Technical Memorandum:

Delta Risk Management Strategy (DRMS) Phase 1

Topical Area:

Subsidence

Final

Prepared by:
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Prepared for:
California Department of Water Resources (DWR)

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Subject: Delta Risk Management Strategy
Final Phase 1 Technical Memorandum – Subsidence

Dear Mr. Bagheban:

We are providing the final Subsidence Technical Memorandum (TM) (dated June 15, 2007) for Phase 1 of the Delta Risk Management Strategy (DRMS) project. Members of the Steering Committee's Technical Advisory Committee and agency staff reviewed the draft TM, and their comments were incorporated before the CALFED Independent Review Panel (IRP) review of the June 26, 2007, draft of the Risk Analysis Report. This final version of this TM addresses the IRP comments provided on the subsidence sections of the Risk Analysis Report.

This document was prepared by Steven Deverel (Hydrofocus, Inc.). This technical memorandum was reviewed by Drs. Said Salah-Mars (URS) and Marty McCann (JBA). Internal peer review was provided in accordance with URS' quality assurance program, as outlined in the DRMS project management plan.

Sincerely,

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Topical Area: Subsidence

Preamble

In response to Assembly Bill (AB) 1200 (Laird, chaptered, September 2005), the California Department of Water Resources (DWR) authorized the Delta Risk Management Strategy (DRMS) project to perform a Risk Analysis of the Sacramento–San Joaquin Delta (Delta) and Suisun Marsh (Phase 1) and to develop a set of improvement strategies to manage those risks (Phase 2).

AB 1200 amends Section 139.2 of the Water Code to read: "The department shall evaluate the potential impacts on water supplies derived from the Sacramento–San Joaquin Delta based on 50-, 100-, and 200-year projections for each of the following possible impacts on the Delta:

1. Subsidence
2. Earthquakes
3. Floods
4. Changes in precipitation, temperature, and ocean levels
5. A combination of the impacts specified in paragraphs (1) to (4) inclusive."

AB 1200 also amended Section 139.4 to read: "(a) The Department and the Department of Fish and Game shall determine the principal options for the Delta. (b) The Department shall evaluate and comparatively rate each option determined in subdivision (a) for its ability to do the following:

1. Prevent the disruption of water supplies derived from the Sacramento–San Joaquin Delta.
2. Improve the quality of drinking water supplies derived from the Delta.
3. Reduce the amount of salts contained in Delta water and delivered to, and often retained in, our agricultural areas.
4. Maintain Delta water quality for Delta users.
5. Assist in preserving Delta lands.
6. Protect water rights of the "area of origin" and protect the environments of the Sacramento–San Joaquin river systems.
7. Protect highways, utility facilities, and other infrastructure located within the Delta.
8. Preserve, protect, and improve Delta levees.…"

To meet the requirements of AB 1200, the DRMS project has been divided into two parts. Phase 1 involves the development and implementation of a Risk Analysis to evaluate the impacts of various stressing events on the Delta. Phase 2 evaluates the risk reduction potential of alternative options and develops risk management strategies for the long-term management of the Delta.

As part of the Phase 1 work, 12 technical memoranda (TMs), which address individual topical areas, and one risk report have been prepared. This TM addresses the subsidence issues that are considered in Phase 1. The TMs and the topical areas covered in the Phase 1 Risk Analysis are as follows:

1. Geomorphology of the Delta and Suisun Marsh
2. Subsidence of the Delta and Suisun Marsh
3. Seismology of the Delta and Suisun Marsh
4. Climate Change in the Delta and Suisun Marsh
5. Flood Hazard of the Delta and Suisun Marsh
6. Wind-Wave Hazard of the Delta and Suisun Marsh
7. Levee Vulnerability of the Delta and Suisun Marsh
8. Emergency Response and Repair of the Delta and Suisun Marsh Levees
9. Hydrodynamics, Water Quality, and Management and Operation of the Delta and Suisun Marsh (Water Analysis Module)*
10. Ecosystem Impacts to the Delta and Suisun Marsh
11. Impact to Infrastructure of the Delta and Suisun Marsh
12. Economic Consequences to the Delta and Suisun Marsh

*Two separate topical areas—the Hydrodynamics topical area and the Water Management topical area—were combined into one TM because of the strong interaction between them. The resulting TM is referred to as the Water Analysis Module (WAM).

The work products described in all of the TMs are integrated in the DRMS Risk Analysis. The results of the Risk Analysis are presented in a technical report referred to as:

13. Risk Analysis Report

Taken together, the Phase 1 TMs and the Risk Analysis Report constitute the full documentation of the DRMS Risk Analysis.

The Business-as-Usual Delta and Suisun Marsh: Assumptions and Definitions

To carry out the DRMS Phase 1 analysis, it was important to establish some assumptions about the future "look" of the Delta. To address the challenge of predicting the impacts of stressing events on the Delta and Suisun Marsh under changing future conditions, DRMS adopted the approach of evaluating impacts absent major future changes in the Delta as a baseline. Thus, the Phase 1 work did not incorporate or examine proposals for Delta improvements. Rather, Phase 1 identified the characteristics and problems of the current Delta (as of 2005), with its practices and uses. This approach, which allows for consideration of pre-existing agreements, policies, funded projects, and practices, is referred to as the "business-as-usual" (BAU) scenario. Defining a BAU Delta is necessary because one of the objectives of this project is to estimate whether the current practices of managing the Delta (i.e., BAU) are sustainable for the foreseeable future. The results of the Phase 1 Risk Analysis based on the BAU assumption not only maintained continuity with the existing Delta, but also served as the baseline for evaluating the risk reduction measures considered in Phase 2.

The existing procedures and policies developed to address "standard" emergencies in the Delta, as covered in the BAU scenario, do not cover some of the major (unprecedented) events in the Delta that are evaluated in the Risk Analysis. In these instances, prioritization of actions is based on (1) existing and expected future response resources and (2) the highest value of recovery/restoration given available resources.

This study relied solely on available data. In other words, the effects of stressing events (changing future earthquake frequencies, future rates of subsidence given continued farming practices, the change in the magnitude and frequency of storm events, and the potential effects of global warming) on the Delta and Suisun Marsh levees were estimated using readily available engineering and scientific tools or based on a broad and current consensus among practitioners. Using the current state of knowledge, the DRMS project team made estimates of the future magnitude and frequency of occurrence of the stressing events 50, 100, and 200 years from now to evaluate the change in Delta risks into the future.

Because of the limited time available to complete this work, no investigation or research was conducted to supplement the current state of knowledge.

Perspective

The analysis results presented in this TM do not represent the full estimate of risk for the Delta and Suisun Marsh. The full estimate of risk is the probable outcome of the hazards (earthquake, floods, climate change, subsidence, wind waves, and sunny day failures) combined with the conditional probability of the subject outcome (levee failures, emergency response, water management, hydrodynamic response of the Delta and Suisun Marsh, ecosystem response, and economic consequences) given the stressing events. A full characterization of risk is presented in the Risk Analysis Report. In that report, the integration of the initiating (stressing) events, the conditional probable response of the Delta levee system, and the expected probable consequences are integrated to develop a complete assessment of risk to the Delta and Suisun Marsh. In this context, the subject of this TM is one element of the Risk Analysis.

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Acronyms

CV	coefficient of variance
GPS	Geographic Positioning System
KSN	Kjelson, Sinnock, and Neudeck, Inc.
LIDAR	Light Detection and Ranging
NGVD 29	National Geodetic Vertical Datum of 1929
RMSE	root mean square error
RTK	Real Time Kinetic
SRTM	Shuttle Radar Tomography Mission
USGS	U.S. Geological Survey

1.0 Introduction and Background

1.1 Sacramento-San Joaquin Delta

The Sacramento-San Joaquin Delta is the transfer point for water exported to southern California and is the water-supply hub for over 23 million Californians. Assembly Bill 1200 passed in 2005 requires the California Department of Water Resources to evaluate the water-supply impacts of subsidence, floods, earthquakes, and climate change. The Delta Risk Management Strategy project seeks to evaluate these effects through an integrated network of analytical tools and working groups. Subsidence crosses the boundaries of three Delta Risk Management Strategy Working/Topical area groups; levee vulnerability, hydrodynamic modeling, and water management and environmental consequences. Specifically, relative to levee stability, subsidence of organic soils[1] increases hydraulic gradients across levees to drainage ditches which increase seepage through and under levees. Subsidence affects levee static stability within some temporally and spatially variable zone of influence adjacent to levees and at least partially drives the need for levee upgrades[2]. Levee stability is affected by ongoing subsidence because there is an ongoing need to deepen drainage ditches to maintain an aerated root zone for agriculture. There are commonly drainage ditches adjacent to levees on the perimeter of islands.

Levee failure can cause movement of saline water into the Delta during flooding and island inundation in the western Delta during low flow periods represents the primary concern for water quality degradation. For example, levee failure caused 150,000 acre-feet of water to cover Andrus and Brannan islands in June 1972 (Cooke and Coleman, 1973). State and federal water projects released 300,000 acre-feet of additional water from storage to offset the salinity intrusion. The total cost of the flooding and repairs was $22.5 million (over $90 million in 2005 currency).

Future subsidence will increase the volume of water that will flow onto islands during flooding and increase levee vulnerability. Subsidence and levee failure also cause local infrastructural damage. While data for costs for damages are incomplete, 11 of the 28 islands that flooded from 1969 to 1983 cost $177 million (Prokopovitch, 1985) to repair and reclaim. Depending on island location, the volume of flooding influences the extent of saline water intrusion into the Delta and subsequent water management decisions about water exports and releases from upstream reservoirs. Also, subsidence coupled with sea-level rise increases drainage volumes from Delta islands. This occurs because subsidence necessitates deepening of drainage ditches thus increasing the hydraulic gradient onto Delta islands. This increases drainage volumes over time and therefore loads of dissolved organic carbon and other constituents of concern to Delta channels.

[1] Subsidence is the downward movement of land surface. In this paper, we discuss and propose work relative to subsidence of island surfaces.

[2] Available data indicates the subsidence rate near the toe of the levee is substantially less than the island interiors. Recent data for an extensometer on Twitchell Island which is within 500 feet of the levee toe indicated subsidence rates ranging from 0.5 to 0.6 inches per year. These rates are generally consistent with rates measured and reported by Deverel and Rojstaczer (1996) and Rojstaczer and Deverel (1995) for soils with organic matter contents ranging from 5 to 15%. These organic matter percentages are characteristic of soils near the levee toe.

Topical Area: Subsidence

Relative to the environmental consequences working group, subsidence determines the depth of island flooding due to levee failure which influences the resultant habitat. Geomorphologically, the depth of island flooding affects channel flows and therefore influences the extent of scour of adjacent channels and the probability of additional levee failure.

Prior to 1850, the Delta was a freshwater tidal wetland. Farmers and laborers drained Delta soils for agriculture in the late 1800's and early 1900's (Thompson, 1957). This drainage resulted in subsidence or lowering of the land surface on over 60 islands from 5 to over 25 feet below sea level. A levee network protects the islands from flooding and directs water through the Delta. From 1930 to the early 1980's, over 50 Delta islands or tracts flooded due primarily to levee foundation instability (Prokopovitch, 1985). When most of the original Delta levees were constructed, island surfaces were less than 5 feet below sea level. Subsidence reduced the landmass and resistance to hydraulic pressure from adjacent channels. Although levees are periodically strengthened to compensate for this, many remain vulnerable to failure.

The organic or peat deposits of the Delta formed during the past 7,000 years from decaying wetland plants (Atwater, 1982; Shlemon and Begg, 1975). The reported causes of subsidence include aerobic microbial oxidation of soil organic carbon, anaerobic decomposition, consolidation, shrinkage, wind erosion, gas, water and oil withdrawal and dissolution of soil organic matter (Prokopovitch, 1985; Department of Water Resources, 1980; Weir, 1950). Researchers have not quantified the relative importance of different causes of subsidence in the Delta but work in other parts of the world provides relevant insight. For example, Stephens and others (1984) reported that 53 percent of historical subsidence in organic soils in the Florida Everglades was due to microbial oxidation. Schorthorst (1977) reported that compaction, shrinkage, and microbial oxidation caused 28, 20, and 52 percent of subsidence in the Netherlands.

Present-day subsidence of Delta organic soils is caused primarily by microbial oxidation of organic carbon (Deverel and Rojstaczer, 1996). Ongoing oxidation daily removes tens of thousands of cubic yards of soil and creates an equivalent volume below sea level. During the 6,000 to 7,000 years prior to the 1850's, about 5.1 billion cubic meters of tidal marsh sediment accumulated in the Delta. During the past 150 years, half of this volume disappeared. This has created an accommodation space of over 2 billion cubic meters below sea level that can be filled by flood waters (Mount and Twiss, 2005).

Recent subsidence estimates in the Delta are generally lacking. The most recently published rates (Deverel and others, 1998; Deverel and Rojstaczer, 1996; Rojstaczer and Deverel, 1995) range from 0.6 to 4 centimeters per year and are limited to 6 islands. These measurements provide useful information about historic subsidence rates but little information about how land-surface elevations have changed during the past 10 to 20 years. Deverel (1999) estimated historic Delta-wide subsidence rates using topographic maps from the early 1900s and mid-1970s. He estimated errors in these rates that ranged from about 30 to over 150% associated with mapping error.

To estimate elevation changes to 2050, Mount and Twiss (2005) used 1950 to 1980 elevation changes for three islands to adjust elevation changes from Shuttle Radar Tomography Mission (SRTM) data and historic U.S. Geological Survey (USGS) maps

for 1900 to 2000[3]. The SRTM data are reported as vertically accurate to about plus or minus 10 meters (U.S. Geological Survey, see the following Web site: http://seamless.usgs.gov/website/seamless/products/srtm1arc.asp). However, Mount and Twiss (2005) compared SRTM land-surface elevations with those determined with LIDAR and GPS and estimated elevation error to be about +0.24 m for average island elevations. The error is certainly larger at the smaller spatial resolution of individual islands.

Historical subsidence rates varied with soil organic matter content. Rojstaczer and Deverel (1995) showed that subsidence from 1910 to 1988 was significantly correlated with organic matter content on Sherman Island. Moreover, historic subsidence rates for Bacon and Mildred Islands and Lower Jones Tract (Deverel and others, 1998) were substantially higher than those on Sherman Island due to oxidation of higher organic matter soils. In the area affected by subsidence, surface soils range in soil organic matter content from less than 5 to over 50% (Figure 1). Organic matter content generally increases with depth. Highly organic mineral surface soils predominate in the western and northern Delta (Sherman, Twitchell, Brannan, Andrus, Grand, Tyler, Ryer, and northern Staten (Figure 1). True surface organic soils or histosols predominate in the central, eastern and southern Delta (Figure 2).[4] These are predominantly medisaprists[5] and include the Rindge, Kingile, Webile, Shinkee, and Shima soil series (McElhinney, 1992; Tugel, 1993). A small portion of less decomposed medihemist histosols are present in the central Delta (Figure 2) as the Venice soil series (McElhinney, 1992). Depositional environment and time since initial drainage for agriculture influence the present-day soil distribution.

Generally consistent with the recent soil surveys, Cosby (1941) described four primary soil types, Venice, Staten, Egbert, and Roberts, as representing different stages in alteration of the parent peat materials. The Venice soil on Venice, Mandeville, McDonald, and Bouldin Islands represented organic soils closest to the natural state. The Staten series which included soils throughout the central Delta represented further alteration of the virgin peat. The Egbert soils predominated in the western and northern Delta on Sherman, Twitchell, Brannan, Tyler, and northern Staten (similar to the distribution highly organic mineral soils shown in Figure 2). Cosby (1941) described the Egbert soils as having 30 to 40% organic matter. In contrast, the organic matter content of surface soils of the Venice and Staten soils were described as 50% or greater. The Roberts soil represented a further state of alteration and contained less organic matter (about 30% as per Cosby [1941]). The Roberts soils generally predominated in the same areas as the Egbert soils in the western and northern Delta.

[3] Deverel and others (1998) and Rojstaczer and others (1991) evaluated the results of elevation data collected on Lower Jones Tract, Bacon Island and Mildred Island from 1924 to 1981. Mount and Twiss (2005) used these data and estimated the change in subsidence rates from 1950 to 1981 relative to those from 1925 to 1981. The 1950 – 1980 rates were 20 to 40% less than the 1925 – 1981 rates. Conservatively, Mount and Twiss (2005) reduced the 1900 – 2000 elevation changes by 40% and used the reduced rates to predict subsidence rates to 2050.

[4] Histosols are generally defined has having more than 30% organic matter (Buol and others, 1973).

[5] Histosols are divided into four orders based on the degree of decomposition (Buol and others, 1973). Saprists are the most decomposed.

