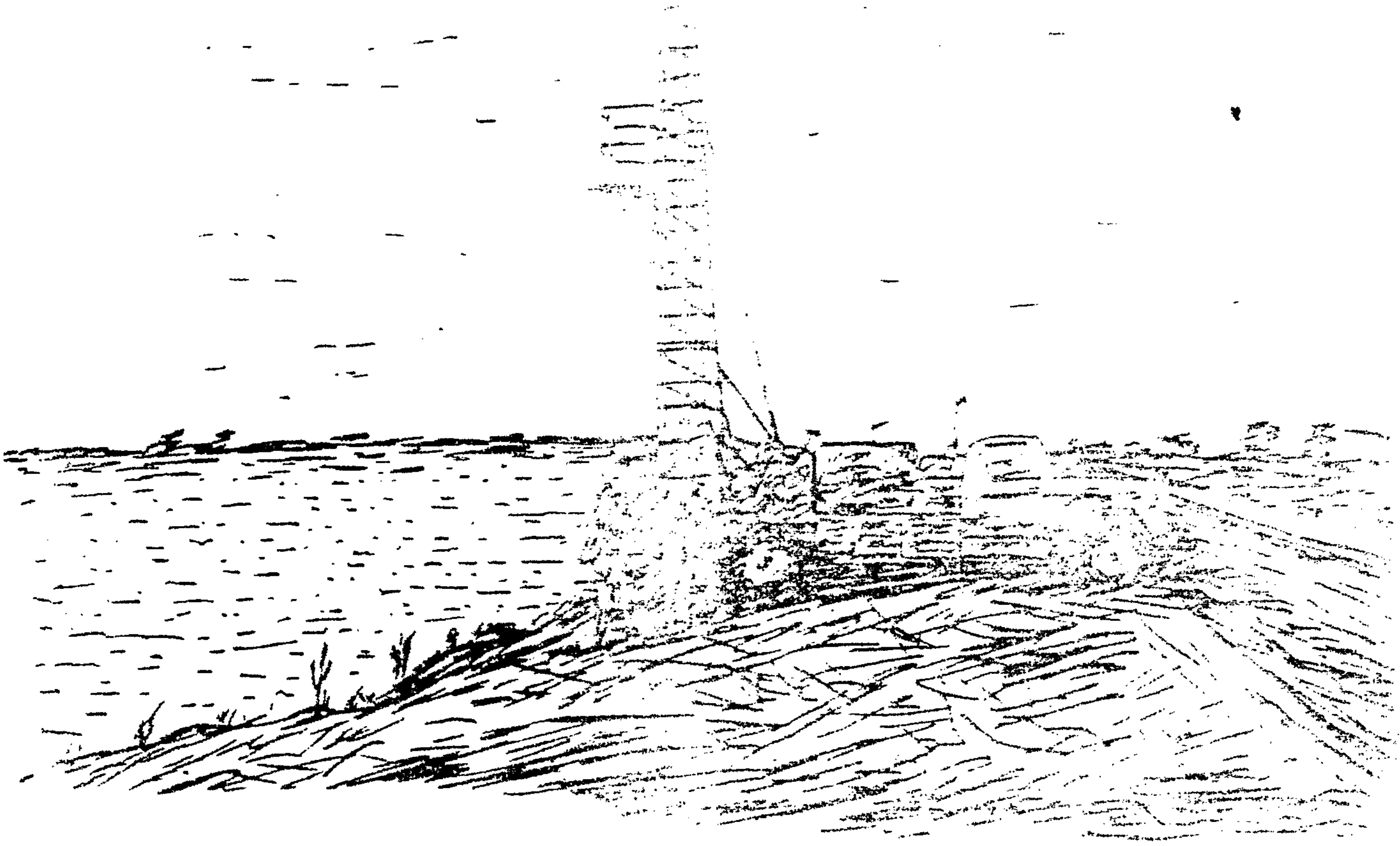
State of California
THE RESOURCES AGENCY
DEPARTMENT OF WATER RESOURCES

SUBSIDENCE OF ORGANIC SOILS IN THE SACRAMENTO-SAN JOAQUIN DELTA



Central District

August 1980

SUBSIDENCE OF ORGANIC SOILS

IN THE

SACRAMENTO-SAN JOAQUIN DELTA

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FOREWORD

The Sacramento-San Joaquin River Delta is a prime agricultural area where rich soils produce crops valued in excess of $375 million annually. Subsidence of peat and other organic soils is occurring throughout most of the central Delta at a rate of from 7.1 to 7.6 centimetres (2.8 to 3.0 inches) per year. It is desirable to control or slow this subsidence to maintain this important agricultural region.

Causes of the subsidence are complex and interrelated, as are possible control measures. The California Water Code, Section 12881.4 directs the Department of Water Resources to investigate the viability of a subsidence control program in the Delta. Water Code, Chapter 3, Section 12225 to Part 4.5 of Division 6 and Section 12987 also authorizes such a study. The Department undertook this study with the following objectives in mind:

1. To identify subsidence areas in the Delta.
2. To determine the amount of subsidence over given time periods.
3. To determine the causes of subsidence.
4. To determine the feasibility of controlling the subsidence.

The investigation on which this report is based did not include studies of the economic feasibility of subsidence controls.

