APPENDIX D

DELTA ISLAND SUBSIDENCE CONTROL PLAN

DELTA LEVEE SYSTEM INTEGRITY PROGRAM

CALFED
Bay-Delta Program

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PRIORITY AREAS FOR SUBSIDENCE MITIGATION IN THE SACRAMENTO-SAN JOAQUIN DELTA

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1.0 Introduction and Background

Prior to 1850, the Sacramento-San Joaquin Delta was a tidal marsh. The Delta was drained for agriculture in the late 1800's and early 1900's. The organic or peat deposits of the Delta formed during the past 7,000 years from decaying plants at the confluence of the Sacramento and San Joaquin Rivers. The drained peat soils on over 100 islands and tracts are highly valued for their agricultural productivity and have undergone continuous subsidence since drainage. A network of levees protects the island surfaces that are now 6 to 21 feet below sea level, from inundation. As subsidence continues, the potential for flooding due to levee failure increases significantly.

Subsidence is caused primarily by the oxidation of soil organic carbon. The peat soil is a complex mass of carbon. Microorganisms such as bacteria and fungi use it as an energy source resulting in peat decomposition and the release of carbon dioxide (CO_2) under drained, oxygen-rich conditions. Studies by the Department of Water Resources and the US Geological Survey (Deverel and Rojstaczer, 1996) demonstrate that the amount of oxidation is proportional to the soil temperature and moisture content. Oxidation and therefore subsidence is lowest when temperatures are cooler and the soil is wet.

Drainage of the Delta islands was essentially complete by the 1930's when the Delta assumed its present configuration of about 100 islands and tracts surrounded by 1,100 miles of man-made levees and 675 miles of channels and sloughs. When most of the existing levees were constructed, the difference between the water level in the channels and island surfaces was less that 5 feet. Because of the decreasing island-surface elevations due to subsidence, the levees are now required to hold substantially more water than when they were originally constructed. This increase in hydraulic pressures on levees that were constructed on foundations of sand, peat and organic sediments contributed to about 35 levee failures since the 1930's. The primary reasons for levee failure are instability, seepage and overtopping.

The cumulative historic cost of levee failures and flood damage is estimated to be in the hundreds of millions of dollars. Levee repair and maintenance can cost over 1 million dollars per mile. Another important detrimental consequence of Delta island flooding is the movement of saline water into the Delta from Suisun Bay. This degradation of the water for two thirds of California residents due to increasing salinity can result from the failure of one of more of the western Delta levees. If the flooded island is not reclaimed, the rate and area of fresh and salt water mixing and evaporation losses increase, causing a long term salinity increase. Even if the island is reclaimed, there can be substantial short term increases in the salinity of the water supply.

Because of the high cost of levee maintenance and repair and the potential for damage to property and wildlife habitat, impaired recreational use and water quality degradation, there is ongoing interest in preventing the flooding of Delta islands. As the islands continue to subside, levee repair and maintenance will become more critical and expensive. A critical factor in preventing future losses due to levee failure is stopping and reversing the effects of subsidence of the peat soils. A key factor in implementing water- and land-management strategies for subsidence control is the delineation of priority areas based on subsidence rates and peat thickness. Higher subsidence rates and thicker peats require more immediate implementation than lower subsidence rates and thin peats.

The California Department of Water Resources previously estimated subsidence rates for the Delta (Department of Water Resources, 1980). The subsidence rates were apparently estimated for entire islands by comparing elevations for topographic maps published in 1952 and 1976 and 1978, and by comparing elevations for topographic maps published in the early 1900's and 1952. The authors also used other miscellaneous measurements such as elevation changes adjacent to the permanent structures. The Department of Water Resources published maps of peat thicknesses and elevations of Delta islands in the Delta Atlas. The elevations of the Delta islands are based on 1978 topographic mappings of the Delta. The peat thickness maps in the Atlas are the result of lithologic data gathered from borehole logs cited in Department of Water Resources (1980). Most of these logs were collected during the 1950's and 1960's.

The objective of the work reported here was to delineate and prioritize areas for subsidence control in the Delta. The general approach was to enter recent available data for the Delta for subsidence rates, depth of peat soils and soil characteristics into a geographic information system (GIS). The estimates presented here for rates of subsidence and peat thickness are an improvement relative to the previous efforts by the Department of Water Resources because 1) the error in the estimated subsidence rate is lower, quantifiable and the result of uniform elevation change measurements, and 2) the estimates for peat thickness are based on more recent and comprehensive data.. Also, the data was entered into a GIS which facilitated the evaluation of the data for delineation of priority areas in greater areal detail than entire islands such as is presented in Department of Water Resources (1980).

2.0 Methods

2.1 Determination of Areal Variability of Subsidence Rates

Two sets of US Geological Survey topographic maps were used to estimate the time-averaged rates of subsidence throughout the Delta from the early 1900's to 1976 through 1978. Specifically, topographic maps for the 1906-1911 mapping of the Delta at 1:31,680 scale were used to estimate land surface elevation on a 500-meter grid. The 1976 to 1978, 1:24,000 scale topographic maps were used to estimate land surface elevation for the same 500-meter grid. The difference in elevation between the two time periods was estimated to be the total depth of subsidence. The time-averaged rate of subsidence was calculated as the total amount of subsidence divided by the time interval that ranged from 60 to 72 years.