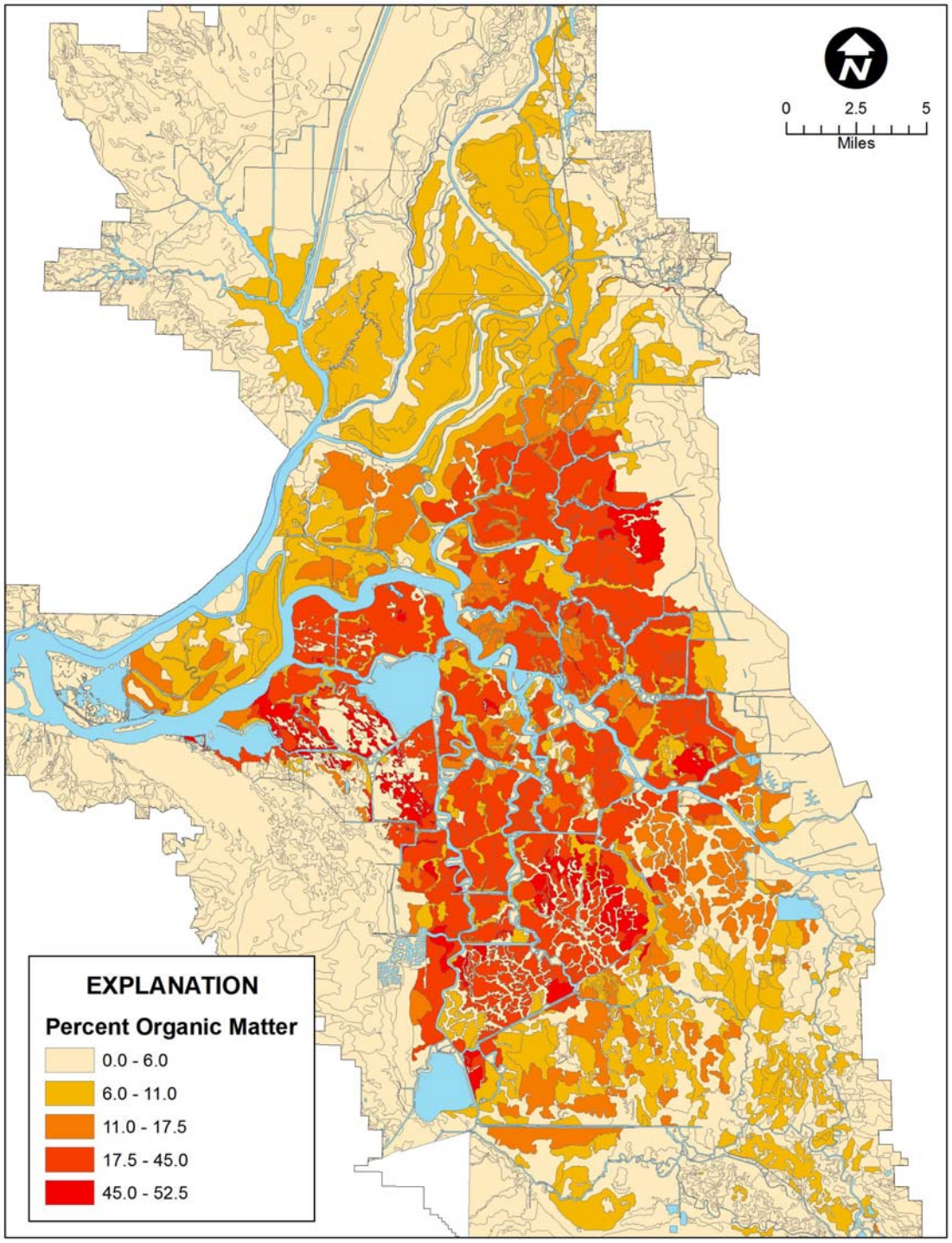

Figure 1 Distribution of percent soil organic matter.

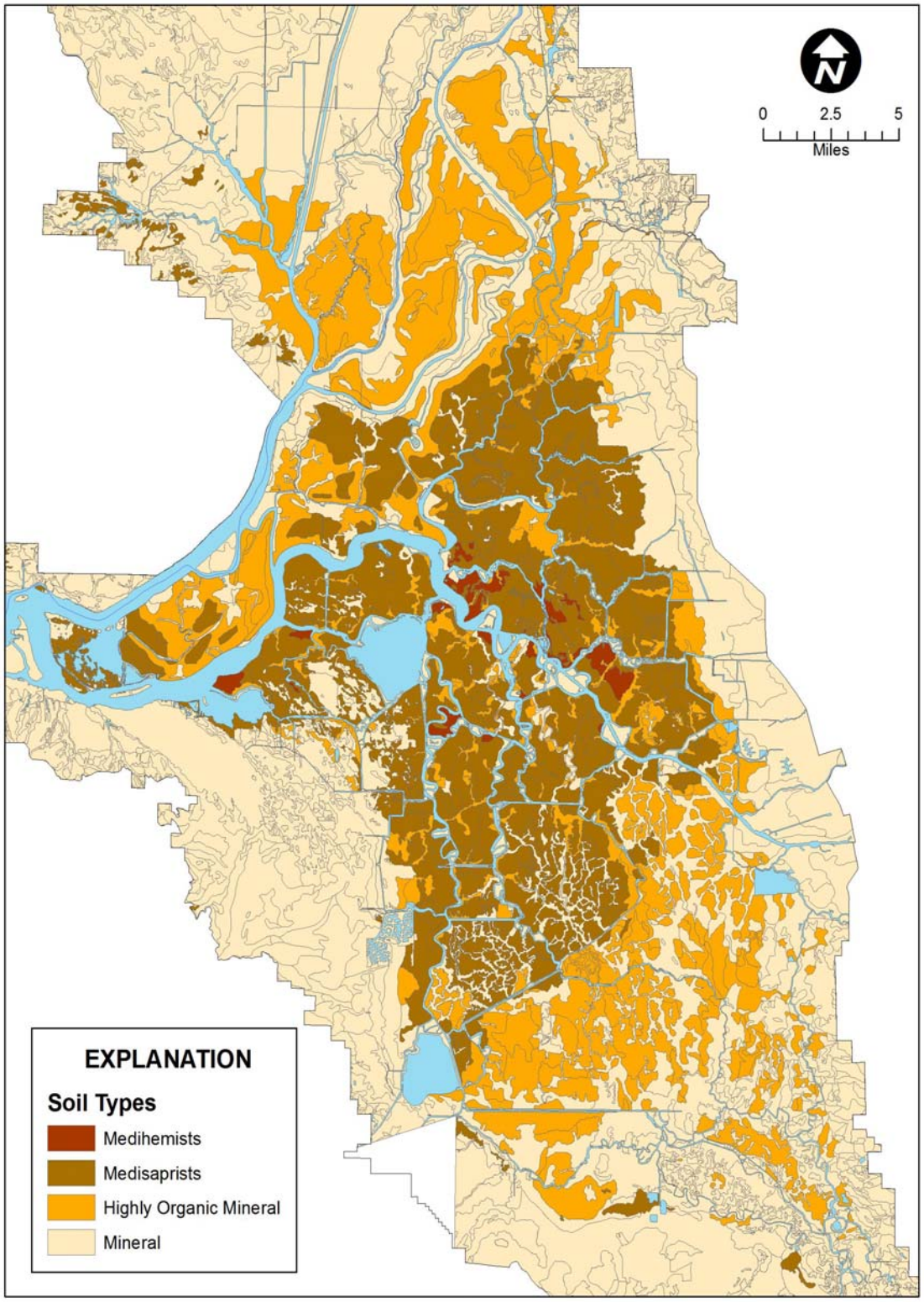

Figure 2 Distribution of soil types.

The lower organic matter soils predominate in areas that were drained prior to 1900 for agriculture and are near the Sacramento River. Figure 3 shows the distribution of dates of initial drainage for agriculture based on data provided in Thompson (1957). In general, islands in the western and northern Delta that coincide with the locations of highly organic mineral soils were initially drained during the latter half of the 19th century. In contrast, islands further east in the central and eastern Delta were initially drained during the late 19th century or early 20th century. Those islands near the Sacramento River may have, prior to development, been subject to greater fluvial mineral deposition relative to the more quiescent environment in the central and eastern Delta.

1.2 Suisun Marsh

The Suisun Marsh area is composed of both organic and mineral soils (Figure 4) (Bates, 1977). The most prominent organic soils are the Suisun peaty muck, the Joice muck, and the Tamba mucky clay. Reported organic matter content for these soil series ranges from 15 to 70 percent. The predominant mineral soils are the Reyes silty clay and Valdez silty clay loam. The Reyes silty clay is typically associated with Tamba mucky clay (Bates, 1977).

Land use in the Suisun Marsh is primarily riparian and native vegetation as reported by the 1994 Department of Water Resources land use survey of Solano County. Most of the land within the marsh consists of diked wetlands which are flooded most of the year. Approximately 85 percent of these wetlands are drained from mid July through mid September (Steven Chappell, November 2006, Suisun Marsh Resource Conservation District, personal communication).

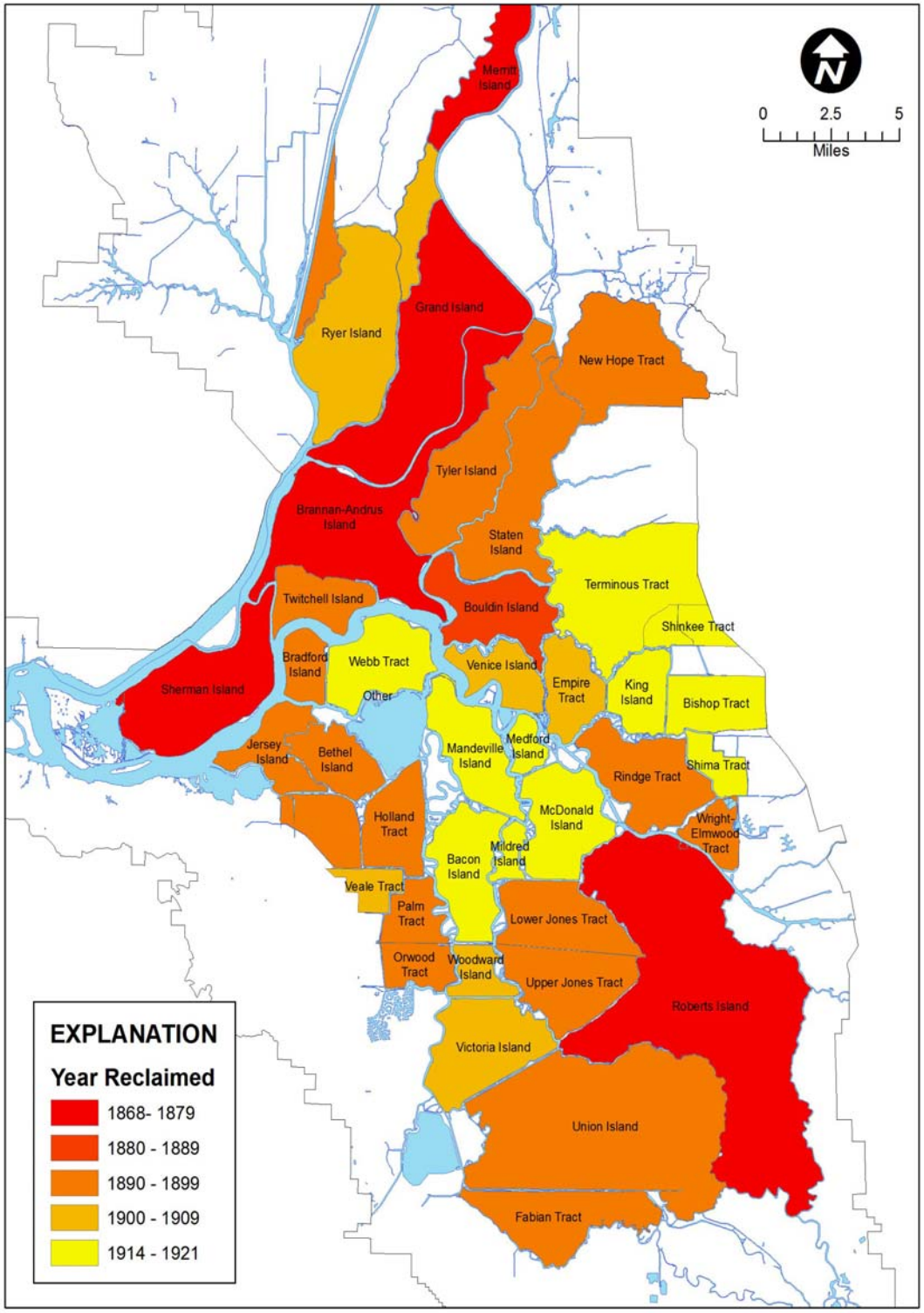

Figure 3 Year of initial drainage.

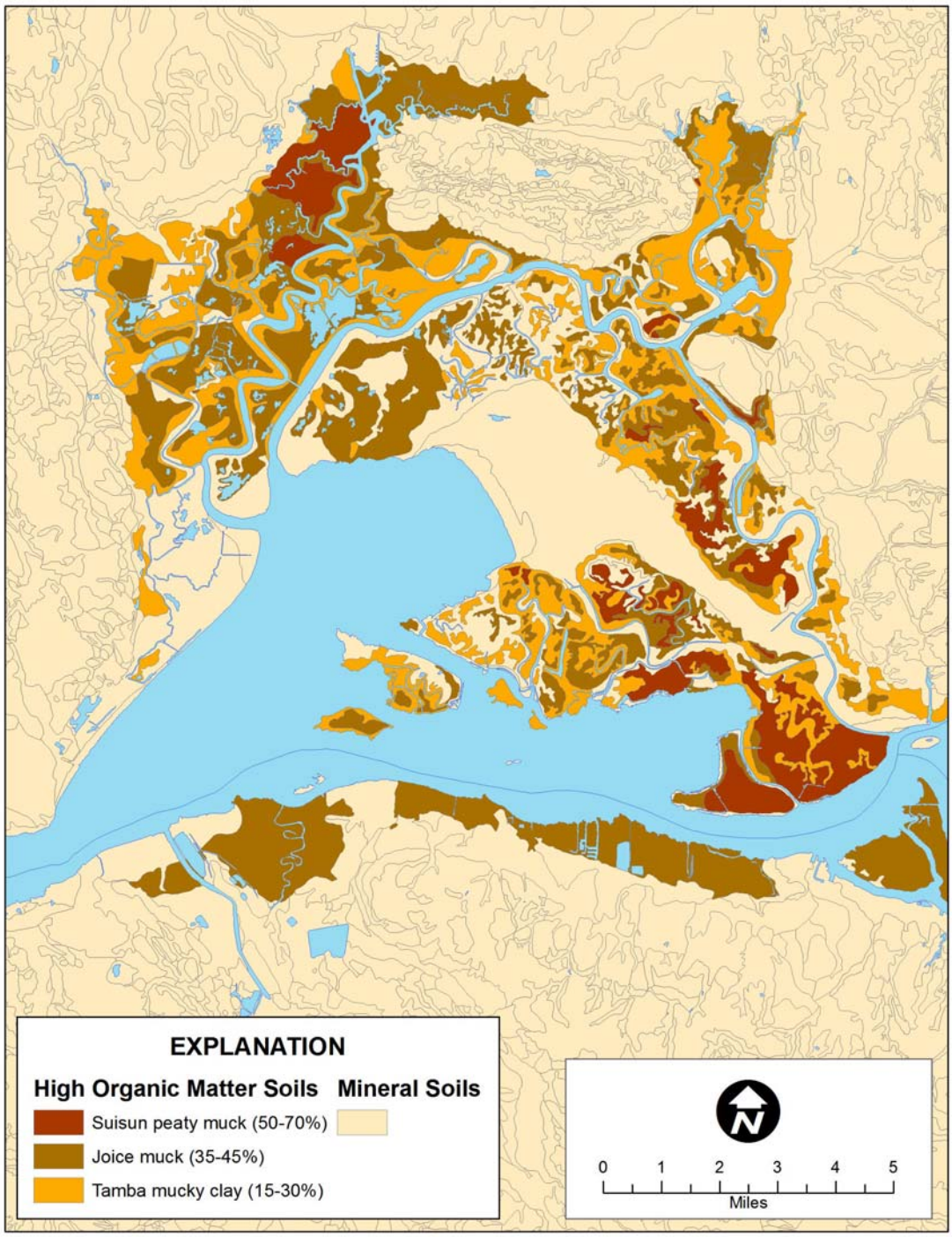

Figure 4 Distribution of soil series in the Suisun Marsh area.

1.3 Purpose and Scope

We utilized Delta-wide and island-specific data for soils and elevation to determine recent subsidence rates and estimate future subsidence rates for the Sacramento-San

Joaquin Delta. We used these data and calculations to estimate future Delta island elevations in 2050, 2100, and 2200. We utilized data for historic elevation changes for Suisun Marsh to estimate future subsidence rates and elevations. Future estimated elevations will be used by other project personnel to estimate effects on levee fragility, water supply, water quality and the ecology. Specific objectives of the work reported here follow.

1. Estimate the spatial distribution of current and future subsidence rates in the area of organic soils in the Sacramento-San Joaquin Delta and Suisun Marsh area.
2. Estimate future land surface elevations.
3. Estimate uncertainty and randomness in subsidence predictions.

