.R. Benjamin & Assoc. (2008). For the 36 subsided islands considered here, the annual probabilities of failure range from 1% to 10% annually, with a mean of 5% (Figure 1; URS and J.R. Benjamin & Assoc. 2009a). The failure probabilities reflect a longstanding literature on the weakness of island levees in the Sacramento–San Joaquin Delta (Houston and Duncan 1978; Duncan and Houston 1983; Finch 1985; Kelly 1998; Torres and others 2000; URS and J.R. Benjamin & Assoc. 2009a).

To simplify, the annual probabilities of island failure are assumed constant over time. While small increases in elevation might somewhat reduce the hydraulic pressure gradient contributing to the risk of levee failure, these risk reductions are likely to be countered or exceeded by increasing risks from other factors. Growing seismic tension, sea level rise, and increased winter flooding from climate change are anticipated to increase the 2005-year probabilities over time (URS and J.R. Benjamin & Assoc. 2009b).

Initial Island Elevations and Land Areas

Initial island elevations form a boundary condition for modeling subsidence reversal. Though Delta island elevations vary internally, this study uses average elevations for 36 subsided Delta islands (Figures 1 and 2) as the starting point for subsidence reversal calculations. These data, from Mount and Twiss (2005), are derived from a high-resolution geospatial database the Shuttle Radar Topography Mission generated in February 2000. Mount and Twiss combined these raw topographic data with digitized Delta maps from the CDWR

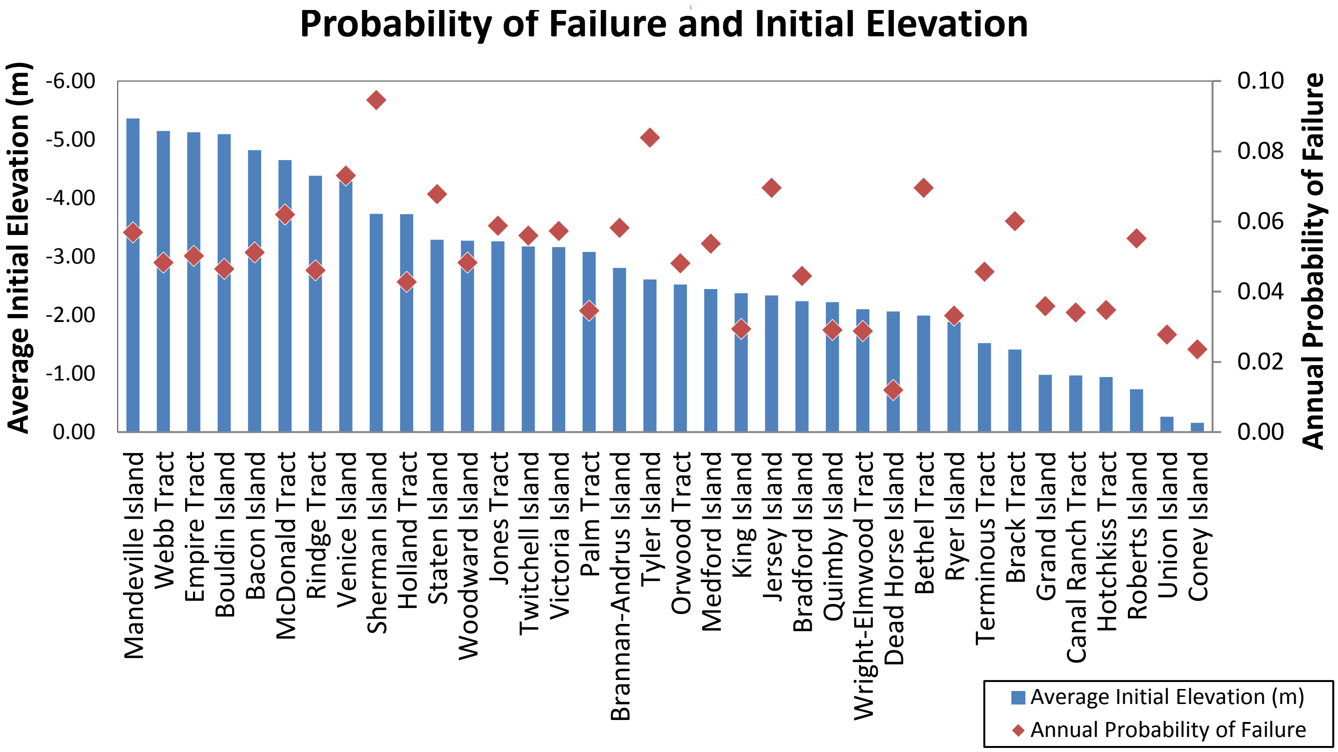

Figure 1 Independent annual probabilities of levee failure and average elevations relative to mean sea level for modeled Sacramento–San Joaquin Delta islands (probability data from URS 2009a; elevation data from Mount and Twiss 2005).

Delta Atlas (1995), which provides island areas, and used geographical information system (GIS) zonal statistics to calculate the mean elevation of each island. The resulting values compare well with previous efforts to assess mean elevations for individual islands, with average island elevations in the year 2000 found to range from 0.16 m to 5.36 m below msl (Figure 1), and with a Delta-wide average elevation estimated at 2.8 m below msl (Mount and Twiss 2005).

Subsidence Reversal Rate

Many examples of natural accretion exist for the Delta and surrounding waters (e.g., Patrick and DeLaune 1990; Gorman and Wells 2000; Drexler and others 2009a), though the greatest sedimentation rates are estimated by Miller and others (2008) for subsidence reversal in engineered Delta marshes. In that study on Twitchell Island, in the western Delta, two deeply subsided plots were shallowly flooded and managed to create permanently impounded ponds. The ponds were planted with tules and became densely vegetated as cattails and other marsh vegetation grew quickly within a few seasons (vegetation was densest in the shallower pond). By accumulating organic material, and to a lesser extent mineral sediments, local elevations increased by –0.5 to +9.2 cm yr^{-1} from 1997 to 2006. The average elevation gain for the entire area was 4 cm yr^{-1} (Miller and others 2008).

The Twitchell Island study results are empirical and include many feedback mechanisms and effects expected for large-scale subsidence-reversal projects, so these observed rates are not anticipated to differ significantly with scale-up. In this study, we assume that an average subsidence reversal gain of 4 cm yr^{-1} is possible for all 36 modeled islands. We expect some variation in reversal rate within and