The error in the subsidence rate estimate results from the error in the elevation estimate for the contours and the change in mean sea level datum from the early 1900's to 1976 to 1978. Early leveling in California used the average of tide level gauges in California for the mean sea level datum (Birdseye, 1925). The sea level datum for the 1976 to 1978 maps is the National Geodetic Vertical Datum of 1929 that was an average of mean sea level data for 21 tide stations in the United States (Ziloski and others, 1992). The apparent error resulting from the comparison of the two datums for mean sea level is on the order of plus 0.5 to 1.0 foot based on a comparison of bench marks for the sets of maps.

The error due to estimating the elevations from the contours is about one-half of the contour interval (5 feet) for the topographic maps or 2.5 feet (Joe Vukovitch, USGS, Denver, personal communication, 1996). The percent error for each subsidence rate was calculated as follows. The subsidence rate was calculated at each grid point as the difference between the elevations on the two maps plus or minus the error, divided by the time interval between the two mappings:

$$\text{subsidence rate} = (\text{Elev1978} - \text{Elev1906} \pm e)/T$$

where Elev1978 is the elevation from the 1976 to 1978 USGS topographic maps,
Elev1906 is the elevation from the 1906 to 1911 USGS topographic maps,
e is the error associated with the elevation contours (½ the contour interval) and,
T is the time interval between the two elevation measurements.

The error was calculated as

e = E1978 + E1906 = +/- 5 feet

where E1978 and E1906 are the errors associated with the two sets of topographic maps (E1978 = E1906 = +/- 2.5 feet).

The percent error was calculated as the absolute value of 5 feet divided by the total subsidence multiplied times 100. The total subsidence is the difference in elevation between the two topographic maps. The percentage error in the subsidence rate is dependent on the amount of subsidence that occurred during the approximately 70 years that elapsed between the surveying for the topographic maps.

2.2 Determination of the Areal Variability of Peat Thickness

Peat thickness was estimated from the basal elevations of the peat deposits mapped by Atwater (1982) and the 1978 elevations on the 500-meter grid. The basal elevation of the peat deposit was subtracted from the elevation from the 1976 to 1978 topographic maps to estimate the peat thickness for each point on the grid. The areal distribution of the basal elevations of the peat deposits was delineated from about 1,200 borehole logs collected through 1980. The majority of the locations of the borehole logs were on or near the levees. The peat thickness data was compared with the delineation of organic soils or highly organic mineral soils in the soil surveys for Contra Costa (Soil Conservation Service, 1978), San Joaquin (Soil Conservation Service, 1992) and Sacramento counties (Soil Conservation Service, 1993). Where there were discrepancies between the two sources of information for the extent of peat soils, the soil survey data was assumed to be correct and a basal peat elevation was assigned based on the nearest borehole information mapped in Atwater (1982).

2.3 Areal Variability of Soil Characteristics

The delineation of soil series as mapped in the soil surveys for Contra Costa (Soil Conservation Service, 1978), San Joaquin (Soil Conservation Service, 1992) and Sacramento counties (Soil Conservation Service, 1993) were entered into the GIS in digital form. The soil organic matter content was the primary soil characteristic of interest. The soil organic matter content was estimated for the 11 soil series which were either organic soils or highly organic mineral soils based on the data provided in the soil surveys. Specifically, the soil surveys for San Joaquin and Sacramento counties provided a range of values for percent soil organic matter. The midpoint of this range was assigned to that series in the GIS data base. The percent organic matter for the soil series mapped in Contra Costa was estimated from the data provided in the soil surveys for San Joaquin and Sacramento Counties.

2.4 Geographic and hydrographic data

Geographic and hydrographic data was obtained as USGS Digital Line Graphs at 1:100,000 scale from the Teale Data Center.