Wayne MacRostie

Wayne MacRostie
Chief, Central District

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CONVERSION FACTORS

Metric to Customary System of Measurement

Quantity	Metric Unit	Multiply by	To get customary equivalent
Length	millimetres (mm)	0.03937	inches (in)
	centimetres (cm) for snow depth	0.3937	inches (in)
	metres (m)	3.2808	feet (ft)
	kilometres (km)	0.62139	miles (m)
Area	square millimetres (mm^2)	0.00155	square inches (in^2)
	square metres (m^2)	10.764	square feet (ft^2)
	hectares (ha)	2.4710	acres (ac)
	square kilometres (km^2)	0.3861	square miles (mi^2)
Volume	litres (l)	0.26417	gallons (gal)
	megalitres	0.26417	million gallons (10^6 gal)
	cubic metres (m^3)	35.315	cubic feet (ft^3)
	cubic metres (m^3)	1.308	cubic yards (yd^3)
	cubic metres (m^3)	0.0008107	acre-feet (ac-ft)
	cubic dekametres (dam^3)	0.8107	acre-feet (ac-ft)
	cubic hectometres (hm^3)	0.8107	thousands of acre-feet
	cubic kilometres (km^3)	0.8107	millions of acre-feet
Flow	cubic metres per second (m^3/s)	35.315	cubic feet per second (ft^3/s)
	litres per minute (l/min)	0.26417	gallons per minute (gal/min)
	litres per day (l/day)	0.26417	gallons per day)(gal/day)
	megalitres per day (Ml/day)	0.26417	million gallons per day (mgd)
	cubic metres per day (m^3/day)	0.0008107	acre-feet per day
Mass	kilograms (kg)	2.2046	pounds (lb)
	tonne (t)	1.1023	tons (short, 2,000 lb)
Velocity	metres per second (m/s)	3.2808	feet per second (ft/s)
Power	kilowatts (kW)	1.3405	horsepower (hp)
Pressure	kilopascals (kPa)	0.145054	pounds per square inch (psi)
	kilopascals (kPa)	0.33456	feet head of water
Specific Capacity	litres per minute per metre drawdown	0.08052	gallons per minute per foot drawdown
Concentration	milligrams per litre (mg/l)	1.0	parts per million
Electrical Conductivity	microsiemens per centimetre ($\mu S/cm$)	1.0	micromho per centimetre
Temperature	degrees Celsius (°C)	(1.8 × °C) + 32	degree Fahrenheit (°F)

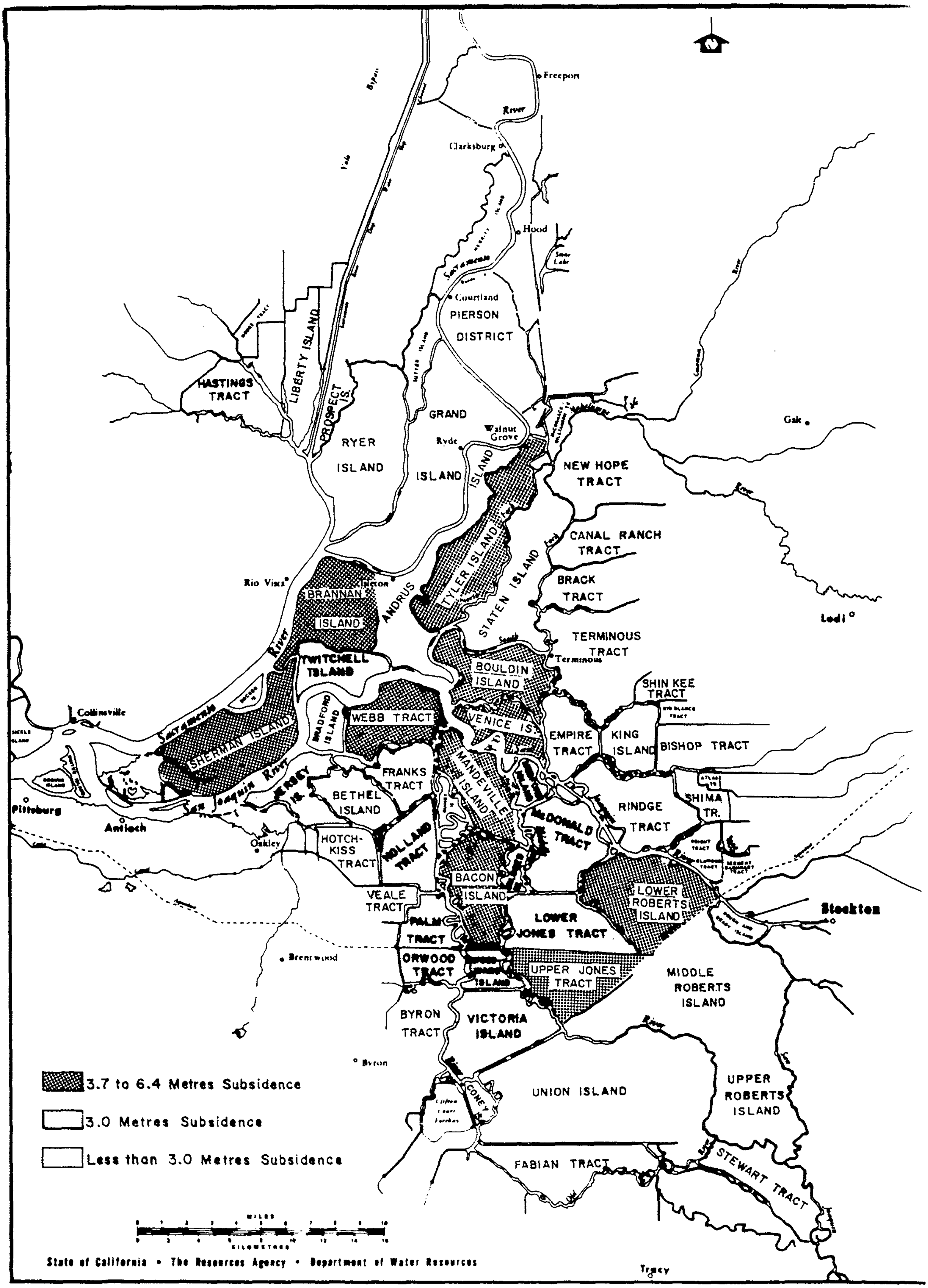

Figure I. AREAS of GREATEST DELTA SUBSIDENCE

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Chapter I. INTRODUCTION

The Sacramento-San Joaquin Delta, located at the confluence of the Sacramento and San Joaquin Rivers, forms the lowest part of California's Central Valley. Before levees were built around the islands to reclaim the land for agriculture, the elevation of the Delta was at about sea level. Today much of the central land area, commonly known as the Delta lowlands, has subsided to below sea level. If the Delta is to remain a prime agricultural region (crops are valued in excess of $375 million annually), it is desirable to control or slow this subsidence of soils.