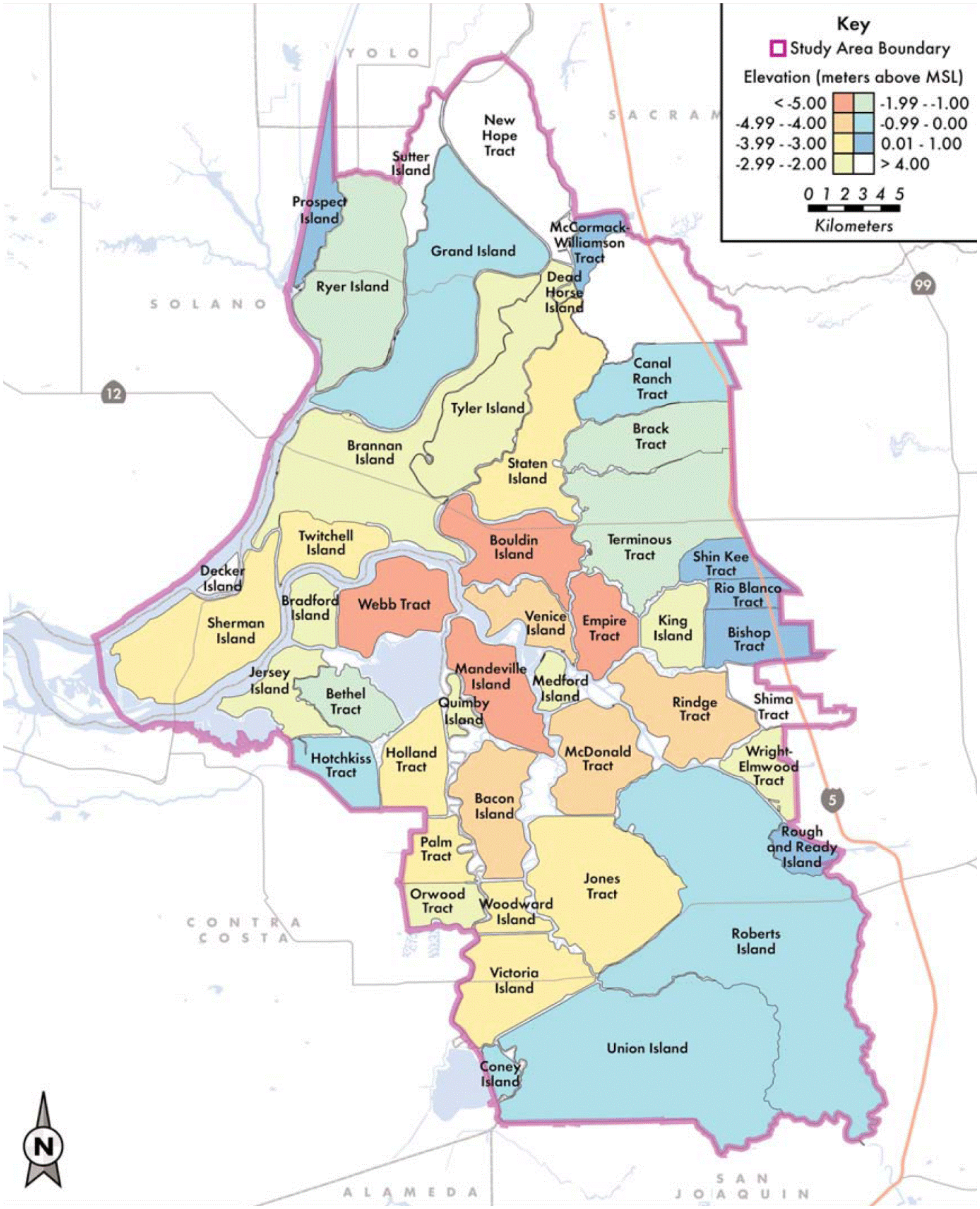

Figure 2 Map of average island elevations throughout the Sacramento–San Joaquin Delta. Source: Mount and Twiss 2005.

between islands, and we examine the sensitivity of ultimate elevation to reversal rate for alternative rates from 2.5 to 36.0 cm yr^{-1}.

Island Agricultural Revenues

Agricultural revenues would be largely lost with development of large-scale subsidence-reversal wetlands. We examine per-acre annual agricultural revenues for islands throughout the Delta with the Delta Agricultural Production (DAP) model, based on typical cropping patterns and growth conditions from recent years (Lund and others 2007). The economic value of agriculture throughout the Delta is non-uniform, with the least profitable islands tending to be in the most subsided parts of the Delta (Figure 3).

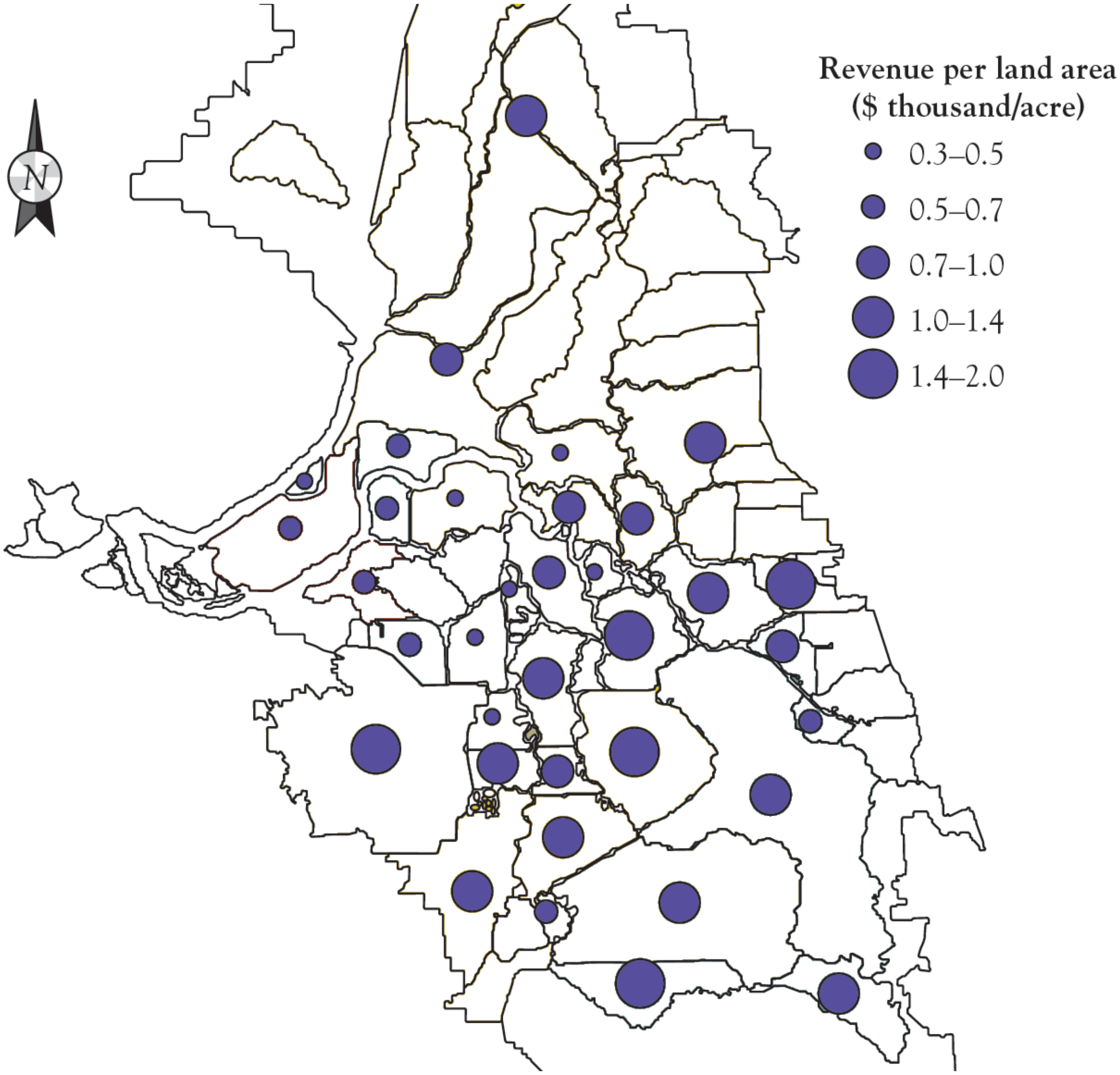

Figure 3 Estimated average per-acre island agricultural revenues throughout the Sacramento–San Joaquin Delta. Source: modified from Lund and others 2007 to show only revenues.

Modeling Probability of Failure

According to elementary probability theory (e.g., Mays 2005; Soong 2004), if P_a is the annual probability of levee failure, then $(1 - P_a)$ is the annual probability of no levee failure. If P_a is independent over time, $(1 - P_a)^t$ is the chance of no levee failure occurring for t consecutive years. The complement of this value, $1 - (1 - P_a)^t$, is the chance of having one or more levee failures in t years. Thus, to model levee failure over time, P_f, the cumulative probability of levee failure in each year t, is defined by:

$$P_f = 1 - (1 - P_a)^t \tag{1}$$

Equation 1 is used to estimate the likelihood of levee failure for each island over the next 100 years.