2.5 Analysis of Spatial Data and Delineation of Priority Areas for Subsidence

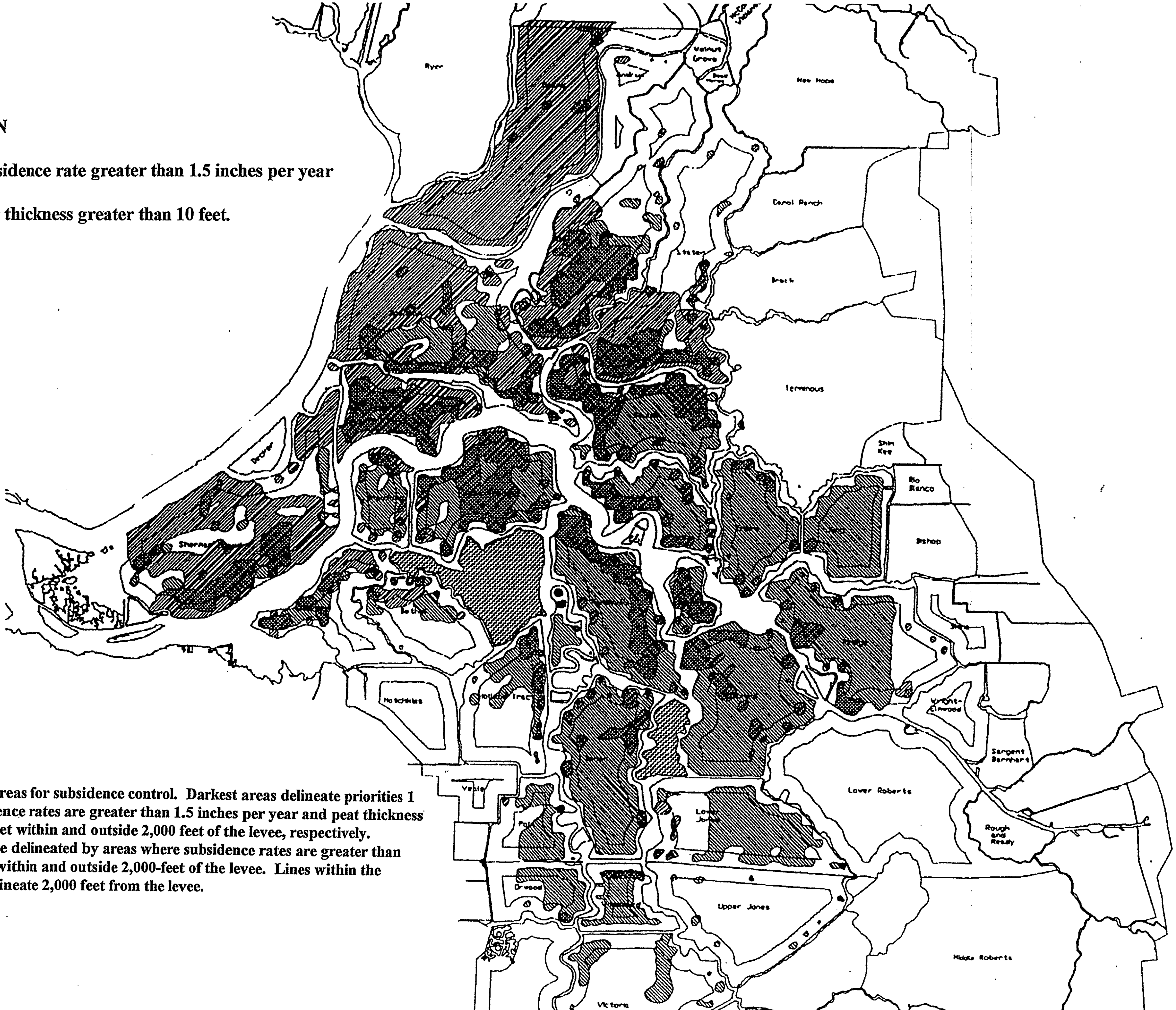
The areal distribution of subsidence rates and peat thickness were used to delineate priority areas for subsidence control. For protection of Delta islands, the areas of highest priority are those within 2,000 feet of the island levees. Within the 2,000-foot boundary, the first priority areas are those where the subsidence rates are high and there is substantial peat remaining. The first priority was delineated as those areas where the time-averaged subsidence rates were greater than 1.5 inches per year (subsidence rates ranged from about 0.4 inches per year to 5 inches per year) and the peat thickness is greater than 10 feet within the 2,000 foot boundary. The second priority areas are those where the time-averaged subsidence rate is greater than 1.5 inches per year and the peat thickness is less than or equal to 10 feet. The third priority includes those areas outside the 2,000 foot boundary (towards the center of the islands) where the subsidence rate is greater than 1.5 inches per year and the peat is greater than 10 feet thick. The fourth priority includes those areas outside the 2,000 foot boundary where the peat is less than or equal to 10 feet thick and the subsidence rate is greater than 1.5 inches per year.

3.0 Results of Spatial Analysis

Figure 1 shows the distribution of the four priority areas in the Delta. Table 1 shows the approximate acreage for each island for priority 1; areas where the peat thicknesses are greater than 10 feet and the time-averaged subsidence rate is greater than 1.5 inches per year. Peat thickness is generally greatest in the western and northern parts of the Delta; the largest areas of peat thickness greater than 10 feet are on Sherman, Twitchell, Brannan-Andrus, Grand, Staten and Tyler islands and Webb Tract. The amount of area in priority 1 varies among these islands according to the subsidence rate.

The largest acreage for priority 1 is on Webb Tract in the west-central Delta (about 2,500 acres). Venice, Bouldin and Mandeville islands in the central Delta also have large acreage assigned to priority 1, between about 950 and 1,360 acres.. In the western Delta, Brannan-Andrus, Twitchell, Bradford, Jersey and Sherman islands have between about 470 and 810 acres in priority 1. Although Grand Island has a large acreage of peat thicker than 10 feet, the subsidence rates are almost all less than 1.5 inches per year. Tyler and Staten islands in the northern Delta have about 730 to 835 acres in priority 1. The total area for priority 1 is about 14,300 acres (Table 1).

Table 1 shows the acreage for priority 2; areas with peat thicknesses less than or equal to 10 feet and having subsidence rates greater than 1.5 inches per year within 2,000 feet of the levee. The islands with the largest areas in priority 2 are in the central Delta where subsidence rates have been historically high and there are large areas of peats that are less than 10 feet thick. MacDonald, Bacon and Mandeville islands and Empire Tract in the Central Delta and Rindge Tract in east-central Delta and Webb Tract in the west-central



EXPLANATION

Subsidence rate greater than 1.5 inches per year

Peat thickness greater than 10 feet.

Figure 1. Priority areas for subsidence control. Darkest areas delineate priorities 1 and 3 where subsidence rates are greater than 1.5 inches per year and peat thickness is greater than 10 feet within and outside 2,000 feet of the levee, respectively. Priorities 2 and 4 are delineated by areas where subsidence rates are greater than 1.5 inches per year within and outside 2,000-feet of the levee. Lines within the island boundary delineate 2,000 feet from the levee.

