State of California
The Resources Agency
DEPARTMENT OF WATER RESOURCES

DELTA SUBSIDENCE INVESTIGATION

Progress Report for Fiscal Years 1986-87 and 1987-88

Department of Water Resources
Central District

October 1989

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Secretary for Resources
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SUMMARY

On July 1, 1985, the Central District began the Delta Subsidence Investigation to review data, contact other concerned agencies, and outline a program to determine causes and rates of shallow and deep subsidence. This determination is important for making decisions regarding land management measures that could slow subsidence. This report describes work during fiscal years 1986-87 and 1987-88 toward meeting those goals. A report published in 1987 describes work during 1985-86.

Work during fiscal years 1986-87 and 1987-88 included extensive contacts with public agencies and private enterprise to obtain funding for extensometer construction and Global Positioning System (GPS) surveys needed to measure subsidence. As a result, funding was received from the California Division of Oil and Gas and from Contra Costa County. A cooperative study has begun with the U.S. Geological Survey, which provides matching federal funds as part of a DWR/USGS agreement.

The funding obtained and negotiations conducted resulted in construction of extensometers on Bacon Island and Bethel Tract (commonly called Bethel Island). In addition, an agreement was made for construction of an extensometer on Bradford Island during summer 1988. In conjunction with the extensometer construction, a GPS bench mark on Bacon Island and a GPS baseline network for the Delta were also established.

Other accomplishments included field and office surveys to determine the amount of Delta gas field production and a field survey to locate areas of extensive ground water use from wells in the Delta.

Chapter 1. INTRODUCTION

The Delta at the confluence of the Sacramento and San Joaquin river systems in California is a unique and valuable resource. It occupies more than 700,000 acres, including over 700 miles of waterways and 60 leveed islands and tracts. Most of the Delta is reclaimed marshland, lying near sea level and as much as 30 feet below sea level. A network of levees totaling about 1,100 miles is necessary to protect the islands and tracts against flooding. The Delta as described by the California Legislature is shown in Figure 1.

Deposition of sediments in the Delta began 25 million to 175 million years ago. In general, sediment deposition during the past million years occurred during alternate cycles of deposition and erosion. Delta peats began to form about 11,000 years ago during one of the rises in sea level (see Appendix A).

Since 1980, 24 Delta islands and tracts have flooded. Many of the levee breaks were caused by structural failure due to unstable organic soils that constitute the levees and their foundations and by subsidence of the island surface. Continued subsidence causes increasing hydrostatic pressure on the levees, which can contribute to the failure of a section of levee.

The importance of Delta subsidence was formally recognized in 1976, when the California Legislature passed Assembly Bill 4193 (see Appendix B). The Bill set up a study to determine causes of and possible solutions to subsidence.

The future of the Delta depends heavily on the extent to which levees are maintained, and subsidence is a controlling factor in the amount and type of maintenance required. Understanding the processes of subsidence is critical when attempting to maintain the levee system.

Department of Water Resources studies for improving Delta levees date back 25 years or more (see Appendix B). The Department began the present subsidence investigation on July 1, 1985, as part of the Delta Levee Subventions component of the Public Safety and Prevention of Damage Program. Authority and funding are provided in the Governor's Budget, Section 3860.

The purpose of this report is to describe progress on the Delta Subsidence Investigation through fiscal year 1987-88.

Objectives and Scope of Study

Objectives of the subsidence investigation for fiscal years 1986-87 and 1987-88 have been to:

- Coordinate with the U.S. Geological Survey and with Contra Costa County in constructing extensometers (compaction recorders).
- Coordinate with the U.S. Geological Survey in Global Positioning System surveying of the Delta.
- Coordinate with other governmental agencies and private industry in studying Delta subsidence.
- Evaluate and interpret data from extensometers.
- Cooperate with DWR Division of Land and Right of Way Survey Unit in evaluating whether historical leveling data should be further analyzed and, if so, outline the type of analysis and furnish a cost estimate for the analysis.
- Recommend a long-term subsidence program.

Initial emphasis has been on areas of historically high subsidence rates, areas of greatest peat thickness, and areas where subsidence is of special local concern because of past or planned gas production or ground water withdrawal.

Method of Study

This study has included:

- Collection and evaluation of reports and data,
- Contacts with private firms and public agencies to obtain funds for extensometer construction,

- Contract writing and negotiations for extensometer construction and GPS surveys,

- Field supervision and coordination of extensometer construction on Bacon and Bethel islands,

- Field and office surveys to determine amount and location of oil and gas production, and

- Field inspections to determine areas of extensive use of ground water.

Extensometer construction and GPS surveys described in this report were part of an ongoing cooperative agreement between the Department of Water Resources and the U.S. Geological Survey. Extensometers were constructed by USGS personnel under the general direction of DWR geologists. GPS networks were established by the USGS in cooperation with the DWR Division of Land and Right of Way. As part of the cooperative agreement, the USGS provided matching federal funds for the extensometer and GPS work.

Funding for extensometer construction was also provided by the California Division of Oil and Gas ($20,000) and by Contra Costa County ($115,000).

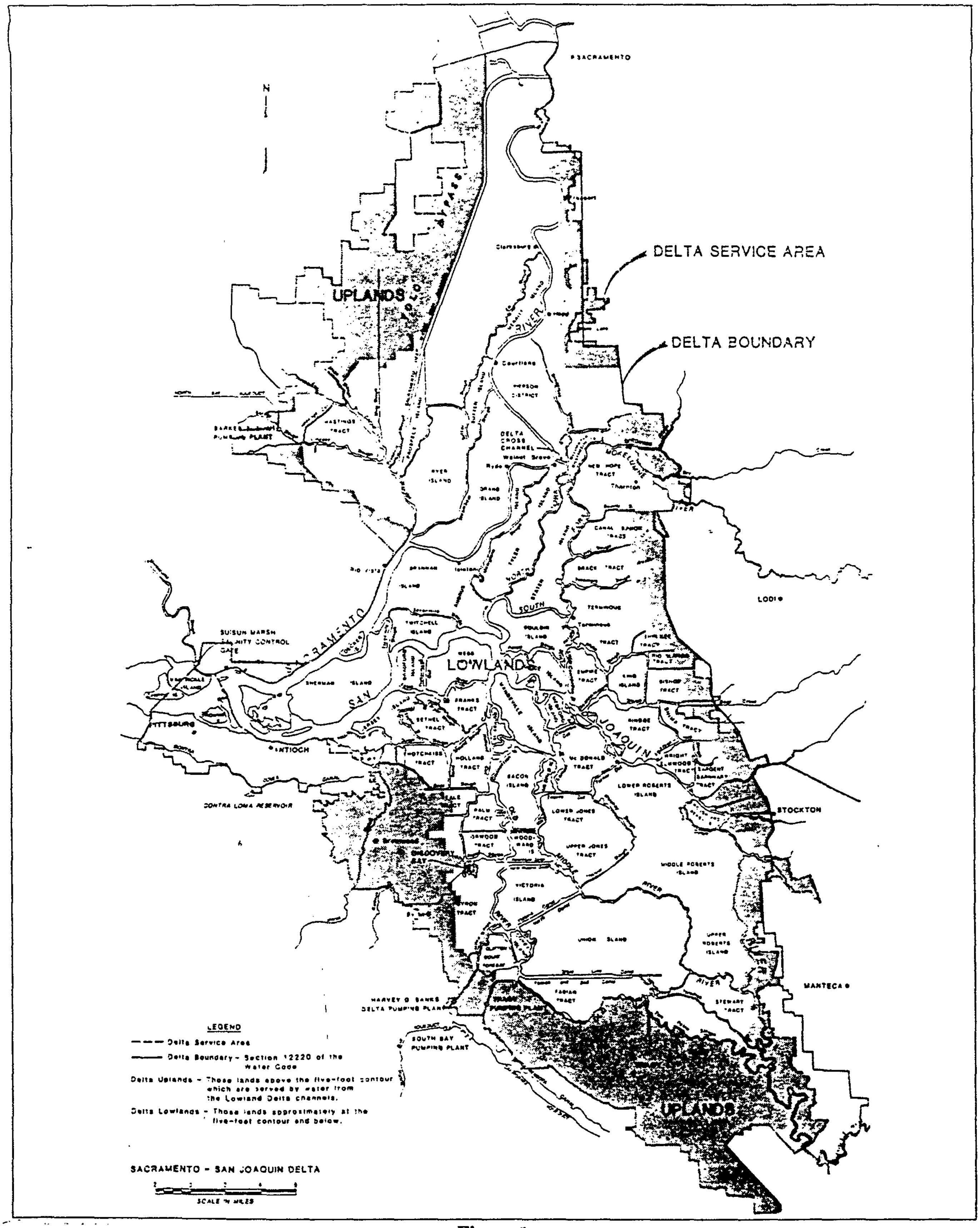

Figure 1
STATUTORY DELTA, SERVICE AREA, UPLANDS AND LOWLANDS

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Chapter 2. CONCLUSIONS AND RECOMMENDATIONS

Information compiled and work accomplished during the first three years of this investigation, including the cooperative program with the U.S. Geological Survey, has resulted in the conclusions and recommendations listed below. Additional possible actions that would help to evaluate the effect of subsidence in the Delta are listed in Chapter 6.

Conclusions

- Shallow subsidence is believed to be the primary cause of land surface lowering in the Delta. Extensometers will provide data on rates of shallow soil loss.

- When using National Geodetic Survey data for subsidence analysis, adjustments in bench mark elevations and use of data sets from different leveling programs must be evaluated carefully.

- Preliminary evaluation indicates that restudy of past field notes and survey work of the National Geodetic Survey will cost about $112,000. However, such restudy probably will not provide substantial new or more reliable information.

- There are indications, such as along part of the Walter Weir transect, that subsidence rates have slowed. Evaluation of an average elevation profile indicates that the subsidence rate along the Weir Transect on Lower Jones Tract slowed from 2.61 inches per year for the period 1922-1945 to 1.57 inches per year for 1945-1981.[1] However, even if the subsidence rate were still declining, it would still be a major problem.

- Fewer deep extensometers may be necessary to determine deep subsidence rates and the zone of subsidence than was first believed. Instead, a larger number of shallow extensometers may provide more useful data.

- Survey data provided by space satellite (GPS) surveying techniques have established a surface elevation data base with which to evaluate future subsidence.

- Even if the National Geodetic Survey data from conventional surveying were usable, it would still be necessary to develop a geodetic correction factor that would allow correlation of surveying data obtained by space satellite or conventional techniques.

- With the exception of Bethel Island and peripheral areas of the Delta, there are few large capacity water wells that produce ground water from aquifers underlying the Delta.

Recommendations

- Construct additional extensometers (compaction recorders) to obtain data on subsidence rates in the zone of organic material and, where appropriate, in the zone from which ground water is withdrawn to determine the amount of subsidence in each zone. The extensometers should be operated for a minimum of 10 years, using state-of-the-art data recording technology.

- In conjunction with the extensometer construction, use state-of-the-art methods to obtain land surface elevation data from which subsidence amounts and rates can be determined. Bench marks should be resurveyed at reasonable intervals for at least 10 years. At present, 1- or 2-year intervals appear to be reasonable.

- Evaluate and report annually on subsidence amounts and rates based on data obtained from the extensometers and from land surface elevation surveys.

- Continue to collect all Delta drill hole and soil data. Convert these data to a standard format, and show location of all data.

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1 George Newmarch, *Delta Subsidence Investigation Progress Report* (California Department of Water Resources, Central District, Sacramento, 1986).

Chapter 3. GAS AND GROUND WATER PRODUCTION

In other parts of the world, extraction of hydrocarbons and ground water has been documented as the cause of land surface subsidence. Because of these occurrences, local, state, and federal officials and the public are concerned that gas and ground water removal may be causing subsidence in the Delta. Therefore, information on subsidence caused by hydrocarbon and ground water removal in other parts of the world and gas and ground water production data for the Delta have been collected and evaluated as part of the subsidence investigation. Preliminary analysis of data from this study indicates that decomposition of organic soils, rather than hydrocarbon or ground water extraction is presently the major cause of elevation loss within the Delta.

In areas outside the United States, subsidence due to removal of hydrocarbons has been documented in the Bolivar Coast oil fields in Venezuela[2], the Gröningen gas field in the Netherlands[3], and several oil and gas fields in the USSR[4].

Subsidence due to the extraction of gas and water has occurred in the Po Delta area in northeast Italy and in the Niigata area of Honshu, Japan.[5]

In the United States, subsidence due to hydrocarbon extraction has occurred in the Goose Creek oil field in Texas.[6] In California, subsidence due to hydrocarbon extraction has occurred in the Wilmington[7], Inglewood, Buena Vista Hills, Santa Fe Springs, and Huntington Beach oil fields of the Los Angeles area[8]

In areas outside the United States, subsidence due to ground water removal has been documented in Germany[9], the Taipei Basin in the Republic of China[10], Hungary[11], and Japan[12].

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2 W. van der Knapp and van der Vlis, "On the Cause of Subsidence in Oil-Producing Areas," 7th World Petroleum Congress, (Mexico City, 1967), Vol. 3, pp. 85-105.

3 J. B. Schoonbeek, "Land Subsidence as a Result of Natural Gas Extraction in the Province of Groningen," Society of Petroleum Engineers of AIME, SPE Paper 5751, presented at the SPE-European Spring Meeting, 1976 (Amsterdam, The Netherlands).

4 A. S. Ilijn, "The Earth Surface Subsidence at the Areas of Gas and Oil Pumping," Proceedings of the Second International Symposium on Land Subsidence (Anaheim, California, 1977), International Association of Hydrological Sciences Publication 121, p. 665.

5 Thomas L. Holzer, "Ground Failure Induced by Ground-water Withdrawal from Unconsolidated Sediment," *Reviews in Engineering Geology*, Vol. VI (Geological Society of America, 1984).

6 W. E. Pratt and D. W. Johnson, "Local Subsidence of the Goose Creek Field," *Journal of Geology*, Vol. 34, No. 1, 1926, pp. 577-590.

7 J. Gilluly and U. S. Grant, "Subsidence in the Long Beach Harbor Area, California," *Geological Society of America Bulletin*, Vol. 60, pp. 461-530, 1949.

8 R. O. Castle and Others, "A Linear Relationship Between Liquid Production and Oil-Field Subsidence," Proceedings of the Tokyo Symposium of Land Subsidence (published jointly by the International Association of Scientific Hydrology, Braamstraat 61 (rue des Ronces), Gentbrugge (Belgium), and Unesco, Place de Fontenoy, 75 Paris-7), 1970.

9 R. Dolezal and M. Peterson. "Subsidence in the North German Coastal Region," Land Subsidence Symposium (Japan, 1969), Vol. 1.

10 Jui-Ming Hwang and Chian-Min Wu, "Land Subsidence Problems in Taipei Basin," Land Subsidence Symposium (Japan, 1969), Vol. 1.