2.0 Methodology

2.1 Elevation Determinations and Soil Sample Collection and Analysis in the Sacramento-San Joaquin Delta

To provide information about present-day subsidence rates, we determined elevations along the route described by Weir (1950) on Bacon Island. Walter Weir and colleagues measured land surface elevations starting in 1922 on Mildred Island, Bacon Island, and Lower Jones Tract (Figure 5). All elevations were determined relative to benchmark EBMUD 10.88 which has a current NGVD[6] 1929 elevation of 10.85 feet. Weir (1950) used an elevation of 10.88 feet. The last survey was completed in 1981. Rojstaczer and others (1991) analyzed the survey data and compiled elevations at discrete intervals along the survey route. We used copies of the original survey notes and maps to delineate the route on Bacon Island. (Mildred Island flooded in 1983 and was never drained. We could not measure elevations on Lower Jones Tract because the corn was too high when this work was approved).

[6] National Geodetic Vertical Datum of 1929.

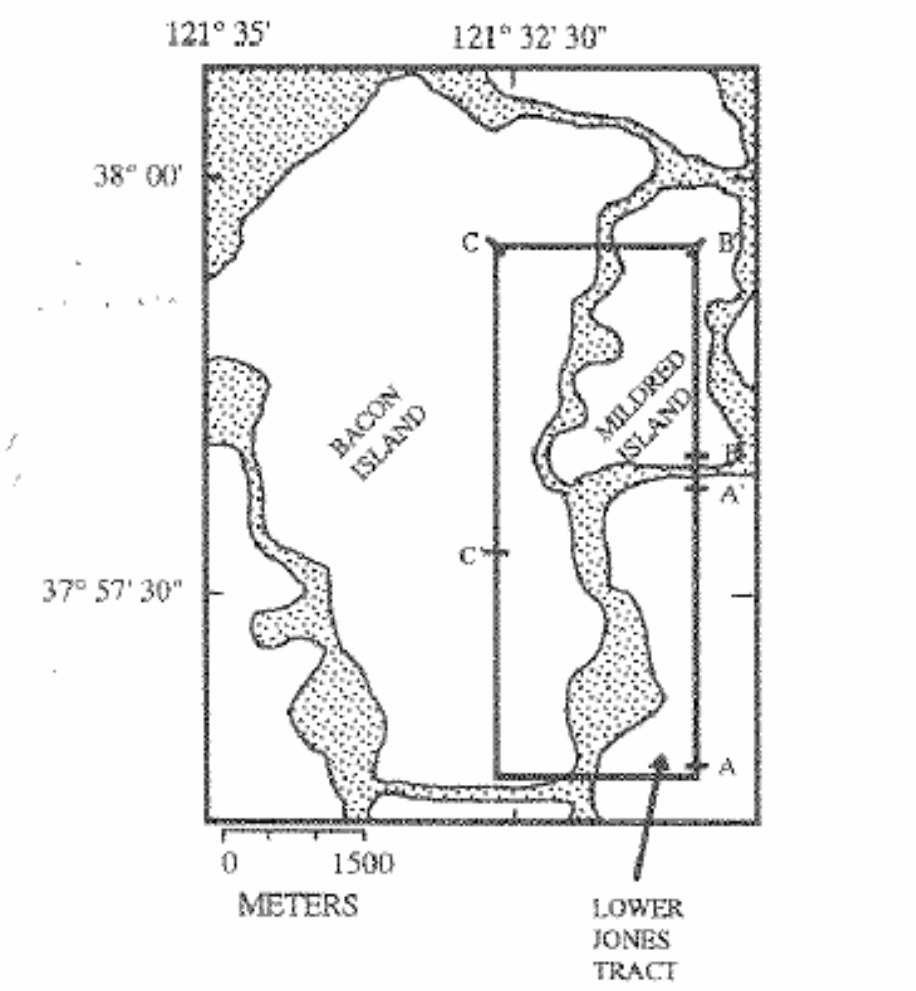

Figure 5 Approximate survey route followed by Weir et al. 1950.

Using traditional survey methods and Real Time Kinetic (RTK) and static Geographic Positioning System (GPS) measurements, we determined elevations and horizontal coordinates at 51 locations where Rojstaczer and others (1991) determined elevations in 1978 from survey notes provided by the University of California (Figure 6). (Land-surface elevations were not determined on Bacon Island in 1981.) The Bacon Island elevation and horizontal coordinate data were collected by Kjelson, Sinnock, and Neudeck, Inc. (KSN) of Stockton, California, as follows.

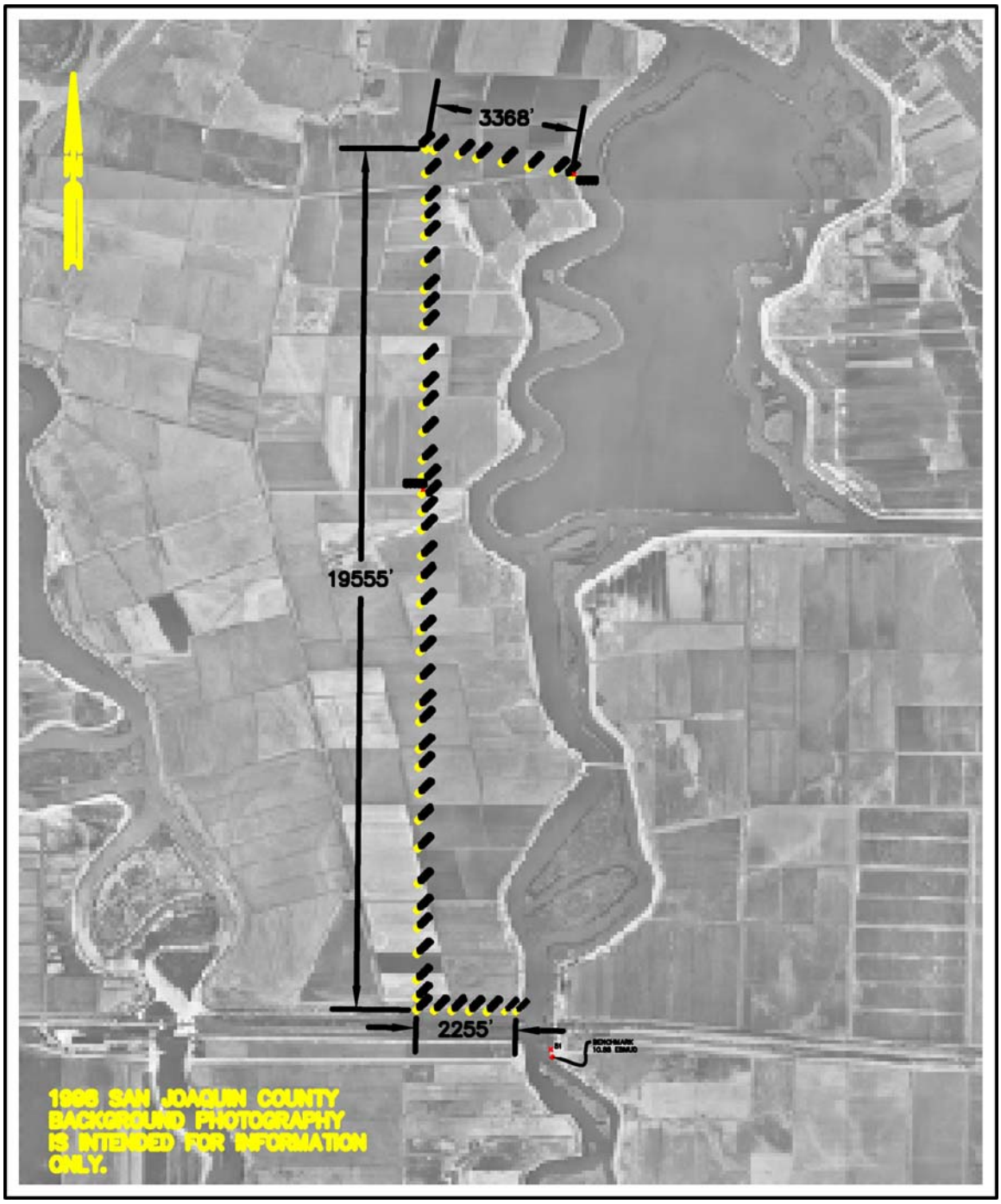

Figure 6 Locations of Elevation Determination on Bacon Island.

A primary static GPS control network of 3 points was established for the survey. The initial point for processing all GPS baselines was control point KSN 51. This control point was initially established in June 2004 with a thorough static GPS network that included several NGS control points within the Sacramento-San Joaquin River Delta GPS/Vertical Project. This point was adjusted to the 1997.30 epoch date. The elevation of control point 51 was determined by a closed loop level run from NGS Benchmark 10.88

EBMUD (PID HS3876) as part of the 2006 survey. We recovered the 10.88 EBMUD bench mark in good condition under approximately four feet of fill dirt. NGS has assigned a superseded National Geodetic Vertical Datum of 1929 (NGVD 29) elevation of 10.85 feet to this point, which was used for the 2006 survey.

Two control points were set for the survey; KSN 50001 and KSN 50002. The control points were used as temporary benchmarks to close out and adjust open level circuits. The static occupations for the primary network took place on July 20, 24, and 28 of 2006. Trimble Geomatics Office version 1.63 was utilized for processing and adjusting the GPS baselines. The average loop length for the network was 12,453.84 meters (40861.061 feet). The average horizontal misclosure was 0.00085 m (0.028 feet) and the average vertical misclosure was 0.002 m (0.007 feet). This translates to a 0.746 part per million error. A minimum constrained least square adjustment was performed and the network passed the chi square test at 95% with a 0.96 network reference factor. Orthometric elevations (NGVD 29) were determined with Geoid 2003. Estimated errors for the geoid separation across the network were 0.02 m (0.07 feet).

Each of the 51 points was located with RTK GPS from KSN control point 51. The elevation of these points was then determined with conventional differential leveling, with the exception of a series of 13 temporary benchmarks that were located in corn fields. In these areas line of sight leveling was not practical. These points, numbered 44010 – 44022, were occupied with RTK GPS from two different base stations (51 and 50001), and on two different days, under two different satellite geometry configurations. This ensured acceptable vertical tolerances for the position of the temporary benchmarks located in the corn fields. The elevations of the temporary benchmarks numbered 44001 – 44009 were determined with conventional differential leveling using the elevation at control point 50001. The elevations of the temporary benchmarks numbered 44023 – 44051 were also established with conventional differential leveling using the established elevations for 10.88 EBMUD and KSN control point 50002. Table 1 shows the coordinates and elevations of the control points and benchmark. Elevation differences between the two surveys (2006 and 1978) were used to estimate recent subsidence rates.

Table 1 Locations and Elevations of the Control Points and Benchmarks

Point Number	Northing	Easting	Elevation	Description
51	2165891.92	6264107.10	8.45	KSN Control
50001	2185763.19	6264640.89	7.46	KSN Control
50002	2178600.17	6261204.50	-10.06	KSN Control
	N/A	N/A	10.85	10.88 EBMUD (PID HS3876)
	N/A	N/A	16.73	16.75 EBMUD (PID HS3875)
	N/A	N/A	4.61	R 478 (PID HS3412)

Survey control is based on the North American Datum of 1983 (NAD 83) and converted to the California Coordinate System of 1983, Zone 3 (CCS83-Iii) as referenced by available NGS published control monuments. Elevations shown are base on the National Geodetic Vertical Datum of 1929 (NGVD 29) as referenced by available NGS and local published benchmarks. Units shown are based on the U.S. Survey Foot, Epoch Date 1997.30

In 1988 on Sherman Island, Rojstaczer and others (1991) determined soil loss at power pole foundations constructed in 1910, 1952, and 1963. At thirteen 1910 power poles, we

determined soil loss using identical methods to those described in Rojstaczer and others (1991). We did not measure soil loss against the 1952 power-pole foundations because they were re-installed since 1988 and the power line was re-positioned on Sherman and Jersey islands. Results presented in Rojstaczer and others (1991) indicated that the 1963 power-pole foundations were unreliable for estimating soil loss.

Rojstaczer and Deverel (1995) showed a correlation between soil organic matter content and subsidence for the 1910 and 1952 power pole foundations. We collected soil samples adjacent to the Sherman 1910 power pole foundations and at 43 of the temporary benchmarks on Bacon Island. Soil samples were collected with a 10-cm (4-inch) diameter bucket auger at 30 and 60 cm. The soil from the 0 to 30 cm and 30 to 60 cm depth intervals was mixed in the field and a subsample was collected in plastic bag and refrigerated. Samples were analyzed for total organic matter content by loss on ignition (Nelson and Sommers, 1982).

2.2 Analysis of Historical Subsidence Rates and Soils Data in the Sacramento-San Joaquin Delta

Using standard multiple regression analysis, we evaluated data for percent soil organic-matter from McElhinney (1992) and Tugel (1993) and historic elevation changes relative to location and year of drainage (Thompson, 1957) to preliminarily evaluate possible processes affecting subsidence rates.

2.3 Estimation of Future Subsidence Rates in the Sacramento-San Joaquin Delta

We estimated spatially variable future subsidence rates for 50, 100 and 200 years by using the correlation of soil percent organic matter and subsidence rates. In 25-year intervals, we assigned a range of subsidence rates (see Section 4, Uncertainty Analysis of Subsidence Rates) to each soil series based on the soil organic matter-subsidence rate correlation, projected temperature changes and variance in soil organic matter. For the medisaprist and medihemist soils in the central and eastern Delta, we used the regression equation for the subsidence rate-soil organic matter relation for the Bacon Island data. For the organic mineral soils and the Rindge series soils in the western and northern Delta, we assigned subsidence rates based on the power-pole and soils data collected on Sherman Island.

For future subsidence estimates, we assumed that for each soil series that the subsidence rate will change as a function of soil organic matter content. We estimated the change in soil organic matter content and subsidence rate as follows. For each 30 cm of subsidence, we estimated the mass of mineral material remaining and incorporated this into the next 60 cm of soil and calculated the new organic matter content. This new soil organic matter content was used to estimate a new subsidence rate based on the regression of subsidence rate to organic matter content. The underlying organic soil was assumed to have 30 to 40% more organic matter than the subsided 30 cm of surface soil based on data presented in Deverel (1983) and data for Twitchell Island provided by Jacob Fleck at the USGS. Primary uncertainties in these estimates include 1) the soil-organic matter-subsidence rate regression equation and 2) the spatial variability in soil organic-matter content.

Future soil temperatures will likely increase in the Delta due to predicted climate change. Deverel and Rojstaczer (1996) showed that the logarithm of soil carbon loss, the primary cause of subsidence, was significantly correlated with soil temperature. For estimates of temperature effects on future subsidence we assumed that shallow (30 cm) soil temperatures will change proportional to atmospheric temperatures. Probability distributions of future estimates of air temperature changes were provided by Phil Duffy (Lawrence Berkeley Laboratory, 2006). These were based on probabilistic projections of changes in seasonal-mean near-surface air temperatures obtained from Mike Dettinger of the USGS and UC San Diego. The probabilistic nature of the projections arise from using results from 13 independent climate models and 3 greenhouse gas emissions scenarios.

We estimated that subsidence rates will increase based on the temperature dependence of the logarithmic change in carbon emissions from Deverel and Rojstaczer (1996). For the mean for future estimates, we used the average of the equations for Jersey Island, Orwood Tract, and Sherman Island. This resulted in the approximate doubling (1.95 times) of carbon flux (and therefore the subsidence rate) with a 10°C temperature rise. For the high and low future subsidence estimates, we used the range of values for temperature effects for the data reported by Deverel and Rojstaczer (1996). Specifically, for the low and high estimates, this would result in 1.6 and 2.4 fold increases in subsidence rates with 10° C temperature rises, respectively. We seasonally weighted the temperature effect based on data described in Deverel and Rojstaczer (1996). Specifically, the majority of carbon loss occurred during summer and fall due to higher temperatures and lower groundwater. We therefore, weighted the temperature effect on subsidence by multiplying the change in the estimated subsidence rate by the seasonal percentage and adding the products and dividing by 100. The primary uncertainty in this estimate results from the probabilistic nature of the temperature predictions and the uncertainty in the temperature-soil organic matter relation.

Using ARC GIS Spatial Analyst, we calculated new land-surface elevations for 2050, 2100, and 2200 based on the temperature-dependent spatially variable subsidence rates described above. Specifically, for the mean estimate we used the regression relations for western and central soils based on the regression equations for Sherman and Bacon islands. We also used the mean temperature-carbon flux relation which results in a 1.95 fold increase in the subsidence rate with a 10° C temperature increase. We also used the median of the range of values for soil organic matter content provided in Tugel (1993) and McElhinney (1992). For the low and high subsidence estimates, we used 1) the upper and lower range of the 95% confidence intervals for the slope and intercept for the subsidence rate-soil organic matter regression relations, 2) the upper and lower values from the range of soil organic matter content values in Tugel (1993) and McElhinney, (1992) and, 3) the upper and lower values for the regression equation parameters for the temperature-carbon flux relations from Deverel and Rojstaczer (1996).