Delta have areas in priority 1 that range from about 1,020 to 2,160 acres. Other central Delta islands (Lower Jones Tract, Bouldin Island and Venice Island) have areas in priority 2 that range from about 450 to 620 acres. The islands and tracts of the western and northern Delta generally have low acreage in priority 2 because of the low subsidence rates.

Table 1. Acreage by island for the 4 priorities for subsidence control. Priority 1 includes areas within 2,000 feet of the levee where the subsidence rate is greater than 1.5 inches per year and the peat thickness is greater than 10 feet. Priority 2 includes areas within 2,000 feet of the levee where the subsidence rate is greater than 1.5 inches per year and the peat thickness is less than or equal to 10 feet. Priority 3 includes areas beyond 2,000 feet of the levee where the subsidence rate is greater than 1.5 inches per year and the peat thickness is greater than 10 feet. Priority 4 includes areas beyond 2,000 feet of the levee where the subsidence rate is greater than 1.5 inches per year and the peat thickness is less than or equal to 10 feet.

Priority 1		Priority 2		Priority 3		Priority 4	
Island	**Acres**	**Island**	**Acres**	**Island**	**Acres**	**Island**	**Acres**
Quimby	35	Quimby	35	Rindge	130	Staten	83
Grand	51	Staten	61	Medford	130	Sherman	152
King	68	King	68	Bacon	163	Bethel	265
Bethel	68	Brannan	74	Grand	194	Woodward	308
Woodward	131	Bethel	82	McDonald	299	Orwood	392
Holland Tract	413	Tyler	178	Staten	565	Palm	405
Medford	438	Sherman	233	Mandeville	581	Tyler	428
Rindge	468	Bradford	234	Bouldin	794	Victoria	482
Sherman	473	Holland Tract	413	Brannan	883	Holland Tract	521
Empire	546	Lower Jones	433	Twitchell	1,003	Bradford	622
McDonald	613	Bouldin	1,293	Sherman	1,007	Venice	667
Bacon	626	Orwood	450	Webb Tract	1,403	Webb Tract	1,087
Jersey	668	Victoria	522	Tyler	1,453	Mandeville	1,307
Bradford	707	Venice	607	**Total**	**8,607**	Brannan	1,363
Twitchell	715	Palm	619			King	1,410
Tyler	728	Empire	1,019			Empire	1,547
Brannan	814	Mandeville	1,040			Bouldin	1,647
Staten	836	Rindge	1,105			Lower Jones	1,911
Venice	952	Webb Tract	1,315			Bacon	2,402
Bouldin	1,066	Bacon	1,423			Rindge	2,577
Mandeville	1,362	McDonald	2,157			McDonald	2,778
Webb Tract	2,518	**Total**	**13,360**			**Total**	**22,354**
Total	**14,295**						

Other data provides concurrence that subsidence rates for the central Delta are high relative to the western Delta. The soils of the central Delta are generally higher in organic matter content and have subsided faster than the western Delta islands (Rojstaczer and Deverel, 1995; Deverel and others, 1997). Rojstaczer and Deverel (1995) reported subsidence rates of 2 to 3 inches per year on Lower Jones Tract and Mildred and Bacon islands compared with 1.25 inches or less for Sherman and Jersey islands. The total area for priority 2 is about 13,360 acres (Table 1). The combined acreage for priorities 1 and 2 is about 27,700 acres.

Priority 3 includes those areas beyond 2,000 feet of the levee where the peat thicknesses are greater than 10 feet and the time-averaged subsidence rate is greater than 1.5 inches per year. The islands with the largest areas in this priority are primarily the areas of deep peats in the western, west-central and northern Delta. Twitchell, Brannan-Andrus and Sherman islands and Webb Tract in the western and west-central Delta and Tyler Island in the northern Delta have the largest acreage in this priority ranging from about 880 to 1,450 acres (Table 1). Bouldin Island in the central Delta also has large areas of peat thickness greater than 10 feet and high subsidence rates and almost 800 acres in priority 3. Mandeville Island in the west-central Delta, Staten Island in the northern Delta, Medford, Bacon and McDonald islands in the central Delta and Rindge Tract in the east-central Delta have between about 130 to 580 acres in priority 3. The total acreage for priority 3 is about 8,600 acres. The combined acreage for priorities 1, 2 and 3 is about 36,300 acres.

Priority 4 includes those areas beyond 2,000 feet of the levee with high subsidence rates and less than 10 feet of peat soil. Table 1 shows the acreage for the different islands for priority 4. The majority of the islands with large areas in priority 4 are in the central Delta. The central Delta islands of McDonald, Bacon, Bouldin and Lower Jones, and

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Empire tracts have acreage in priority 4 that range from about 1,550 to 2,780 acres. Venice Island also in the central Delta has about 670 acres in priority 4. Rindge Tract in the east-central Delta has about 2,580 acres in priority 4. Webb Tract in the central-western Delta has about 1,090 acres. The total area for priority 4 is about 22,350 acres. The total area for priorities 3 and 4 is about 31,000 acres. The total area for all 4 priorities is about 58,600 acres.

The percent soil organic matter is a key factor in determining the subsidence rates and therefore the acreage in the different priorities. On Sherman Island, the subsidence rates are generally low due to the relatively low percent organic matter of the near surface soils (Rojstaczer and Deverel, 1996). Therefore, the amount of area for priority 1 on Sherman Island is relatively small even though there are large areas of peats that are thicker than 10 feet. In contrast, Twitchell Island has large areas of peats that are thicker than 10 feet and some areas where surface soils have high organic matter contents (Roger Fujii, US Geological Survey, personal communication, 1996) which correspond to large subsidence rates. A similar situation apparently exists on Webb Tract.