11 I. Orloci, "Water Balance Investigation Based Upon Measurements of Land Subsidence Caused by Ground Water Withdrawal," Land Subsidence Symposium (Japan, 1969), Vol. 1.

12 Shauzow Komaki, "On the Variation of Artesian Head and Land-Surface Subsurface Due to Ground-water Withdrawal," Land Subsidence Symposium (Japan, 1969), Vol. 1.

In the United States, subsidence due to ground water withdrawal is documented in Arizona, California, Nevada, and Texas[13]. In areas of south-central Arizona where water levels have declined, the land surface has been subsiding as much as 0.2 feet per year in places[14].

In California, subsidence due to ground water withdrawal has been documented in the San Joaquin and Santa Clara Valleys[15]. Land subsidence in the San Joaquin Valley due to ground water withdrawal began in the mid-1920s, and maximum subsidence exceeded 28 feet by 1970[16]. In the Santa Clara Valley near Alviso, about 6 feet of subsidence occurred due to ground water withdrawal from 1934 to 1967. However, no data have been collected to show elevation change in this area in recent years[17]. Also in the Santa Clara Valley, as much as 12.7 feet of subsidence occurred in San Jose as a direct result of artesian head decline from ground water withdrawal[18].

In the Knights Landing-Zamora area of the Sacramento Valley, the U.S. Geological Survey has noted 2 feet or more of subsidence presumed to be due to ground water withdrawal. DWR and USGS are engaged in a cooperative Sacramento Valley Ground Water Study to determine the precise amount of subsidence and to document the cause.

In addition, ground water withdrawal is reportedly the cause of subsidence near the Delta, at Stockton[19].

Gas and Water Withdrawal in the Delta

Because of the documented subsidence due to removal of hydrocarbons and ground water, and because much of the Delta consists of soft, compressible soil, there is concern that future ground water and hydrocarbon removal may cause subsidence in the Delta. Therefore, a reconnaissance survey was made to locate areas where ground water and gas are being pumped from beneath the Delta.

Delta gas field production information was obtained from the California Division of Oil and Gas[20]. In addition, field observations were made of Delta gas wells. Table 1 gives cumulative gas production for each field. In most of the gas fields listed, water occurs with the gas in the geologic formation and comes to the surface along with the gas.

The water is usually highly mineralized and is known as formation water or brine. Table 1 also gives cumulative water production for Delta gas fields.

A field survey of central Delta islands and tracts was made to obtain information on types and location of water wells. The survey generally confirms information given in the 1986 progress report[21]. Figure 12 in the 1986 progress report shows the location of water wells in the Delta based on Water Well Drillers' Reports. The progress report showed the greatest density of water wells on the eastern and southern perimeters of the Delta.

13 Holzer, op. cit.
14 R. L. Laney and L. W. Pankratz, "Investigations of Land Subsidence and Earth Fissures near the Salt-Gila Aqueduct, Maricopa and Penal Counties, Arizona" (U.S. Geological Survey Miscellaneous Investigations Series, Map I-1892-a, 1:36,000), 1987.
15 J. F. Poland and R. L. Ireland, "Land Subsidence in the Santa Clara Valley, California, as of 1982" (U.S. Geological Survey Professional Paper 497-F), 1988.
16 J. F. Poland and Others, "Land Subsidence in the Santa Clara Valley, California, as of 1972" (U.S. Geological Survey Professional Paper 437-H), 1975.
17 San Francisco Bay Conservation and Development Commission, *Sea Level Rise: Predictions and Implications for San Francisco Bay*, 1987, pp. 30-31.
18 Poland and Ireland, op. cit.
19 Delta Advisory Planning Council, "Delta Agriculture and Soils," Delta Plan Technical Supplement 1 (Sacramento Regional Area Planning Commission, Sacramento, 1976), p. 13.
20 California Department of Conservation, *72nd Annual Report of the State Oil and Gas Supervisor* (Division of Oil and Gas Publication No. PR06, 1986.)
21 Newmarch, op cit.

Table 1
DELTA GAS FIELD PRODUCTION

Field Name	Well Type*	Cumulative Gas Production** (MMcf)	Water (bbl)
Brentwood	OG	51,082	2,771,661
	DG	6,075	3,235
Brentwood East	DG	45,804	6,864
Clarksburg	DG	9,683	1,581
Dutch Slough	DG	115,617	2,667
Freeport	DG	2,870	-
French Camp	DG	6,242	-
Grand Island	DG	1,506	-
Greens Lake	DG	338	-
Lathrop	DG	328,736	416,970
Lathrop Southwest	DG	98	-
Liberty Cut	DG	179	-
Liberty Island	DG	27,436	-
Lodi Airport	DG	10	-
Lindsey Slough	DG	231,706	175,017
Maine Prairie	DG	156,143	93,410
McDonald Island	DG	183,552	-
McMullen Ranch	DG	62,087	2,417
Merritt Island	DG	1,614	-
Miller	DG	130,475	195,083
Oakley	DG	2,985	53,999
Oakley South	DG	66,963	18,396
Rio Vista	DG	3,276,913	210,115
River Break	DG	10,692	437
River Island	DG	136,619	16,983
Roberts Island	DG	33,026	11,771
Ryer Island	DG	123,933	1,897
Saxon	DG	33,689	49,854
Sherman Island	DG	32,133	1,782
Stone Lake	DG	1,177	3,621
Thornton	DG	54,323	32
Todhunters Lake	DG	84,987	541
Tracy	DG	14,059	-
Union Island	DG	166,292	93,141
Van Sickle Island	DG	11,700	4,006
Winchester Lake	DG	1,309	30

Source: California Department of Conservation, Division of Oil and Gas. 1986. *72nd Annual Report of the State Oil and Gas Supervisor.* Publication No. PRO6.
* OG = Oil and Associated Gas
DG = Dry (Nonassociated) Gas
** As of December 31, 1986

A sizeable number of small domestic water wells were seen on many central Delta islands and tracts. For most of the area, the more populated the island or tract, the greater the number of small domestic wells. There may be 200 or more of these small wells throughout the Delta. The greatest number were on Bethel Tract. Table 2 gives information on ground water well depths and discharges at eight Delta islands or tracts, based on Water Well Drillers' Reports. Pumping test discharges listed are those measured during the drillers' tests on completion of the wells. Other islands and tracts also contain water wells, and a search for records at those locations will be made during future phases of the subsidence investigation.

The domestic wells are small-capacity wells, and most are at homes or farm sheds near levees. Many may produce ground water from aquifers that are in hydraulic continuity with the adjacent surface water channels. Such wells would have little if any measurable effect on ground water levels.

Large-capacity water wells were observed at the following locations:

Andrus Island	2 Municipal Wells
Bethel Tract	7 Municipal Wells
	1 Golf Course Well
Brannan Island	2 State Park Wells
Tyler Island	3 Walnut Grove Municipal Wells

From the data analyzed thus far, there are no indications of subsidence caused by pumping central Delta water wells. However, there may be undetected subsidence, and future subsidence could occur as more wells are installed and pumped.

Dewatering by using large pumps that divert drainage ditch water from islands and tracts into adjacent channels may cause subsidence of shallow organic soils (peats). The drainage dewaters the soils, allowing shrinkage and oxidation. Up to 18 inches of this type of subsidence may have occurred in the last 9 years at one Bethel Island location (Appendix C).

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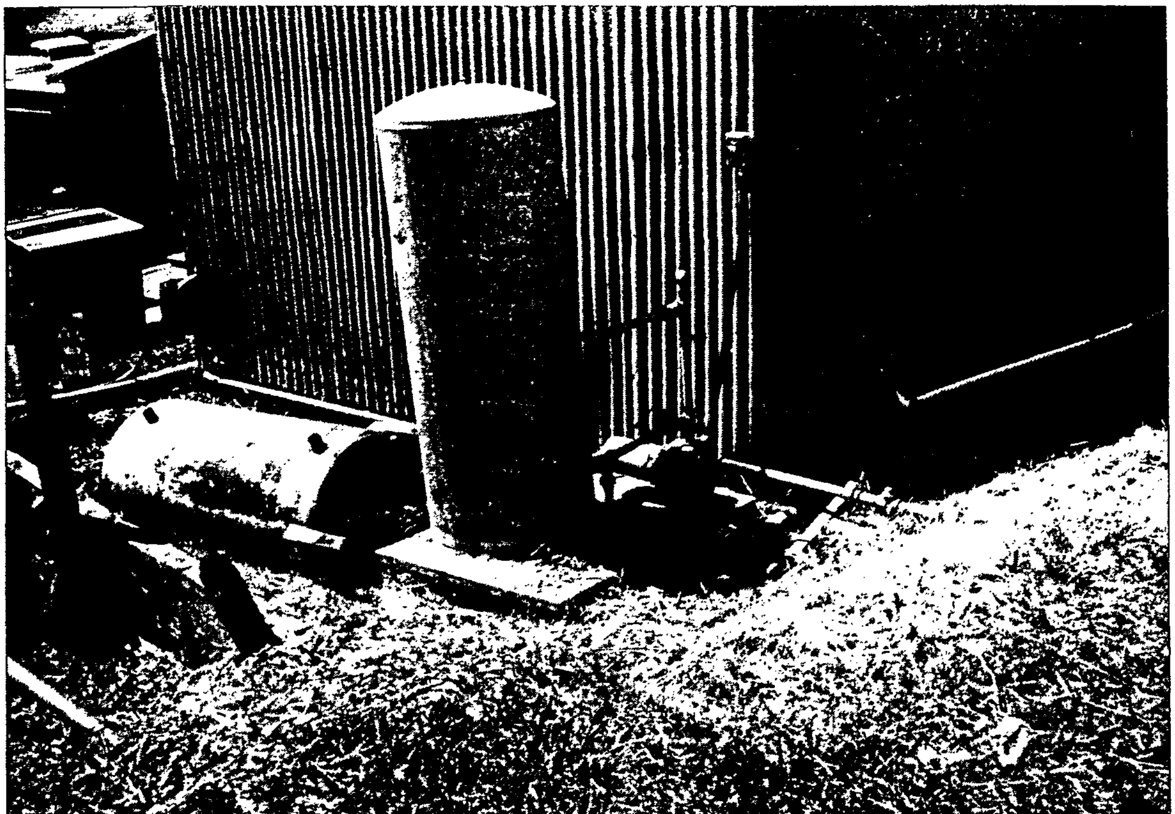

Above: Pressure tank for small-capacity water well adjacent to Turner Cut, in San Joaquin County.
Below: Large-capacity water well at Brannan Island State Park, in Sacramento County, has about a 4-inch discharge pipe.

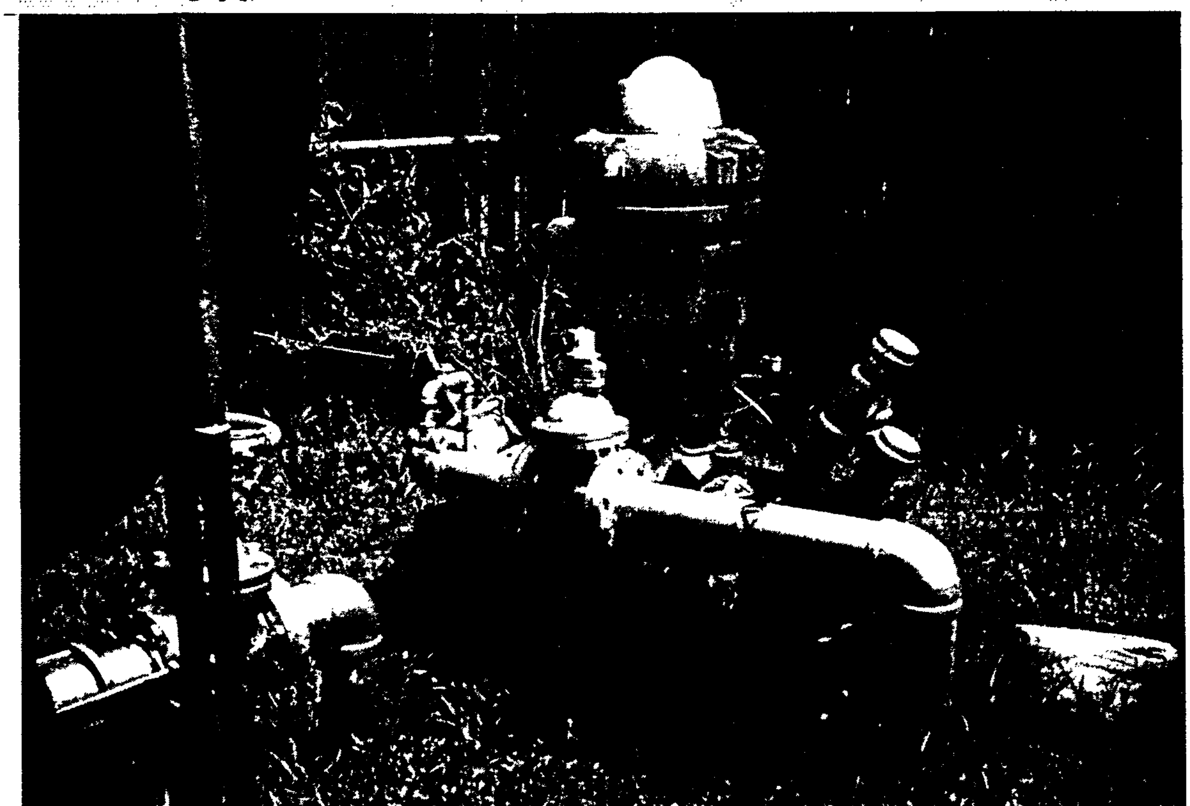

Table 2
WATER WELL DEPTHS AND DISCHARGES AT EIGHT DELTA LOCATIONS*

Location	Range of Well Depths (feet)	Range of Pumping Test Discharges (GPM)**	Range of Dates Drilled	Number of Water Well Drillers' Reports	Type of Well
Andrus Island	100-214	20-85	1968-1987	20	Domestic
(Isleton)	28-607	500	1929-1930	2	Municipal
Bacon Island	48-256	15-30	1953-1982	5	Domestic
Bethel Tract	61-575	40-300	1977-1985	35	Domestic
				1	Irrigation
Brannan Island	249-416	100-795	1959-1971	2	Domestic
	405	800	1964	1	Irrigation
	495	1,200	1982	1	Industrial
McDonald Island	77-287	20-30	1954-1979	7	Domestic
Lower and Middle Roberts Island	38-240	20-60	1953-1986	18	Domestic
Terminous Tract	54-678	?	1956-1979	4	Domestic
Tyler Island	10-251	?	1953-1984	8	Domestic
(Walnut Grove)	278	?	1931	1	Industrial
	130	?	1969	1	Irrigation
	190	150	1987	1	Municipal

* Based on Water Well Drillers' Reports on file at the DWR, Central District.
** Well pumping tests made by driller on completion of the well.