We used the bottom elevation of the organic soil or peat as the constraint for the extent of soil loss[7]. We incorporated the distribution of the peat bottom elevation as a grid file into ARC GIS. The grid spacing is about 61 meters. This distribution was based on over 6,000 borings and data reported by Atwater (1982). We proceeded to subtract elevation based

[7] URS Corporation provided a grid file with bottom of peat elevations on October 20, 2006.

on estimated subsidence rates at 10-year intervals. This represented about 30 cm of subsidence for the highest organic matter soils. If the organic mineral soil or histosol disappeared in this time frame, the subsidence rate was set to zero. Further assumptions follow.

- Land use will not change except for rice growing areas.
- For rice-growing areas on Bouldin Island, Bract Tract, and Wright-Elmwood Tract, we set the subsidence rate as zero based on data from Miller and others (2000).
- For specific pasture areas as determined from Department of Water Resources Land Use maps for Sherman, Jersey, and Bradford islands, we adjusted subsidence rates based on observed shallower water tables based on information provided in Stephens and others (1984). For example, a groundwater table of about 30 cm below land surface results in about 20% of the subsidence rate compared to a groundwater table at 120 cm for identical soil organic matter content and temperature regimes.
- We set the subsidence rate to zero where or when the soil organic matter content was less than or equal to 2%.

2.4 Suisun Marsh Elevation Changes

We were unable to find data for historical subsidence rates for Suisun Marsh. We estimated historical subsidence rates at 151 points by comparing elevations posted on 7.5-minute quad maps (Figure 7) with 2006 elevations determined using Light Detection and Ranging (LIDAR) technology obtained from the Department of Water Resources (Joel Dudas, DWR, November, 2006).

Elevation data posted on the most recent 7.5-minute quad maps covering the Suisun Marsh area (Denverton, Fairfield South, Honker Bay, and Vine Hill) were determined from surveys conducted in 1948-50. Posted elevations were generated from level line or stadia traverse surveying. These have an accuracy of about plus or minus 1.0 ft (John Sellars, U.S. Geological Survey Geodetic Control Office, Denver, Colorado, November 7, 2006). We estimated uncertainty associated with the LIDAR data by comparing the LIDAR elevations with the elevations at National Geodetic Survey control points determined using GPS methods. The root mean square error (RMSE) calculated from the difference between the LIDAR and control point elevations was 1.18 ft.

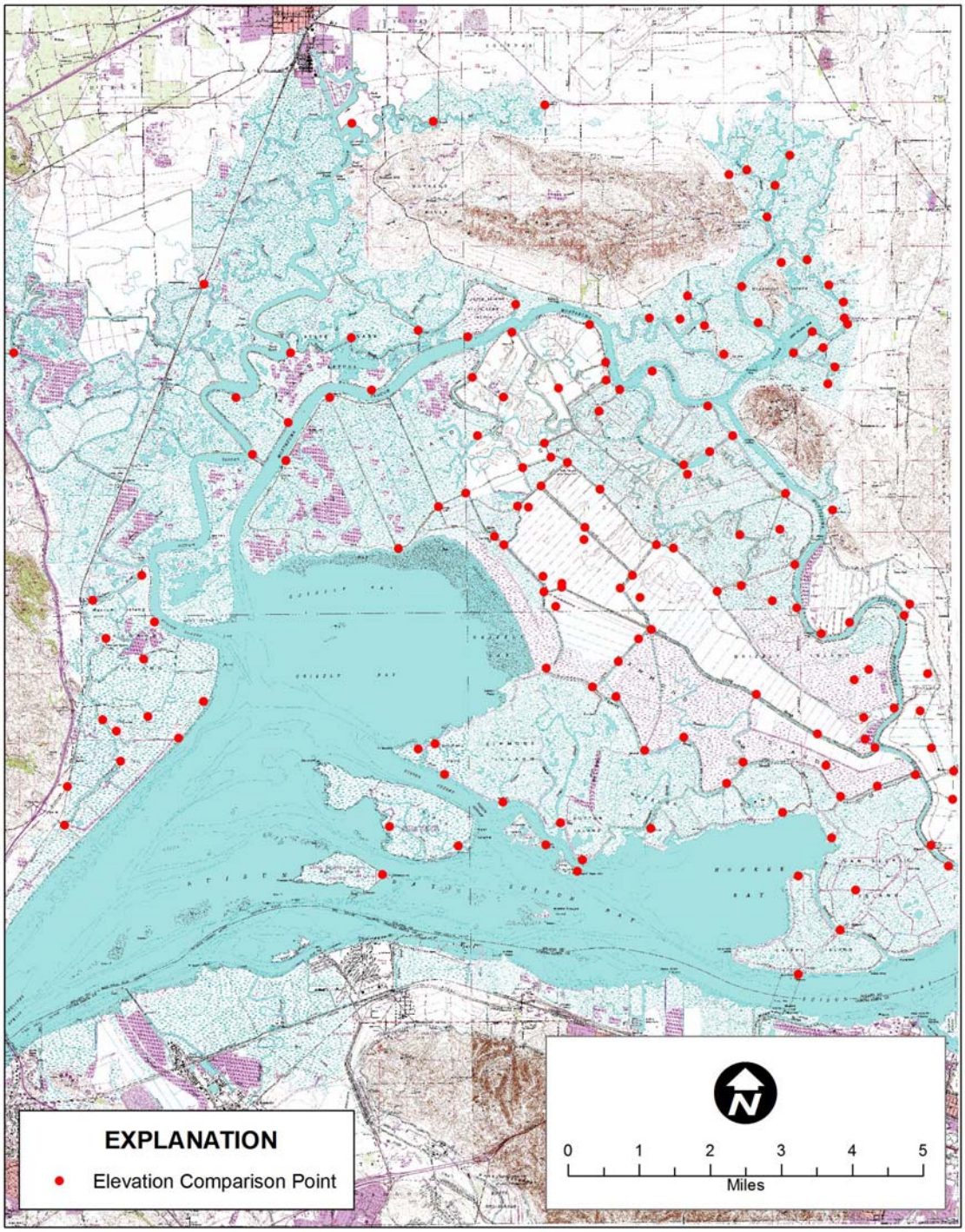

Figure 7 Location of points used to estimate Suisun Marsh subsidence rates.

We calculated the difference between the elevations posted on the maps and the elevations in the LIDAR dataset and used the elevation differences to estimate rates for this 56-58 year period. We used the uncertainties associated with these elevations to estimate the upper and lower bounds of our Suisun Marsh subsidence estimates. These

rate estimates are summarized by soil series in Table 2. Negative rates represent an increase in elevation.

Table 2 Subsidence Rate Estimates for Suisun Marsh by Soil Series

Soil	Data Points	Rate, cm/yr		
		Low	Median	High
Alviso silty clay loam	1	-1.22	0.00	1.13
Antioch-San Ysidro complex	2	0.70	1.84	2.97
Joice muck	11	0.24	1.43	2.80
Pescadero clay loam	1	-2.50	-1.34	-0.18
Reyes silty clay	42	0.12	1.34	2.53
Suisun peaty muck	2	1.14	2.47	3.79
Tamba mucky clay	43	0.23	1.58	2.88
Tidal marsh	10	0.23	1.60	3.16
Valdez silt loam	1	-0.58	0.61	1.80
Valdez silty clay loam	38	0.08	1.62	3.02

Because we had no information about rates and processes affecting subsidence, we assumed that future subsidence rates would equal historic rates shown in Table 2. Due to the uncertainty in the elevation estimates, the uncertainty in the estimated historic subsidence rates from about 1950 to 2006 was almost 100%. We used the range of rates shown in Table 2 to estimate the range of future elevation changes.

3.0 Results

3.1 Recent and Historic Subsidence Rates and Soil Organic Matter in the Sacramento-San Joaquin Delta

Figure 8 shows the average change in elevation for Bacon Island from 1922 to 2006. Average land-surface elevation changes along the transect have remained relatively constant since 1958. From 1924 to 1955, the subsidence rate was 7.2 cm/year (2.83 inches/year). The average annual rate from 1958 to 2006 was about 2.9 cm (1.16 inches) (40% less than the 1924 – 1955 rate). The 1958 – 2006 rate was slightly higher than the average subsidence rate from 1978 to 2006 of 2.2 cm/year (0.87 inch/year) measured during this study. The 1978-2006 rate was 30% of the 1922 – 1955 rate. The rate change from the pre-1955 period to the present was in large part due to changing land-management practices.

Specifically, prior to 1960, burning for weed and disease control was common. Weir (1950) stated that 3 to 5 inches of soil were lost during burning which occurred every 3 to 5 years. There was no burning on Bacon Island after the 1950's (Alan Carlton, former UC Cooperative Extension Specialist, personal communication, 1997). Wind erosion also contributed to subsidence primarily where the soil was bare during the spring in asparagus fields (Schultz and Carlton, 1959; Schultz and others, 1963). Rojstaczer and others (1991) showed that asparagus was grown throughout the 1970's along the Bacon transect so it is unlikely that less wind erosion caused the subsidence-rate change from pre to post 1955 shown in Figure 8. Crops that cover the soil during the spring (corn, alfalfa, and safflower) are currently grown on Bacon Island.

Figure 9 indicates that that the Bacon Island average subsidence rate declined exponentially since the 1920's. Data collected by Weir and colleagues on Mildred Island and Lower Jones Tract also indicate exponential or logarithmic declines in subsidence rates.

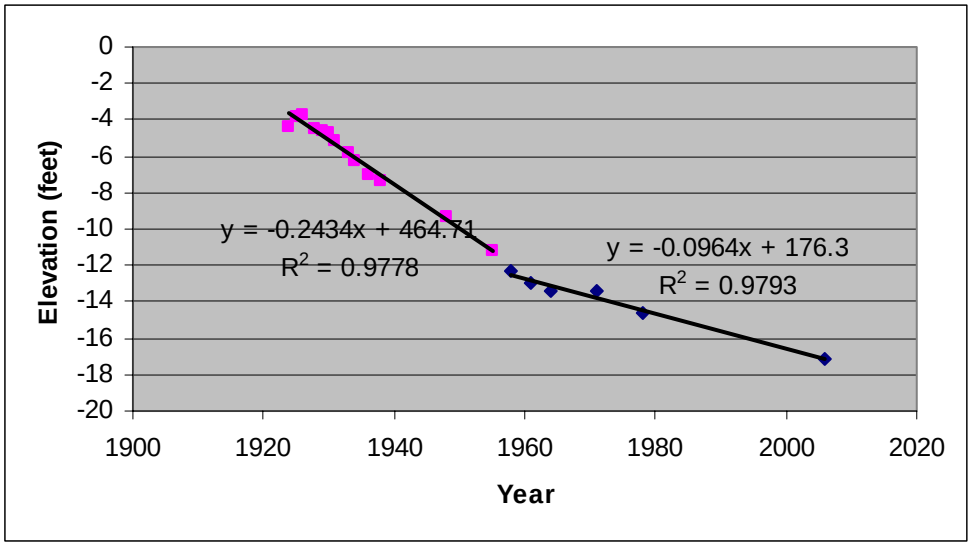

Figure 8 Average elevation change on Bouldin Island.

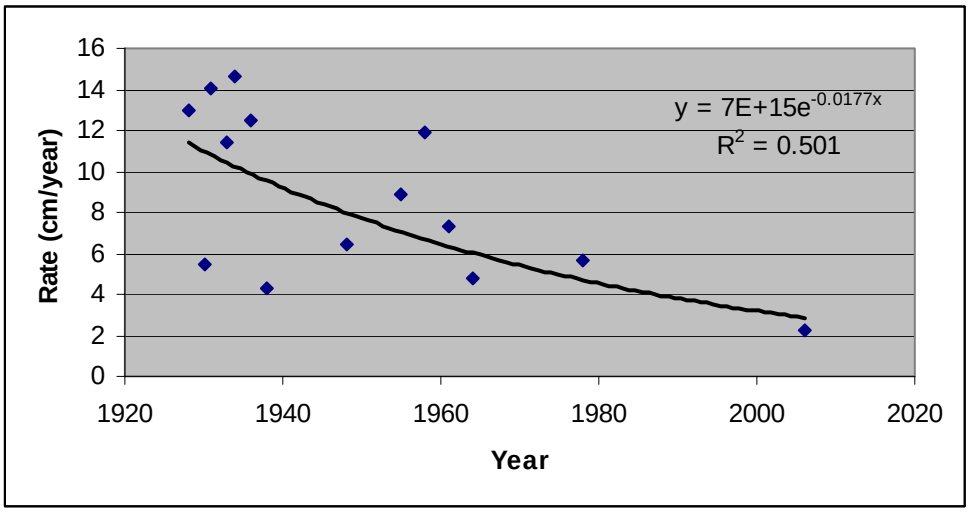

Figure 9 Subsidence rate changes on Bacon Island.

Figure 10 shows that the relation of subsidence rates and soil organic matter percent for the Bacon Island histosols explains about 56% of the variance in subsidence rates. The Rindge and Kingile series are the predominant soil series on Bacon Island and the only histosols present on the transect. Both are classified as medisaprists (McElhinney, 1992).

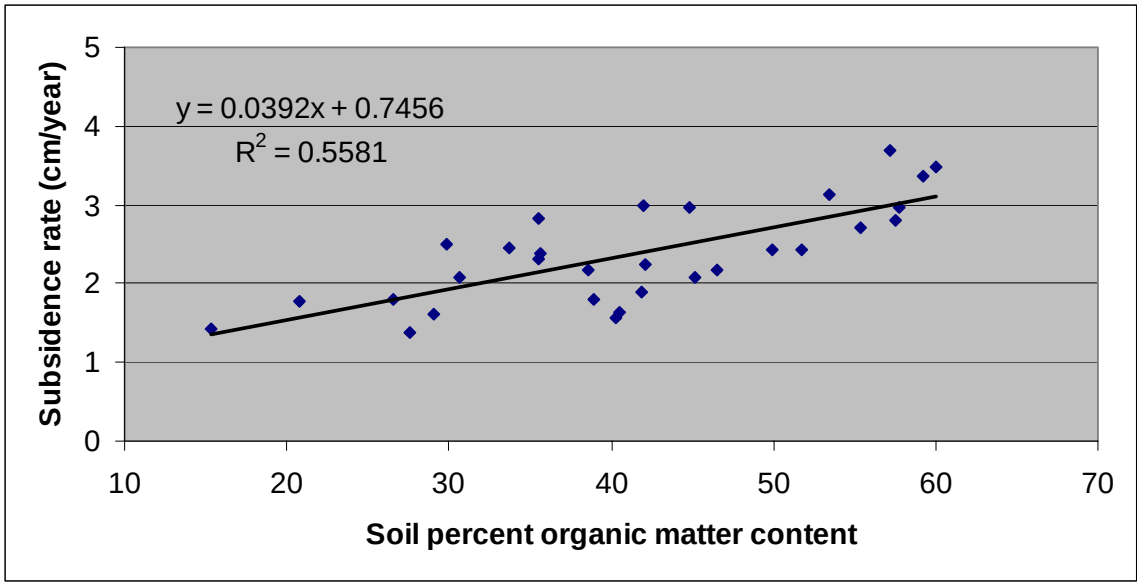

Figure 10 Relation of subsidence rates to soil organic matter content for Bouldin Island.

For Sherman Island, Figure 11 shows subsidence rates have slowed relative to data presented in Rojstaczer and others (1991). For 3 of the 13 power pole foundations, calculated soil loss rates were greater than historical rates. However, for power pole 274, the original notes stated that there were new foundations in 1988 so the original measurements may not have truly reflected the 1910-1988 rate. Power pole 287 overlies and is adjacent to a disposal area containing used tires, machinery, etc. The uneven terrain probably affected our ability to effectively measure elevations. For power pole 281, the original field notes indicated uncertainty in the survey measurements. Soil organic matter content varied from 0.93 to 19.6%. The average subsidence rate for the measured power poles from 1988 to 2006 was 1.38 cm/year. The average rate for same power poles measured in 1988 was 2.01 cm/year from 1910 to 1988 or about 35% greater than the 1988-2006 rate.

Figure 12 shows that there was a significant correlation between subsidence rates and percent organic matter for the power pole foundations located on the Gazwell soil series[8]. All of the power pole foundations were located on the highly organic mineral soil, Gazwell mucky clay soil except for pole number 280 which was located on the mineral soil Columbia silt loam.

[8] For figure 12, we removed the power pole foundation data for pole numbers 274 (new power poles in 1988), 287 (disposal area), and 299 because there was measurement uncertainty in the original notes.