Modeling Elevation Gain

In estimating the expected elevation of each Delta island over time, subsidence-reversal activities increase land elevation each year by the subsidence-reversal rate:

$$E_t = E_o + t \times r \tag{2}$$

where E_t is the subsided depth of the island in year t, E_o is the initial island elevation, t is the number of years since subsidence reversal was initiated, and r is the estimated annual elevation gain. Equation 2 is used to estimate the elevation of each island over the next 100 years. Together, Equations 1 and 2 show the probability distribution of mean elevations at time of failure for each island.

Simulating Delta Levee Failure

Monte Carlo simulations of Delta levee failure illustrate how the future of the western and central Delta (where subsidence and likelihoods of levee failure are highest) seems likely to evolve. Equations 1 and 2 simultaneously calculate the cumulative probability of levee failure (P_f) and the expected elevation (E_t) for each island in each year. When an island's elevation reaches zero meters msl, we assume it no longer floods permanently. A random number with a uniform distribution, R, representing the unique environmental conditions contributing to the risk of flooding, is generated for each island in each year for each of 10,000 simulations. In each simulation, the first year in which a yet-unflooded island's increasing probability of levee failure equals or surpasses that year's R value is considered to be that island's year of flooding (Equation 3):

$$\text{If } P_f \geq R \text{ and } E_t < 0\text{, then island floods,} \\ \text{else island does not flood.} \tag{3}$$

Criteria-based Analysis

Ideally, subsidence reversal would continue until each island's elevation returned to mean sea level. If preferences exist for sub-msl elevations, subsidence reversal can also encourage island flooding at more desirable elevations. For example, flooded elevation could contribute to different types of aquatic vegetation, fish, or recreational activities being intentionally managed (Moyle 2008). The rationale for desiring particular elevations can be complex, involving local hydrodynamics, societal influences and the habitat preferences of various plants and animals, but it seems reasonable that ranges of more desirable elevations exist by which subsidence-reversal projects can be preferentially ranked (Kiker and others 2005). Actual determination of these ranges will require further study and debate, and depend on legal conditions and the preferences of project funders (Suddeth 2011), which is beyond the scope of this analysis. In this present investigation, we use a plausible desirable elevation range to highlight the types of analyses and evaluations relevant for subsidence-reversal projections, and illustrate some challenges and difficulties for widespread subsidence-reversal activities.

Here, subsidence reversal is proposed to help restore specific ecological functions. In this example, an aggressive species of submerged invasive waterweed (e.g., *Egeria densa*) is specifically targeted for management via subsidence reversal. The invasive weed is presumed to prefer and dominate native growth in elevations from roughly 1.5 to 4.6 m (5 to 15 ft) below mean sea level. Islands flooding above this range are presumed dominated by native cattails and tules, especially if intentionally managed, and more deeply subsided islands flooding below –4.6 m msl are presumed to avoid further invasion. Subsidence-reversal projects will be considered successful if they move islands into the elevation range where native plants can compete, even if islands cannot reach mean sea level. Secondarily, subsidence-reversal activities that reduce an island's flooded volume without encouraging further invasive growth are preferred to no action. Subsidence reversal also incurs costs for management and from lost agricultural revenues.

RESULTS AND DISCUSSION

Delta Flooding Projections and Simulations

The estimated elevation of each island over a 100-year period is projected with Equation 2, with a uniform subsidence-reversal rate of 4 cm yr^{-1}. The results (Table 1, first 75 years shown), depict each island moving from deep elevations (below –4.6 m msl, blue) through the middle elevations (–4.6 to –1.5 m msl, orange, corresponding to the example undesired range), and into more shallow waters (–1.5 to 0 m msl, green, corresponding to the example goal range) and eventually to mean sea level (0 m msl and above, gray), and are ordered by initial average elevation. Because a fixed subsidence-reversal rate is applied uniformly, the differences in elevation between islands remain constant through time until reversal activities end.

The probability that each island floods within a given time-frame is calculated separately using Equation 1 for 100 years (Table 2, first 75 years shown). These results are also ordered by initial average elevation, and show islands moving from moderate risk of flooding (under 25%, white) to high risk (25% to 50%, light grey), to very high risk (50% to 75%, medium grey), and extreme risk (above 75%, dark grey), unless they rise above mean sea level. The thin black lines cutting diagonally across the table identify the probabilities of islands failing before they transition between the deep, middle, shallow, and above-msl elevation ranges charted above. For example, the probability of islands flooding before reaching mean sea level, at a subsidence reversal rate of 4 cm yr^{-1}, is shown immediately below the lowermost diagonal black line in Table 2, which parallels the border between the green and gray elevation ranges in Table 1.

Together, these projections estimate the probability distribution of island elevations at time of failure and show the expected results of universal subsidence reversal for several decades. Given the high annual probabilities of failure the DRMS study estimates, most islands are not expected to make substantial elevation gains before they flood at a reversal rate of 4 cm yr^{-1}. The probabilities of failure increase quickly, with the median-risk island reaching a 50% chance of flooding after only 14 years. Here, given the assumed subsidence-reversal rate of 4 cm yr^{-1}, only 56 cm would be gained before many islands could flood. The mean and median times before islands reach a 75% chance of failure are 28 and 30 years, respectively. These time-horizons correspond to expected elevation gains of 1.12 to 1.2 m before flooding. A 2-m elevation gain, at the rate of 4 cm yr^{-1}, requires 50 years, long after many islands may have flooded. The over 5-m elevation gain needed for the deepest islands to reach mean sea level, at this rate, requires about 130 years.

The high probabilities of levee failure and long time needed for effective subsidence reversal imply a high likelihood of islands flooding below mean sea level, which makes it prudent to consider relaxed elevation goals based on other management criteria when considering subsidence reversal. Using the –1.5 m msl boundary of the aquatic habitat example as a goal, it would require about a decade for the first few Delta islands below this threshold to rise into the desired range. Most remaining islands would enter this range within 50 years, though the most subsided islands could only cross this threshold after 95 years of subsidence reversal. Even with this relaxed elevation goal, almost all islands have a 15% to 40% chance of flooding before they enter the desired elevation range.

Table 1 Independent elevation projections for subsided Delta islands given a subsidence reversal rate of 4 cm yr^{-1}; middle-depth "undesired range" from 1.5- to 4.6-m below msl, first 75 years shown. Dark diagonal lines correlate probabilities with elevations in each range in each year.