Figure 1 is a map of the study area that shows the locations of greatest subsidence. Subsidence occurs generally in peat and other organic soils throughout the central Delta area. Lowest elevations occur on the west side. The greatest amounts of subsidence since the times of island reclamation range from 3.7 to 6.4 metres (12 to 21 feet). These high amounts occur on 10 central and west side islands and tracts. At least 11 other islands and tracts have experienced 3.0 metres (10 feet) of subsidence (Table 1).

Estimates for the years 1911 to 1952 show that subsidence occurred at a rate of at least 7.6 centimetres (3.0 inches) per year on 17 Delta islands or tracts. Subsidence within individual islands is generally greatest toward the center, but small low areas sometimes occur at other places, such as at the north end of Mandeville Island.

Geologic studies relative to the viability of subsidence control programs began in June 1976 and continued through June 1980, with the following objectives:

1. To identify subsidence areas in the Delta.
2. To determine the amount of subsidence over given time periods.
3. To determine the causes of subsidence in the Delta.
4. To determine the feasibility of controlling subsidence.

TABLE 1

LOCATION OF GREATEST AMOUNTS OF DELTA SUBSIDENCE
(Since Reclamation of the Particular Island or Tract)

Location	Amount Metres	(feet)	Location	Amount Metres	(feet)
Tyler Island	6.4	(21)	Holland Tract	3.0	(10)
Brannan Island	5.2	(17)	Jersey Island	3.0	(10)
Webb Tract	5.2	(17)	Lower Jones Tract	3.0	(10)
Mandeville Island	4.6	(15)	Medford Island	3.0	(10)
Sherman Island	4.6	(15)	Mildred Island	3.0	(10)
Venice Island	4.6	(15)	McDonald Island	3.0	(10)
Bacon Island	4.3	(14)	Orwood Tract	3.0	(10)
Bouldin Island	4.3	(14)	Palm Tract	3.0	(10)
Upper Jones Tract	4.0	(13)	Twitchell Island	3.0	(10)
Lower Roberts Island	3.7	(12)	Victoria Island	3.0	(10)
			Woodward Island	3.0	(10)

The studies included drilling and sampling 34 subsurface exploration holes on 12 islands and tracts, collecting logs and profiles pertinent to Delta subsidence, studies to develop a technique to differentiate mineral and organic soils by using aerial photographs, and gathering seismic and fault location information.

In addition, the Department of Water Resources (DWR) gathered and analyzed literature to identify possible processes, causes, and rates of Delta subsidence. Leveling (elevation) data were collected and analyzed to determine elevation changes of the Delta islands since their reclamation. Literature relative to wind and wind erosion and on the probability of levee failure was also analyzed.

Subsidence areas in the Delta were identified through analyses of existing data and reports, as were amounts and average rates of subsidence. After identifying areas and average rates of subsidence for the Delta as a whole, Mandeville Island was chosen for detailed studies of possible control methods. Details of the Mandeville Island study and of related studies by others are presented in Appendix A.

The depletion of organic soils is a major controlling factor in the future of the Delta. The number of years before depletion is directly proportional to the thickness of organic soils on each island. Therefore, theoretical estimates can be made for depletion times of t[illegible] soils (Table 2). The estimates were [illegible]puted by dividing estimated maximum [illegible]ganic soil thicknesses by estimated subsidence rates and assuming all su[illegible]dence is due to loss of organic soils. Actual depletion times may be conside[illegible]ably different because of such variat[illegible] as tectonic movement, land leveling, importation, or changes due to floodi[illegible]

Depletion of organic soils would not necessarily mean an end to Delta farm operations. In some cases animals or crops such as corn, grapes, and alfal[illegible] could be raised on the remaining mine[illegible] soils. On the other hand, the floors [illegible] some islands and tracts will become increasingly lower as organic soils ar[illegible] depleted, and flood protection will become increasingly difficult.

For this reason, levee stability must also be considered. A report written [illegible] the U. S. Army Corps of Engineers (USC[illegible] in 1978 discussed the probability of Delta levee failure within the next 40 years based on structural analyses of existing levees. More recently, a 197[illegible] USCE report predicted the number of le[illegible] failures per 100 years that will occur due to overtopping and levee instabili[illegible] The predictions range from zero for so[illegible] islands and tracts along the outer edge of the Delta to 20 failures per 100 yea[illegible] for some of those more centrally locate[illegible] The probability of levee failure may be reduced, but not eliminated, by subsidence control.

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[1] W. N. Houston and J. M. Duncan, Probability of Failure of Levees in the Sacramento-San Joaquin Delta, California, Study under contract with U. S. Army Corps of Engineers, Sacramento, CA, February 1978, pp. 12, 13, and G4.

[2] U. S. Army Corps of Engineers, Sacramento District, Sacramento-San Joaquin Delta Investigation: Information Brochure on Alternatives for Flood Control and Related Water Resources Problems, Sacramento, July 1979, pp. 6 and 8.