Figure 2 shows the distribution of percent soil organic matter in the Delta (Figure 2 is too large to fit in this report and therefore not included. It is available through the CALFED office. The lines shown in figure 2 generally represent the outlines of soil series for which organic matter contents were determined as part of the data collection efforts for the soil survey. The distribution of soil organic matter content generally reflects the distribution of subsidence rates (figure 1). For example, the highest organic matter contents (greater than 15 and 30 percent) were mapped in the central, east-central and the west-central Delta (Twitchell Island, Bradford Island, Webb Tract, Bouldin Island, Venice Island, Empire Tract, Rindge Tract, King Island, Bacon Island, Lower Jones Tract). The subsidence rate for the majority of these islands is greater than 1.5 inches per year (figure 1). Islands where organic matter contents are generally lower than 15 percent such as Sherman Island, Brannan-Andrus Island, Staten Island, Terminous Tract, Upper Jones Tract and Victoria Island are generally at the periphery of the Delta. The subsidence rates on these islands are generally less than 1.5 inches per year.

On individual islands, the subsidence rate generally corresponds to the soil percent organic matter shown in figure 2. For example, on Brannan-Andrus Island, much of the southern island has organic matter contents greater than 15 and 30 percent corresponding to areas where subsidence rates are greater than 1.5 inches per year. Similarly on Tyler Island, the southwest part of the island has soils with organic matter contents greater than 15 and 30 percent corresponding to areas where subsidence rates are larger than 1.5 inches per year.

The use of subsidence rates in determining priorities for subsidence control reflects the primary cause of subsidence, oxidation of soil organic matter. The total amount of subsidence as reflected in the land surface below sea level map in the Delta Atlas reflects not only the subsidence rate but also the amount of time since the island was first reclaimed. For example, an assignment of priorities based on the land surface elevation shown in the Delta Atlas would include large areas of Sherman and Brannan-Andrus islands in priority 1 and 3 where land-surface elevations are some of the lowest in the Delta. These were also some of the first islands leveed and drained in the Delta (Thompson, 1958). However, the time-averaged subsidence rates are less than 1.5 inches per year based on the data for this report and in previous studies (Rojstaczer and Deverel, 1995, Rojstaczer and others, 1991).

4.0 Uncertainty in the Spatial Analysis

The primary uncertainties in the spatial analysis are the result of uncertainties in the estimated basal elevation of the peat soil and the error in the estimation of the subsidence rate. The subsidence rate error is the result of errors associated with the use of topographic elevations as described above and the use of different datums for the 2 surveys for the topographic maps published in 1906 to 1911 and 1976 to 1978. Figure 3 shows the distribution of the error in the subsidence rate as the result of error in topographic maps (Figure 2 is too large to fit in this report and therefore not included. It is available through the CALFED office. In general, large errors in the subsidence rates correspond to areas of the lowest subsidence rates.

Figure 3 shows that the error in the subsidence rate estimate due to the mapping error is 50 percent or less for much of the Delta. Specifically, the error in the subsidence rate on the central Delta islands, Bouldin, Island, Venice Island, Empire Tract, Mandeville Island, Bacon Island, Lower Jones Tract, McDonald Island and Empire Tract is generally less than 50 percent. Also, the error in the subsidence rates for the west-central and east-central islands, Webb Tract, Twitchell Island, Bradford Island, Rindge Tract and King Island is also generally lower than 50 percent. The error in the subsidence rate generally increases as one approaches the periphery of the Delta. The error in the western, eastern, southern and northern edges of the Delta generally approaches or exceeds 100 percent.

Figure 4 shows the exponential decrease in the percent error in the subsidence rate as the result of mapping errors with increases in the subsidence rate (Figure 4 is too large to fit in this report and therefore not included. It is available through the CALFED office. The error was calculated for the average time between elevation measurements of 69 years for the topographic maps used in determining the total elevation change. The key questions related to the error for the purpose of assigning the priority based on subsidence rates are: 1) Is the distribution of subsidence rates consistent with the what is known about the distribution of present-day subsidence rates? and 2) What is the error associated with assignment of areas to one of the two categories (less than and greater than 1.5 inches per year) for subsidence rates?

The first question can be answered qualitatively based on recently collected data for subsidence for selected areas of the Delta. Specifically, data from Rojstaczer and Deverel (1995), Rojstaczer and others (1991) and Deverel and Rojstaczer (1996) are consistent with the spatial distribution of subsidence rates presented here. Subsidence rates in the central Delta (Lower Jones Track, Bacon and Mildred islands) are greater than in the western Delta (Sherman and Jersey islands). However, subsidence has not been measured extensively throughout the Delta so that it is impossible to compare rates for all the islands. The subsidence rates in figure 1 are generally consistent with what is known about subsidence and organic soils in the Delta. The highest soil organic matter contents and subsidence rates are in the central Delta. The soils are lower in organic matter content and subsidence rates are lower approaching the margins of the Delta

The second question can be answered based on the distribution of error for subsidence rates. Further error analysis using the data shown in figures 3 and 4 was used to determine the effect of the distribution of error on the assignment of priorities. Considering the data used in figures 3 and 4, the lowest rate that could be erroneously classed as a rate of over 1.5 inches per year is 0.7 inches per year (the error associated with this rate is 122 percent). The highest subsidence rate that could be classed under 1.5 inches per year is 2.3 inches per year (the error associated with this rate is 36 percent). To evaluate the effect on the amount of acreage in each priority, data for Sherman Island and Webb Tract was used to determine the range in acreage for the priority classes based on the estimated error for the subsidence rate.