Subsidence Reversal		Projected Elevation by Year (m, msl)															
Island Name	**Elev.**	**Yr: 1**	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**	**55**	**60**	**65**	**70**	**75**
Mandeville Island	−5.36	−5.32	−5.16	−4.96	−4.76	−4.56	−4.36	−4.16	−3.96	−3.76	−3.56	−3.36	−3.16	−2.96	−2.76	−2.56	−2.36
Webb Tract	−5.15	−5.11	−4.95	−4.75	−4.55	−4.35	−4.15	−3.95	−3.75	−3.55	−3.35	−3.15	−2.95	−2.75	−2.55	−2.35	−2.15
Empire Tract	−5.13	−5.09	−4.93	−4.73	−4.53	−4.33	−4.13	−3.93	−3.73	−3.53	−3.33	−3.13	−2.93	−2.73	−2.53	−2.33	−2.13
Bouldin Island	−5.09	−5.05	−4.89	−4.69	−4.49	−4.29	−4.09	−3.89	−3.69	−3.49	−3.29	−3.09	−2.89	−2.69	−2.49	−2.29	−2.09
Bacon Island	−4.82	−4.78	−4.62	−4.42	−4.22	−4.02	−3.82	−3.62	−3.42	−3.22	−3.02	−2.82	−2.62	−2.42	−2.22	−2.02	−1.82
McDonald Tract	−4.65	−4.61	−4.45	−4.25	−4.05	−3.85	−3.65	−3.45	−3.25	−3.05	−2.85	−2.65	−2.45	−2.25	−2.05	−1.85	−1.65
Rindge Tract	−4.38	−4.34	−4.18	−3.98	−3.78	−3.58	−3.38	−3.18	−2.98	−2.78	−2.58	−2.38	−2.18	−1.98	−1.78	−1.58	−1.38
Venice Island	−4.29	−4.25	−4.09	−3.89	−3.69	−3.49	−3.29	−3.09	−2.89	−2.69	−2.49	−2.29	−2.09	−1.89	−1.69	−1.49	−1.29
Sherman Island	−3.73	−3.69	−3.53	−3.33	−3.13	−2.93	−2.73	−2.53	−2.33	−2.13	−1.93	−1.73	−1.53	−1.33	−1.13	−0.93	−0.73
Holland Tract	−3.73	−3.69	−3.53	−3.33	−3.13	−2.93	−2.73	−2.53	−2.33	−2.13	−1.93	−1.73	−1.53	−1.33	−1.13	−0.93	−0.73
Staten Island	−3.29	−3.25	−3.09	−2.89	−2.69	−2.49	−2.29	−2.09	−1.89	−1.69	−1.49	−1.29	−1.09	−0.89	−0.69	−0.49	−0.29
Woodward Island	−3.27	−3.23	−3.07	−2.87	−2.67	−2.47	−2.27	−2.07	−1.87	−1.67	−1.47	−1.27	−1.07	−0.87	−0.67	−0.47	−0.27
Jones Tract	−3.26	−3.22	−3.06	−2.86	−2.66	−2.46	−2.26	−2.06	−1.86	−1.66	−1.46	−1.26	−1.06	−0.86	−0.66	−0.46	−0.26
Twitchell Island	−3.17	−3.13	−2.97	−2.77	−2.57	−2.37	−2.17	−1.97	−1.77	−1.57	−1.37	−1.17	−0.97	−0.77	−0.57	−0.37	−0.17
Victoria Island	−3.16	−3.12	−2.96	−2.76	−2.56	−2.36	−2.16	−1.96	−1.76	−1.56	−1.36	−1.16	−0.96	−0.76	−0.56	−0.36	−0.16
Palm Tract	−3.08	−3.04	−2.88	−2.68	−2.48	−2.28	−2.08	−1.88	−1.68	−1.48	−1.28	−1.08	−0.88	−0.68	−0.48	−0.28	−0.08
Brannan−Andrus Is.	−2.81	−2.77	−2.61	−2.41	−2.21	−2.01	−1.81	−1.61	−1.41	−1.21	−1.01	−0.81	−0.61	−0.41	−0.21	−0.01	0.19
Tyler Island	−2.61	−2.57	−2.41	−2.21	−2.01	−1.81	−1.61	−1.41	−1.21	−1.01	−0.81	−0.61	−0.41	−0.21	−0.01	0.19	0.39
Orwood Tract	−2.52	−2.48	−2.32	−2.12	−1.92	−1.72	−1.52	−1.32	−1.12	−0.92	−0.72	−0.52	−0.32	−0.12	0.08	0.28	0.48
Medford Island	−2.45	−2.41	−2.25	−2.05	−1.85	−1.65	−1.45	−1.25	−1.05	−0.85	−0.65	−0.45	−0.25	−0.05	0.15	0.35	0.55
King Island	−2.38	−2.34	−2.18	−1.98	−1.78	−1.58	−1.38	−1.18	−0.98	−0.78	−0.58	−0.38	−0.18	0.02	0.22	0.42	0.62
Jersey Island	−2.34	−2.30	−2.14	−1.94	−1.74	−1.54	−1.34	−1.14	−0.94	−0.74	−0.54	−0.34	−0.14	0.06	0.26	0.46	0.66
Bradford Island	−2.24	−2.20	−2.04	−1.84	−1.64	−1.44	−1.24	−1.04	−0.84	−0.64	−0.44	−0.24	−0.04	0.16	0.36	0.56	0.76
Quimby Island	−2.22	−2.18	−2.02	−1.82	−1.62	−1.42	−1.22	−1.02	−0.82	−0.62	−0.42	−0.22	−0.02	0.18	0.38	0.58	0.78
Wright−Elmwood Tr.	−2.10	−2.06	−1.90	−1.70	−1.50	−1.30	−1.10	−0.90	−0.70	−0.50	−0.30	−0.10	0.10	0.30	0.50	0.70	0.90
Dead Horse Island	−2.06	−2.02	−1.86	−1.66	−1.46	−1.26	−1.06	−0.86	−0.66	−0.46	−0.26	−0.06	0.14	0.34	0.54	0.74	0.94
Bethel Tract	−1.99	−1.95	−1.79	−1.59	−1.39	−1.19	−0.99	−0.79	−0.59	−0.39	−0.19	0.01	0.21	0.41	0.61	0.81	1.01
Ryer Island	−1.88	−1.84	−1.68	−1.48	−1.28	−1.08	−0.88	−0.68	−0.48	−0.28	−0.08	0.12	0.32	0.52	0.72	0.92	1.12
Terminous Tract	−1.52	−1.48	−1.32	−1.12	−0.92	−0.72	−0.52	−0.32	−0.12	0.08	0.28	0.48	0.68	0.88	1.08	1.28	1.48
Brack Tract	−1.41	−1.37	−1.21	−1.01	−0.81	−0.61	−0.41	−0.21	−0.01	0.19	0.39	0.59	0.79	0.99	1.19	1.39	1.59
Grand Island	−0.98	−0.94	−0.78	−0.58	−0.38	−0.18	0.02	0.22	0.42	0.62	0.82	1.02	1.22	1.42	1.62	1.82	2.02
Canal Ranch Tract	−0.97	−0.93	−0.77	−0.57	−0.37	−0.17	0.03	0.23	0.43	0.63	0.83	1.03	1.23	1.43	1.63	1.83	2.03
Hotchkiss Tract	−0.94	−0.90	−0.74	−0.54	−0.34	−0.14	0.06	0.26	0.46	0.66	0.86	1.06	1.26	1.46	1.66	1.86	2.06
Roberts Island	−0.73	−0.69	−0.53	−0.33	−0.13	0.07	0.27	0.47	0.67	0.87	1.07	1.27	1.47	1.67	1.87	2.07	2.27
Union Island	−0.27	−0.23	−0.07	0.13	0.33	0.53	0.73	0.93	1.13	1.33	1.53	1.73	1.93	2.13	2.33	2.53	2.73
Coney Island	−0.16	−0.12	0.04	0.24	0.44	0.64	0.84	1.04	1.24	1.44	1.64	1.84	2.04	2.24	2.44	2.64	2.84

Key: 🟦 **Deep Water** 🟧 **Middle Water** 🟩 **Shallow Water** ⬜ **Land Above MSL**

Table 2 Probability–of–failure projections for subsided Delta islands given a subsidence reversal rate of 4 cm yr^{-1}; dark diagonal lines correlate probabilities with elevations in each range in each year, first 75 years shown.