TABLE 2

DEPLETION TIMES OF ORGANIC SOILS

Area	Estimated Maximum Thickness of Organic Soils Metres	(feet)	Estimated Subsidence Rate per Year cm	(inches)	Estimated* Time Until Depletion (years)
Andrus Island	16.2	(53)	4.1	(1.6)	>200
Bacon Island	5.5	(18)	7.6	(3.0)	72
Bethel Island	3.0	(10)	Insufficient data		--
Bouldin Island	9.4	(31)	7.6	(3.0)	124
Brack Tract	3.7	(12)	Insufficient data		--
Bradflord Island	6.1	(20)	4.1	(1.6)	150
Brannan Island	8.8	(29)	4.1	(1.6)	>200
Byron Tract	1.5	(5)	4.1	(1.6)	38
Coney Island	1.2	(4)	4.1	(1.6)	30
Empire Tract	5.5	(18)	Insufficient data		--
Fabian Tract	Insufficient data		--	--	--
Franks Tract	Insufficient data		--	--	--
Grand Island	11.6	(38)	Insufficient data		--
Holland Tract	7.3	(24)	7.6	(3.0)	96
Hotchkiss Tract	4.9	(16)	Insufficient data		--
Jersey Island	9.1	(30)	7.6	(3.0)	120
King Island	1.5	(5)	Insufficient data		--
Lower Jones Tract	4.0	(13)	7.4	(2.9)	54
Lower Roberts Island	5.2	(17)	4.1	(1.6)	128
Mandeville Island	10.4	(34)	7.1	(2.8)	146
Medford Island	6.7	(22)	7.6	(3.0)	88
Mildred Island	Insufficient data		--	--	--
McDonald Island	Insufficient data		--	--	--
Orwood Tract	4.3	(14)	4.1-7.6	(1.6-3.0)	56-105
Palm Tract	3.0	(10)	7.6	(3.0)	40
Quimby Island	Insufficient data		4.1	(1.6)	--
Rindge Tract	4.9	(16)	2.8	(1.1)	175
Rough and Ready Island	Insufficient data		--	--	--
Ryer Island	Insufficient data		--	--	--
Sherman Island	Insufficient data		7.6	(3.0)	--
Terminous Tract	Insufficient data		--	--	--
Twitchell Island	12.2	(40)	7.6	(3.0)	160
Tyler Island					
Northern Portion	9.8	(32)	4.1	(1.6)	>200
Southern Portion	9.8	(32)	11.7	(4.6)	83
Union Island					
Eastern Portion	1.8	(6)	Insufficient data		--
Western Portion	1.8	(6)	Insufficient data		--
Upper Jones Tract	2.4	(8)	7.4	(2.9)	33
Veale Tract	0.6	(2)	4.1	(1.6)	15
Venice Island	9.1	(30)	7.6	(3.0)	120
Victoria Island	2.1	(7)	7.6	(3.0)	28
Webb Tract	10.1	(33)	7.6	(3.0)	132
Woodward Island	4.9	(16)	7.6	(3.0)	64

*Assumes all subsidence is due to loss of organic soils. Estimates are theoretical. They are computed by dividing estimated maximum organic soil thickness by estimated subsidence rates. Actual depletion times may be considerably different depending on such variables as earth movement, land leveling, soil importation, irrigation practices, and flooding.

Conclusions

Following are conclusions relative to the physical viability of subsidence control in the Delta.

1. Delta organic soils are subsiding at average estimated rates as great as from 7.1 to 7.6 cm (2.8 to 3.0 inches) per year on at least 17 islands and tracts.

2. Delta subsidence is caused by several complex and interrelated factors, which include: oxidation, wind erosion, tectonic movement, compaction, consolidation, burning, and export by people. Anaerobic decomposition may be occurring, but its occurrence could not be determined.

3. The six main methods of slowing subsidence are: ground water level control, wind control, consolidation control, burning control, export control, and addition of plant residues.

4. Crop and land use manipulation is the best means of achieving ground water level controls thereby preventing oxidation and shrinkage. It would also aid in wind control.

5. Present rates of subsidence of Delta organic soils may be reduced by up to 30 percent, but probably cannot be reduced more than that as long as agricultural use of the islands and tracts continues.

Recommended Future Studies

1. A leveling network should be established to determine elevation changes in central portions of Delta islands and tracts. This would allow for more accurate predictions of subsidence rates.

2. Additional subsurface exploration holes are needed in central portions of islands and tracts to more accurately determine thickness and configuration of organic soils. Proposed general locations of these holes are shown on Plate 1.

3. Research should be done to determine the presence or absence of anaerobic decomposition of Delta organic soils.

4. Test areas should be established for testing various methods of subsidence control.

Chapter II. CAUSES OF SUBSIDENCE IN THE DELTA

Several possible causes of Delta subsidence identified are shown on Table 3. The following sections discuss these causes in detail.

A literature search and an inquiry to the University of California at Davis revealed no studies to correlate certain crop or tillage practices with subsidence rates. However, crops and tillage practices that aerate and dewater soils may contribute to increased subsidence rates.

TABLE 3

ESTIMATED AVERAGE SUBSIDENCE RATES FROM VARIOUS CAUSES

Cause	Rates per Year Centimetres	(inches)	Reference
	Found Generally Over Most of Delta		
Oxidation (Aerobic Decomposition)	3.6-6.1	(1.4-2.4)	This Study
Shrinkage (Dewatering)	1.8	(0.71)	This Study
Wind Erosion (Deflation)	0.6-1.3 0.25	(0.25-0.5) (0.1)	Weir[a3] Carlton[a9]
Tectonic Movement	0.02	(0.006)	Curtin[a10]
Compaction Due to Farm Equipment (near surface)	Practically Zero		This Study
Anaerobic Decomposition	Not Determined		
	Found Locally (See Text)		
Consolidation (Natural)	1.0	(0.4)[b]	Curtin[a10]
Consolidation (Gas Withdrawal)	0.4-1.3	(0.15-0.5)[c]	Curtin[a10]
Burning (Where Practiced)	0.2-0.3	(0.08-0.13)	This Study
Export by People	Practically Zero except Franks Tract[d]		This Study

[a]Refer to numbered footnote in text.
[b]Consolidation of mineral sediments occurs between Clarksburg and Walnut Grove.
[c]Probably limited to areas close to gas fields where gas has been withdrawn.
[d]Mining by dragline occurred after tract became flooded.

Oxidation

Oxidation is a major cause of subsidence in agricultural areas.[3] Such oxidation occurs in the Delta when organic soils are dewatered thus introducing oxygen, with resulting aerobic decomposition. The process is accelerated by repeated tilling, which exposes new surfaces to oxygen. However, tillage is not essential to the oxidation process, and some subsidence occurs where soils have not been tilled for years.

Weir[4] describes such a situation as follows:

> "An example of this is a house on Lower Jones Tract around and under which the soil has subsided about 4 feet. This house is built upon pilings driven into the mineral soils underlying the peat.
>
> "Obviously neither compaction by tillage equipment or burning have contributed to the subsidence under this house. Oxidation is believed to be the major cause of subsidence in the farmed lands of the Delta area and it is believed that it occurs at a rate readily measured by the methods employed."

In a caption under a 1935 photograph of the house, Weir states that the house was 20 years old. If the bottom of the house were at ground surface when it was built, the rate of subsidence caused by oxidation would be 6.1 cm (2.4 inches) per year for the period 1915 to 1935. This differs only slightly from the 5.7 cm (2.2 inches) per year average subsidence rate measured on the Weir Transect (see Appendix A) for the period 1922 to 1964. However, it indicates that oxidation probably is a major cause of subsidence in the Delta.