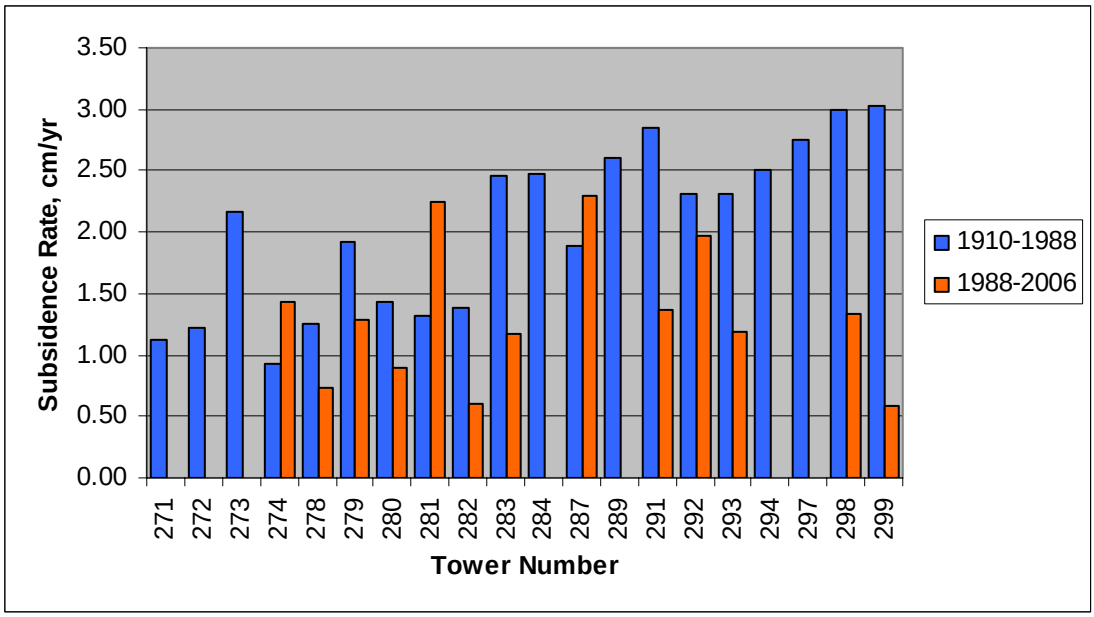

Figure 11 Subsidence rates measured against power pole foundations on Sherman Island.

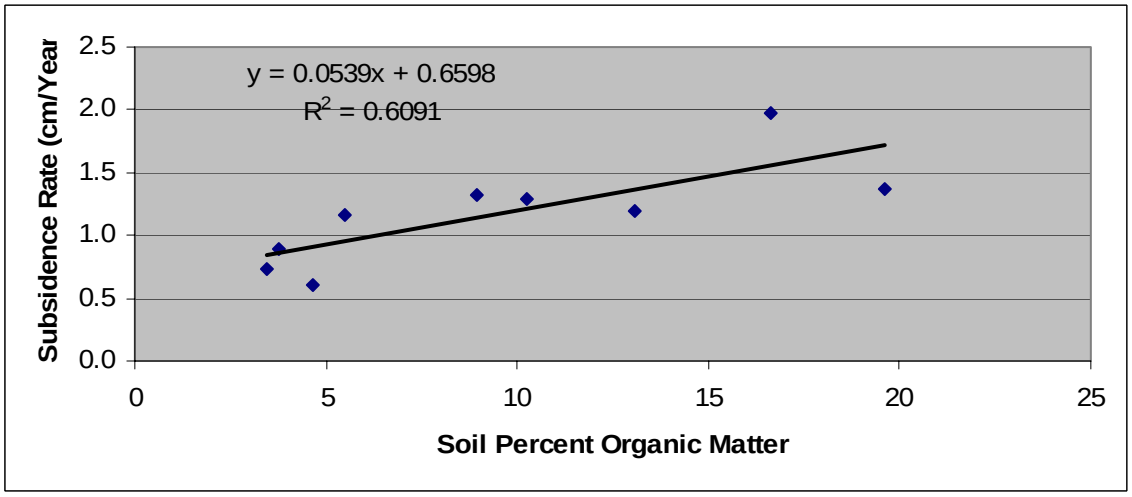

Figure 12 Relation of subsidence rate to organic matter content for Sherman Island data.

3.2 Delta-Wide Relation of Historical Subsidence Rates and Soil Organic Matter Content

For the entire Delta, we also evaluated the relation of soil organic matter content and historical subsidence rates from about 1906 to 1998. We used topographic maps for the circa 1906 elevations and IFSAR data (Damon and Daniel, 2000) for the 1998 elevations. We calculated the difference between the two elevations divided by the intervening time

as the historic subsidence rate. We obtained soil organic matter percentages from Tugel (1993) and McElhinney (1992). The relation of subsidence rates to percent organic matter is statistically significant (alpha = 0.01) (r^2 = 0.13) and the equation, subsidence rate (cm/year) = 0.0436 x percent organic matter + 1.959 is similar in slope to the equation shown in Figure 10 and Figure 15 (below). Multiple regression analysis using date of initial drainage substantially improved the explanation of the variance in subsidence. Specifically, the regression equation

> rate,(cm/yr) = - 91.95 + 0.027 x soil organic matter fraction + 0.05 x date of initial drainage,

explained 26% of the variance in subsidence rates. This regression relation was statistically significant at alpha = 0.01.

Date of initial drainage varied regionally, as shown in Figure 3. In general, western and northern islands that were drained first in the late nineteenth century. Central Delta islands were drained in the early 20th century. Multiple regression analysis using location (east and central versus western and northern) as an independent variable yielded a similar r^2 value to the regression using date of initial drainage. However, addition of island location (eastern central versus western and northern) as a third independent variable in the multiple regression equation was not statistically significant. A key source of uncertainty in the regression analysis is the soil organic matter percent. There is a range in soil organic matter percentage for the soil series which is not represented in the regression analysis as we used the midpoint of the range reported in Tugel (1993) and McElhinney (1992).

3.3 Estimation of Future Subsidence Rates in the Sacramento-San Joaquin Delta

We estimated future subsidence rates based on estimated increased mineral content of the surface soil due to loss of organic matter. We used the relation of subsidence rate to soil organic matter to estimate changing subsidence rates. Consistent with the observed trends in subsidence rates for Bacon Island, Mildred Island, and Lower Jones Tract, this methodology resulted in an exponential decline in soil organic matter content and subsidence rates. However, there is little data with which to compare our results. For Bacon Island, Mildred Island, and Lower Jones Tract, there is no available soil organic matter data for comparison and development of equations relating historic subsidence to soil organic matter content.

There are some historic data for Sherman Island. Specifically, Deverel and Rojstaczer (1996) reported soil organic matter content for soil samples collected adjacent to power pole foundations in 1991. Also, Cosby (1941) reported an approximate 1935 organic matter content for western Delta soils of 30 to 40%. (Cosby [1941] did not provide data but provided these two values in the report narrative). We used these data to assess the validity of our approach for estimating future soil organic matter content and subsidence rates. Figure 13 shows the estimated soil organic-matter content changes from 1935 to 1988 for Sherman Island compared with the Rojstaczer and Deverel (1995) data. Considering the spatial variability in soil organic matter content and the uncertainty in Cosby's numbers, Figure 13 indicates general agreement. This and the exponential

decrease in subsidence rates observed on Bacon Island, Mildred Island, and Lower Jones Tract point to the general validity of our approach for estimating changes in organic matter content and changing subsidence rates.

However, uncertainty remains in how the soil organic matter-subsidence rate relation will change over time. For example, the regression equation for the Sherman data in Rojstaczer and Deverel (1995) was

rate,(cm/yr) = 1.4 + 4.34 x fraction soil organic matter.

For the 2006 data, the equation was

rate,(cm/yr) = 0.66 + 5.34 x fraction soil organic matter.

We attempted to capture this uncertainty by using the known range of soil organic matter content values and the regression equation variance as described in the uncertainty discussion.

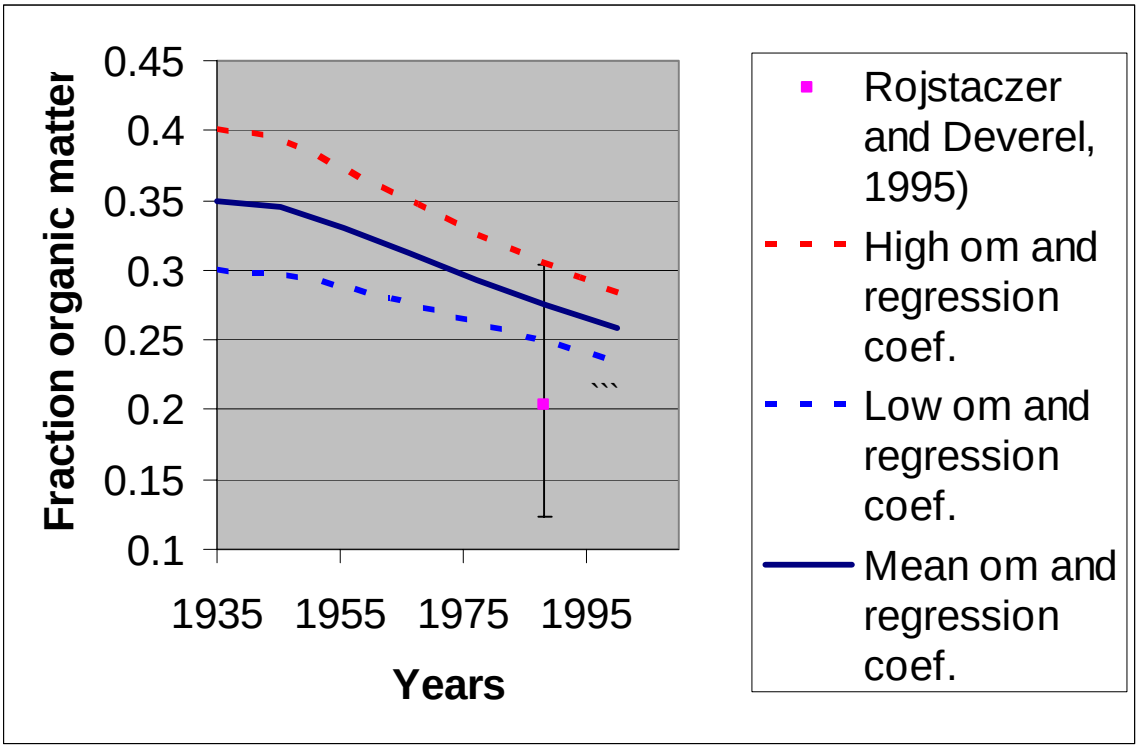

Figure 13 Estimated change in soil organic matter content for Sherman Island.

Figure 14 shows the estimated future change in soil organic matter content for a typical central Delta soil (Kingile muck) having an initial organic matter content of 40%. The fitted lines show the exponential decline in the fraction of soil organic matter and subsidence rates. We used an initial soil organic matter content of 40% and estimated subsidence rates to 200 years based on the organic matter – subsidence relation for the Bacon Island data.

As a check on our calculations, we compared the estimated the carbon loss rate resultant from our methodology and that reported in Deverel and Rojstaczer (1996). Deverel and

Rojstaczer reported carbon losses for Jersey Island, Sherman Island, and Orwood Tract for soils that ranged from 20 to 28% organic carbon. As an example on Jersey Island, the reported organic matter content was 20% and the bulk density was 0.96. Using the regression equation, we estimated a subsidence rate of 1.5 cm/year. Assuming 50 percent porosity and that the organic matter is 50% carbon (Broadbent, 1960), 30 cm of subsidence liberates about 22 kg of carbon in 20 years. This corresponds to a carbon flux of about 0.0003 g C/cm^2-day, which his consistent with results of carbon flux measurements shown in Figure 2 of Deverel and Rojstaczer (1996). Similarly, for Orwood Tract and Sherman Islands (soil organic matter contents of 24 and 28%, respectively) we estimated carbon fluxes of about 0.0004 g/ cm^2-day.

Projected temperature effects on future subsidence rates initially offset the effect of decreasing organic matter content and result in minimal change in estimated initial future subsidence rates. Average temperature increases to 2050 and 2099 ranged from 1.6 to 2.6^{o}C and 2.4 to 3.7^{o}C, respectively. As described above, we adjusted the effect on the subsidence rate seasonally and using the temperature-carbon flux relations described in Rojstaczer and Deverel (1995). We attempted to account for the varying effect of temperature on subsidence rates by considering the estimated variation in future temperature increases and the temperature-subsidence rate relation (see Section 4, Uncertainty Analysis of Subsidence Rates, for more detail).

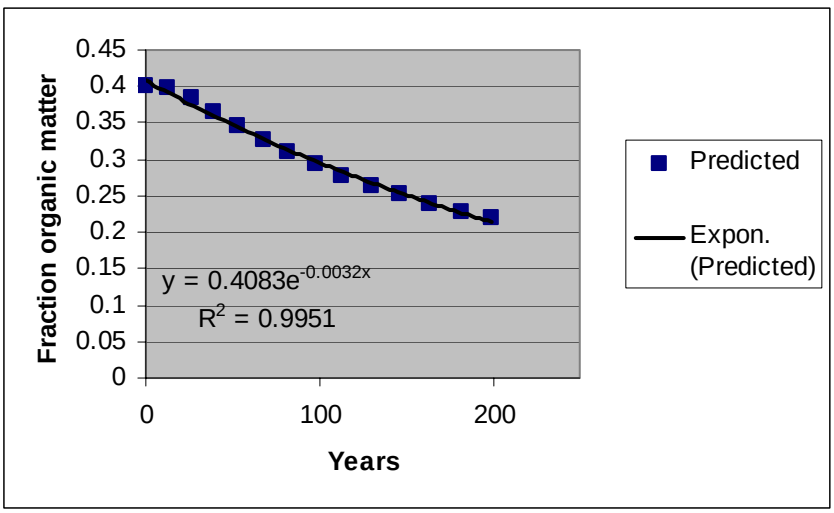

Figure 14 Estimated changes in soil organic matter content for typical Central Delta soil.

3.4 Estimated Future Subsidence Rates for Suisun Marsh

Estimated Suisun Marsh subsidence rates ranged from 0.0 to 2.47 cm/yr for 151 observation points shown in Figure 7. Elevation comparisons showed a positive rate (accretion) for some of the observation points. We assumed that estimated accretion was probably due to error in elevation measurements and that there was no change in land surface elevation changes. Organic soils had the highest observed subsidence rates and the rates were significantly correlated with average soil organic mater content for those soils having organic matter content data (Figure 15). Data obtained for soil organic matter

from Bates (1977) ranged from about 2% to 70%. Rates were generally lower than historic rates for Sacramento-San Joaquin Delta soils with similar organic matter content. This is probably the result or wetter conditions under different management practices.

For the prediction of future subsidence rates, we assumed that future subsidence rates would be similar to past rates. We recognize that many of the points used to determine elevation differences are on or near levees. However, over the 56- to 58 year period between elevation measurements, the elevation differences probably primarily reflect organic soil subsidence. The correlation of soil organic matter content and subsidence rates provides evidence for this. Due to lack of data we did not simulate changes in soil organic matter content or future subsidence rates. We assigned an upper and lower rate based the uncertainty in the elevation data used to estimate the historic rates. Mineral soils were given low and mean rates of zero.

The high subsidence rate for mineral soils was determined from the Topo-LIDAR elevation change analysis. Non-zero subsidence rates were assigned to Reyes silty clay which is a non-organic soil based on the description in Solano County Soil Survey (Bates, 1977). However, the Reyes silty clay is poorly drained soil associated with the Tamba Mucky clay. We therefore assumed that estimated subsidence rates associated with this soil series are probably the result of oxidation of organic matter. We used the same GIS methods used for the Delta to estimate future land surface elevations for 2050, 2100, and 2200.

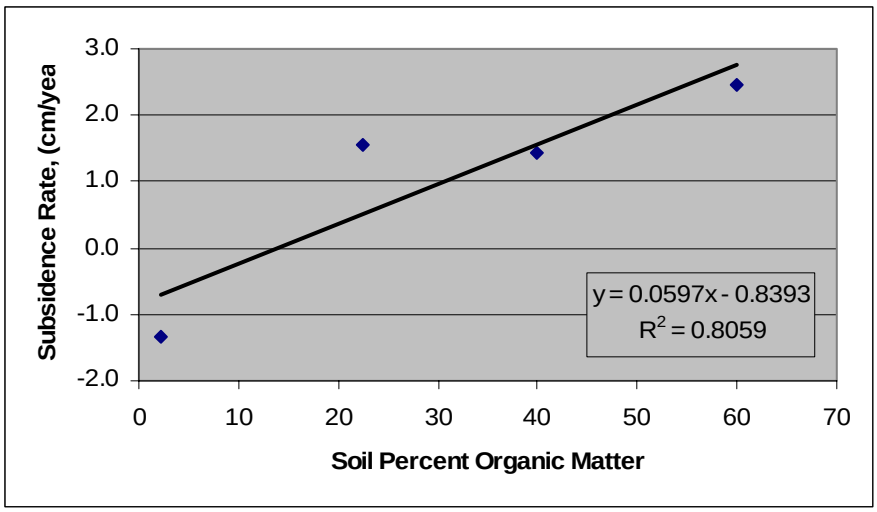

Figure 15 Relation of subsidence rate to organic matter content for Suisun Marsh.