Effects of Ground Water Withdrawal on the Hydrologic Balance

Ground water withdrawal in the Delta is important, not only for its potential effect on subsidence, but as a factor in calculating hydrologic water balances for the Delta. The overall amount of ground water pumped yearly from Delta water wells is not known, and the ground water withdrawal amount is one of the outflow values needed in the hydrologic water balance equation. The wells may be withdrawing ground water from aquifers that are hydraulically connected with Delta channels. Determination of the amount of ground water withdrawal from the Delta will have a two-pronged benefit: (1) it will give answers on whether ground water withdrawal is causing subsidence, and (2) it will provide additional data for hydrologic water balances for the Delta.

Chapter 4. MEASUREMENT OF LAND SURFACE ELEVATION

Measuring rates of subsidence and determining causes of subsidence requires an accurate determination of land surface elevation. Land surface elevation can be measured by conventional surveying methods and by use of earth-orbiting satellites.

Department of Water Resources first order vertical control surveys from 1974 through 1977 using conventional surveying methods show that bench marks in the Delta are not stable. Therefore, it is necessary to identify more stable bench marks on the periphery of the Delta. These stable bench marks will be used to establish a vertical datum (see Appendix D).

In addition, a Global Positioning System survey network has been established in the Delta (see Figure 2) as part of the cooperative subsidence investigation between the Department of Water Resources and U.S. Geological Survey. This network will be used to obtain vertical control (land surface elevations) to determine areas and rates of subsidence. The network includes both GPS and conventional surveying bench marks. Continued measurement of the same GPS network is required to derive subsidence information (see Appendix D).

Periodic measurement of land surface elevation must continue for as long as necessary to determine the rate of subsidence. A baseline of at least 10 years will probably be needed to establish subsidence rates as related to land use.

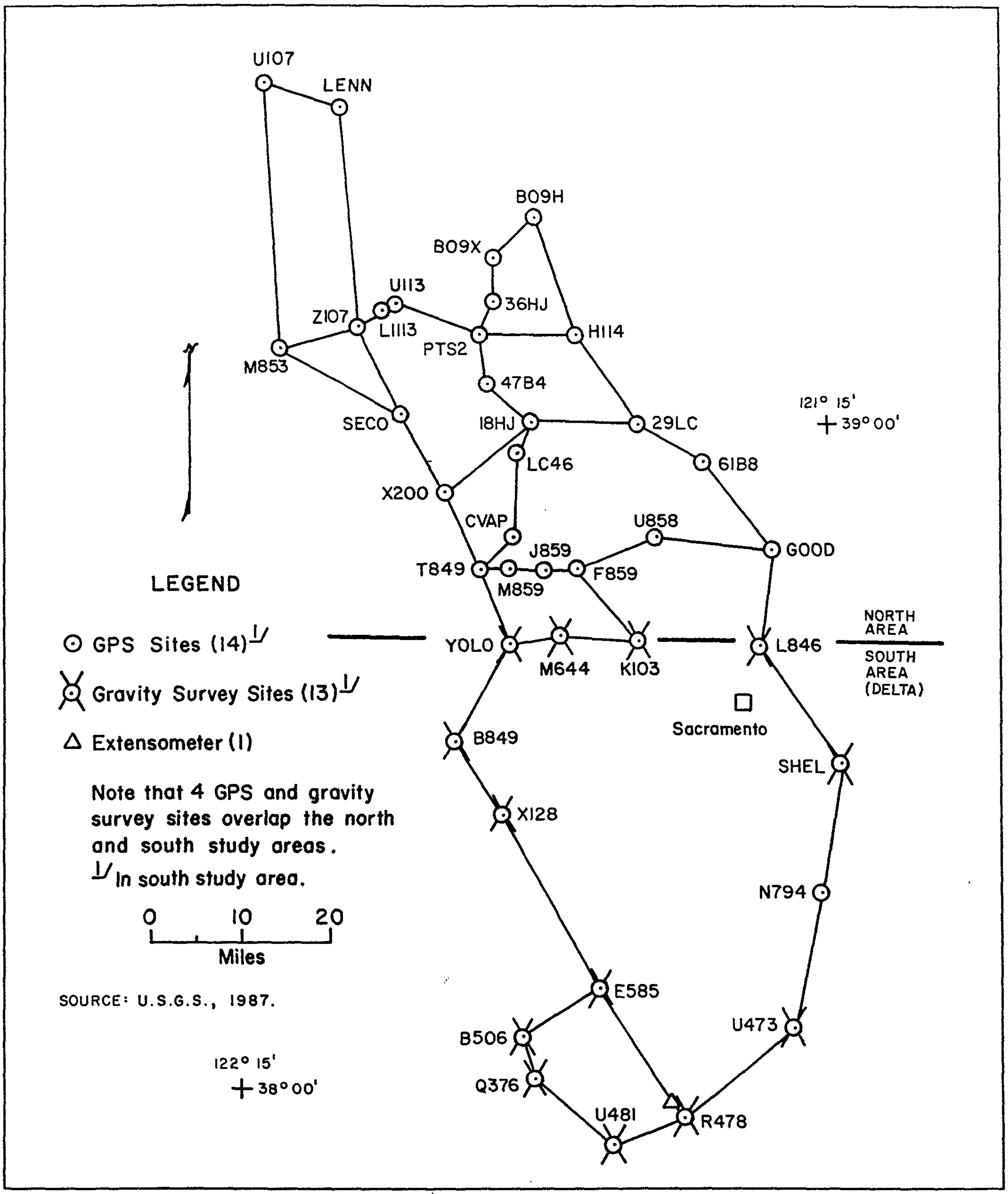

Figure 2
GLOBAL POSITIONING SYSTEM BASELINE NETWORK
Sacramento Subsidence Study, 1986

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Chapter 5. MEASUREMENT OF SITE-SPECIFIC SUBSIDENCE

Extensometers (compaction recorders) can measure site-specific subsidence. This chapter describes Department of Water Resources work toward installation of an extensometer network in the Delta.

Potential Data from Extensometers

One extensometer station (Bacon Island) is operating, and a second was completed in the summer of 1988 (Bethel Island). The operating extensometer station was built on Bacon Island by the Department of Water Resources and U.S. Geological Survey, with financial assistance from the California Division of Oil and Gas (see Appendix E). The second station, on Bethel Island, was built cooperatively by DWR, USGS, and Contra Costa County. These stations and those planned for construction at other Delta locations have the potential to furnish site-specific data on:

- Subsidence amounts in the zone of organic material (shallow subsidence), and
- Subsidence amounts in the zone of ground water withdrawal (deep subsidence) where water is being withdrawn. In some parts of the Delta, there are only a few small capacity domestic water wells, and only a small amount of ground water is extracted.

Combined with an accurate land surface elevation survey network, the extensometers can measure the overall rate of subsidence and differentiate the rate of deep subsidence from the rate of shallow subsidence.

Possible causes of deep subsidence are:

Ground water withdrawal
Gas and oil withdrawal
Natural consolidation
Tectonic movement

Causes of shallow subsidence include:

Oxidation of peat and other organic soils
Shrinkage (drying)
Erosion by wind (deflation)
Compaction by farm equipment, structures, and levees
Anaerobic decomposition
Burning
Export by people

Because the extensometers will not penetrate gas-bearing zones, they will not provide direct data on subsidence amounts that may be caused by gas and associated fluid withdrawal. A well deep enough to provide compaction data on the gas-producing zone would have to be 12,000 to 15,000 feet deep. Such wells would cost $1 million or more, and are beyond the scope of the present program. However, the amount of subsidence due to gas withdrawal, if any, can be estimated by combining data from the extensometers with theoretical estimates of subsidence caused by natural consolidation and tectonic movement. It is planned to construct extensometers in gas field areas, as well as in areas where no gas is produced, to obtain data that would be useful in making such comparative estimates.

Bacon Island Extensometer Station

The Bacon Island site was chosen because:

- There is road and bridge accessibility.
- There are no recorded levee breaks on Bacon Island since 1915.
- Bacon Island is outside the gas fields.
- Bacon Island is in an area of maximum subsidence rate, organic soil thickness, and historical amount of subsidence.

Extensometers at the Bacon Island site will measure both shallow and deep subsidence.

The Bacon Island extensometer station was planned for installation in the northeastern part of the island near a 1976 subsidence exploration hole. For the

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following reasons, the station was constructed on the west side of the island instead (see Appendix E).

- The property manager for the Rancho del Rio landowner wanted it at the west side of the island, where it would not disrupt traffic and crop packaging.
- Piling construction for farm sheds indicated peat is 14 feet thick in the western area. This is at least as thick as at the northeast site.
- According to the property manager, the ground surface has subsided up to 2 feet within the past 7 or 8 years (3 inches per year) near the western site.
- The ground is compacted enough at the western site to provide a relatively stable base for drilling equipment.
- The western site is far enough from overhead powerlines so as not to be a risk for rig operators, but close enough to allow access to electricity.
- Drilling water is easily obtainable from Old River, near the western site.
- The western site is near a recently constructed USGS acoustical velocity meter station and a recently surveyed global positioning system/spirit leveling bench mark.
- Telephone service to allow remote data collection from the field instruments is available at the western site from lines extending to nearby farm buildings.
- Access to the extensometer station is easy at the western site.

Nearby vehicular traffic may cause fluctuations of the extensometer and water levels in the extensometer well. However, data anomalies caused by these unnatural events are easily identifiable and may be mathematically separated from the other data.

Contra Costa County Extensometers

The Department of Water Resources is completing an extensometer station on Bethel Island under a reimbursable contract with Contra Costa County. The contract provides for Contra Costa County to pay the Department up to $115,000 for installation of subsidence monitoring stations. Construction is being done by the U.S. Geological Survey under the direction of DWR geologists as part of the cooperative agreement with the Department of Water Resources.

The Bethel Island extensometer station is toward the north side of the island. Figure 3 shows the location and a schematic of the station. The primary reason for this station is to collect data on subsidence or lack of subsidence due to withdrawal of ground water in the area. The station includes an extensometer to measure subsidence between ground surface and 545 feet in depth. It also includes piezometers to measure aquifers at 40 feet, 320 feet, and 440 feet in depth.

The contract with Contra Costa County also provides for construction of a shallow extensometer station on the southeast side of Bradford Island (Figure 4). This extensometer will also be constructed by the USGS under the direction of DWR geologists.

The Bradford Island site was chosen because:

- The land owner was agreeable to providing land and right of way for the site.
- There is weekday access to the site by ferry and road.
- There is only one recorded levee break (in 1983) since counting began in 1915.
- This area of Bradford Island has thick organic soil (peat) deposits.
- The rate of maximum historical subsidence has been relatively low (1.6 inches per year), as compared to 3 inches per year on many Delta islands.

The Bradford Island extensometer will measure shallow subsidence of the organic soil.

Instrumentation of the Bethel Island and Bradford Island extensometers and piezometers will include state-of-the-art sensors and recording devices similar to those described for the Bacon Island extensometer station. As-built drawings and costs of the stations will be available when they are completed.

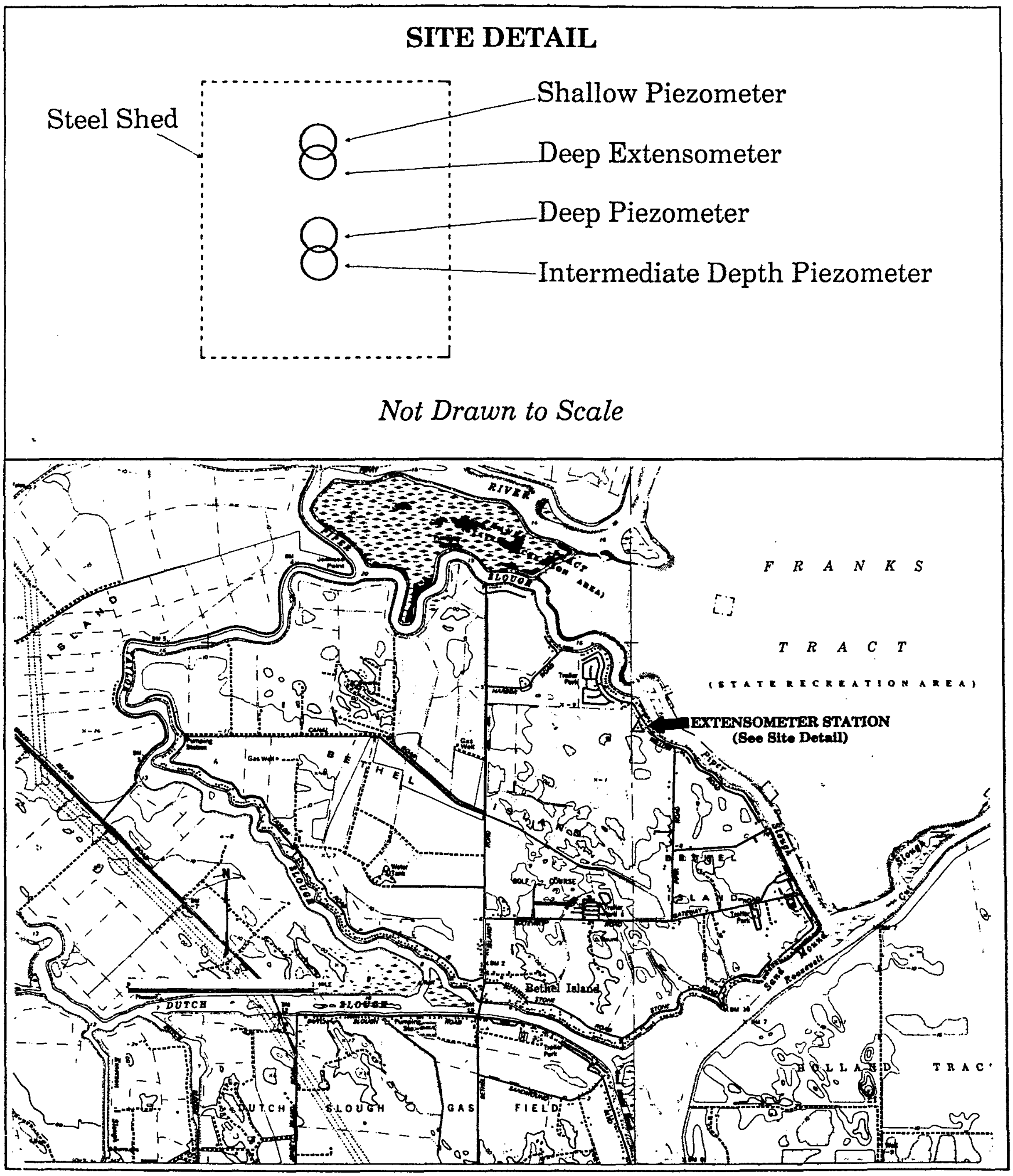

Figure 3
BETHEL ISLAND EXTENSOMETER STATION

Bethel Island is of particular interest in the subsidence investigation because:

- It is one of the more highly populated Delta islands.
- More ground water is probably being pumped annually on Bethel Island than on any other central Delta island.
- Natural gas is being extracted from beneath Bethel Island.
- Subsidence is occurring on the island (Appendix C). At least one site has subsided 12 to 18 inches since 1979.