The data for these islands represent the apparent variability in the data set. About 80 percent of the area of Sherman Island in the western Delta has peat greater than 10 feet thick but the subsidence rates were below 1.5 inches per year. In contrast, Webb Tract has experienced subsidence at rates generally greater than 2.5 inches per year and about 50 percent of the island has peat soils greater than 10 feet thick. Webb Tract has the largest acreage in priority 1 and the third and second largest areas in priority 2 and 3, respectively. The acreage on Sherman Island is about the median in priorities 1 and 2. Sherman Island has one of the largest acreage in priority 3 and one of the smallest acreage in priority 4.

The results of the error analysis are shown in Table 2. The range of acreage on Webb Tract for priority 1 represents a 24 % decrease and 4% increase in the estimated acreage shown in Table 1. Similarly, for priorities 2 and 3, the changes in the acreage range from 2 to 18 percent (Table 2). For priority 4, the low estimate is 35 percent below, and the high estimate is 8 percent above, the acreage in Table 1.

In contrast, the range of acreage in each priority for Sherman Island is large, ranging up to 1,000 percent. The subsidence rates for Sherman are lower than Webb and therefore the error associated with the subsidence-rate estimate is higher and the range of acreage classified in each priority is large. The subsidence rates over much of the island are about 1 to 1.5 inches per year. Also, the peat thicknesses over most of Sherman Island are greater than 10 feet so the area in priorities 1 and 3 increase substantially when the limit of the subsidence rate decreases. The area for priority 1 ranges from a low of 0 to a high of 1,083 acres. For priority 2, the area ranges from a low of 41 and high of 513 acres. For priority 3, the area ranges from a low of 0 to a high of 4,331 acres. For priority 4, the area ranges from a low of 0 to a high of 1,694 acres. The results of this analysis point to a need for additional data collection in the western Delta where implementation of subsidence control measures is more critical than other parts of the Delta.

Table 2. Range in acreage for each priority for Sherman Island and Webb Tract.

	Priority 1		**Priority 2**		**Priority 3**		**Priority 4**	
	low	high	low	high	low	high	low	high
Sherman	0	1,083	41	513	0	4,331	0	1,694
Webb	612	2,518	1,149	1,475	1,156	1,425	710	1,176

The error in the subsidence rate associated with the change in datums for the two maps is systematic and small, on the order of 0.5 to 1.0 foot that would be subtracted from the total subsidence for all the data points. This would change the subsidence rates by about 0.1 to 0.2 inch per year and would not alter the relative distribution of the subsidence-rate values because the same amount would be added to all the values.

The error association with the mapping of peat thickness is related to the number of data points that was used to determine the distribution of peat thickness. Table 3 shows the number and average density of data points from borehole logs used to estimate the peat thickness. The data in Table 3 does not present the entire picture relative to the density of data points for peat thickness. Some data points were used for islands besides those for which they are assigned in Table 3 since the data for peat thickness can be extrapolated across channels. Also, most of the data points are on the levees so that the range of area without borehole data for each island varies substantially. In general, data densities greater than 200 acres per point result in moderate to high uncertainty in the estimation of peat thickness for large areas of the islands.

Of those islands where the density of peat thickness data is greater than 200 acres per point, only 6 have acreage in the 4 priorities (Orwood Tract, Victoria Island, Brannan-Andrus Island, King Tract, Tyler Island and Grand Island). Brannan-Andrus Island, King Tract and Tyler Island have significant acreage in the 4 priorities. Grand Island is mapped as having a large area of deep peat but has little area in the 4 priorities because of the low subsidence rates. Tyler, Grand and Brannan-Andrus islands are in the western Delta.

Table 3. Number of data points, acreage and data density for each island used to delineate the distribution of peat thickness.

Island	Number of points	Acreage	Data density (acres/point)
Medford	31	1,219	39
Jersey	60	3,471	58
Bradford	28	2,051	73
Palm	32	2,436	76
Mandeville	68	5,300	78
Woodward	23	1,822	79
Bethel	43	3,500	81
Bacon	66	5,625	85
Sherman	105	9,937	95
Webb Tract	58	5,490	95
Twitchell	36	3,516	98
Venice	31	3,220	104
Empire	28	3,430	123
Canal Ranch	23	2,996	130
Holand	31	4,060	131
Coney	7	935	134
Bouldin	44	6,006	137
Staten	61	9,173	150
McDonald	39	6,145	158
Lower Jones	33	5,894	179
Hotchkiss	17	3,100	182
Byron	36	6,933	193
Rindge Tract	35	6,834	195

Terminous	50	10,470	209
Lower Roberts	48	10,600	221
Upper Jones	27	6,259	232
Orwood	13	4,138	318
Brack	14	4,873	348
Victoria	19	7,250	382
Brannan-Andrus	31	13,000	419
Bishop	3	2,169	723
King	4	3,260	815
New Hope	8	9,300	1,163
Tyler	7	8,583	1,226
Grand	3	17,010	5,670
Veale	0	1,298	____
Shin Kee	0	1,016	____
Rio Blanco	0	705	____
Union	0	22,202	____
Shima	0	2,394	____
Ryer	0	11,880	____

5.0 Status of Subsidence Mitigation Alternatives

The primary factor contributing to subsidence in the Delta is oxidation of soil organic matter. The oxidation of soil organic matter is directly proportional to soil temperature and generally decreases with increasing soil moisture. The results of studies conducted by the US Geological Survey and Department of Water Resources (Deverel and others, 1997) demonstrated that permanent shallow flooding reversed the effects of subsidence on Twitchell Island. Permanent shallow (about 1 foot) flooding results in a net carbon accumulation and accretion of the land surface. Other water-management strategies that were evaluated; seasonal flooding during the late fall and winter with and without irrigation during the spring and summer, resulted in a net carbon loss and are not viable strategies for stopping subsidence.