Computations reported by Stephens and Spier[5] indicate that oxidation accounts for at least 50 percent of peat losses in the Everglades. At a Delta subsidence rate of 7.1 to 7.6 cm (2.8 to 3.0 inches) per year, 50 percent would be 3.6 to 3.8 cm (1.4 to 1.5 inches) attributable to oxidation.

Research by Broadbent[6] also shows the importance of the oxidation process. His laboratory experiments indicate that raising the pH in organic soils may increase the rate of decomposition due to oxidation, but the rate per unit pH change has not been determined. The decomposition increase is probably due to the ability of organic matter to absorb oxygen from the air in an alkaline medium. This absorption results in the conversion of some organic carbon into carbon dioxide.

If raising the pH increases decomposition of organic soils in the field as it does in the laboratory, the effect could occur in areas where sea water is intruding, where organic soils are mixed with mineral soils, or where burning is practiced. All these could raise the pH of the organics and could increase subsidence rates.

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3 Walter W. Weir, Subsidence of Peat Lands of the Sacramento-San Joaquin Delta, Summary, Agricultural Extension Service, Stockton, CA, Reprinted 1971, p. 10.

4 Walter W. Weir, "Subsidence of Peat Lands of the Sacramento-San Joaquin Delta, California", Hilgardia, Vol. 20, No. 3., 1950, p. 50.

5 John C. Stephens and William H. Spier, "Subsidence of Organic Soils in the USA", Land Subsidence Symposium, Vol. II, 1969, p. 533.

6 F. E. Broadbent, "Factors Influencing the Decomposition of Organic Soils of the California Delta", Hilgardia, Vol. 29, No. 13, 1960, p. 589 and 600-605.

Shrinkage

Organic Delta soils shrink up to 50 percent in volume when they become thoroughly dry.[7] This is evident as shrinkage cracks become readily visible in newly excavated materials when they dry. Shrinkage becomes a factor in Delta subsidence as water tables are lowered to compensate for loss of surface and near surface soils due to other causes, such as oxidation or wind loss.

An estimate of subsidence due to shrinkage can be made by assuming that 50 percent of the 7.1 to 7.6 cm (2.8 to 3.0 inches) per year overall subsidence rate is from surface loss. Then if the water table were lowered an equal amount and 50 percent shrinkage occurred, the rate of subsidence from shrinkage would be about 1.8 cm (0.7 inch) per year.

Wind Erosion

Wind erosion plays a part in Delta subsidence because the dry peat soils are light and easily carried by winds. Weir[8] estimated the rate of subsidence caused by wind erosion to range from 0.6 to 1.3 cm (0.25 to 0.5 inch) per year. Carlton[9] estimated that peat loss due to wind erosion might be about 0.25 cm (0.1 inch) per year and that the amount of peat soil removed by wind greatly increases as wind velocity exceeds about 6.7 metres per second (15 miles per hour).

Wind erosion is accelerated by tilling, traffic on unpaved areas, and by burning (which produces easily eroded ash).

Tectonic Movement

Experts do not agree on whether tectonic subsidence is occurring. If it is, the rate is negligible in comparison to other causes. For instance, about 1 000 metres (3,000 feet) of alluvial materials underlie the Sacramento Valley, most of which was deposited above sea level.[10] Assuming the base of these deposits moved downward due to tectonic subsidence, and knowing they are about 6 million years old, a subsidence rate of 0.015 cm (0.006 inches) per year can be calculated. Whether this is valid for the Delta area cannot be determined.

The western portion of the Delta is tectonically active and the most recent known movement, in the vicinity of Antioch, occurred between 1962 and 1969, during earthquakes with magnitudes ranging from 2.5 to 5.0 on the Richter scale. Though the rate of subsidence due to tectonics would be negligible, the many unconsolidated and water-saturated Delta soils are susceptible to local failures during earthquakes.

A map showing the locations of faults and epicenters in and near the Delta is available (at $1.50) from the Department of Water Resources, P. O. Box 388, Sacramento, CA 95802.

Compaction

No data are available to indicate compaction due to farm equipment, and this cause is probably negligible in relation to others.

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7 Department of Water Resources, Delta Test Levees Investigation, November 1963, pp. 105 and 127.

8 Walter W. Weir, Subsidence of Peat Lands of the Sacramento-San Joaquin Delta, Summary, Agricultural Extension Service, Stockton, CA, Reprinted 1971, p. 10.

9 University of California, Davis, Oral communication with Alan Carlton, Department of Soils and Plant Nutrition, December 1976.

10 Department of Water Resources, Land Subsidence Studies in the Sacramento District, Progress Report, June 1967, pp. 11-12,

Anaerobic Decomposition

Anaerobic decomposition is that which occurs where there is no air or free oxygen, and it could contribute to Delta subsidence. Data are insufficient to determine the presence or absence of anaerobic decomposition in the Delta.

Stephens[11] established that in Florida peats most decomposition occurs in the aerobic layer above the water surface. He developed the equation

$$14.77\,x = y - 2.45$$

to express the relationship between the subsidence rate and the depth of water in Florida (x = subsidence rate in inches per year; y = annual depth of water table in inches). However, when this equation is applied to the Delta annual subsidence rate of 7.1 to 7.6 cm (2.8 to 3.0 inches), an average water table depth of 111.3 to 118.9 cm (43.8 to 46.8 inches) would be required. This is deeper than normally occurs in actual field practice, indicating anaerobic decomposition could also be occurring in addition to aerobic decomposition.

Waksman and Purvis[12] found abundant populations of anaerobic bacteria in peat profiles at all depths. In lowmoor peat bogs they found that aerobic bacteria populations decreased rapidly with depth but anaerobic bacteria populations increased rapidly below the water.[13]

Laboratory experiments by Broadbent[14] on Staten peaty muck and fibrous peat showed little difference between decomposition rates under aerobic or anaerobic conditions. Some soil samples were incubated at various oxygen levels and others were incubated in nitrogen. Table 4 is a summary of results.