Other Potential Extensometer Sites

Proposed extensometer sites are listed below and shown on Figure 4.

Site	Rank
Brannan Island	1
Lower Jones Tract	1
Medford Island	2
Sherman Island	1
Tyler Island	2
Venice Island	2
Webb Tract	2

Construction is planned when funding becomes available. Sites are ranked according to construction priority (Rank 1 sites first). Ranking procedures were explained in *Delta Subsidence Investigation, Progress Report*[22].

22 Newmarch, op. cit.

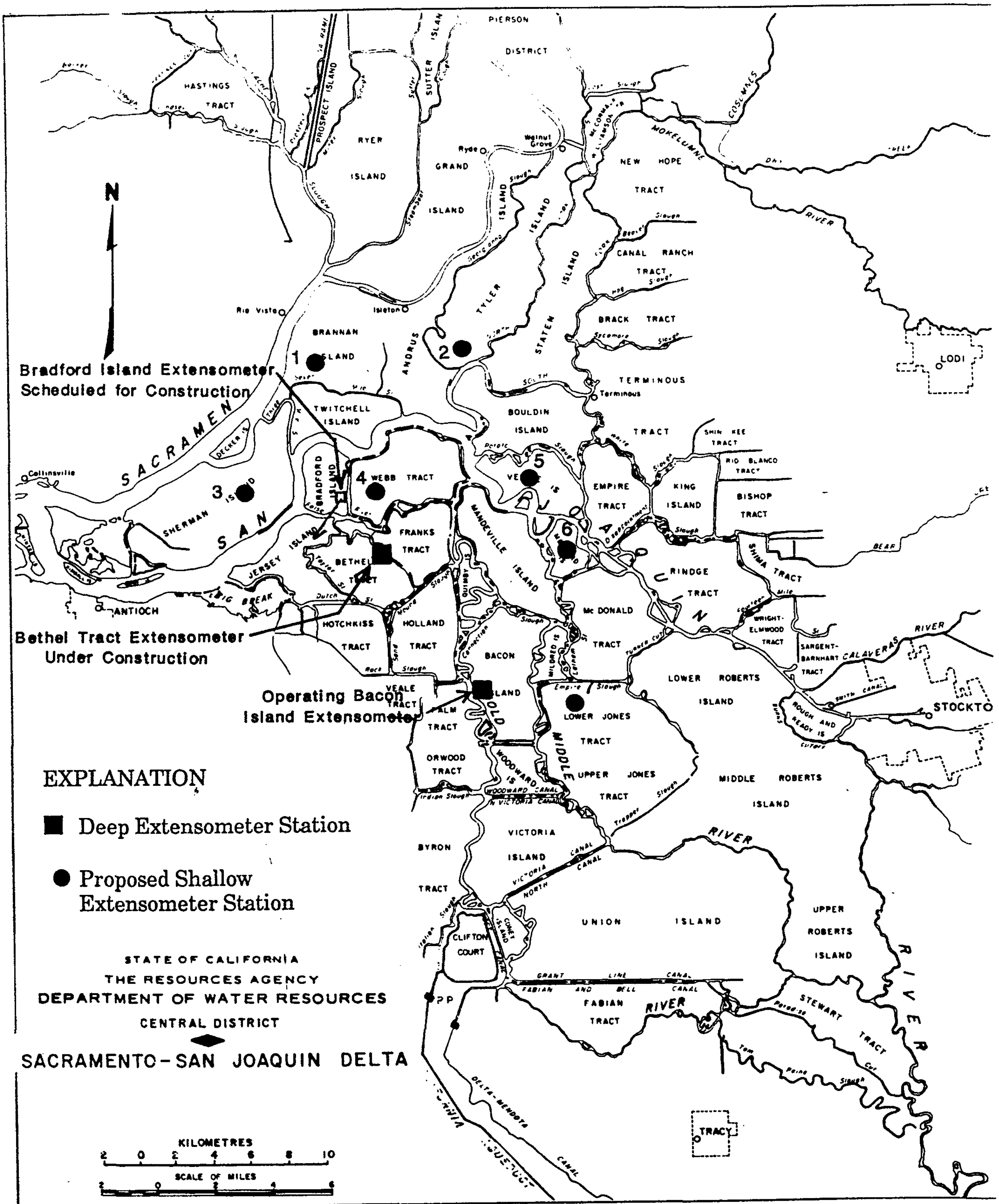

Figure 4
EXISTING AND PROPOSED EXTENSOMETER STATIONS

Chapter 6. LONG-TERM SUBSIDENCE PROGRAM

A long-term work plan and a cost analysis have been prepared showing major tasks and projected costs for fiscal years 1985-86 through 1995-96. The work plan and cost analysis have been furnished to the program manager. Backup data and information are filed at the DWR Central District, Geology and Ground Water Section.

It is expected that this program will continue to receive support and funding at about the same level through 1996. The Department of Water Resources will continue to seek support from other agencies.

Land Use Studies

The long-term subsidence program could include studies to correlate land uses with amounts of subsidence. Crop and land use manipulation is reportedly the best means of achieving ground water level controls and thereby preventing oxidation and shrinkage[23]. Land uses and subsidence need to be correlated so that land use practices that will minimize subsidence can be identified.

Studies of land use and resulting subsidence or absence of subsidence will require extensive research of records and aerial photos, as well as field investigations. It may also involve specifically designed aerial photography repeated at intervals over 10 or more years to correlate land uses with subsidence. In addition to the photography, areas should be established for testing methods of subsidence control. Because it has only recently been reclaimed, construction of a subsidence test site on Little Mandeville Island could provide valuable data on effects of farming practices on subsidence or nonsubsidence of virgin organic soils.

Reevaluation of National Geodetic Survey Leveling Data

The U.S. Coast and Geodetic Survey (now National Geodetic Survey) ran 13 precision-level surveys through the central Delta between 1912 and 1967 as part of a nationwide vertical control network. The Delta portion included 15 vertical control leveling lines. From those surveys, DWR has in its files:

Adjusted elevation data,
Leveling line locations,
Bench mark descriptions, and
Archival cross reference numbers.

In 1975, the DWR Surveys and Photogrammetry Branch (now called Division of Right of Way, Survey Unit) plotted adjusted elevations between 1951 and 1967 for many of the survey lines through the Delta. The resulting plots showed uniform settlement, suggesting that the settlement is the result of mathematical adjustments made as part of field data calculations and is not a real measure of land surface settlement (subsidence).

Because comparisons of NGS adjusted elevations are not an accurate method of determining subsidence, it is desirable to evaluate the 1912-1967 NGS surveys to determine if other data from those surveys or a reevaluation of the data may help to determine Delta subsidence. The reevaluation might provide useful 1912-1967 ground surface elevation data that could be used in conjunction with Global Positioning System elevation survey data to estimate subsidence rates between 1912-1967 and the present. Such an evaluation could be a part of the long-term DWR subsidence program.

23 George Newmarch, *Subsidence of Organic Soils in the Sacramento-San Joaquin Delta* (California Department of Water Resources, Sacramento, 1980)

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Table 3 shows work necessary to evaluate the NGS data before starting field work. The estimate was furnished by the DWR Division of Land and Right of Way Survey Unit.

Table 3
EVALUATION OF
NATIONAL GEODETIC SURVEY DATA

Type of Work	
Collect data	
Compile and analyze data	
Make first order vertical survey of lines selected for evaluation	
Compare and analyze data	
Make final tabulation	
Personnel	
Office Surveys	
Supervising Land Surveyor	1/4 PY
Water Resources Engineering Associate	1/4 PY
Field Surveys	
1 Supervising Land Surveyor	1/6 PY
1 Water Resources Technician II	1/6 PY
1 Water Resources Technician I	1/6 PY
1 Jr. Engineering Technician	1/6 PY
Costs	
Office Surveys	$30,000
Field Surveys	$80,000
Data Gathering, Computer Work, etc.	$ 2,000
Total	$112,000

Installation of Instruments in Levees

Since 1950, an increasing number of levee failures have been from levee instability, rather than from overtopping[24]. This instability may be due, at least in part, to subsidence. Engineering data are needed to maintain and repair present levees and to design new levees. In addition, little information is available on the performance of Delta levees during earthquakes. State-of-the-art instrumentation could be installed in selected levees to record levee performance during earthquakes. If this is done, these data should be collected for at least 10 years to obtain sufficient data for evaluating the effect of earthquakes on levees and for designing levees.

Possible Future Studies

The following studies should be considered for future phases of the subsidence investigation:

- The individual processes that contribute to shallow subsidence in the Delta are not well understood. A study to determine the relative effects of oxidation, shrinkage, wind erosion, compaction, anaerobic decomposition, and agricultural burning on the depletion rate of organic soils would identify those processes that contribute to shallow subsidence in the Delta.

- A correlation between land use and rates of shallow subsidence needs to be developed to identify those land use practices in the Delta that contribute most to the depletion of organic soils. A review and evaluation of land use records and corresponding depletion rates of organic soils could establish this correlation.

- There is little information on the effects of island reclamation practices on the depletion rate of organic soils. Constructing a subsidence test site on Little Mandeville Island to study effects of farming and reclamation practices on subsidence rates would provide this information.

- The thickness and configuration of organic soils in the central portions of most Delta islands and tracts and along many sections of levees are not accurately known. Such information would be useful in estimating depletion times for the organic soils and predicting where thick organic soils may contribute to levee instability. Drilling exploratory holes in the central portions of islands and tracts and along selected sections of levees would provide the data.

- A cursory evaluation of current ground water use in the Delta indicates the total amount pumped is very small. Therefore, it is unlikely that current ground water withdrawal is a major contributing

24 California Department of Water Resources, Bulletin 192-82, *Delta Levees Investigation* (Sacramento, 1982), pp. 4, 20-25, 28-29, 45.

factor to subsidence in the Delta. If ground water extraction rates significantly increase in or adjacent to the Delta, then the potential for minor ground water withdrawal-induced subsidence should be reevaluated.

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BIBLIOGRAPHY

Anonymous. 1981. Papers Prepared for a Conference on the Future of the Delta. Co-sponsored by The Resources Agency, Department of Water Resources, and University of California, Davis. March 16-17, 1981: Sacramento.

Assembly Bill 4193. 1976 Session of California Legislature. Amendment to Section 12881.4 of the Water Code.

Atwater, Brian F. 1982. Geologic Map of the Sacramento-San Joaquin Delta, California. U.S. Geological Survey Map MF-1401.

_____. 1980. "Attempts to Correlate Late Quaternary Climatic Records Between San Francisco Bay, the Sacramento-San Joaquin Delta, and the Mokelumne River, California." Doctor of Philosophy in Geology Dissertation, University of Delaware.

Bilham, Roger. 1988. "Measurement of the Relative Heights of Everest and K2 Using Space Geodesy." In *C.U. Geology News*. The Department of Geological Sciences, University of Colorado at Boulder. 1988.

_____. 1986. "Volcanoes, Earthquakes, and Space Geodesy." In *C.U. Geology News*. The Department of Geological Sciences, University of Colorado at Boulder. Fall 1986.

Brown, James, Thomas Matteran, and Rouse Farnham. 1984. "Surface and Subsurface Sampling of Organic Soils." Seventh International Peat Congress (Dublin).

Burke, H. K. 1980. *Report on Causes of Subsidence in the Sacramento-San Joaquin Delta, and a Strategy for Controlling its Rate*. California Department of Water Resources. Sacramento.

California Department of Conservation. 1986. *72nd Annual Report of the State Oil and Gas Supervisor*. Division of Oil and Gas Publication No. PR06.

California Department of Water Resources. 1983. *Alternatives for Delta Transfer*.

_____. 1982. Bulletin 192-82. *Delta Levees Investigation*.

_____. 1981. *Sacramento-San Joaquin Delta Levees Study*.

_____. 1973. *Delta Levees. What is Their Future?*

_____. 1963. *Delta Test Levees Investigation*.

California Division of Mines. 1956. "Peat." In *Mineral Information Service*. Vol. 9. No. 12.

Castle, R. O. and Others. 1970. "A Linear Relationship Between Liquid Production and Oil-Field Subsidence". Proceedings of the Tokyo Symposium of Land Subsidence. Published Jointly by the International Association of Scientific Hydrology. Braamstraat 61 (rue des Ronces), Gentbrugge (Belgium), and UNESCO, Place de Fontenoy, 75 Paris-7. pp. 162-173.

Cosby, Stanley W. 1941. *Soil Survey in the Sacramento-San Joaquin Delta Area California*.

Craymer, M. R. and P. Vanicek. "Further Analysis of the 1981 Southern California Field Test for Leveling Refraction." *Journal of Geophysical Research*. Volume 91. Number B9. pp. 9045-9055.

Curtin, George. 1967. Progress Report. *Land Subsidence Studies in the Sacramento District.* Department of Water Resources, Sacramento District.

Davis, George H. 1963. *Formation of Ridges Through Differential Subsidence of Peatlands of the Sacramento-San Joaquin Delta, California.* U. S. Geological Survey Professional Paper 473-C. p. C163.

Delta Advisory Planning Council. 1976. Delta Plan Technical Supplement 1. *Delta Agriculture and Soils.* Sacramento Regional Area Planning Commission. Sacramento. p. 13.

Delta Levee Maintenance Law. 1973. California Water Code, Section 12981.

Dolezal, R. and M. Peterson. 1969. "Subsidence in the North German Coastal Region." *Land Subsidence Symposium* (Japan). Vol. 1.

Eide, O. and Others. 1984. "Unconventional Concepts for Dykes and Dams on Soft Clay Foundations." Norwegian Geotechnical Institute Publication 151. Oslo.

Finch, Michael O. 1988. "Estimated Performance of Twitchell Island Levee System, Sacramento-San Joaquin Delta, Under Maximum Credible Earthquake Conditions." *Bulletin of the Association of Engineering Geologists.* Vol. XXV. No. 2. pp. 207-218.

_____. 1987. "Liquefaction Potential of the Sacramento-San Joaquin Delta, California." Master's Thesis in Geology. University of California, Davis.

_____. 1985. "Earthquake Damage in the Sacramento-San Joaquin Delta." *California Geology.* California Division of Mines and Geology. February.

Gilluly, J. and U. S. Grant. 1949. "Subsidence in the Long Beach Harbor Area, California." Geological Society of America Bulletin. Vol. 60. pp. 461-530.