Other water- and land-management strategies are being evaluated that may stop or reverse the effects of subsidence include capping the organic soil with mineral material and reverse wetland flooding. Preliminary results by the USGS (Lauren Hastings, personal communication, 1996) indicate that capping the unsaturated peat soil with 2 feet of dredge sand reduces the oxidation rate by about 50 percent. Capping saturated peat soil with dredge material would provide upland habitat in shallow flooded wetlands. Capping of the peat reduces the transport of oxygen and carbon dioxide in and out of the soil, causing the oxidation rate to decrease. Reverse wetland flooding involves shallow flooding during the spring and summer and drainage during the fall and winter. This may reduce oxidation when it is usually the greatest and result in organic matter accumulation The USGS is currently evaluating this as a subsidence mitigation strategy.

6.0 Limitations of the Analysis

The primary limitation of this analysis is the error in the spatial distribution and age of the data for the key variables, peat thickness and subsidence rates. The plotted subsidence rates are based on data for topographic maps spaced about 70 years apart. The error associated with the calculation of subsidence rates due to mapping error is discussed above and ranges from less than 30 to over 150 percent. The error associated with the use of different datums is systematic and about 0.5 to 1.0 feet.

The error in assignment of areas to priorities for subsidence control varies by island depending on the subsidence rate and the depth of peat. Where the time-averaged subsidence rate is high, the error associated with assignment of priorities is low as is illustrated in the example on Webb Tract. The opposite is true for assignment of priorities to areas where the time-averaged subsidence rate is relatively low as is illustrated in the example on Sherman Island. The error associated with assignment of priorities based on the depth of peat is related to the level of confidence in the peat thickness as determined by the density of borehole data.

The assignment of priorities based on distribution of subsidence rates in figure 1 is consistent with what is known about the spatial variability of subsidence rates in the Delta based on previous studies cited above. Also, subsidence rates are correlated with soil organic matter content and the distribution of subsidence is consistent with the distribution of soil organic matter content (figure 2). High subsidence rates correspond with soil organic matter contents greater than 30 percent in the central Delta. Towards the margins of the Delta, subsidence rates are lower and the soil organic matter content generally decreases to less than 15 percent. Based on available information, subsidence rates shown in figure 1 are distributed similarly to present day subsidence rates. Similarly, the distribution of peat thickness estimates, although 20 years old, reflect the current distribution of peat thicknesses because the primary process causing change in peat thickness, the relative distribution of subsidence rates, has not changed in the last 20 years because land use has not changed significantly.

D-031660

7.0 Conclusions and Recommendations

7.1 Conclusions

Time-averaged subsidence rates and peat-thickness estimates were used to determine priorities for subsidence control in the Sacramento-San Joaquin Delta. Subsidence rates were determined from two sets of topographic maps from the early 1900's and 1978-76. The peat-thickness distribution in the Delta was determined from borehole logs and the 1976-1978 elevation data. Four priorities for subsidence control were determined as follows.

- Priority 1 is the area within 2,000 feet of the levee where time-averaged subsidence rates are greater than 1.5 inches per year and peat thicknesses are greater than 10 feet.
- Priority 2 includes those areas that are within 2,000 feet of the levee and the subsidence rates are greater than 1.5 inches per year and the peat is less than or equal to 10 feet thick.
- Priority 3 includes those areas beyond 2,000 feet from the levee where subsidence rates are greater than 1.5 inches per year and the peat thickness is greater than 10 feet.
- Priority 4 includes those areas beyond 2,000 feet from the levee where subsidence rates are greater that 1.5 inches per year and the peat is less than or equal to 10 feet thick.

The largest acreage for priority 1 are in the west central and central Delta (Webb Tract, Venice, Bouldin and Mandeville islands). In the western Delta, Brannan-Andrus, Twitchell, Bradford, Jersey and Sherman islands have between about 470 and 810 acres in priority 1. Tyler and Staten islands in the northern Delta have about 730 to 835 acres in priority 1. The total area for priority 1 is about 14,300 acres.

The islands with the largest areas in priority 2 are in the central Delta where subsidence

D-031661

rates have been historically high. MacDonald, Bacon and Mandeville islands and Empire Tract in the Central Delta and Rindge in east-central Delta and Webb Tract in the west-central Delta have areas in priority 1 that range from about 1,020 to 2,160 acres. Other central Delta islands (Holland Tract, Lower Jones Tract, Bouldin Island and Venice Island) have areas in priority 2 that range from about 450 to 620 acres. The islands and tracts of the western and northern Delta generally have low acreage in priority 2 because of the low subsidence rates. The total area for priority 2 is about 13,360 acres. The combined acreage for priorities 1 and 2 is about 27,700 acres.