Subsidence Reversal		Probablity of Failure by Year															
Island Name	**Risk.**	**Yr: 1**	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**	**55**	**60**	**65**	**70**	**75**
Mandeville Island	0.057	0.06	0.25	0.44	0.58	0.69	0.77	0.83	0.87	0.90	0.93	0.95	0.96	0.97	0.98	0.98	0.99
Webb Tract	0.048	0.05	0.22	0.39	0.52	0.63	0.71	0.77	0.82	0.86	0.89	0.92	0.93	0.95	0.96	0.97	0.98
Empire Tract	0.050	0.05	0.23	0.40	0.54	0.64	0.72	0.79	0.84	0.87	0.90	0.92	0.94	0.95	0.96	0.97	0.98
Bouldin Island	0.047	0.05	0.21	0.38	0.51	0.61	0.70	0.76	0.81	0.85	0.88	0.91	0.93	0.94	0.95	0.96	0.97
Bacon Island	0.051	0.05	0.23	0.41	0.55	0.65	0.73	0.79	0.84	0.88	0.91	0.93	0.94	0.96	0.97	0.97	0.98
McDonald Tract	0.062	0.06	0.27	0.47	0.62	0.72	0.80	0.85	0.89	0.92	0.94	0.96	0.97	0.98	0.98	0.99	0.99
Rindge Tract	0.046	0.05	0.21	0.38	0.51	0.61	0.69	0.76	0.81	0.85	0.88	0.91	0.93	0.94	0.95	0.96	0.97
Venice Island	0.073	0.07	0.32	0.53	0.68	0.78	0.85	0.90	0.93	0.95	0.97	0.98	0.98	0.99	0.99	1.00	1.00
Sherman Island	0.095	0.09	0.39	0.63	0.77	0.86	0.92	0.95	0.97	0.98	0.99	0.99	1.00	1.00	1.00	1.00	1.00
Holland Tract	0.043	0.04	0.20	0.35	0.48	0.58	0.66	0.73	0.78	0.83	0.86	0.89	0.91	0.93	0.94	0.95	0.96
Staten Island	0.068	0.07	0.30	0.50	0.65	0.75	0.83	0.88	0.91	0.94	0.96	0.97	0.98	0.99	0.99	0.99	0.99
Woodward Island	0.048	0.05	0.22	0.39	0.52	0.63	0.71	0.77	0.82	0.86	0.89	0.92	0.93	0.95	0.96	0.97	0.98
Jones Tract	0.059	0.06	0.26	0.45	0.60	0.70	0.78	0.84	0.88	0.91	0.93	0.95	0.96	0.97	0.98	0.99	0.99
Twitchell Island	0.056	0.06	0.25	0.44	0.58	0.68	0.76	0.82	0.87	0.90	0.93	0.94	0.96	0.97	0.98	0.98	0.99
Victoria Island	0.057	0.06	0.26	0.45	0.59	0.69	0.77	0.83	0.87	0.91	0.93	0.95	0.96	0.97	0.98	0.98	0.99
Palm Tract	0.035	0.03	0.16	0.30	0.41	0.51	0.59	0.65	0.71	0.76	0.79	0.83	0.86	0.88	0.90	0.91	0.93
Brannan-Andrus Is.	0.058	0.06	0.26	0.45	0.59	0.70	0.78	0.83	0.88	0.91	0.93	0.95	0.96	0.97	0.98	0.98	0.99
Tyler Island	0.084	0.08	0.35	0.58	0.73	0.83	0.89	0.93	0.95	0.97	0.98	0.99	0.99	0.99	1.00	1.00	1.00
Orwood Tract	0.048	0.05	0.22	0.39	0.52	0.63	0.71	0.77	0.82	0.86	0.89	0.91	0.93	0.95	0.96	0.97	0.98
Medford Island	0.054	0.05	0.24	0.42	0.56	0.67	0.75	0.81	0.86	0.89	0.92	0.94	0.95	0.96	0.97	0.98	0.98
King Island	0.029	0.03	0.14	0.26	0.36	0.45	0.53	0.59	0.65	0.70	0.74	0.78	0.81	0.83	0.86	0.88	0.89
Jersey Island	0.070	0.07	0.30	0.51	0.66	0.76	0.84	0.89	0.92	0.94	0.96	0.97	0.98	0.99	0.99	0.99	1.00
Bradford Island	0.045	0.04	0.20	0.37	0.49	0.60	0.68	0.74	0.80	0.84	0.87	0.90	0.92	0.93	0.95	0.96	0.97
Quimby Island	0.029	0.03	0.14	0.26	0.36	0.45	0.52	0.59	0.64	0.69	0.74	0.77	0.80	0.83	0.85	0.87	0.89
Wright-Elmwood Tr.	0.029	0.03	0.14	0.25	0.35	0.44	0.52	0.58	0.64	0.69	0.73	0.77	0.80	0.83	0.85	0.87	0.89
Dead Horse Island	0.012	0.01	0.06	0.11	0.17	0.21	0.26	0.30	0.34	0.38	0.42	0.45	0.49	0.52	0.54	0.57	0.60
Bethel Tract	0.070	0.07	0.30	0.51	0.66	0.76	0.84	0.89	0.92	0.94	0.96	0.97	0.98	0.99	0.99	0.99	1.00
Ryer Island	0.033	0.03	0.16	0.29	0.40	0.49	0.57	0.64	0.69	0.74	0.78	0.82	0.84	0.87	0.89	0.91	0.92
Terminous Tract	0.046	0.05	0.21	0.37	0.50	0.61	0.69	0.75	0.81	0.85	0.88	0.90	0.92	0.94	0.95	0.96	0.97
Brack Tract	0.060	0.06	0.27	0.46	0.61	0.71	0.79	0.84	0.89	0.92	0.94	0.95	0.97	0.98	0.98	0.99	0.99
Grand Island	0.036	0.04	0.17	0.31	0.42	0.52	0.60	0.67	0.72	0.77	0.81	0.84	0.87	0.89	0.91	0.92	0.94
Canal Ranch Tract	0.034	0.03	0.16	0.29	0.41	0.50	0.58	0.65	0.70	0.75	0.79	0.82	0.85	0.88	0.90	0.91	0.93
Hotchkiss Tract	0.035	0.03	0.16	0.30	0.41	0.51	0.59	0.65	0.71	0.76	0.80	0.83	0.86	0.88	0.90	0.92	0.93
Roberts Island	0.055	0.06	0.25	0.43	0.57	0.68	0.76	0.82	0.86	0.90	0.92	0.94	0.96	0.97	0.98	0.98	0.99
Union Island	0.028	0.03	0.13	0.25	0.34	0.43	0.51	0.57	0.63	0.68	0.72	0.76	0.79	0.82	0.84	0.86	0.88
Coney Island	0.024	0.02	0.11	0.21	0.30	0.38	0.45	0.51	0.57	0.62	0.66	0.70	0.73	0.76	0.79	0.81	0.83

While elevation growth is linear over time, the risk of failure for most islands grows nonlinearly, and quickly approaches 100% (Figure 4), as noted by Suddeth and others (2008, 2010) and Mount and Twiss (2005). Delta flooding simulations confirm the pattern in Figure 4, and give additional insights into the variability in Delta flooding expected from the DRMS data. Without subsidence reversal (Figure 5), flooding simulations predict that nearly 800 km^2 of the total 1,057 km^2 of modeled island area will be submerged within 30 years, on average, and within 50 years, within two standard deviations of the mean.

With uniform subsidence reversal implemented across the Delta at a rate of 4 cm yr^{-1} (Figure 6), large-scale flooding can still be expected, but with reduced frequency and magnitude. This significant investment would push the reference expected 800 km^2 of flooded area back by about 15 years and reduce the eventual expected flooded area by almost 20%, on average. Within two standard deviations of the mean, the total flooded area in 30 years could be as little as 525 km^2. Thus, substantial net benefits may occur through universal subsidence reversal, even when per-island probabilities of levee failure remain high, though this probably would involve high costs.

Sensitivity of Results to Subsidence Reversal Rate

Other subsidence-reversal rates can also be considered. Table 3 shows elevation gains over time for various subsidence-reversal rates in addition to the 4 cm yr^{-1} Twitchell Island average. Large rates might be possible with improved technology and management, or if engineered accretion is locally augmented with mechanical materials placement.