3.5 Estimated Future Land Surface Elevations and Volume Below Sea Level in the Sacramento-San Joaquin Delta

We used the projected subsidence rates and GIS methodology described above to estimate future land surface elevations for 2050, 2100, and 2200 and volume below sea level for 1998, 2050, and 2100 for the Delta. Table 3 shows the volumes below sea level for 1998, 2050, 2100 based on the uncertainty in subsidence rates described below. We assumed a sea level rise of 0.20, 0.50, and 1.1 feet by 2050 and 0.36, 1.1, and 2.4 feet by

2100 for the five scenarios, respectively based on Cayan and others (2006). Our estimates indicate an average increase of about 655,000 acre-feet below sea level (plus or minus about 400,000 acre-feet) by 2050. By 2100, we estimated the average increase in volume below sea level will be 1,289,00 acre-feet (plus or minus about 700,000 acre-feet). We did not estimate volumes for 2200 due to uncertainty in sea level rise.

Table 3 Estimated Volumes Below Sea Level for 1998, 2050 and 2100 in Acre-Feet

Year	Lowest Estimate	Intermediate Low Estimate	Mean Estimate	Intermediate High Estimate	Highest Estimate
1998			1,893,500		
2050	2,289,100	2,436,200	2,556,500	2,660,800	2,880,600
2100	2,680,300	2,949,900	3,163,400	3,323,100	3,641,200

Figures 16A, 16B, and 16C show the distribution of estimated elevation change in the Delta for the periods 1998–2050, 1998–2100, and 1998–2200, respectively. Our calculations indicate 3 to over 4 feet of subsidence will occur in the central Delta by 2050. Less elevation loss (1 to 3.3 feet) will occur in the western, northern, and southern Delta where soil organic matter contents are lower. Specifically, elevation losses on Sherman, Brannan-Andrus, Grand and other western, northern, and southern islands range from less than 0.3 foot to about 3.3 feet. We estimated very low subsidence for areas of Sherman Island where pasture is the primary land use and soil organic matter contents are low. We estimated that over 9 feet of subsidence will occur in the central Delta by 2100. By 2200, we estimated that over 18 feet of subsidence will occur in some parts of the central Delta. Subsidence rates depend on the soil types with larger elevation decreases corresponding to higher soil organic matter contents shown in Figure 2.

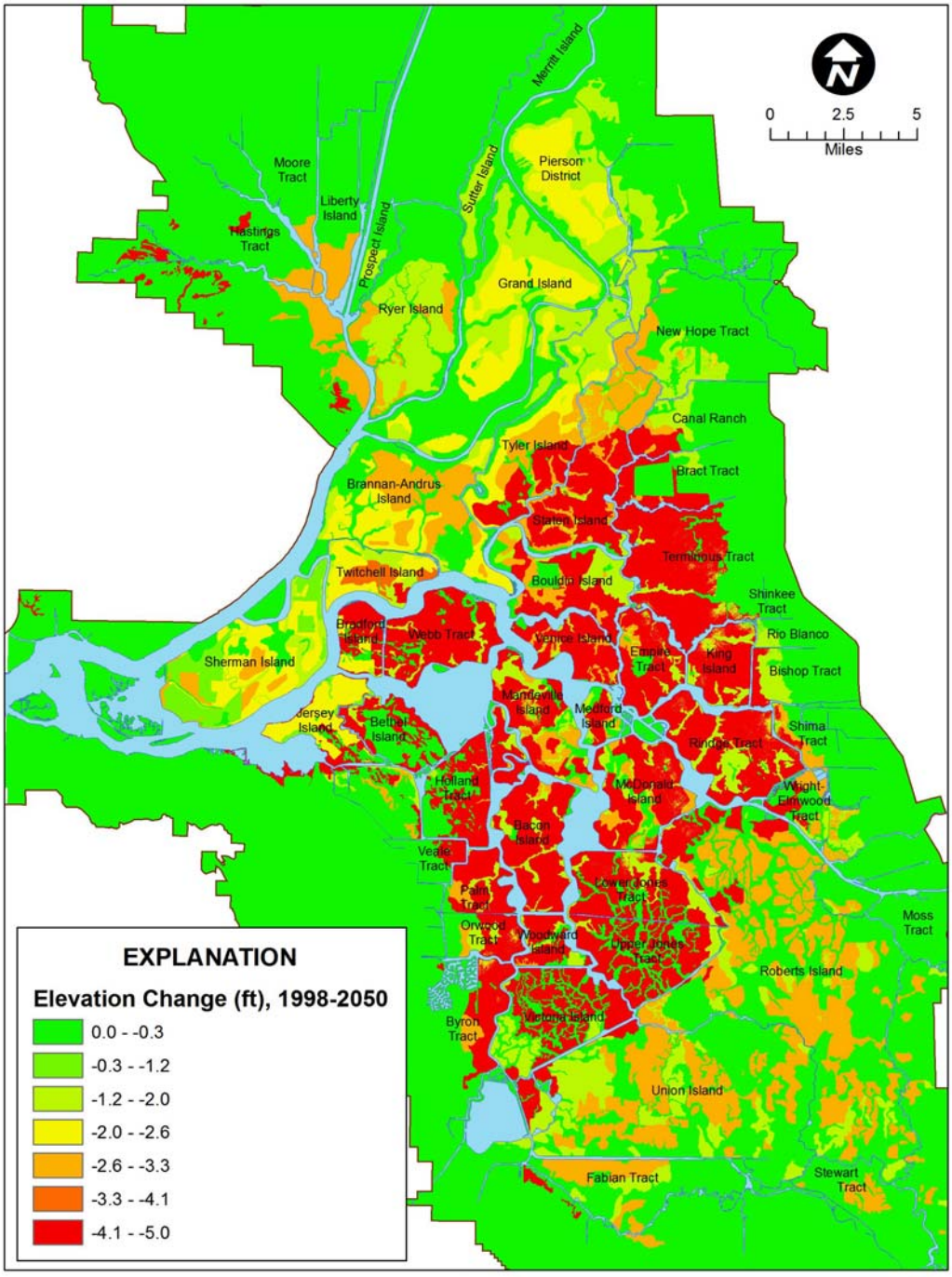

Figure 16A Estimated land-surface elevation changes from 1998 to 2050 for the Delta.

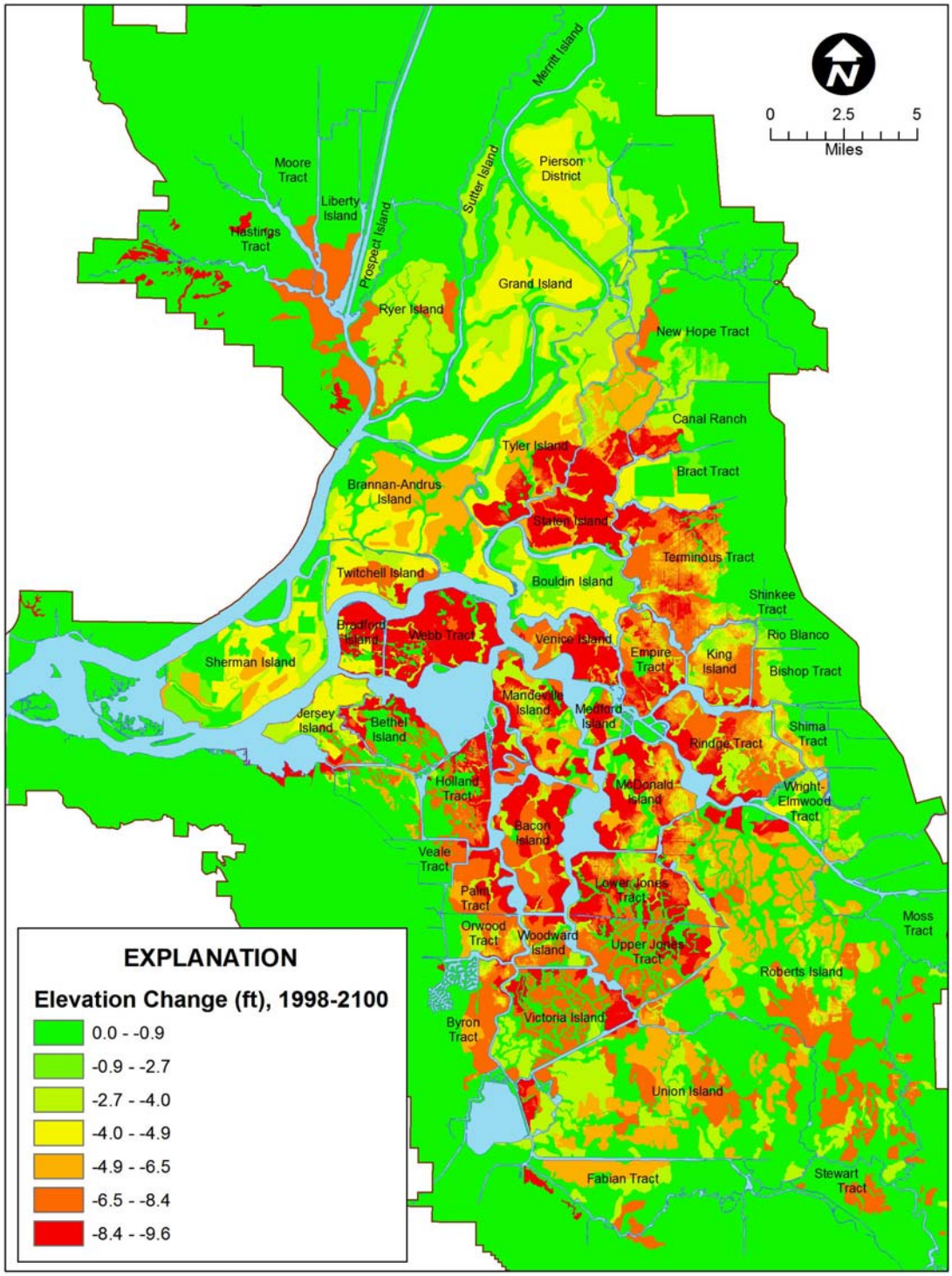

Figure 16B Estimated land-surface elevation changes from 1998 to 2100 for the Delta.

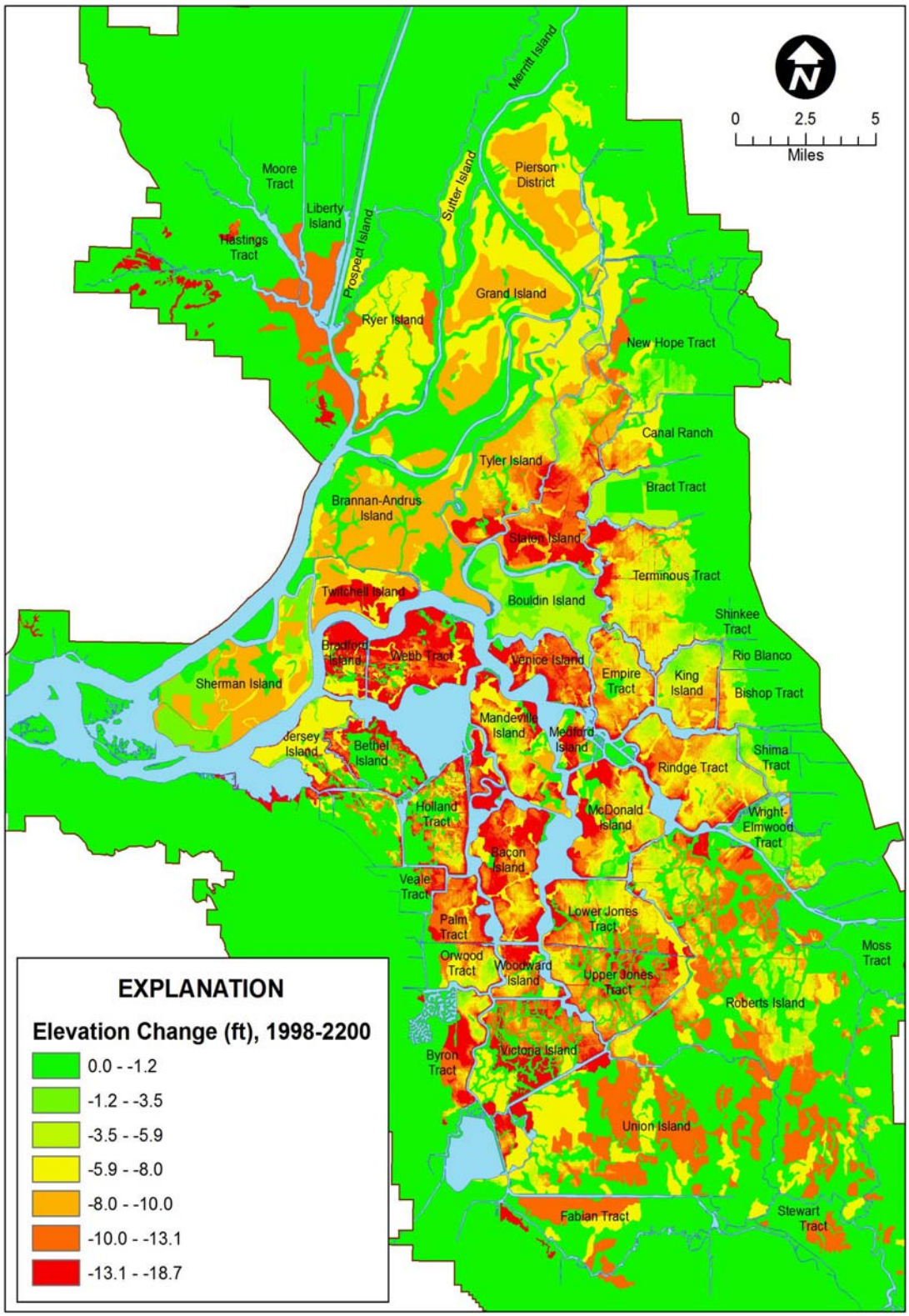

Figure 16C Estimated land-surface elevation changes from 1998 to 2200 for the Delta.

Figures 17A and 17B show the distribution of volume change for the periods 1998-2050 and 1998-2100, respectively. The percent increase in volume below sea level varies primarily by island size within the area of histosols and highly organic mineral soils. Specifically, Roberts, Staten, Terminous, and Union Islands contribute the largest percentage of volume increase. Table 4 shows the volume below sea level by island for 2050 and 2100 and the percent of volume increase attributable to each island. For both 2050 and 2100, over 65 percent of the volume increase was due to subsidence on the following islands: Bacon, Brannan-Andrus, Grand, Lower and Upper Jones, Mandeville, McDonald, Rindge, Ryer, Sherman, Staten, Terminous, Tyler, Union, Victoria, and Webb.

3.6 Estimated Future Land Surface Elevations and Volume Below Sea Level in Suisun Marsh

We used the projected subsidence rates and GIS methodology described above to estimate future land surface elevations in Suisun Marsh for 2050, 2100, and 2200 and volume below sea level for 2006, 2050, and 2100. Table 5 shows the volumes below sea level for 2006, 2050, and 2100 for the range of estimated subsidence rates. We used the same sea level rise estimates as were used for the volume calculations for the Delta.

Our estimates indicate an average increase in volume below sea level of about 37,000 acre-feet by 2050 and 134,500 by 2100. The volume increase by 2050 ranges from about 5,600 acre-feet for the lower subsidence rates to about 126,000 acre-feet for the upper rates. By 2100, the volume increase ranges from about 15,000 to about 410,000 acre-feet for the range of subsidence rates.

Figures 18A, 18B, and 18C show the distribution of estimated elevation change in Suisun Marsh for 2006-2050, 2006-2100, and 2006-2200, respectively. Our calculations indicate that up to 3.6 feet (+/- 2.0 feet) of subsidence will occur in Suisun Marsh by 2050. By 2100 up to 7.6 feet (+/- 4.2 feet) of subsidence will occur and by 2200 we estimate that up to 15.7 feet (+/- 8.5 feet) of subsidence will occur.

Figure 17A Percent volume-below-sea-level contribution by island from 1998 to 2050.

Figure 17B Percent volume-below-sea-level contribution by island from 1998 to 2100.