Hobbs, N. B. 1986. "Mire Morphology and the Properties and Behavior of Some British and Foreign Peats." *Quarterly Journal of Engineering Geology.* London. Vol. 19. pp. 7-80.

Holzer, Thomas L. (Ed.) 1984. "Man-Induced Land Subsidence." *Review in Engineering Geology.* Vol. VI. The Geological Society of America, Boulder, Colorado.

_____. 1984. "Ground Failure Induced by Groundwater Withdrawal from Unconsolidated Sediment." *Review in Engineering Geology.* Vol. VI. The Geological Society of America..

"How to Tell When the Sea Rises." 1986. *Nature.* Vol. 324. p.105.

Huntley, Edward F. 1985. Interview with George Newmarch. California Department of Water Resources, Central District. September 13, 1985.

Hwang, Jui-Ming and Chian-Min Wu. 1969. "Land Subsidence Problems in Taipei Basin." *Land Subsidence Symposium* (Japan). Vol. 1.

Ilijn, A. S. 1977. "The Earth Surface Subsidence at the Areas of Gas and Oil Pumping." *Proceedings of the Second International Symposium on Land Subsidence* (Anaheim, California). International Association of Hydrological Sciences Publication 121. p. 665.

Irving, Ray. 1987. Estimate to Evaluate NGS Survey Data. California Department of Water Resources Memorandum, Ray Irving to Carl Hauge. February 17, 1987.

______. 1986. Cost/Savings Analysis, Standard Survey Procedure vs. Global Positioning System (GPS). California Department of Water Resources Memorandum, Ray Irving to Eldon Rinehart. January 7, 1986.

Ito, Sam. 1985. Interviews with George Newmarch. California Department of Water Resources, Central District. September 1985.

Johnson, Karen L. and Michael J. Pierce. 1986. *Ground-water and Surface-water-level Data at Rindge Tract on the Stockton Deep Water Ship Channel, San Joaquin County, California, 1983-84*. U. S. Geological Survey Open File Report 85-573.

Kearney, Charles. 1980. *Seismicity Hazards in the Sacramento-San Joaquin Delta.* Department of Water Resources, Central District.

Komaki, Shauzow. 1969. "On the Variation of Artesian Head and Land-Surface Subsurface Due to Ground-water Withdrawal." *Land Subsidence Symposium* (Japan). Vol. 1.

Kroger, Peter M. and Others. 1986. "Mobile Very Long Baseline Interferometry and Global Positioning System Measurement of Vertical Crustal Motion." *Journal of Geophysical Research*. Vol. 91. No. B9. pp. 9169-9176.

Lambert, Dr. J. M. 1952. "The Past Present and Future of the Norfolk Broads." *Norfolk and Norwich Natural History Society Transactions*. Vol. 17. pp. 223-258.

"Land of the Rising Sun is Falling." 1987. *Water Equipment News*. July.

Laney, R. L. and L. W. Pankratz. 1987. *Investigations of Land Subsidence and Earth Fissures near the Salt-Gila Aqueduct, Maricopa and Penal Counties, Arizona*. U.S. Geological Survey Miscellaneous Investigations Series. Map I-1892-a, 1:36,000.

Lofgren, Ben E. 1961. "Measurement of Compaction of Aquifer Systems and Areas of Land Subsidence." In *Short Papers in the Geologic and Hydrologic Sciences*. Articles 1-146. U.S. Geological Survey Professional Paper 424-B. pp. B-49-54.

Lao, Chester. 1965. *Land Subsidence Study*. California Department of Water Resources. Central District Office Report

Lucas, Clifford V. and Dennis E. Maclain. 1967. "Stability of Levees on Organic Soil Foundations." *Structural Engineering Conference* (Seattle). American Society of Civil Engineers.

Lyzenga, Gregory A. and Others. 1986. "Tectonic Motions in California Inferred from Very Long Baseline Interferometry Observations, 1980-84." *Journal of Geophysical Research*. Vol.91. No. B9. pp. 9473-9487.

Marachi, Dean N., David J. Dayton, and Corey T. Dare. 1983. "Geotechnical Properties of Peat in San Joaquin Delta." In *Testing of Peats and Organic Soils*. ed. P. M. Jarrett. American Society for Testing Materials. pp. 207-217.

McClure, C. R. 1956. Report No. 1. *Investigation of the Sacramento-San Joaquin Delta Ground Water Geology*. Water Project Authority of California.

Mendoza, Rosendo, 1988. Delta Bench Mark Elevations. Office Memo to Peter Rabbon, Delta Alternatives Planning, Central District.

Miller, R. E. 1961. "Compaction of an Aquifer System Computed from Consolidation Tests and Decline in Artesion Head." In *Short Papers in the Geologic and Hydrologic Sciences*. Articles 1-146. U.S. Geological Survey Professional Paper 424-B. pp. B-54-58.

Mulqueen, J. 1986. "Hydrology and Drainage of Peatland." *Environmental Geology and Water Science*. Vol. 9. No. 1.

Murphy, Irene L. 1970. "The Politics of Federal Water Pollution Control: A Bureau and Its Subsystem." Columbia University Ph.D. in the Faculty of Political Science.

Nazar, Paul G. and Charles V. Swearington. 1975. *Preliminary Soil Survey Report, Isleton Quadrangle, San Joaquin County, California*. U.S. Department of Agriculture, Soil Conservation Service.

Newmarch, George. 1986. *Delta Subsidence Investigation Progress Report*. California Department of Water Resources. Central District. Sacramento.

_____. 1981. "Subsidence of Organic Soils." *California Geology*. California Division of Mines and Geology. Vol. 34. No. 7.

_____. 1980. *Subsidence of Organic Soils in the Sacramento-San Joaquin Delta*. California Department of Water Resources. Sacramento.

Newmarch, George and Carl Hauge. 1985. *Seismicity*. California Department of Water Resources, Central District. Technical Information Record 1462-CD-08.

Nork, Diane M. 1986. Letter to Carl J. Hauge, California Department of Water Resources on October 10. U. S. Department of the Interior, Geological Survey.

Oakshott, Gordon B. 1978. *California's Changing Landscapes, a Guide to the Geology of the State*. McGraw-Hill Book Company. San Francisco.

Orloci, I. 1969. "Water Balance Investigation Based Upon Measurements of Land Subsidence Caused by Ground Water Withdrawal." *Land Subsidence Symposium* (Japan). Vol. 1.

Poland, Joseph F. (ed.). 1984. *Guidebook to Studies of Land Subsidence Due to Ground-water Withdrawal*. Proposal for the International Hydrological Programme, Working Group 8.4. Studies and Reports in Hydrology 40. UNESCO. United Nations.

Poland, J. F. and Others. 1975. Land Subsidence in the San Joaquin Valley, California, as of 1972. Studies of Land Subsidence. U. S. Geological Survey Professional Paper 437-H.

Poland, Joseph F. and R. L. Ireland. 1988. *Land Subsidence in the Santa Clara Valley, California, as of 1982*. U.S. Geological Survey Professional Paper 497-F.

_____. Reprinted 1979. *Land Subsidence and Aquifer-System Compaction, Santa Clara Valley, California, USA*. Miscellaneous Field Studies Map MF-336. U. S. Geological Survey. Denver, Colorado.

Pratt, W. E. and D. W. Johnson. 1926. "Local Subsidence of the Goose Creek Field." *Journal of Geology*. Vol. 34. No. 1. pp. 577-590.

Prokopovich, N. P. 1985. *Subsidence of Peat in California and Florida*. Bulletin of the Association of Engineering Geologists. Vol. XXII. No. 4. pp. 395-420.

Sandwell, David T. and Others. 1986. "Global Nondynamic Orbit Improvement for Altimetric Satellites." *Journal of Geophysical Research*. Vol. 91. No. B9. pp. 9447-9451.

UCD PSL

1A705 A1E55 A1A8

San Francisco Bay Conservation and Development Commission. 1987. *Sea Level Rise: Predictions and Implications for San Francisco Bay.*

Schoonbeek, J. B. 1976. "Land Subsidence as a Result of Natural Gas Extraction in the Province of Groningen." *SPE-European Spring Meeting*. (Amsterdam, The Netherlands). Society of Petroleum Engineers of AIME, SPE Paper 5751.

Senate Bill 1390. 1976 Session of California Legislature. Amendment to Section 12987 and Addition of Chapter 3 to Part 4.5 of Division 6 of the Water Code.

Shlemon, R. J. and E. L. Begg. 1975. "Late Quarternary Evolution of the Sacramento-San Joaquin Delta, California." In *Quarternary Studies*. ed. R. P. Suggate and M. M. Cresswell. The Royal Society of New Zealand. Wellington. pp. 259-266.

Stein, Ross S. and Others. 1986. "Saugus-Palmdale, California, Field Test for Refraction Error in Historical Leveling Surveys." *Journal of Geophysical Research*. Vol. 96. No. B9. pp. 9031-9044.

Swan, Christopher C. 1986. "An Anti-pipe Dream--One Man's Case for Delta Flooding." *The Sacramento Bee*. September 21.

Traham, D. B. 1984. *Results from Geopressured-Geothermal Subsidence Studies*. Louisiana Geological Survey. Baton Rouge.

U.S. Army Corps of Engineers, Sacramento District. 1982. *Sacramento-San Joaquin Delta, California, Draft Feasibility Report and Draft Environmental Impact Statement.*

van der Knaap, W. and van der Vlis. 1967. "On the Cause of Subsidence in Oil-Producing Areas." *7th World Petroleum Congress*. (Mexico City). Vol. 3. pp. 85-105.

vonPost, L. 1922. "Sveriges Geologiska Undersonkings Torvinventering Och Nogra av Dess Hittils Vunna Resultat (SGU Peat Inventory and Some Preliminary Results)." *Svenska Mosskulturforeningens Tidskrift*. (Jonkoping, Sweden.) Vol. 36. pp. 1-37.

Ware, Randolph and Cristian Rocken. 1986. "A Global Positioning System Baseline Determination Including Bias Fixing and Water Vapor Radiometer Corrections." *Journal of Geophysical Research*. Vol. 91. No. B9. pp. 9183-9192.

Weir, Walter W. 1971 (Reprint). *Subsidence of Peat Lands of the Sacramento-San Joaquin Delta, California*. Summary by Agricultural Extension Service, Stockton, CA.

______. 1952. *Soils of San Joaquin County California*. University of California College of Agriculture, Division of Soils. Agricultural Experiment Station, Berkeley.

______. 1950, "Subsidence of Peat Lands of the Sacramento-San Joaquin Delta, California." *Hilgardia*. Vol. 20. No. 3.

Welch, Lawrence E. et al. 1974. *Soil Survey of Contra Costa County, California*. U. S. Department of Agriculture. Soil Conservation Service. An Interim, Unedited Report.

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Appendix A
GEOLOGY OF THE DELTA

Geologic formations underlying the Sacramento-San Joaquin Delta area include deposits ranging in age from pre-Cretaceous to Recent[1] (see Figure A-1 and Table A-l). It is generally believed that at some unknown depth a basement complex of pre-Cretaceous igneous and metamorphic rocks underlies all of the Delta area. Figure A-2 shows Delta surface sediment types.

Depositional History

Deposition of sediments in the Delta began about 25 million to 175 million years ago, as sediments and natural gas accumulated in a marine environment.[2] In general, sediment deposition during the past million years (late Quaternary time; see Figure A-1) occurred during alternate cycles of deposition and erosion. Some of these cycles were probably caused by exchanges of water between the ocean and large continental ice sheets, which caused a rise and fall in sea level relative to the land.

Delta peats and organic soils began to form about 11,000 years ago during one of the rises in sea level.[3] At that time a gradual, slow rise in sea level provided a suitable environment for the formation and deposition of the peat at or near sea level.

As the peat was forming in the central portion of the Delta, streams were entering from the north, east, and south. These included the Sacramento, San Joaquin, and Mokelumne rivers. As the rivers merged, they formed a complex pattern of islands and interconnecting sloughs. The river and slough channels were repeatedly incised and backfilled with sediments with each major climatic fluctuation. These processes were complicated by concurrent subsidence and tectonic changes in land surface.

1 C. R. McClure et al., *Investigation of the Sacramento-San Joaquin Delta Ground Water Geology*, Water Project Authority of California, Report No. 1, 1956.

2 Brian F. Atwater, "Geologic Map of the Sacramento-San Joaquin Delta, California", U.S. Geological Survey Map MF-1401, 1982.

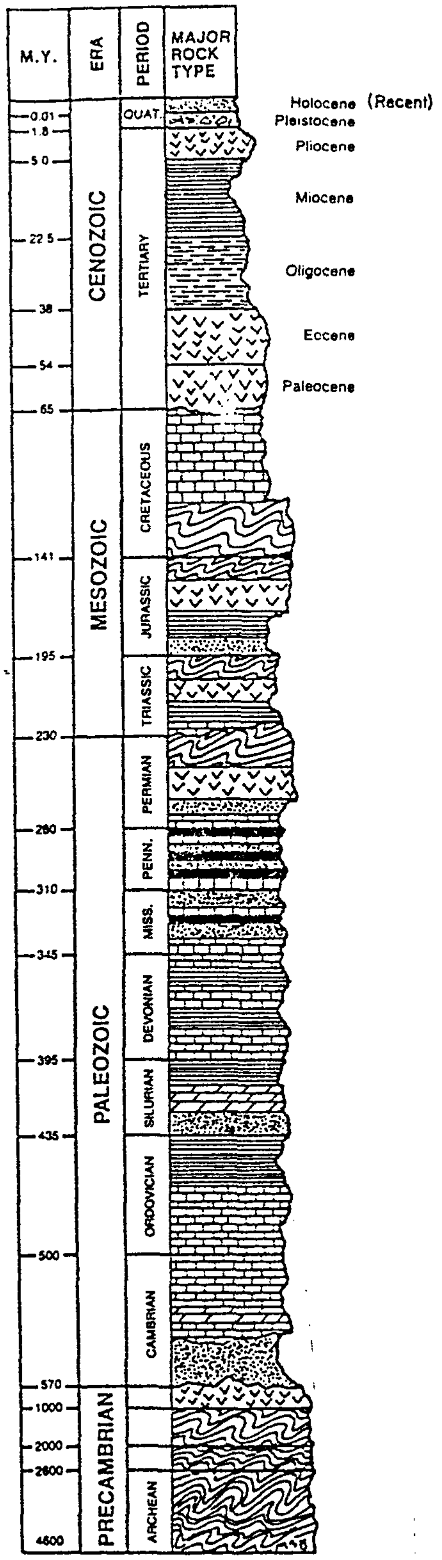
3 R. J. Shlemon and E. L. Begg, "Late Quaternary Evolution of the Sacramento-San Joaquin Delta, California," *Quaternary Studies*, ed. R. P. Suggate and M. M. Cresswell, The Royal Society of New Zealand, Wellington, 1975, pp. 259-266.