With a subsidence reversal rate near the 9.2 cm yr^{-1} maximum found in the Twitchell Island study, an elevation gain of about 1$^1/_3$ m can be expected before the median island reaches a 50% chance of flooding. This could bring some shallower islands to mean sea level but would leave many deeper islands still meters underwater. For subsidence reversal to be effective given the DRMS probabilities of failure, reversal rates on the order of 18 to 36 cm yr^{-1} are needed. These higher subsidence-reversal rates could essentially bring all islands to mean sea level by the time the median island reached a 50% chance of failure, dramatically reducing the total, long-term simulated flooded area (Figure 7). With these enhanced subsidence reversal rates, islands that do flood below mean sea level would flood at higher elevations, which may be desirable for ecological or other purposes.

Elevation-based Subsidence Reversal Strategies

Table 4 summarizes the chance of each island flooding in the undesired range of the aquatic habitat example (between –4.6 and –1.5 m msl) with subsidence reversal. The probability of flooding into the example undesired range with 4 cm yr^{-1} subsidence reversal is correlated strongly with initial elevation ($R^2 = 0.92$). Different strategies seem best suited for different groups of islands, roughly categorized by initial elevation. Eight islands (with bold probabilities and a green background, top of Table 4) have initial elevations near or above the –1.5 m msl threshold. These islands need no additional subsidence reversal to satisfy program objectives, and are already in the goal elevation range where native plants are presumed to compete (though subsidence-reversal wetlands may still provide useful habitat and help keep up with sea level rise). Six additional islands (with bold probabilities and a blue background, bottom of Table 4), are initially subsided below the lower –4.6 m msl threshold of the undesired range. While these islands are not presumed susceptible to further invasion, they could pose a water supply threat in the event of an abrupt island failure due to their large empty volumes below sea level (e.g., Lund and others 2007). Subsidence reversal for some of these islands could reduce flooded volume as long as it is not implemented for islands near the –4.6 m msl threshold, where it could counterproductively bring islands into the undesired ecological range.

The remaining 22 islands (with non-bold probabilities and a orange background, middle of Table 4) have initial elevations in the undesired

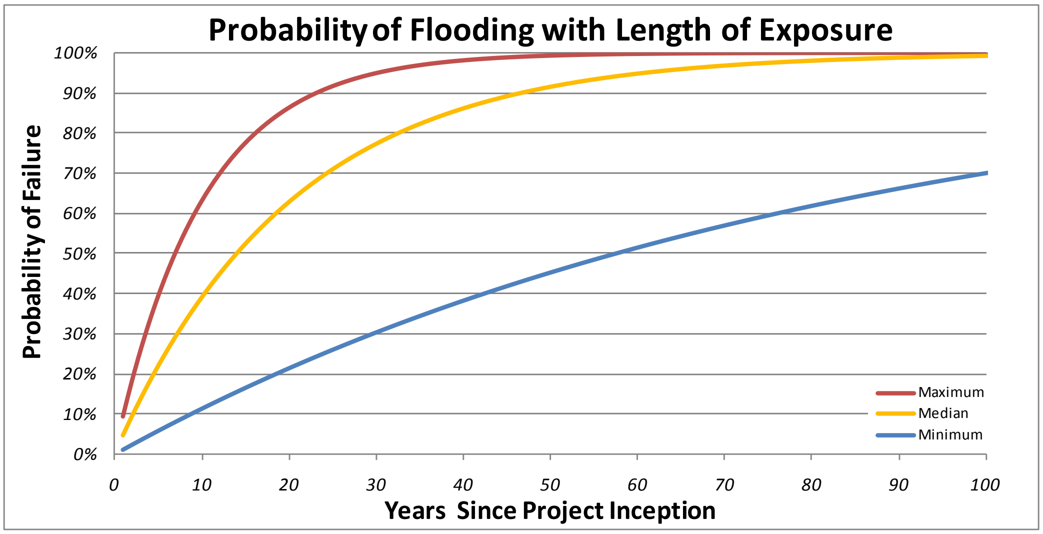

Figure 4 The chance that the minimum, median, and maximum probability islands will flood in a given interval; following Suddeth and others (2010, 2008) for the 36 modeled islands using URS and J.R. Benjamin & Assoc. (2009a) cumulative probabilities of levee failure from seismic, flood and other risks for the 2005 base year.

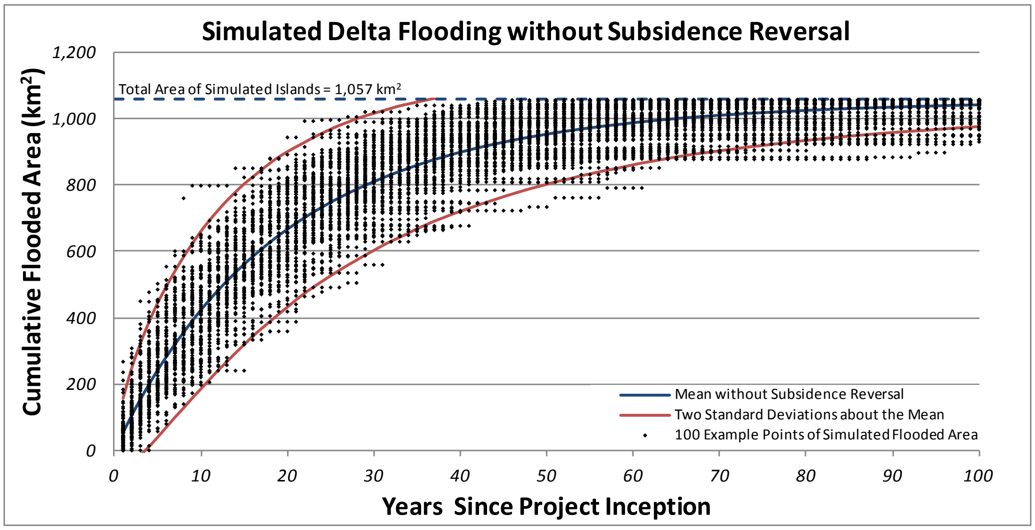

Figure 5 Results of 10,000 random simulations of Delta island flooding without subsidence reversal, showing cumulative flooded area over time. Values for the mean and two standard deviations about the mean are shown along with one hundred random sample data points per year. Source: author data, based on URS and J.R. Benjamin & Assoc. (2009a) probabilities of levee failure and CDWR (1995) island areas.

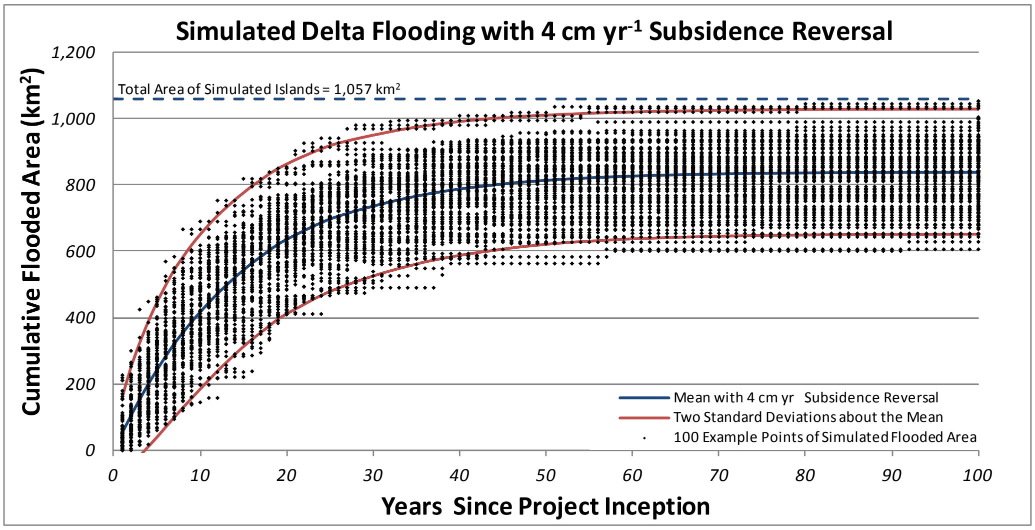

Figure 6 Results of ten-thousand random simulations of Delta island flooding with 4 cm yr^{-1} subsidence reversal, showing cumulative flooded area over time. Values for the mean and two standard deviations about the mean are shown along with one hundred random sample data points per year. Source: author data, based on URS and J.R. Benjamin & Assoc. (2009a) probabilities of levee failure and CDWR (1995) island areas.