Table 4 Estimated Volumes Below Sea Level and Percent Contribution by Island for 2050 and 2100

Island	Volume (acre-feet)		Percent of Volume Increase from 1998	
	2050	2100	2050	2100
Atlas Tract	30	50	0.0%	0.0%
Bacon Island	90,734	112,882	3.6%	3.6%
Bethel Island	20,150	26,352	1.1%	1.0%
Bishop Tract	8,912	12,581	0.6%	0.6%
Bouldin Island	83,999	87,374	0.4%	0.5%
Bract Tract	37,489	39,763	1.2%	0.8%
Bradford Island	22,566	29,813	1.1%	1.1%
Brannan-Andrus Island	183,748	211,567	4.2%	4.3%
Browns Island	2	3	0.0%	0.0%
Byron Tract	31,707	41,377	1.7%	1.6%
Canal Ranch	21,679	28,316	1.1%	1.1%
Coney Island	7,507	10,754	0.5%	0.5%
Dead Horse Island	1,309	1,736	0.1%	0.1%
Decker Island	1	2	0.0%	0.0%
Empire Tract	67,990	79,910	2.3%	2.1%
Eucalyptus Island	1	1	0.0%	0.0%
Fabian Tract	4,828	11,676	0.6%	0.8%
French Island	0	33	0.0%	0.0%
Grand Island	133,684	160,925	4.0%	4.2%
Hastings Tract	2,036	4,657	0.2%	0.3%
Holland Tract	44,244	54,528	2.1%	1.8%
Ida Island	0	0	0.0%	0.0%
Jersey Island	34,165	41,768	1.4%	1.3%
Kimball Island	0	0	0.0%	0.0%
King Island	41,675	50,379	2.0%	1.7%
Liberty Island	2	3,606	0.0%	0.3%
Little Hastings Tract	0	499	0.0%	0.0%
Little Mandeville Island	441	1,778	0.1%	0.1%
Lower Jones Tract	79,023	97,010	3.3%	3.1%
Mandeville Island	90,919	105,558	2.8%	2.5%
McCormack-Williamson Tract	525	2,045	0.1%	0.1%
McDonald Island	104,899	122,724	3.5%	3.1%
Medford Island	15,151	18,561	0.6%	0.5%
Merritt Island	95	194	0.0%	0.0%
Moore Tract	378	1,436	0.1%	0.1%
Moss Tract	229	291	0.0%	0.0%
New Hope Tract	7,852	13,917	0.6%	0.8%
Orwood tract	21,797	27,002	1.0%	0.9%
Palm Tract	30,337	39,862	1.6%	1.5%
Pierson District	29,273	44,814	2.1%	2.3%
Prospect Island	295	634	0.0%	0.0%
Quimby Island	10,031	13,069	0.5%	0.5%

Island	Volume (acre-feet)		Percent of Volume Increase from 1998	
	2050	2100	2050	2100
Rindge Tract	106,584	127,862	4.3%	3.8%
Rio Blanco	1,946	2,525	0.1%	0.1%
Roberts Island	150,705	206,115	7.2%	8.0%
Rough and Ready Island	1,058	1,950	0.1%	0.1%
Ryer Island	76,580	98,912	3.0%	3.3%
Sherman Island	113,853	132,451	2.8%	2.9%
Shima Tract	5,222	6,997	0.4%	0.3%
Shinkee Tract	2,229	2,746	0.1%	0.1%
Staten Island	144,509	176,577	5.4%	5.2%
Stewart Tract	1	10	0.0%	0.0%
Sutter Island	4,447	6,942	0.3%	0.3%
Terminous Tract	120,944	146,165	5.7%	4.8%
Tinsley Island	1	1	0.0%	0.0%
Twitchell Island	50,111	60,544	1.6%	1.6%
Tyler Island	107,759	132,428	3.9%	3.9%
Union Island	55,535	92,931	4.1%	5.0%
Upper Jones Tract	60,979	80,550	3.3%	3.2%
Veale Tract	5,094	7,205	0.3%	0.3%
Venice Island	60,734	73,317	2.1%	2.0%
Victoria Island	75,422	95,814	3.2%	3.2%
Ward Island	0	0	0.0%	0.0%
Webb Tract	93,076	114,662	3.6%	3.5%
West Island	1	1	0.0%	0.0%
Woodward Island	23,946	29,928	1.0%	1.0%
Wright-Elmwood Tract	14,392	15,704	0.7%	0.4%
Other	43,558	70,218	2.6%	3.4%

Table 5 Estimated Suisun Marsh Volumes Below Sea Level for 2006, 2050, and 2100 (in Acre-Feet)

Year	Low Estimate	Mean Estimate	High Estimate
2006	5,758		
2050	11,379	42,907	131,834
2100	20,848	140,272	416,329

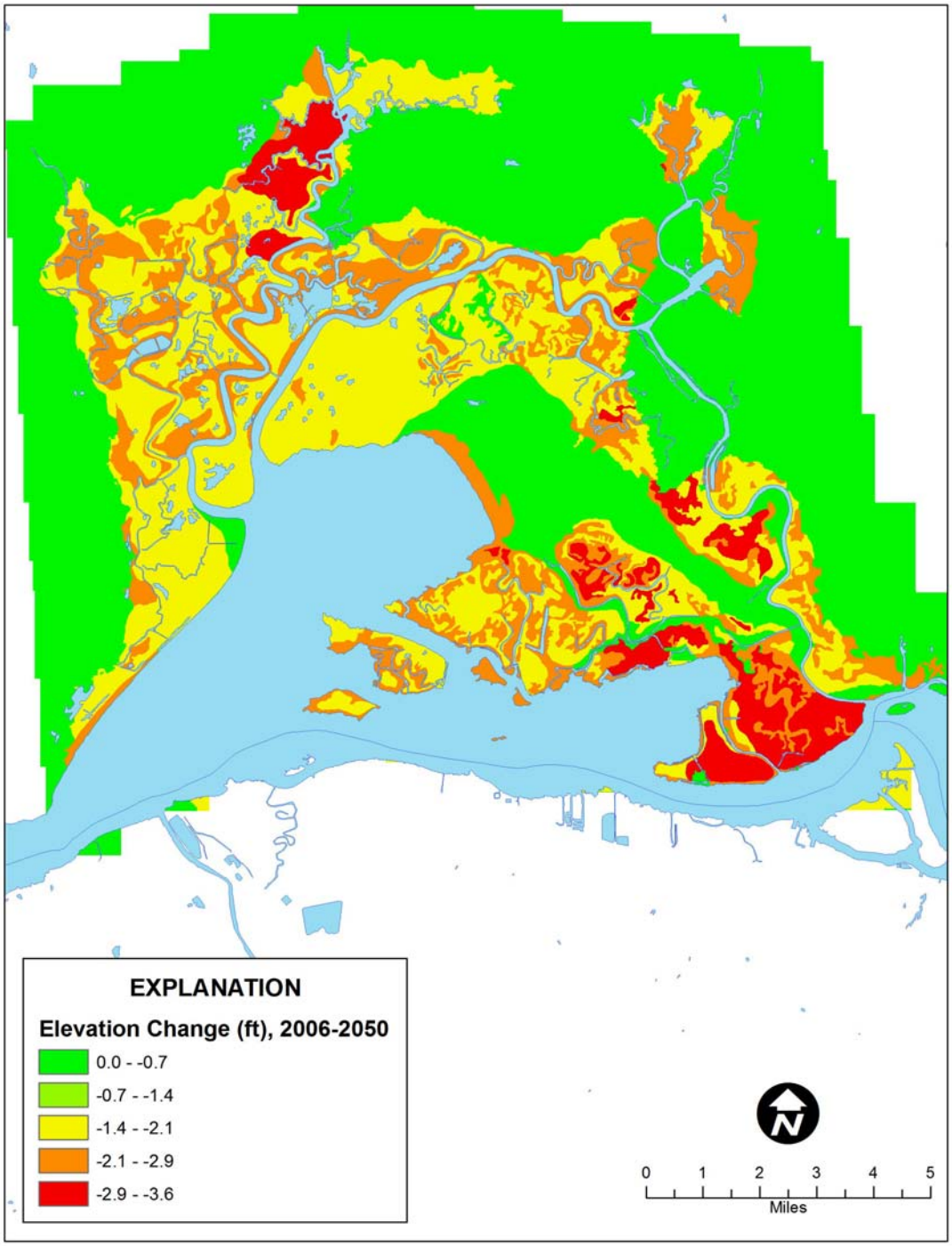

Figure 18A Estimated land-surface elevation changes from 2006 to 2050 for the Suisun Marsh.

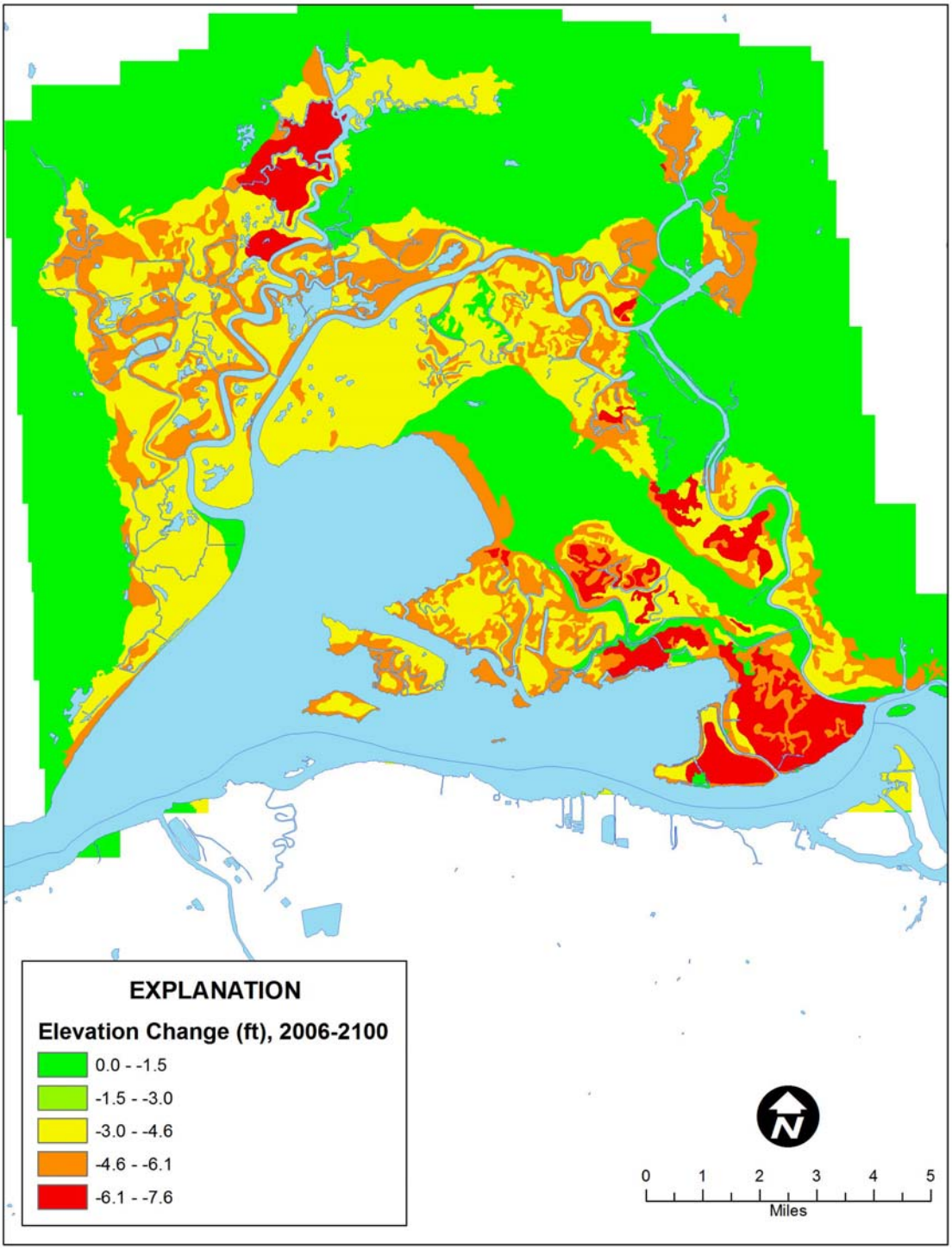

Figure 18B Estimated land-surface elevation changes from 2006 to 2100 for the Suisun Marsh.

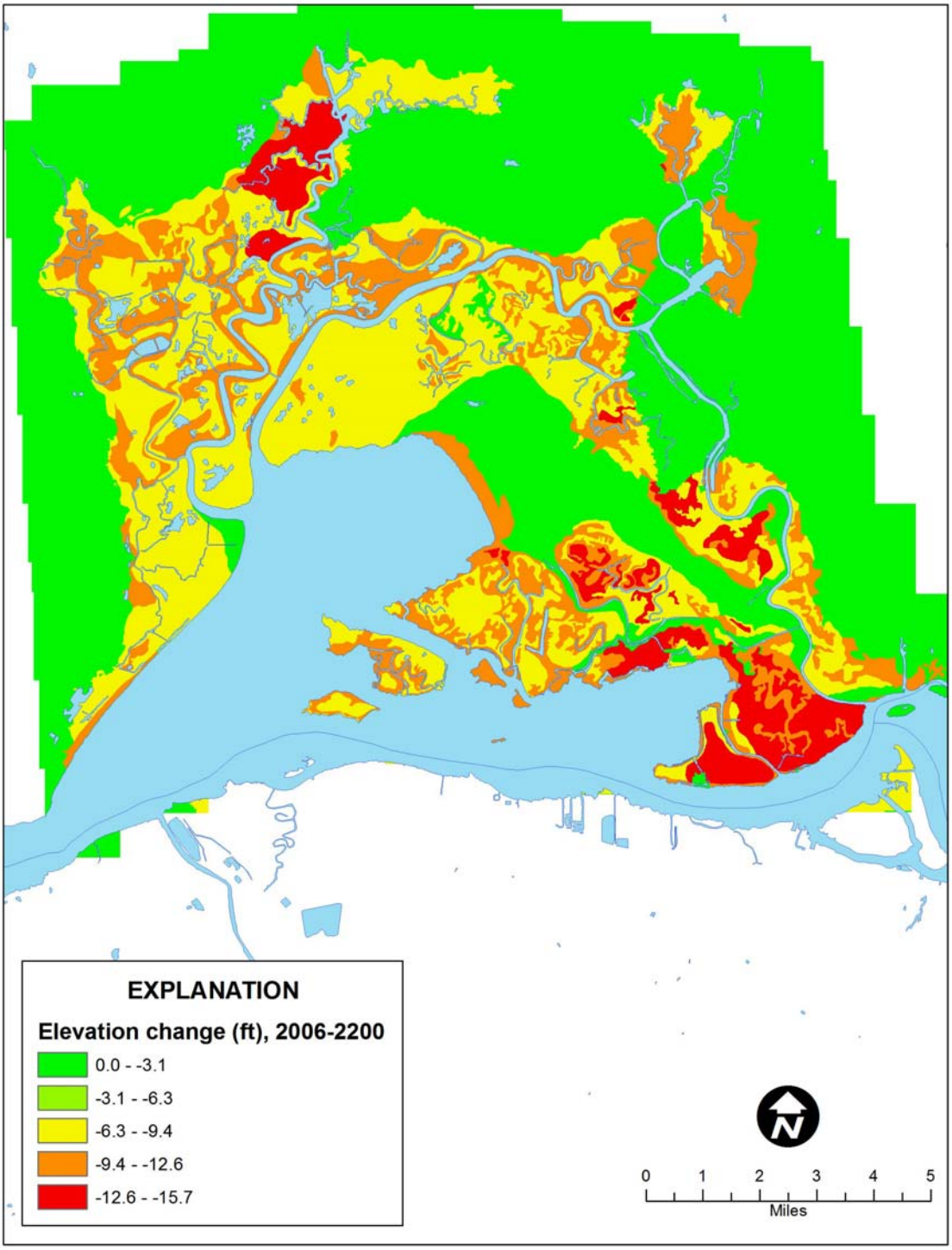

Figure 18C Estimated mean land-surface elevation changes from 2006 to 2100 for the Suisun Marsh.

4.0 Uncertainty Analysis of Subsidence Rates

4.1 Uncertainty Analysis for Sacramento-San Joaquin Delta

Uncertainty in current and future subsidence estimates result from two primary factors; 1) our inability to fully quantify processes affecting subsidence due to lack of process-related knowledge (epistemic uncertainty) and 2) random variability in soil processes and factors that affect the spatial variability in subsidence rates (aleatory uncertainty). In the first case, additional field and laboratory data could provide greater predictive ability. In the second case, it would be impossible to collect sufficient data to fully quantify the stochastic nature of subsidence throughout the Delta. Subsidence-rate variability is due to: variations in soil organic matter content, temperature, texture, and soil moisture, thickness of the unsaturated zone, variations in soil physical factors such as porosity and bulk density, variability in the soil microbial populations and land use. Based on the available data and literature, the primary factors are soil temperature and organic matter content and thickness of the unsaturated zone. All these factors and processes that affect soil properties and biogeochemistry have deterministic and random components which are discussed below under epistemic and aleatory uncertainty, respectively.

4.1.1 Epistemic Uncertainty

We attempted to account for epistemic uncertainty by estimating the range in subsidence rates for the different soil types as affected by the known variability in soil organic matter content, the soil-organic matter-subsidence rate relation and temperature effects. Subsidence estimates depend on 4 primary factors for similar management conditions and groundwater levels as follows.

- The empirical regression relation between soil organic-matter content and subsidence rates.
- Soil organic matter content.
- Future soil temperature increases.

The empirical regression relation of subsidence rates to soil temperature.
For our epistemic uncertainty analysis for each soil type, we used the scheme shown in Figure 19 to estimate the range of subsidence rates given the estimated and/or likely variance in the above four factors. Specifically, we assumed three realizations for the regression equation for soil organic-matter content and subsidence rates which included mean and upper and lower confidence intervals for equation coefficients. For each of these realizations, we varied the soil organic matter content by plus and minus sigma for three estimates for each regression equation realization. For each soil organic matter content value, we varied the projected soil temperature increase by plus or minus the standard deviation. For each of the three soil temperature increases, we varied the relation of subsidence rates to soil temperature by plus and minus the confidence intervals for the parameters in the soil temperature-subsidence regression equation (the log of subsidence varies with soil temperature). This resulted in 81 subsidence estimates shown in Figure 20 in the cumulative frequency plot for the Rindge soils series. Our five future mapped elevation and volume estimates are located in the middle and upper and lower ranges of the 81 realizations. For future land surface elevation and volume estimates, we used the

initial subsidence rates of 0.052, .066, 0.08, 0.098, and 0.124 foot/year which approximately represent the 5, 25, 50, 75, and 95 percentiles. We performed similar analyses for the other soil series.