Table A-1
GEOLOGIC FORMATIONS, SACRAMENTO AREA

Geologic Age		Formation and Symbol	Approximate Thickness	Physical Characteristics
Quaternary (Sacramento-San Joaquin Delta Deposits*)	Recent	Sacramento-San Joaquin Delta Deposits (Qs, Qsc, Qb)	100 feet	Predominately impervious clays and silts, with some sand. Becomes highly organic in central Delta area.
Quaternary (Sacramento-San Joaquin Delta Deposits*)	Recent / Pleistocene	Victor Formation and Related Continental Sediments (Qal, Qf)	150 feet	Unconsolidated gravel, sand, silt, and clay deposits, with extensive sand and gravel stringers.
Quaternary (Sacramento-San Joaquin Delta Deposits*)	Pleistocene	Arroyo Seco Gravel and Unnamed Pleistocene Gravels	150 feet	Sand, gravel, silt, and clay.
Quaternary (Sacramento-San Joaquin Delta Deposits*)	Pleistocene	Older Alluvium (Qoal)	Unknown	Sand, gravel, silt, and clay.
Quaternary / Tertiary (Sacramento-San Joaquin Delta Deposits*)	Pleistocene / Pliocene	Montezuma Formation, Tehama Formation, Laguna Formation, Tulare Formation (TQc)	500 to 1,000 feet	Poorly sorted sand, gravel, silt, and clay.
Tertiary	Miocene	Mehrten Formation	400 feet	Conglomerate, silt, and clay, with interbedded lenses of black sands and agglomeratic material derived from andesitic mudflows.
Tertiary	Miocene	Valley Springs Formation	500 feet	Consolidated rhyolitic tuffs, conglomerates, clay-shales, and sandstones.
Tertiary	Miocene	San Pablo Group	1,000 feet	Interbedded massive sandstones and shale of continental and marine origin. Contemporaneous in part with the Mehrten and Valley Springs formations.
Tertiary	Eocene	Markley Formation and Undifferentiated Lower Eocene Formations	Unknown	Marine sands and shales.
Cretaceous		Moreno Formation, Panoche Formation, Chico Formation	Unknown	Marine sands and shales.
Pre-Cretaceous		Pre-Cretaceous Consolidated Rock	Unknown	Igneous and metamorphic rocks.

* The delta deposits comprise impervious clays and silts, with some sand and gravel.

Source: Cole R. McClure, *Investigation of the Sacramento-San Joaquin Delta, Ground Water Geology*, Report No. 1, Water Project Authority of the State of California, May 1956.



Source: American Geological Institute, *Earth Science*, Vol. 39, No. 2, 1966.

Figure A-1
GEOLOGIC TIME SCALE

Sedimentary debris produced by hydraulic mining during the gold rush of the mid-1800s disrupted the natural depositional history of the Delta. Hundreds of thousands of tons of soil and sediment were washed from the Sierra Nevada into the Delta. The debris filled stream channels and caused them to overflow during high runoff periods. As the water overflowed the channels, the coarser sediments (debris) being carried by the water were deposited on the natural levees along the channels. Thus, the elevation of the natural levees was gradually raised by the hydraulic mining debris.

Continuing geologic processes in the Delta include:

- Erosion and deposition in rivers, streams, and sloughs.
- Tectonic subsidence.
- Diagenesis of deeper sediments.
- Erosion and deposition on islands due to levee breaks.
- Ponding of water on islands.

Geologic deposits of the Delta (Figure A-2) include:

- Dune sand deposits.
- Stream channel deposits.
- Alluvial fan deposits.
- Peat and organic soils.
- Pleistocene nonmarine deposits.
- Marine deposits (in the subsurface).

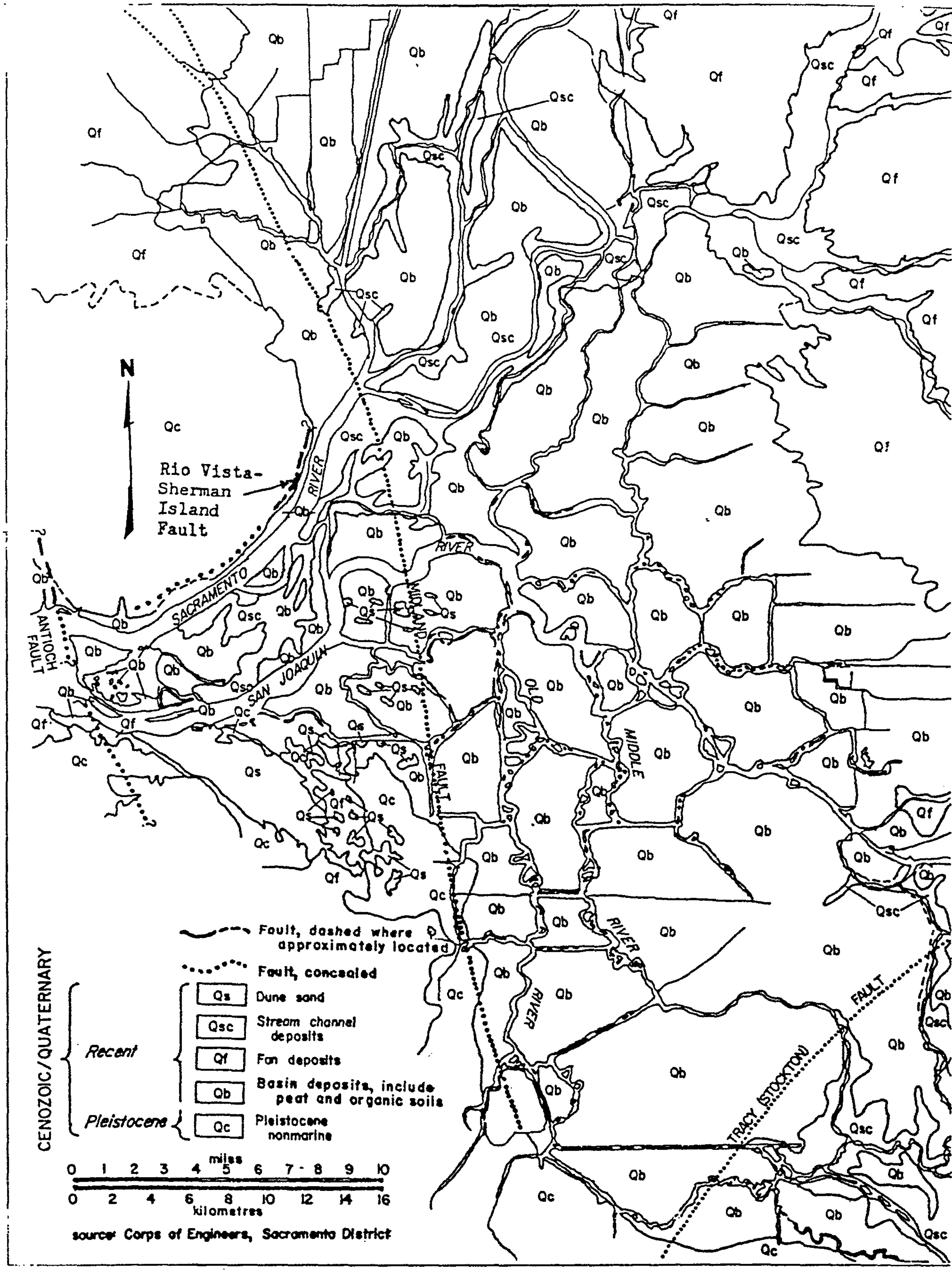


Figure A-2
SURFACE GEOLOGY OF SACRAMENTO-SAN JOAQUIN DELTA

Geology and depositional history of the Delta are given in *Geologic Maps of the Sacramento-San Joaquin Delta, California.*[4] Descriptions of geologic materials are given in *Investigation of the Sacramento-San Joaquin Delta, Report No. 1, Ground Water Geology.*[5]

Tectonic History

In early Cenozoic time (about 46 million years ago), the San Andreas fault system began to form along the line of convergency of the oceanic and continental plates. Relatively intact rocks of the Great Valley sequence were pushed westward and upward over Jurassic rocks of the Franciscan complex; this formed the Coast Ranges.[6] In early and mid-Tertiary time (about 35 million years ago), deposits were being laid down in the Great Valley, then a shallow sea. These continental and marine deposits were deformed by periodic folding and faulting through mid-Cenozoic time (about 30 million years ago). This deformation was caused by the eastward underthrusting of the oceanic plate beneath the overlying continental plate.

The tectonic process gradually changed from plate thrusting to right-lateral strike-slip faulting and movement (Figure A-3). The north-northwesterly trend and strike-slip movement is now typical of major faults of the Delta and surrounding area. The Midland fault that passes under the Delta also trends northwesterly (Figure A-2).

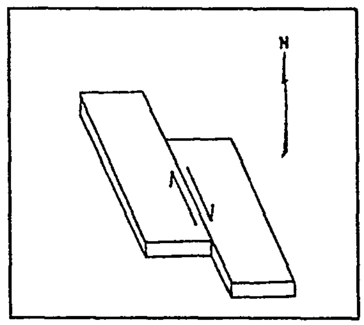


Figure A-3
Right-Lateral Strike Slip
Fault Movement

Delta Peat

Maps at 1:24,000 scale by Atwater[7] show the contact between tidal and nontidal deposits. This contact approximates the limit of peat and other organic soils thicker than 5 feet. The maps are useful in determining thickness and extent of organic soils.

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4 Atwater, op. cit.
5 McClure, op. cit.
6 Gordon B. Oakshott, *California's Changing Landscapes, A Guide to the Geology of the State*, McGraw-Hill, San Francisco, 1978. 379 p.
7 Atwater, op. cit.

The peat was formed over the past 11,000 years during a gradual, slow rise in sea level that provided a continuously suitable environment for its formation and deposition at or near sea level. Almost continuous submergence of the peat prevented or greatly retarded natural decomposition through oxidation. The lack of oxidation enabled vegetation to accumulate and form a great thickness of peat. The peat in the Delta is accumulated dead vegetal matter. Peat in Canada, Great Britain, the Soviet Union, and other high latitude areas actually grows. Details on Delta peat are contained in *Delta Subsidence Investigation, Progress Report.*[8]

Faults

Faults in and near the Delta are important because:

- Movement along a fault within the Delta could cause surface rupture, which could intersect levees, causing failure.
- Movement along a fault within the Delta or surrounding area could cause earthquakes that could result in levee failure due to shaking.

An earlier Department of Water Resources study of seismicity hazards[9] concluded that no levee failures were known to be directly related to earthquakes, but that a major earthquake today could cause serious damage. More recently, the Department has received eyewitness reports of levee damage caused by the Coalinga and Pittsburg earthquakes in 1983 and by earthquakes in 1979 and 1980; other earthquakes may also have caused damage.[10], [11]

The effect of earthquake shaking on levees remains unknown. Delta levees should be routinely inspected after each earthquake that causes shaking in the Delta so that any change or lack of change can be documented. This is particularly important in view of the potential for liquefaction of many of the levees.[12]

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8 George Newmarch, *Delta Subsidence Investigation Progress Report*, California Department of Water Resources, Central District, Sacramento, 1986.

9 Charles Kearney, *Seismicity Hazards in the Sacramento-San Joaquin Delta*, Department of Water Resources, Central District, 1980.

10 George Newmarch and Carl Hauge, *Seismicity*, California Department of Water Resources, Central District, Technical Information Record 1462-CD-08, 1985, pp. 17-18

11 Michael Finch, "Earthquake Damage in the Sacramento-San Joaquin Delta," *California Geology*, California Division of Mines and Geology, February 1985.

12 Newmarch and Hauge, op. cit. and Finch, op. cit.

Appendix B
LEGISLATION AND DEPARTMENT REPORTS RELATED TO SUBSIDENCE

D-030510

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Assembly Bill No. 4193

CHAPTER 970

An act to authorize a levee subsidence program, and to amend Section 12881.4 of the Water Code, relating to water projects.

[Approved by Governor September 14, 1976. Filed with Secretary of State September 14, 1976.]

LEGISLATIVE COUNSEL'S DIGEST

AB 4193, Mobley. Water projects.

(1) Existing law provides for the development by the Department of Water Resources and submittal to the Reclamation Board for adoption by the board of criteria for the maintenance and improvement of levees in the Sacramento-San Joaquin Delta which are not project facilities under the State Water Resources Law of 1945. There are no provisions for studies for the control of subsidence of land in the delta.

This bill would require an investigation by the Department of Water Resources of the viability of a subsidence control program in the Sacramento-San Joaquin Delta.

(2) Existing law requires preference for Davis-Grunsky Act grants and loans to be given to projects involving the development of new basic water supplies.

This bill would permit consideration to be given to projects which would rehabilitate a dam and reservoir for water supply purposes, if the water supply function of a dam and reservoir facility is operationally limited or eliminated for dam safety purposes, pursuant to the department's authority to supervise dams and reservoirs.

The people of the State of California do enact as follows:

SECTION 1. Section 12881.4 of the Water Code is amended to read:

12881.4. In the administration of this chapter, the department and the commission shall give preference to projects involving the development of new basic water supplies. If the water supply function of a dam and reservoir facility is operationally limited or eliminated for dam safety purposes, pursuant to Part 1 (commencing with Section 6000) of Division 3, the department and the commission may give consideration to projects which would rehabilitate the dam and reservoir for water supply purposes. The rehabilitation of facilities may include comparable replacement facilities.

SEC. 2. The Legislature finds and declares that:

(a) Peatlands in the Sacramento-San Joaquin Delta are subsiding up to three inches per year due to soil oxidation, compaction, and wind erosion.

(b) Because of continued subsidence, much of the delta lands have fallen below sea level, and larger and larger levees have had to be constructed in order to restrain tidal and flood waters from permanently inundating these valuable delta agricultural lands.

(c) Without major levee works or without preventing subsidence, local levee maintenance districts will have increased economic difficulties in maintaining a viable levee system.

(d) A partial alternative to costly state and federal major levee works would be a subsidence control program undertaken along the landside of levees, if such control is determined to be economically and engineeringly viable.

SEC. 3. The Department of Water Resources is hereby directed to undertake an investigation of the viability of a subsidence control program in the Sacramento-San Joaquin Delta. The department shall report its findings to the Legislature.

Legislation and Department Reports Related to Subsidence

1963. *Delta Test Levees Investigation*

This report presents data and evaluations on detailed field investigations at selected Delta levee test sites.

1973. Delta Levee Maintenance Act (Way Bill)

As part of this act, the Legislature declared that the physical characteristics of the Delta should be preserved essentially in their present form. The Legislature further declared in this act that the key to preserving the Delta's physical characteristics is the system of levees defining the waterways and producing the adjacent islands (Water Code Section 12981 *et seq.*).