Table 3 Expected elevation gain with various subsidence-reversal rates

Years since project inception			**5**	**10**	**15**	**20**	**30**	**40**	**50**
Median probability of failure in interval			**22%**	**39%**	**52%**	**63%**	**77%**	**86%**	**92%**
Elevation gain (m) at a rate of:	2.5	cm yr^{-1}	0.13	0.25	0.38	0.50	0.75	1.00	1.25
	4	cm yr^{-1}	0.20	0.40	0.60	0.80	1.20	1.60	2.00
	9	cm yr^{-1}	0.45	0.90	1.35	1.80	2.70	3.60	4.50
	18	cm yr^{-1}	0.90	1.80	2.70	3.60	5.40	7.20	9.00
	36	cm yr^{-1}	1.80	3.60	5.40	7.20	10.80	14.40	18.00

range and can be categorized into three strategic subgroups. The first subgroup of islands is subsided only slightly below −1.5 m, and these islands have mild enough probabilities of failure that substantial elevation gains might be possible before they flood. Many islands in this subgroup could reach the −1.5 m threshold within the second decade of the project, with a 40% to 85% chances of success. Given the goals of the example, these islands seem most suitable for subsidence-reversal investment.

The high probability of islands in the second subgroup flooding in the undesired range renders subsidence reversal here almost pointless for the example criterion (although there might be benefits for reducing abruptly flooded volumes, etc.). At 4 cm yr^{-1}, the 1- to 2-m elevation gains that many of these islands need could only be realized after half a century, after many of them are expected to have flooded. With 70% to 95% chances of flooding before the −1.5 m threshold is reached, subsidence-reversal investments here would be very risky. These islands will likely be problematic under any circumstances.

A different strategy emerges for islands in the third subgroup. Here, continued, or even intensified, farming could encourage further subsidence for islands near the −4.6 m lower threshold. Continued farming could retain land in profitable production and avoid subsidence reversal costs and, with each passing year, the islands become less likely to flood into the undesired ecological evaluation range.

Economic Subsidence Reversal Strategies

Management and lost agricultural revenues incur costs for subsidence reversal. Management costs might include upkeep of the island's levees, creating subsidence-reversal beds, planting initial groundcover, salaries for project staff, etc., and are expected to be similar, per acre, for islands throughout the Delta. Variations in lost agricultural revenue, as Lund and others (2007) estimated, are expected to be less uniform and potentially larger.

For the −1.5 m elevation goal of the aquatic habitat example, investment in subsidence reversal can be thought of as "buying" reductions in the risk of failing in an undesired range. [Risk reductions from subsidence reversal are found by subtracting the probabilities of failing in the avoidance zone with subsidence reversal (Table 4) from the probabilities of failing in the avoidance zone without subsidence reversal.] These reductions in risk can be compared with anticipated lost agricultural revenues to assess the relative cost-effectiveness of subsidence-reversal investment in each island (Figure 8). Ideal candidate islands for subsidence reversal would have both a high reduction in risk and little forgone agricultural revenue. Where this is lacking, trade-offs must be made. Opportunities to pursue subsidence reversal without incurring agricultural losses may increase in the future as arable farmland is projected to continue to become too wet to farm because of continued subsidence, sea level rise, and other factors (Deverel 2013).

Once flooded, it seems unlikely that the estimated tens or hundreds of millions of dollars in dewa-

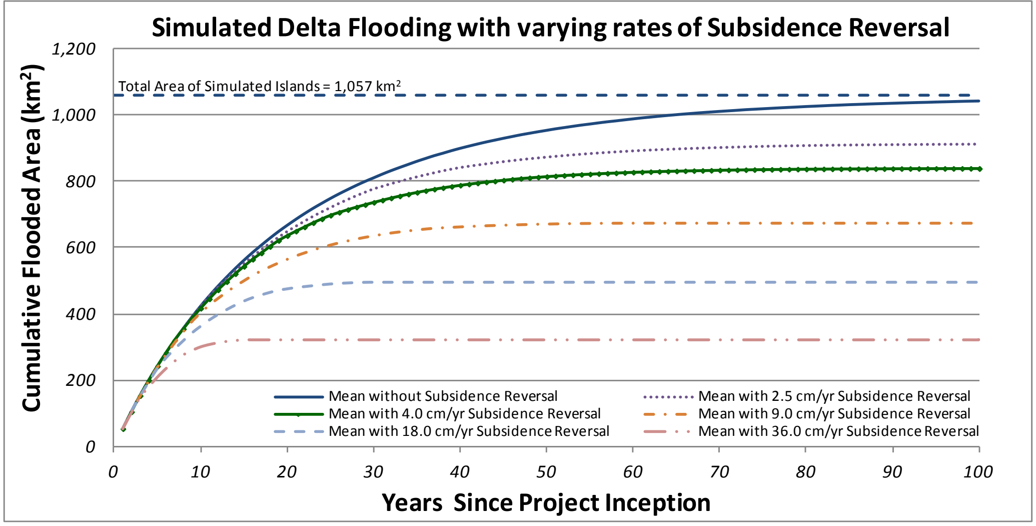

Figure 7 Sensitivity of mean simulated flooded area to changes in the rate of universal subsidence reversal. Source: author data, based on URS and J.R. Benjamin & Assoc. 2009a probabilities of levee failure and CDWR 1995 island areas.

tering and repair cost (URS and J.R. Benjamin & Assoc. 2009a) will be spent to return a deeply flooded island to a subsidence reversal marshland that provides little economic return. Thus, the major lasting benefit from the cost of many subsidence-reversal projects may only be the decimeters of elevation gained between project inception and island failure.

Limitations and Extensions

Time to failure and changes in average elevation under subsidence reversal have been modeled for islands as individual units. While islands do tend to flood as a unit, island elevations are non-uniform—and modeling whole islands with average elevations is a generalization. Implementing subsidence reversal in the shallower portions of a greater number of islands may be preferable to implementing subsidence reversal on entire islands. Nevertheless, the results presented here provide some insights for the potential value and limitations of subsidence-reversal programs. Future work might focus on identifying sub-island areas most suitable for subsidence reversal in terms of economic and ecological trade-offs.

As a conservative approach to modeling levee failure, the annual probabilities of failure are assumed constant over the modeled period. While small increases in elevation would somewhat reduce the hydraulic pressure gradient and risk of levee failure, these risk reductions are probably overshadowed by other increasing risks. Growing earthquake potential, sea level rise and winter flood inflows from climate change are likely to increase probabilities of levee failure over the next 50 to 100 years (URS and J.R. Benjamin & Assoc. 2009b). The approach used here also ignores any reduced reliability of neighboring islands from increased wave fetch as islands flood, as well as increased reliabilities from levee investments.

For simplicity, the desired and undesired elevation ranges specified in the aquatic habitat example are derived from a single hypothetical ecological criterion. In practice, in a process more varied and complex, multiple criteria could be used to tailor island depths to meet specified goals (Kiker and others 2005). The ecological well-being of newly flooded islands depends on many factors other than elevation, and a portfolio of management strategies targeting many species should be considered in seeking holistic ecological health (Santos and others 2009).