TABLE 4

RELATIVE DECOMPOSITION RATES OF STATEN PEATY MUCK IN AIR AND NITROGEN (during 57 days incubation at 75°F)

Soil	Moisture Content(%)	Atmosphere	Relative Rate of Decomposition
Surface Soil	100	Air	100
	200	Air	71
	100	Nitrogen	81
	200	Nitrogen	64
Subsoil	150	Air	100
	350	Air	79
	150	Nitrogen	81
	350	Nitrogen	79

11 J. C. Stephens, "Subsidence of Organic Soils in the Florida Everglades", Soil Science Society of America Proceedings, Vol. 20, 1956, pp. 79-80.

12 S. A. Waksman and E. R. Purvis, "The Microbiological Population of Peat", Soil Science, Vol. 34, 1932, pp. 95-109.

13 S. A. Waksman and K. R. Stevens, "Contribution to the Chemical Composition of Peat: The Role of Microorganisms in Peat Formation and Decomposition", Soil Science, Vol. 23, 1929, pp. 315-339.

14 F. E. Broadbent, "Factors Influencing the Decomposition of Organic Soils of the California Delta", Hilgardia, Vol. 29, No. 13, 1960, p. 589 and 600-605.

rch[15] reports that when a dry soil is moistened in the laboratory an initially rapid period of decomposition is followed by a declining rate that attains a slow, steady state after a few days. This pattern is repetitive with successive wetting and drying cycles, and appears to be common to all soils. The recurrent pattern of decomposition is due to the high metabolic activity of organisms in their physiological youth following the wetting process, and a decline in activity as the population becomes older.[16] Successive wetting and drying speeds up the decomposition.

Consolidation

Consolidation of sediments below the organic deposits in the Delta may occur due to pore pressure reduction caused by gas and ground water withdrawal. However, there is little data to substantiate or disprove this theory. For instance, some of the lowest Delta elevations occur on Brannan, Twitchell, and Tyler Islands, which overlie producing gas fields (Figure 2). However, similar low elevations occur on Bacon, Bouldin, Mandeville, and Venice Islands, which are away from areas of gas production.

Changes in land elevations overlying Delta gas fields were observed[17] at selected bench marks and are related to changes in gas reservoir pressure. Table 5 lists total changes in elevation and calculated rates of change for the gas field areas. Such subsidence is probably limited to areas close to the listed gas fields. However, additional subsidence of this type could occur if new areas are subjected to gas or water withdrawal.

Subsidence was also detected in areas that do not have highly organic soils, gas production, or ground water production. For example, an area between Clarksburg and Walnut Grove had an average subsidence rate of about 1.0 cm (0.4 inch) per year, based on bench mark elevation comparisons between 1939 and 1951. Movement was attributed to natural consolidation.

TABLE 5

SUBSIDENCE DUE TO GAS REMOVAL

Gas Field	Time Period	Total Change Centimetres(feet)		Subsidence Rate per year Centimetres(inches)	
Rio Vista	1936-64	33.5	(1.1)	1.3	(0.5)
River Island	1942-64	18.3	(0.6)	0.8	(0.3)
West Thornton-Walnut Grove	1942-64	12.2	(0.4)	0.5	(0.2)
Roberts Island	1952-64	6.1	(0.2)	0.5	(0.2)

15 H. F. Birch, "The Effect of Soil Drying on Humus Decomposition and Nitrogen Availability", Plant and Soil, Vol. 10, 1958, pp. 9-31.
16 F. E. Broadbent, "Factors Influencing the Decomposition of Organic Soils of the California Delta", Hilgardia, Vol. 29, No. 13, 1960, p. 589 and 600-605.
17 Department of Water Resources, Land Subsidence Studies in the Sacramento District, Progress Report, June 1967, pp. 11-12, Figures 7 and 13-16.