1975. *Plan for Improvement of the Delta Levees*, Bulletin 192

This bulletin presents a plan to preserve the present physical configuration of the Delta. The plan suggests that capital and replacement costs for improving the levees and providing recreation features should be shared 50 percent Federal, 30 percent State, and 20 percent local. Maintenance costs would be shared 60 percent local and 40 percent State.

1976. Nejedly-Mobley Delta Levees Act (Water Code Section 12226.1)

This act adopted the conceptual plan for levee improvement set forth in Bulletin 192. The act directed the Department of Water Resources to develop further plans for preservation of the Delta levees and to make recommendations to the Legislature concerning construction, cost sharing, land use, zoning, flood control, recreation, fish and wildlife habitat, and esthetic values.

1976. Water Code Section 12881.4 Section 3

This legislation directed the Department of Water Resources to investigate the viability of subsidence control in the Delta.

1980. *Subsidence of Organic Soils in the Sacramento-San Joaquin Delta*

This report gives results of an investigation to determine the viability of subsidence control in the Delta.

1982. *Delta Levees Investigation*, Bulletin 192-82

This report is the response to 1976 legislation that directed the Department of Water Resources to prepare a plan for preserving the Sacramento-San Joaquin Delta levees.

SUBSIDENCE ON BETHEL TRACT
Site Investigation, 1988

On February 29, 1988, Todd Nelson, geologist with Contra Costa County Community Development Department, telephoned George Newmarch, geologist with Department of Water Resources Central District, regarding subsidence on Bethel Tract. Specifically, a home owner had reported to Mr Nelson that the land surface surrounding a well drilled in 1979 on his property had subsided about 18 inches, leaving the well casing sticking out of the ground.

George Newmarch visited the well on March 4, 1988, and obtained the following information. The well is in a parcel of land located on the south side of Bethel Tract about 1.5 miles northwest of the intersection of Bethel Island Road and Taylor Road.

The concrete pad still attached to the well casing was 12 to 18 inches above ground surface, depending on where measurements are taken. Soil of the area is organic "peat". The ground surface was very irregular and contained many pot holes. The pot holes and irregularity are probably due to shrinkage cracks, trails and hoofprints of grazing livestock, and ruts made by farm equipment.

The 8- to 10-acre parcel, where the well is located, is bordered on the east and west by north-south drainage ditches discharging to an east-west canal located to the north of the parcel. That canal flows west to a pumping station that discharges the drainage water into Taylor Slough (see photo below). From the levee above the pumping station, one can look eastward and see that the land is lowest in the area drained by the canal and its drainage ditches. Without a bench mark seated in the inorganic soil below the organic soil, it is not certain, but it appears that subsidence has been caused by the dewatering of the organic soil. The dewatering has allowed shrinkage and oxidation of that soil. It is probable that dewatering of the organic soils (rather than the pumping of water wells) has resulted in subsidence in this area of Bethel Tract, including the parcel where the well is located.

Pumping station on the west side of Bethel Island.
Photo taken April 27, 1988.

Appendix D
VERTICAL CONTROL SURVEYS

A series of 15 vertical control leveling lines was run through the central Delta as part of a nationwide network established by the U.S. Coast and Geodetic Survey (now National Geodetic Survey). The first net was run in 1912 and the last in 1966-67. NGS has run 13 precision level surveys in the study area. The last seven were a joint effort of the Department of Water Resources and NGS under a 1959 agreement to share the cost of precise levels for elevation control.

Preliminary plans have been formulated for a vertical control survey to determine elevation changes in central portions of Delta islands. Those plans, as described in a Department of Water Resources memorandum[1], are summarized below and are included at the end of this appendix.

Conventional Surveys

Department of Water Resources first order vertical control surveys from 1974 through 1977 using conventional surveying methods have shown that bench marks in the Delta are not stable. Therefore, it is necessary to identify more stable bench marks on the periphery of the Delta. These stable bench marks will be used to establish a vertical datum.

The first step will be to analyze the data of first order National Geodetic Survey vertical control lines to identify those bench marks that appear to be stable. Changes in elevation for bench marks in specific areas will be compared to determine their stability.

Those bench marks that appear to be most stable will be located in the field. First order spirit levels will be run between several bench marks in each line to establish the relationship between each line of bench marks. Several groups of stable bench marks bounding the Delta will be chosen to establish vertical control.

Elevation differences between these groups of bench marks will be measured by the Global Positioning System method. GPS measurements will be evaluated to identify

1 Rosendo Mendoza (Division of Land and Right of Way), Office Memo to Peter Rabbon (Central District), Delta Bench Mark Elevations, 1988.

the most suitable bench mark from each group. One bench mark from each group will thus become a primary bench mark.

GPS measurements of elevation differences will be made from those primary bench marks on the Delta perimeter to bench marks in central portions of islands. The primary bench marks will be supplemented by GPS bench marks recently set by the U.S. Geological Survey and by the bench mark on Highway 12 at the Mokelumne River bridge, which is based on a 1985 spirit leveling survey by Murray, Burns, and Kienlen, Consulting Engineers.

Global Positioning System Survey

A survey network has been established in the Delta as a part of the DWR cooperative subsidence investigation with USGS (Figure D-1). This network will be used to obtain vertical control (land surface elevations) to determine areas and rates of subsidence. The network includes both GPS and conventional surveying bench marks.

The GPS is a space geodesy land elevation and location surveying method that uses Earth-circling satellites and Earth-based radio telescopes to obtain geodetic measurements. GPS uses the Very Long Baseline Interferometry method.

The VLBI method uses two radio telescopes at different locations that are pointed at a remote radio source in the sky. The radio signal represents a random time series that is correlated by tracking data from the radio telescopes. By knowing the instantaneous delay between the arrival of the signal at each radio telescope and by tracking several radio sources while the Earth rotates, it is possible to calculate the separation of the radio telescopes to centimeter accuracy in three dimensions.

The radio source for GPS surveying is one of seven (eventually to be 18) NAVSTAR satellites orbitting the Earth at a radius of about 24 000 kilometers.[2] Measurements made from the radio signals are relative distances from the center of mass of the Earth. The distances, therefore, are

——— GLOBAL POSITIONING SYSTEM (GPS) NETWORK
——— CONVENTIONAL SURVEYING NETWORK
▣ GPS BENCHMARK
• CONVENTIONAL BENCHMARK
▲ EXTENSOMETER
SOURCE: U. S. Geological Survey, Nov. 1987.

SYMBOL EXPLANATION FOR FIGURE D-1

2 Roger Bilham, Volcanoes, Earthquakes, and Space Geodesy, *C. U. Geology News*, Dept. of Geological Sciences, Univ. of Colorado at Boulder, Fall 1986, p. 4-5.

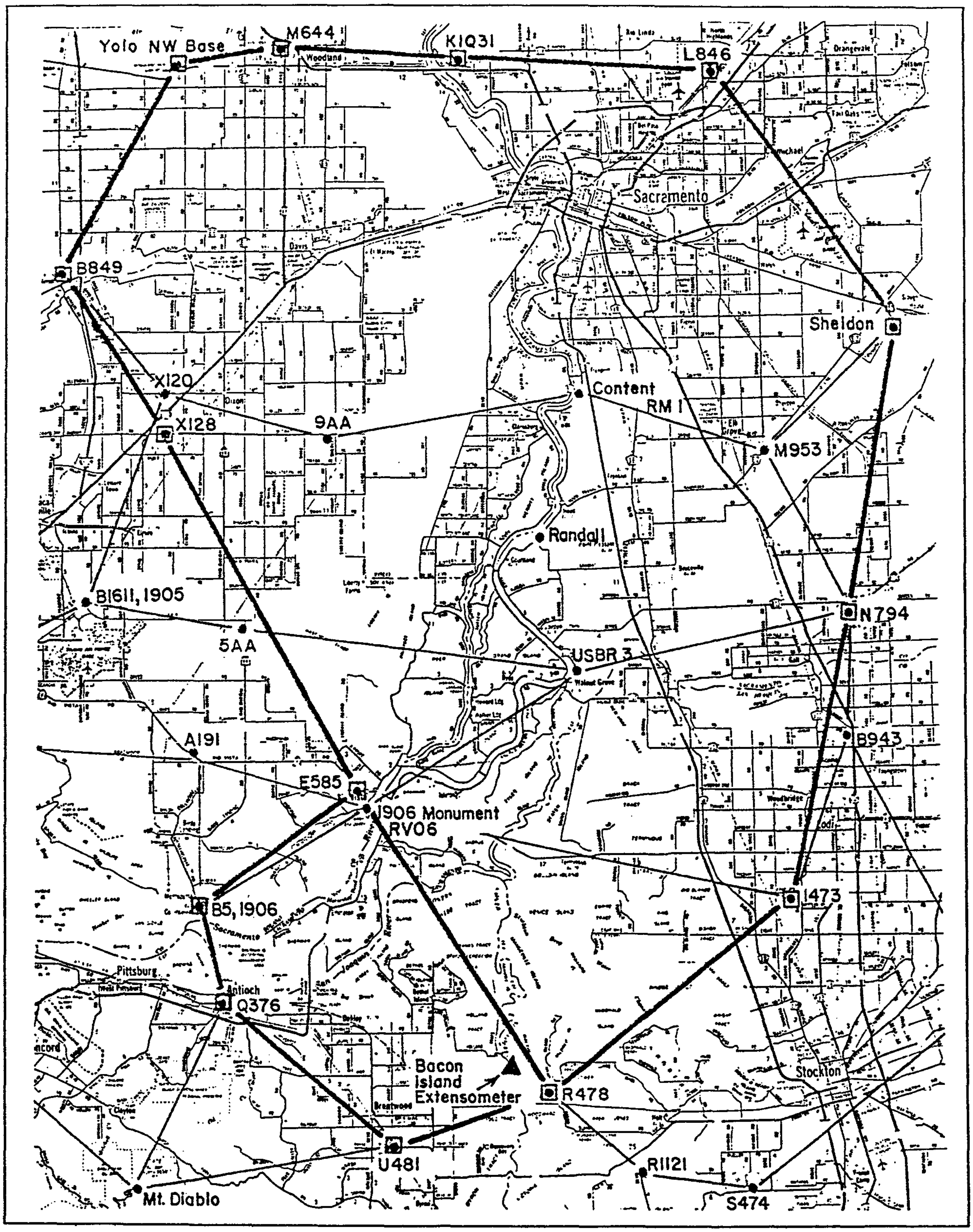
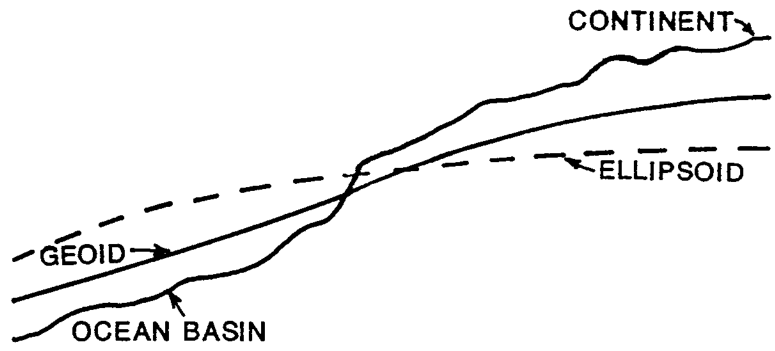


Figure D-1
DELTA SURVEY NETWORK
(Symbol Explanation on Page 44)

D-030516

heights above a theoretical ellipsoid (mathematical Earth). An accurate estimate of the geoid (real Earth) in the Delta region must be made to convert the height above the theoretical ellipsoid to sea level. The geoid estimate is made by testing the local slopes of the geoid at several points using a blend of precise leveling, gravity surveys, and GPS measurements[3] (Figure D-2). Future measurements of the same GPS network are required to derive subsidence information.



Relationship (exaggerated) between an ellipsoid and a geoid. Deviations are due to variations in the gravitational field caused, in part, by unequal mass distribution of crustal materials.

SOURCE: U.S. Geological Survey, Implementing North American Datum 1983 for the National Mapping Program (San Rafael Quadrangle)

Figure D-2
RELATIONSHIP BETWEEN ELLIPSOID AND GEOID

The potential of GPS surveying is illustrated by recent GPS geodetic measurements designed to monitor Icelandic land surface deformation. In July 1986, 26 GPS receivers were operated simultaneously in Alaska, Canada, Greenland, Iceland, Sweden, and the United States by more than 40 scientists from 16 nations. In Iceland, 250 geodetic baselines were measured (with many additional statistical repetitions) in 12 days over an area of 60 000 square kilometers, a task that would have taken conventional surveying many months.[4]

Results of a DWR/USGS test in the Sutter Buttes area indicated that the GPS will be a usable surveying tool for establishing land surface altitude in the Delta and that the cost will be significantly lower than the cost of using conventional leveling techniques. GPS hardware and software have been purchased by the DWR Division of Land and Right of Way for use in the Delta and on other surveys.

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3 Roger Bilham, "Measurement of the Relative Heights of Everest and K2 Using Space Geodesy," *C.U. Geology News*, Dept. of Geological Sciences, Univ. of Colorado at Boulder, 1988, p. 3.
4 Bilham, 1986 op. cit.

Global Positioning System Network

The cooperative DWR/USGS subsidence study in the Sacramento Valley south area has established a GPS baseline network in and around the Delta (see Figure 2, Chapter 4). Sites already surveyed by GPS and included in the Delta network include:

14 GPS Bench Marks
13 Gravity Survey Sites
1 Extensometer Site

Four of the GPS bench marks and gravity survey sites are also part of the Sacramento Valley north area subsidence baseline network. Additional sites will be surveyed by GPS in the future.

These bench marks and gravity survey sites, in conjunction with extensometers, will be used to establish a vertical control network to document the rate and magnitude of subsidence in the Delta.

The GPS bench mark on Bacon Island (Figure D-3) will provide vertical control for the extensometer site as well as for the acoustical velocity meter sites in Old River and Middle River, adjacent to Bacon Island. The AVM sites measure water velocity and stage heights in the two channels.

Measurement of Land Surface Elevation

Periodic measurement of land surface elevation must continue for as long as necessary to determine the rate of subsidence. A baseline of at least 10 years will probably be needed to establish subsidence rates as related to land use.

The GPS seems to be the most economical method for determining land surface elevations in the Delta at this time. In addition to GPS surveys, however, conventional leveling techniques will continue to be used to establish local baselines that are tied to the satellite system data.