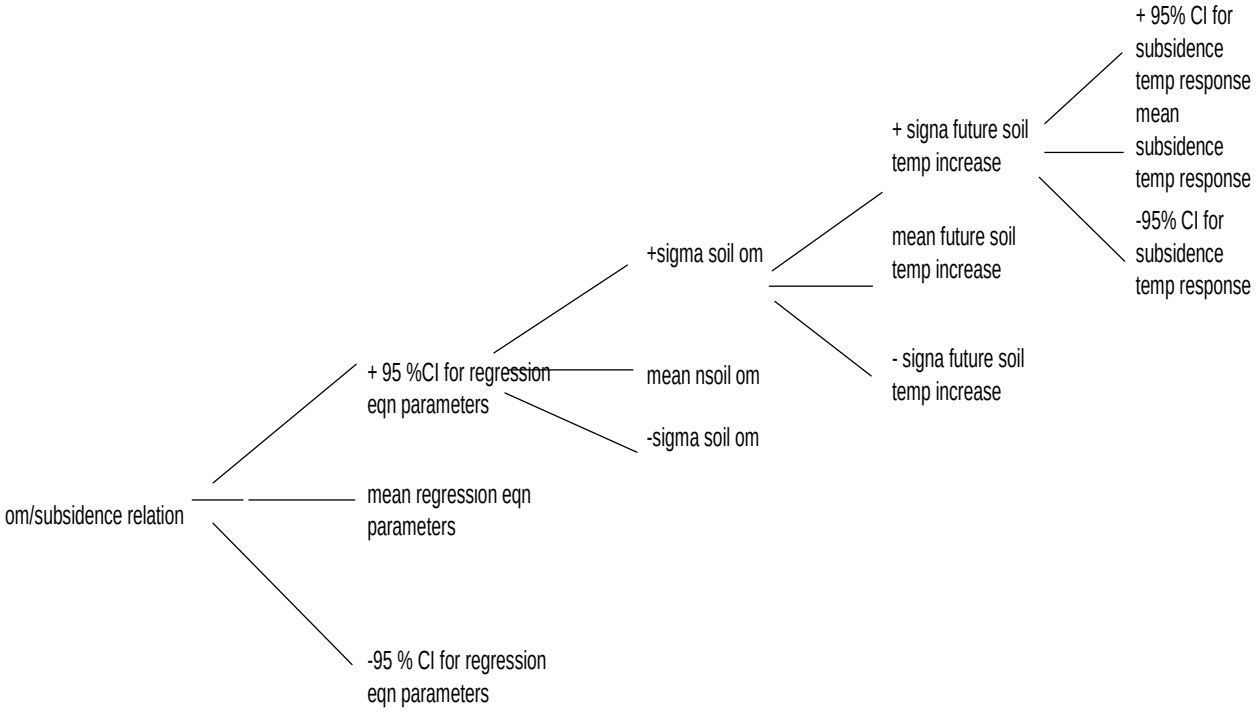

Figure 19 Schematic for calculations for the range of subsidence rates.

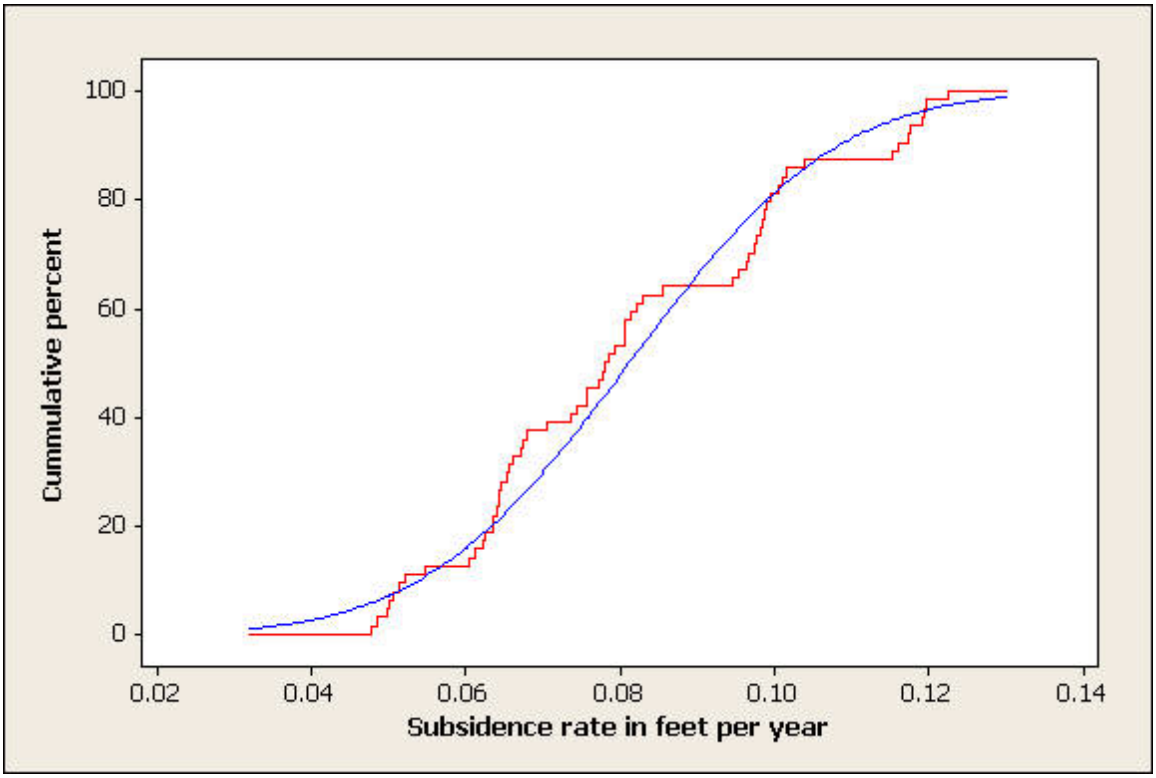

Figure 20 Cumulative distribution plot for the range of subsidence rates for the Rindge soil based on the scheme shown in Figure 19.

The red line represents actual values and the blue line represents the theoretical cumulative distribution function.

4.1.2 Aleatory Uncertainty

The primary random uncertainty results from the spatial variability of soil characteristics and processes affecting the distribution and oxidation of soil organic matter. Soil characteristics, processes and factors affecting the distribution and microbial oxidation of soil organic matter are of primary concern and soil organic matter content is the key variable. We attempted to assess aleatory uncertainty by evaluating the effect of the random spatial variability of soil organic matter distribution and the soil organic matter-subsidence relation on our subsidence and volume-change estimates.

The samples collected on Bacon and Sherman Island provided information about the spatial variability of the soil organic matter. The coefficient of variance (CV) (mean/standard deviation) expressed as a percentage indicates the magnitude of the spatial variability. For Bacon Island soil organic matter content, the CV for the histosol samples was 29%. For all the soil samples, the CV was 35%. For sample results reported in Rojstaczer and Deverel (1995) the CV for Sherman Island soil organic matter content was 56%. Other soil properties that affect subsidence rates include soil bulk density and soil texture. Warrick and Nielson (1980) reported CV values ranging from 17 to 42% for soil texture variations and 7 to 11% for the distribution of bulk density and soil moisture.

To evaluate the effect of spatially varying soil organic matter content and to soil-organic matter-subsidence rate relation on volume changes due to subsidence, we used a Monte-Carlo simulation for two islands; Bacon and Bradford Islands. We initially used Bradford Island because a small number of soil types are represented. Assuming a normal distribution as indicated by the Bacon Island data and using the mean and standard deviation reported above, we developed a program to generate multiple realizations of the organic matter distribution based on random number generation. We also randomized the soil organic matter-subsidence rate relation by including the mean and 95% confidence interval values for the coefficients in the organic soil-subsidence rate equation in the Monte Carlo simulation. We estimated subsidence for 50 years at each point and the island volume change was calculated based on the current and new land-surface elevation distribution for a grid of points (spaced about 30 feet apart) on Bradford and Bacon Islands. We performed 100 simulations and results are shown in Figure 21 for Bradford Island. The volume change ranged from 7,514 to 7,537 acre-feet and the mean was 7,528 acre-feet. Results were similar for Bacon Island. The difference between the maximum and minimum and mean was about 0.15% of the mean. Based on this analysis, we concluded that we can ignore aleatory uncertainty for future subsidence estimates.

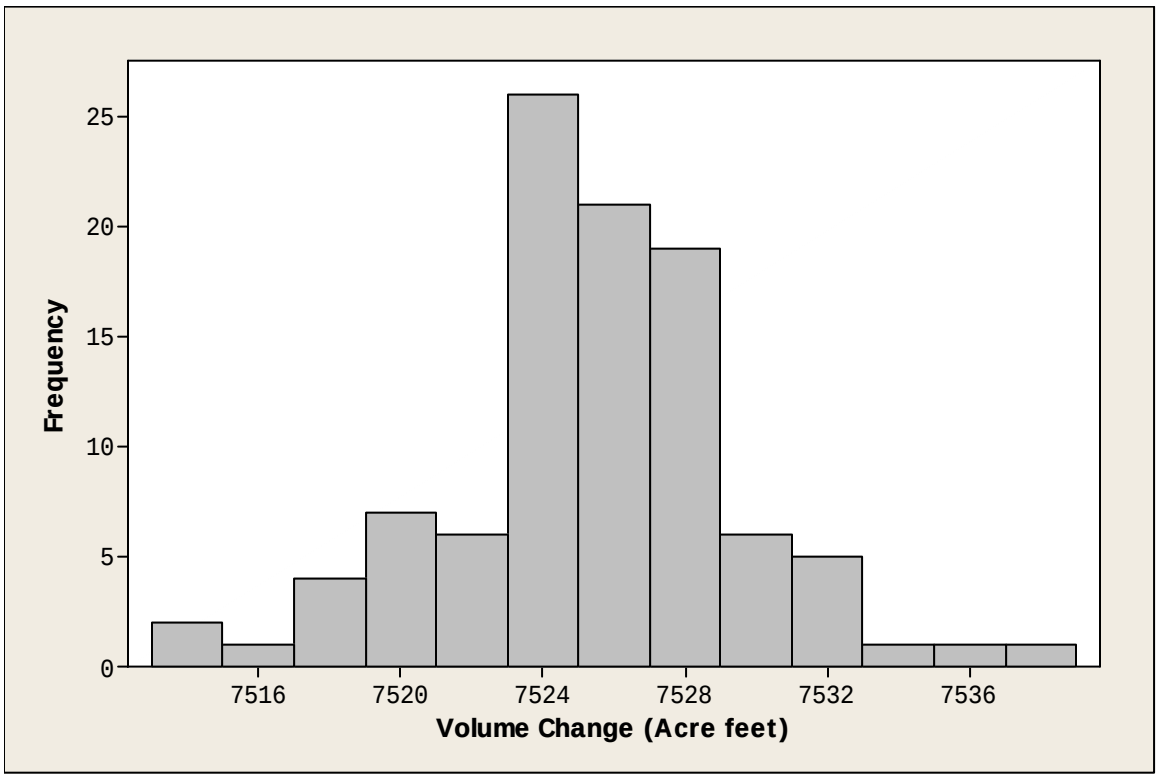

Figure 21 Effect of spatially varying soil organic matter content on estimates of volume change for Bradford Island.

The comparison of estimated versus measured values reflects the random and deterministic uncertainty in measured and calculated subsidence rates (Figure 22). The comparison of our estimated subsidence rates with measured values resulted in an

RMSE[9] of 0.44 inch//year or about 22% of the range in measured values. That is, our estimated subsidence rates are plus or minus about 0.44 inch per year. This range of uncertainty is slightly greater than the range represented by our intermediate subsidence rate estimates (0.79 and 1.18 inch per year) for the Rindge soil which is the predominant soil on the Bacon Island transect.

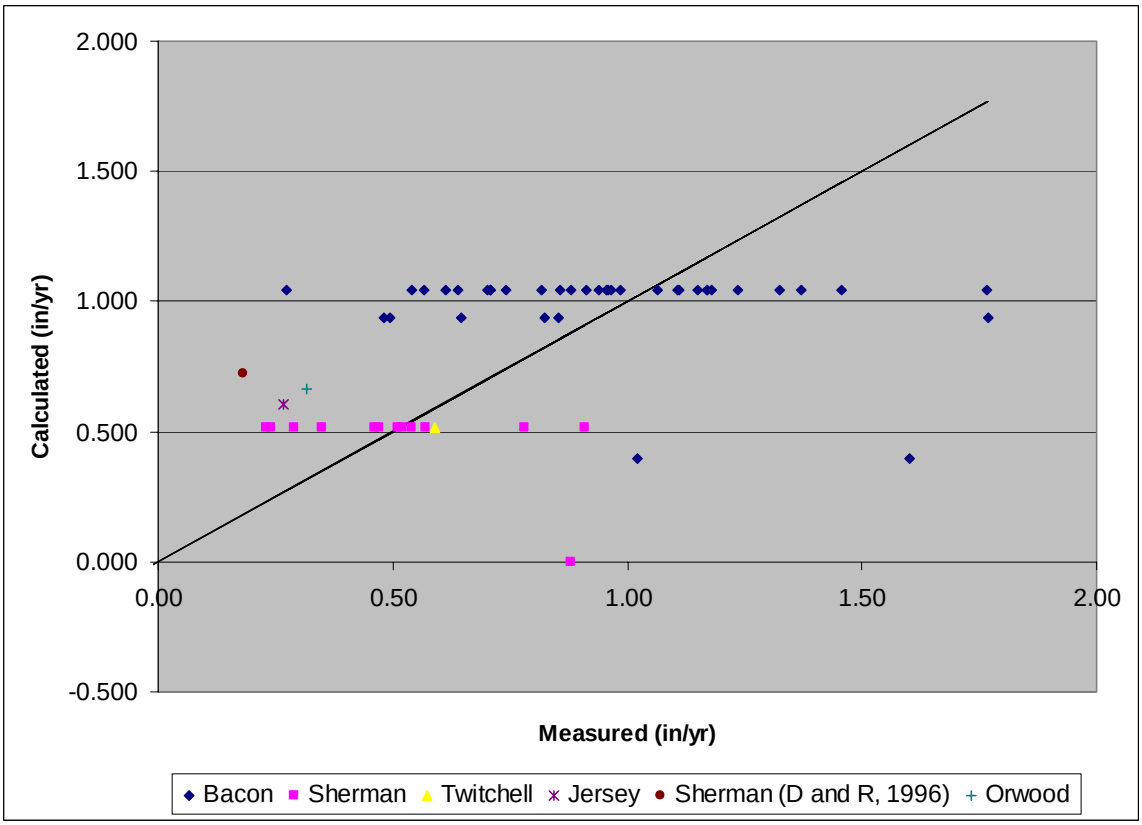

Figure 22 Comparison of measured versus estimated subsidence rates. (Jersey, Sherman, and Orwood are rates reported in Deverel and Rojstaczer, 1996.)

4.2 Suisun Marsh

Our subsidence rate estimates for Suisun Marsh were calculated using elevations posted on 7.5-minute quad maps and elevation data determined in 2006 using LIDAR technology. The elevations posted on the quad maps have an uncertainty of about +/- 1.0 foot. We estimated uncertainty associated with the LIDAR data by comparing the LIDAR elevations with the elevations at National Geodetic Survey control points determined using GPS methods. The RMSE calculated from the difference between the LIDAR and control point elevations was 1.18 ft. We used the uncertainties associated with these elevations to estimate the upper and lower bounds of our Suisun Marsh subsidence estimates.

[9] The root mean square error is calculated as the square root of 1/number of observations times the sum of the squared differences of measured minus estimated.

5.0 Summary and Conclusions

We used historic and recent soils and subsidence data to develop a methodology for estimating future subsidence rates. The following bullets summarize our methods and results.

- We collected elevation and soils data on Bacon and Sherman Islands in 2006 to gain insight about present-day subsidence rates.
- We used regression equations for soil organic matter and subsidence rate data to estimate how future subsidence rates will change as organic matter decreases.
- We estimated temperature effects on subsidence rates using data presented in Deverel and Rojstaczer (1996).
- We used estimated future subsidence rates to estimate future land-surface elevation changes and volumes below sea level.
- Available data and our predictions indicate a future exponential decline in soil organic matter content.
  Projected future subsidence rates:
- Estimated elevation decreases range from 0 to 5 feet by 2050, from 0 to over 9 feet by 2100, and from 0 to over 18 feet by 2200.
- From 1998 to 2050, estimated increases in volume below sea level range from 327,000 to almost 1,100,000 acre-feet.
- From 1998 to 2100, estimated increases in volume below sea level range from 637,000 to about 2,000,000 acre-feet.

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