While this example has focused on the implications of the elevation of newly flooded islands for aquatic habitat, other effects remain to be explored. For example, how does flooded depth affect wave activity, erosion, and water-quality mixing? Does

Table 4 Probabilities of islands in the Sacramento–San Joaquin Delta flooding between −1.5 and −4.6 m below mean sea level (the undesired range of the aquatic habitat example), given a uniform subsidence reversal rate of 4 cm yr^{-1}. Islands in bold have approximate initial subsided depths either above or below this range.

Island Name	Initial elevation (in year 2000; meters, msl)	Risk of failure in undesired range w/SR	Strategy (based on sub-msl elevation criterion)
Coney Island	**-0.16**	**0**	No action needed; retain as marshy habitat. Subsidence reversal may help keep up with sea-level rise.
Union Island	**-0.27**	**0**	
Roberts Island	**-0.73**	**0**	
Hotchkiss Tract	**-0.94**	**0**	
Canal Ranch Tract	**-0.97**	**0**	
Grand Island	**-0.98**	**0**	
Brack Tract	**-1.41**	**0**	
Terminous Tract	**-1.52**	**0.05**	
Dead Horse Island	-2.06	0.16	Good potential for subsidence reversal to achieve elevation goal, but investment may be risky.
Ryer Island	-1.88	0.26	
Wright-Elmwood Tract	-2.10	0.35	
Quimby Island	-2.22	0.41	
King Island	-2.38	0.48	
Bradford Island	-2.24	0.56	
Bethel Tract	-1.99	0.58	
Orwood Tract	-2.52	0.72	Very risky, subsidence reversal not recommended as a means to achieve sub-msl elevation goal.
Medford Island	-2.45	0.73	
Palm Tract	-3.08	0.75	
Jersey Island	-2.34	0.78	
Brannan-Andrus Island	-2.81	0.86	
Woodward Island	-3.27	0.89	
Victoria Island	-3.16	0.91	
Twitchell Island	-3.17	0.91	
Holland Tract	-3.73	0.91	
Tyler Island	-2.61	0.91	
Jones Tract	-3.26	0.93	
Staten Island	-3.29	0.96	
Rindge Tract	-4.38	0.97	Continue farming to promote subsidence beyond the lower (4.6m msl) threshold?
Venice Island	-4.29	1.00	
Sherman Island	-3.73	1.00	
McDonald Tract	**-4.65**	**0.93**	
Bacon Island	**-4.82**	**0.72**	Subsidence reversal may help reduce flooded volume.
Bouldin Island	**-5.09**	**0.52**	
Empire Tract	**-5.13**	**0.50**	
Webb Tract	**-5.15**	**0.49**	
Mandeville Island	**-5.36**	**0.32**	

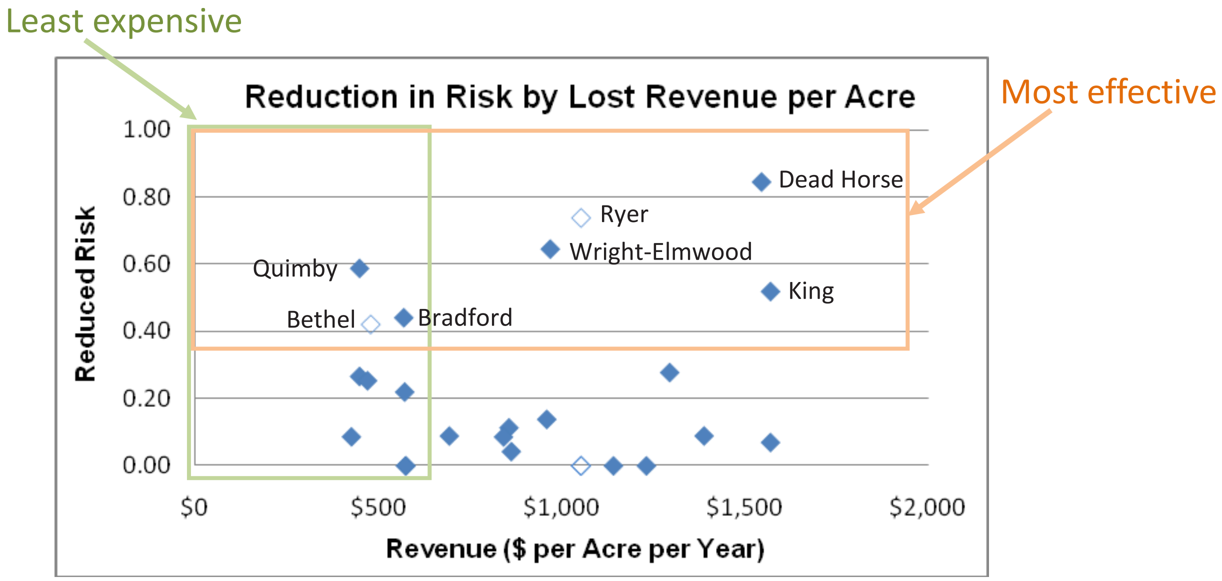

Figure 8 Annual per-acre lost agricultural revenues with expected reductions in the risk of failing in the undesired range of the aquatic habitat example with subsidence reversal. Islands lacking revenue estimates (hollow points) are given annual lost revenues similar to surrounding islands. (Revenue estimates from Lund and others 2007, 2010).

the flooded volume for a particular island contribute significantly to water supply and treatment costs through altered retention times, organic contaminants, and salinity gradients? How would changes to tidal hydraulics and sediment dynamics change management in the Delta and San Francisco Bay? How would recreational boating and sport fishing respond? Answers to these and other questions can help guide the development of elevation goals for evaluating subsidence-reversal proposals.

CONCLUSIONS

Subsidence reversal has received considerable policy and scientific attention for the Sacramento–San Joaquin Delta. However, for observed rates of elevation gain, most islands are unlikely to gain substantial elevation or reach mean sea level without a high risk of flooding. Subsidence has occurred since reclamation and farming began in the late 1800s (Thompson 1957), and with subsidence-reversal rates similar to the rates of continued agricultural subsidence (Deverel and Leighton 2010; Miller and others 2008), efforts to reverse elevation losses can be expected to take roughly as long as it took to produce them.

Based on projections from the DRMS data (URS and J.R. Benjamin & Assoc. 2009), many islands may have less than a 50% chance of surviving intact for more than a few decades (Suddeth and others 2008, 2010; Tables 1 and 2; Figures 4–6). Even if subsidence-reversal techniques can be improved or mechanically augmented to increase rates of elevation gain by an order of magnitude, about a quarter of the currently subsided Delta area may still flood within a decade or two (Figure 7), although the more productive islands would likely be repaired.

Subsidence reversal seems to be an often poor investment, if restoring mean sea level is the only objective. However, even limited elevation gains for ecological or other benefit can be useful where small increases in elevation dramatically improve outcomes. As shown through a hypothetical aquatic habitat example, an elevation-based analysis can identify candidate islands for more detailed subsidence-reversal consideration.

Economic factors also are likely to influence the selection of future subsidence reversal projects. Project maintenance costs, per acre, are expected to be high, but are not expected to vary greatly across the Delta. However, costs from foregone agricultural revenues will vary. Ideal subsidence reversal candidate islands would have high probabilities (or large increases in the probability) of meeting criteria-based elevation goals, with little lost agricultural revenue. Barring this, trade-offs between likely outcome and project costs will be required. Once flooded, it seems unlikely that millions of dollars in dewatering and repair costs will be spent to return deeply flooded islands to subsidence-reversal wetlands. Thus, with a finite period of time in which to make elevation gains, subsidence reversal seems likely to be a useful part of a successful Delta solution only if its purpose and benefits are carefully considered in a systematic, criteria-based framework.

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