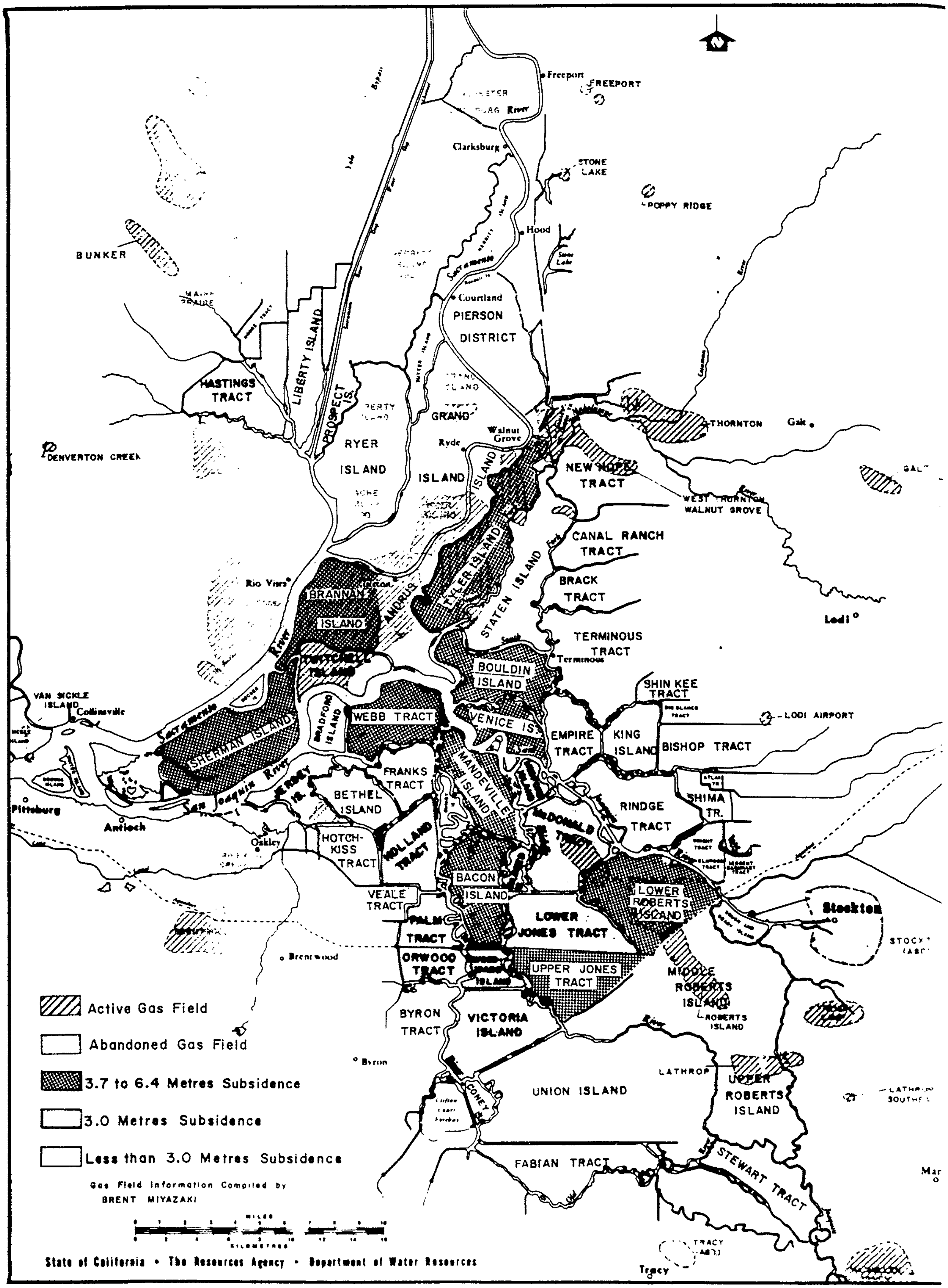

Figure 2. RELATIONSHIP of GAS FIELDS to SUBSIDENCE AREAS

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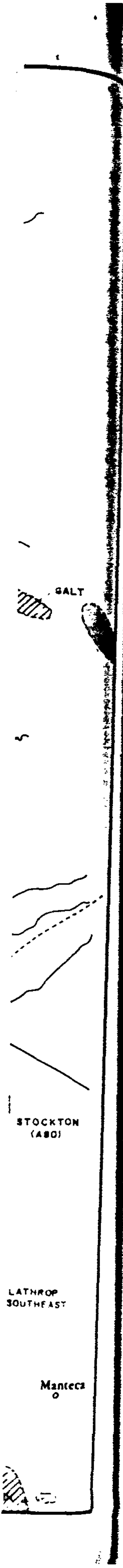

Burning

Organic soils have been intentionally burned to destroy weeds, plant pests, and diseases. During World War II, burning was done to add potash to soils to increase potato and sugar beet production.

Burning permits were examined for Delta areas within which organic soils occur. (Varying amounts of mineral soils also occur within this area.) Table 6 shows the number of permits issued by Sacramento and San Joaquin counties during 1978 and 1979. The table also shows the approximate size of the areas to be burned, as shown on the permits.

Parts of Contra Costa County contain organic soils also, but burning data are incomplete and are therefore not listed. The size of areas actually burned and whether they were on mineral or organic soils were not recorded.

According to the permits, waste to be burned included asparagus, barley stubble, bermuda, corn stubble, field stubble, grain stubble, grass, milo, potato vines, safflower stubble, weeds, and wheat stubble.

Although sheer numbers of permits issued and the verbal reports of observers regarding "peat fires" suggest that significant burning of organic soils is taking place, documentation is insufficient to estimate amounts of organic soils recently burned.

Weir[18] reports that in the 26 years covered by his report, every portion of the area (presumably his transect) was burned at least once to a depth of 7.6 to 12.7 cm (3 to 5 inches), and some portions were burned three or four times. However, Weir says natural oxidation has probably contributed more to subsidence than has burning.

Assuming a 100 percent soil loss and a cultivation period of 40 years over the entire Delta, a rate of soil loss from burning can be determined as ranging from 0.25 to 0.3 cm (0.08 to 0.13 inch) per year if burned only once, or from 0.8 to 1.3 cm (0.3 to 0.5 inch) per year if burned four times within the 40-year period.

TABLE 6

BURN PERMITS ISSUED IN
SACRAMENTO AND SAN JOAQUIN COUNTIES

Year	County	Approximate Areas to be Burned: Hectares	(Acres)	Number of Permits Issued
1979	Sacramento	2,400	(6,000)	143
	San Joaquin	4,000	(10,000)	43
1978	Sacramento	3,600	(9,000)	184
	San Joaquin	3,600	(9,000)	22

18 Walter W. Weir, Subsidence of Peat Lands of the Sacramento-San Joaquin Delta, Summary, Agricultural Extension Service, Stockton, CA, Reprinted 1971,

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Export by People

Some organic soils cling to root crops, such as sugar beets, and are exported from the Delta. No data are available to determine amounts, but they are probably relatively negligible.

Peat has been dredged from Franks Tract since about 1955. (Franks Tract has been under water since levee breaks flooded it in 1937.) Mining of peat recently began in the river/slough area just south of Venice Island. Because both mining areas are under water, the removal of peat has not contributed to subsidence of Delta farmlands. No other peat mining operations were discovered during this study.

Chapter III. METHODS OF SLOWING DELTA SUBSIDENCE

Possible methods of slowing Delta subsidence are discussed in this chapter.

Table 7 shows estimates of the percent reduction of subsidence under ideal conditions where prevention measures could be fully implemented. The percent by which subsidence can be reduced may be determined only by pilot projects in the field. However, the present 7.1 to 7.6 cm (2.8 to 3.0 inch) per year rate might be reduced by an average of about 30 percent. The values shown on Table 7 are largely taken from literature; the overall average reduction of 30 percent is based on judgment attempting to take into account the complex interrelated factors causing subsidence, thickness of the organic soils, and the extents of those soils.

Because of the complexity of the subsidence problem, methods to slow subsidence could cause problems of another type. Such potential problems are also discussed in this chapter.