The islands with the largest areas in priority 3 are primarily the areas of deep peats in the western, west-central and northern Delta. Twitchell, Brannan-Andrus and Sherman islands and Webb Tract in the western and west-central Delta and Tyler Island in the northern Delta have the largest acreage in this priority ranging from about 880 to 1,450 acres. Bouldin Island in the central Delta also has a large area of peat thickness greater than 10 feet and high subsidence rates and almost 800 acres in priority 3. The total acreage for priority 3 is about 8,600 acres. The combined acreage for priorities 1, 2 and 3 is about 36,300 acres.

The majority of the islands with large areas in priority 4 are in the central Delta. The central Delta islands of McDonald, Bacon, Bouldin islands and Lower Jones, and Empire tracts have acreage in priority 4 that range from about 1,550 to 2,780 acres. Venice Island also in the central Delta has about 670 to 1,300 acres in priority 4. Rindge Tract in the central eastern Delta has about 2,580 acres in priority 4. Webb Tract in the central-western Delta has about 1,090 acres. The total area for priority 4 is about 22,350 acres. The total area for priorities 3 and 4 is about 31,000 acres. The total area for all 4 priorities is about 58,600 acres.

The uncertainty in the estimation of priorities depends on the magnitude of the subsidence rate and the uncertainty in the estimation of the peat thickness. The error in the subsidence rate estimate is generally less than 50 percent where subsidence rates are greater than 1.5 inches per year. This corresponds to areas in the central Delta. The error in the subsidence rate increases to over 50 and approaches and exceeds 100 percent approaching the margins of the Delta. The error in the subsidence rate has little effect in the assignment of priorities on islands where the subsidence rates are high such as Webb Tract. However, it has a large effect on the assignment of priorities for islands such as Sherman where subsidence rates are lower.

7.2 Recommendations for Additional Data Collection

Eight western Delta islands (Sherman, Jersey, Twitchell, Bradford, Holland, Hotchkiss, Bethel and Webb) encompass a key area for subsidence control because of the potential for water quality deterioration as the result of a levee break on these islands. Figure 1 shows that large areas of Twitchell, Webb and Bradford are included in the four priorities. Relatively small areas of Sherman, Jersey, Bethel, Hotchkiss and Holland are included in the four priorities. However, the error analysis discussed above indicates that the uncertainty in the assignment of priority areas on Sherman Island is as large as 1000 percent. The uncertainty on Webb Tract is small. Examination of the subsidence rates and the error in the subsidence rates for the other western Delta islands is generally similar to those for Sherman Island (Figures 1 and 3).

The uncertainty in the assignment of priorities in these and other areas where subsidence rates are low, points to the need for additional data for subsidence rates in these areas prior to implementation of subsidence control measures. Since subsidence control is critical in the western Delta yet the uncertainty in the subsidence rates is relatively high, additional data about the distribution of subsidence rates on seven of the eight western Delta islands is recommended for a higher level of certainty for the implementation of subsidence control measures. Additionally, analysis by Rojstaczer and others (1991) and Deverel and Rojstaczer (1996) demonstrate that subsidence rates throughout the Delta are decreasing with time. Therefore, the present-day subsidence rates are lower than those reported here and additional information is required to reevaluate priority areas based on present-day subsidence rates.

Uncertainty in the basal peat elevations and current elevations in the Delta also point to the need for additional data. Because the most recent topographic leveling in the Delta was completed in the 1970's, the peat thicknesses presented here are about 20 years old. These peat thicknesses could be in error by as much as 8 feet because of subsidence that has occurred over the past 20 years. However, the relative distribution of peat depths presented here is reasonable because the processes affecting the areal distribution of subsidence have remained stable during the last 20 years. The peat thicknesses are also uncertain for several islands as discussed above.

REFERENCES

Atwater, B.F., 1982, Geologic Maps of the Sacramento-San Joaquin Delta, US Geological Survey, Miscellaneous Field Studies Map MF - 1401

Birdseye, C.H., Spirit leveling in California, 1896-1923, US Geological Survey Bulletin 766.

Deverel, S.J. and Rojstaczer, S.A. 1996, Subsidence of agricultural lands in the Sacramento-San Joaquin Delta, California: Role of aqueous and gaseous carbon fluxes, Water Resources Research, 32, 2359-2367

Deverel, S.J., Wang, Bronwen and Rojstaczer, S.A., 1997, Subsidence in the Sacramento-San Joaquin Delta, *in* (Borchers, J.W., ed.) Proceedings of the Joseph Poland Subsidence Symposium, Association of Engineering Geologists (in press).

Department of Water Resources, 1980, Subsidence of organic soils in the Sacramento-San Joaquin Delta, Central District, Sacramento, California

Rojstaczer, S.A., Hamon, R.E., Deverel, S.J. and Massey, C.A., 1991, Evaluation of selected data to assess the causes of subsidence in the Sacramento-San Joaquin Delta, California, U.S. Geological Survey Open File Report 91 -193.

Rojstazcer, S.A. and Deverel, S.J., 1995, Land subsidence in drained histosols and highly organic mineral soils of California Soil Science Society of America Journal, 59:1162-1167.

Soil Conservation Service, 1993, Soil Survey of Sacramento County

Soil Conservation Service, 1992, Soil Survey of San Joaquin County

Soil Conservation Service, 1978, Soil Survey of Contra Costa County

Thompson, J., 1958, The settlement geography of the Sacramento-San Joaquin Delta, California, Ph.D. dissertation, Stanford University

Zilkoski, D.B., Richards, J.H., Young, G.M., 1992, Results of the general adjustment of the North American Vertical Datum of 1988, Surveying and Land Systems, 52, 133-149