TABLE 7

ESTIMATED REDUCTION OF SUBSIDENCE USING PREVENTIVE MEASURES UNDER IDEAL CONDITIONS[a]

Cause	Prevention Measures	Estimated Percent Reduction
Oxidation, Natural	Ground water level and soil disturbance control	40-75
Shrinkage (Dewatering)	Ground water level control	50-75
Wind Erosion (Deflation)	Trees, Wind Fences	30-50
	Row orientation, minimize soil disturbance, special crops and crop patterns	40-60
Tectonic Movement	None	0[b]
Compaction from Farm Equipment	Use light-weight equipment	98
Anaerobic Decomposition	None known	0
Natural Consolidation	None	0[b]
Consolidation from Gas and Water Removal	Limit Production Reinjection	Almost 0 Unknown
Burning	Prohibition	98
Export by People	Plant Washing Prohibit Mining	90-98 100
TOTAL ESTIMATED REDUCTION IF ALL CONTROL MEASURES COULD BE FULLY IMPLEMENTED		30

[a]Economic feasibility not considered.
[b]Tectonic movement and natural consolidation are part of the on-going earth-forming process.

Ground Water Level Control

Maintaining high ground water levels would help control subsidence due to two major causes, oxidation and shrinkage.

Maintaining high ground water levels would minimize the thickness of soils subjected to the oxidation process. Oxidation could probably be reduced 40 to 75 percent by maintaining high ground water levels.

Shrinkage may be prevented by maintaining soil saturation through high ground water levels.[19] Reduction would be 50 to 75 percent. Unfortunately, those organic soils that have already been subjected to shrinkage cannot be restored to original volumes by new saturation because soil structure is changed, causing permanent reduction of porosities.[20]

Water level control would be achieved by encouraging land uses such as irrigated pasture that allow high ground water levels.

High water tables may cause tillage problems, could cause salts to be deposited in the soils due to lack of leaching, could restrict vehicular travel, and could restrict the type of crops that could be grown. The economic effects of such factors will need to be evaluated in determining whether to use high water tables for subsidence control.

In addition, the pH of soils could be raised by intruding saline water and oxidation rates might be increased as a consequence. However, this has not been proved in the field, and keeping high water tables as a subsidence control measure would counteract the oxidation that might be accelerated by increased pH.

Wind Control

Wind is both an erosional and an evapotranspirational agent -- it can carry soils away and can reduce soil moisture thereby increasing the oxidation process. Thus, by controlling wind velocities, soil losses may be reduced. However, the amount of soil losses due to wind erosion is relatively small.

Planting trees and building wind fences could reduce wind erosion by about 30 to 50 percent.[21, 22] Special crops, narrow row spacing, rows perpendicular to wind direction, and planting during periods of minimum wind velocities might reduce wind erosion by 40 to 60 percent.

Problems include reduction of surface area available for crop use, competition of windbreak plants with crops for soil nutrients, shading of crops by windbreak trees, interference with farming equipment, increased labor costs, costs in implementing and maintaining wind erosion control features, and reduction of farm income due to low-value crops. In addition, higher water levels might limit the types of crops that could be used to reduce wind velocities.

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19 R. J. deGlopper, "Shrinkage of Subsequeous Sediments of Lake Ijssel (The Netherlands) after Reclamation", Land Subsidence Symposium, Vol. II, 1969, pp. 192-197.

20 I. I. Murashko, "Compression of the Peat-Bogs after Draining", Land Subsidence Symposium, Vol. II, 1969, pp. 539, 545.

21 A. W. Zingg, N. P. Woodruff, and C. L. Englehorn, "Effect of Wind-Row Orientation on Erodability of Land in Sorghum Stubble", Agronomy Journal, Vol. 44, No. 5, 1952, P. 230.

22 E. L. Skidmore, N. L. Nossaman, and N. P. Woodruff, "Wind Erosion as Influenced by Row Spacing, Row Direction, and Grain Sorghum Population", Soil Science Society of America Proceedings, Vol. 30, No. 4, 1966, p. 505.

23 U. S. Department of Agriculture Information Bulletin 354, November 1977, pp. 6, 7, and 19.

Compaction Control

Although there is no evidence that compaction is a serious subsidence factor, the use of heavier equipment than necessary should be avoided. Such equipment can cause compaction even in mineral soils outside the Delta area.

If compaction were determined to cause subsidence, it could be reduced by approximately 98 percent.

Consolidation Control

Consolidation from gas or water removal could be prevented if no gas or water removal were permitted; however, this is not practical. Once production is begun and consolidation results, the consolidation continues even when production is stopped. Therefore, the reduction of such consolidation would be almost zero over the short term (20 years).

Reinjection of fluids or gases into affected areas to control consolidation cannot be evaluated at this time because of lack of information.

Burning Control

Although burning may add some potash to soils, the overall value in light of resulting soil loss is negative. The value of burning for weed control is also questionable.[24] Addition of fertilizers and careful use of chemical weed control would be preferable to burning.

If new legislation were enacted to prohibit agricultural burning of peat lands, the reduction of subsidence due to burning is estimated to be 98 percent.

Peat Export Control

Controlling current exports of Delta organic soils is probably not needed because of the small amounts being taken. However, any mining of organic soils on islands or tracts that are not flooded should be avoided.

The small amount of soil being exported along with root crops could be retained by a washing process near the harvest area. Reduction due to this cause would be between 90 to 98 percent.

Addition of Plant Residues

Mixing plant residues with soils may decrease subsidence according to laboratory experiments.[25] Those experiments indicate that additions of calculated amounts of cornstalk residue will balance subsidence losses of Staten peaty muck. Whether this method would actually work in the field and whether it would work in soils other than Staten peaty muck is not known.

A potential problem with this method is that plant residue applied might raise soil pH values, thus accelerating the oxidation process. In addition, the fields would need to lie fallow for a year or two while the plant residue decomposed. Also, mixing the plant residue and soils might require tilling that would increase oxidation and wind erosion.

Although these problems might arise, the application of plant residue to help control or slow Delta subsidence is a method that should not be overlooked.

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24 Delta Advisory Planning Council, Delta Plan Technical Supplement: Delta Agriculture and Soils, Sacramento, CA, May 1976, p. 20.

25 F. E. Broadbent, "Factors Influencing the Decomposition of Organic Soils of the California Delta", Hilgardia, Vol. 29, No. 13, 1960, p. 589 and 600-605.