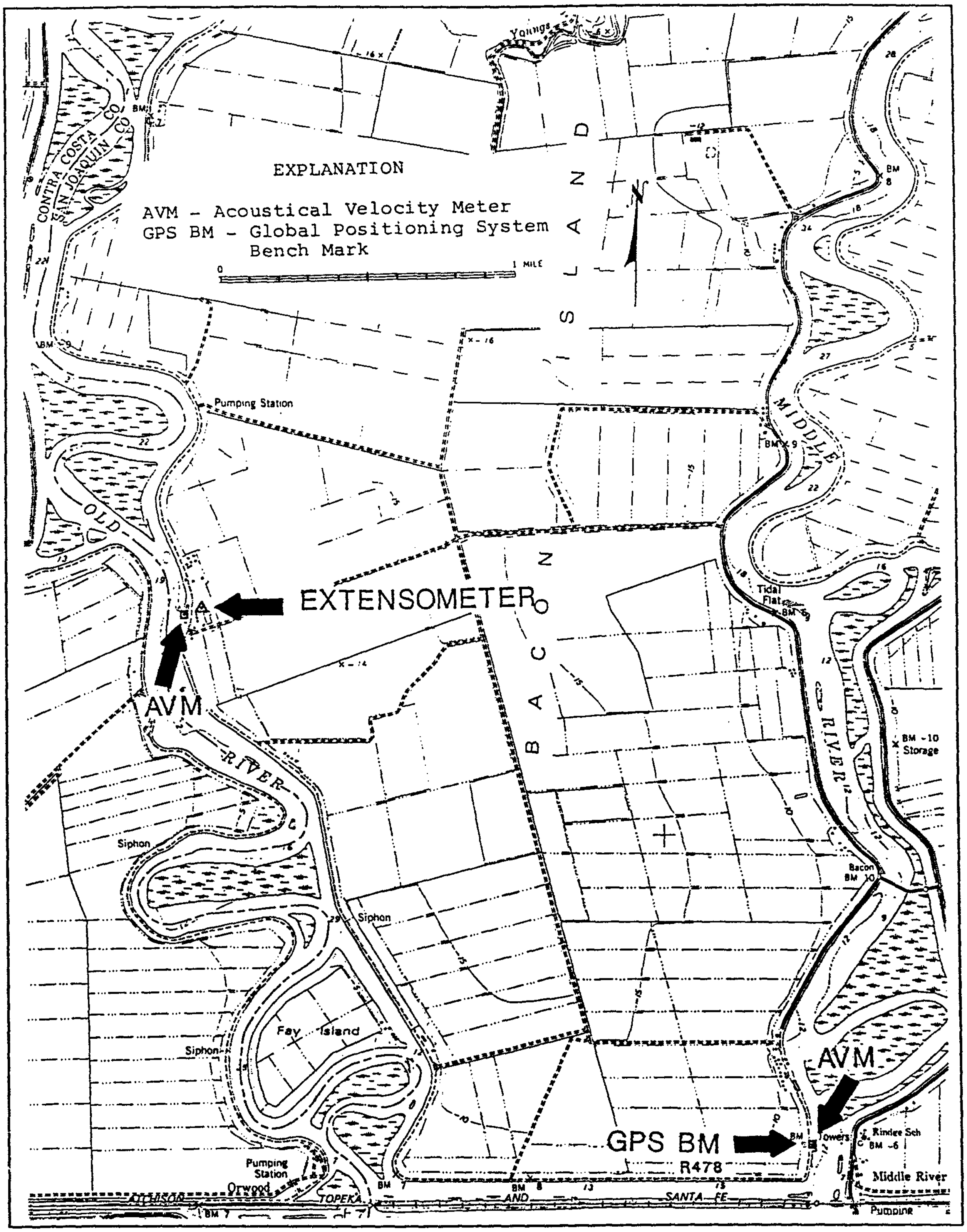
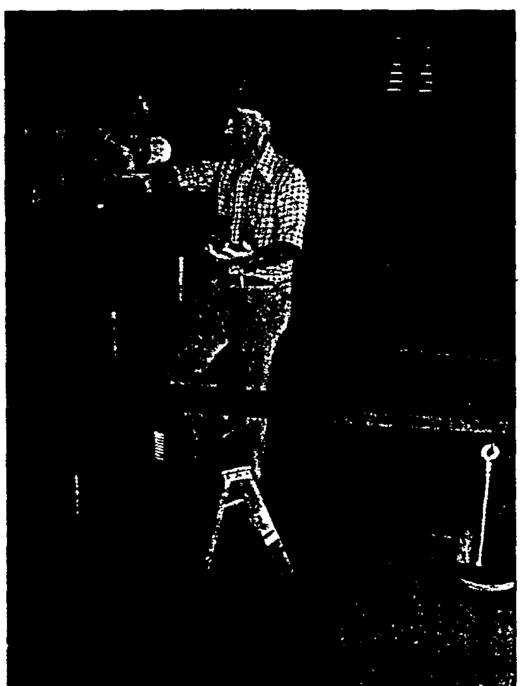


Figure D-3
LOCATION OF BACON ISLAND EXTENSOMETER

Appendix E
DETAILS OF EXTENSOMETER CONSTRUCTION

The Bacon Island extensometer station includes three extensometers and piezometers at one site. Two extensometers measure compaction of organic soils (between 0 and 12 feet deep), and the other measures compaction of mineral soils (between 12 and 444 feet deep), the interval of potential ground water withdrawal. Water levels are monitored in all three zones in which subsidence is being monitored.

The general design of the deep extensometer is shown in Figure E-1. It was constructed by placing a vertical extensometer pipe in a cased well. A special type of recorder mounted over the open well casing is used to measure the rate and magnitude of compaction between the land surface and the bottom of the well. As the land lowers, it appears that the extensometer pipe is rising. Actually, the land surface is moving downward with respect to the top of the pipe (Figure E-2).


DWR geologist takes reading from deep extensometer on Bacon Island.

The well in which the extensometer pipe has been placed is 444 feet deep. The concrete plug at the bottom of the well is about 9 feet long. Embedded in the concrete plug is the 2-inch-diameter steel extensometer pipe that extends to the surface and, by means of cables and weights, is attached to a Stevens A35 drum recorder with a 30-day clock. The Stevens recorder will be replaced by a solid state microdata recorder, Campbell Model 21X. Sensing will be done by a LVDT displacement transducer, Transtech Model 245-000. The 2-inch-diameter extensometer pipe is inside a 6-inch-diameter casing that extends from the surface to a depth of 420 feet, with a slip joint installed at 362 feet to prevent crushing of the

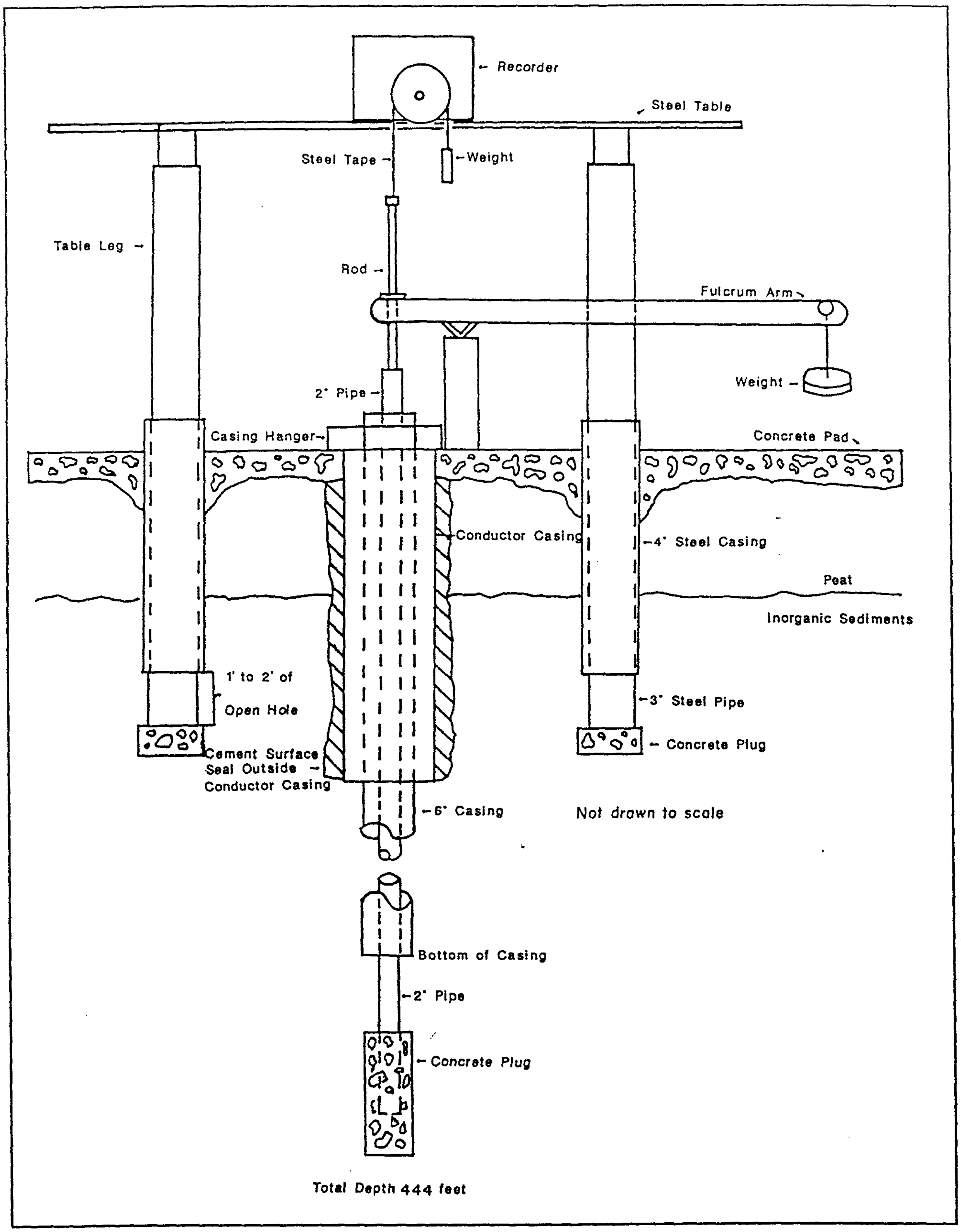


Figure E-1
SIMPLIFIED SCHEMATIC OF A DEEP EXTENSOMETER

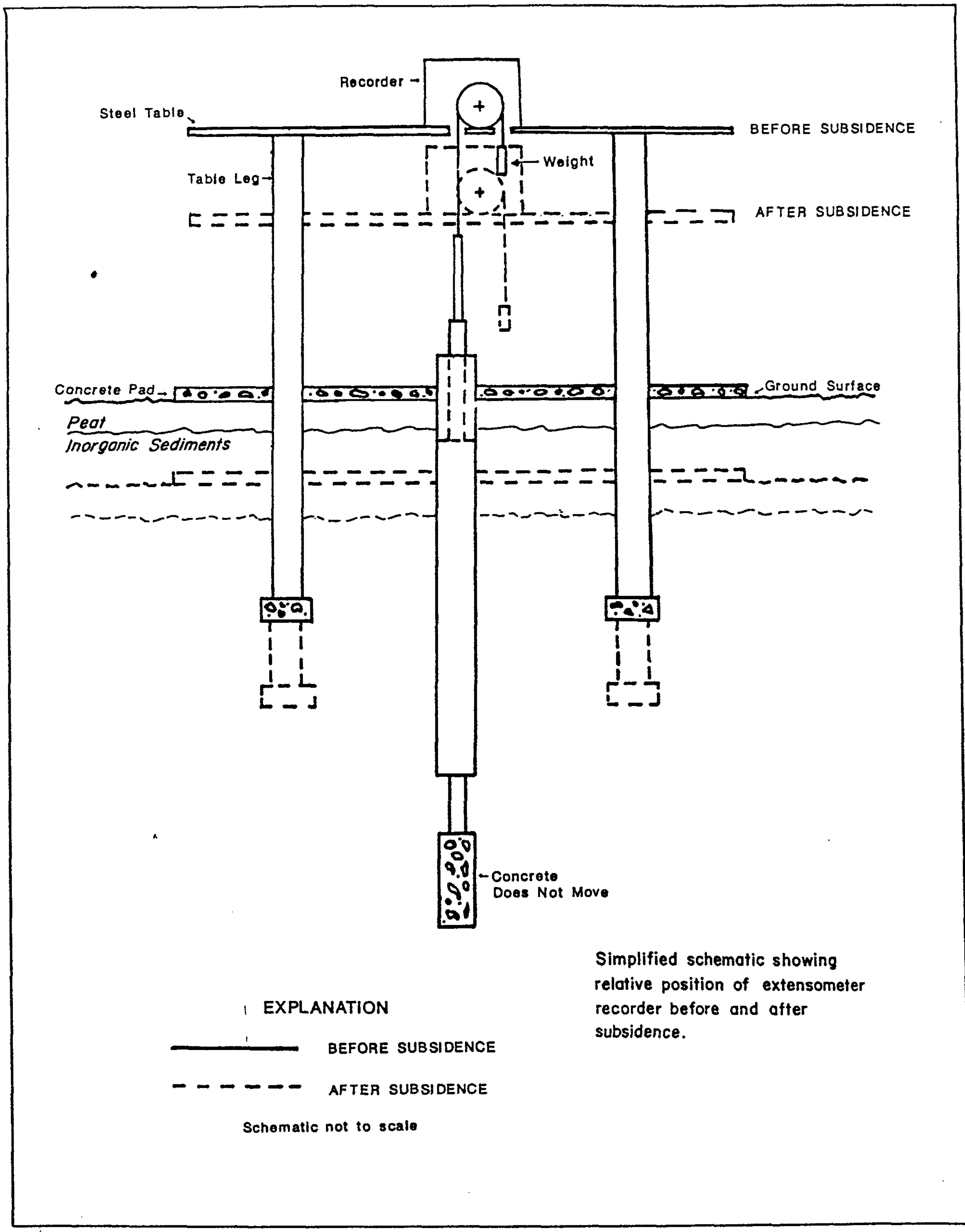


Figure E-2
SIMPLIFIED SCHEMATIC OF A DEEP EXTENSOMETER, BEFORE AND AFTER SUBSIDENCE

D-030522

casing. A conductor casing is cemented from the ground surface to a depth of 35.5 feet. Decisions on depths of the slip joint, casing perforations, and seals were based on interpretations of a geologic log and an electric log of the well (Table E-1 and Figure E-3).

Table E-1
GEOLOGIC LOG OF BACON ISLAND EXTENSOMETER

Following is a geological log of holes drilled for the subsidence/compaction study on Bacon Island. Because of the proximity of the shallow (27-foot total depth) and deep (444-foot total depth) drill holes, on-site logging of both holes was used to compile the following log. The description of the bottom 24 feet is based on geophysical logging information. Both holes were drilled by a U. S. Geological Survey mud rotary rig, November 17-22, 1986.

Depth (ft)		Description
From	To	
0	5.0	Peat; dark brown (5YR 2/1) to black (N1); 90-100 percent organic fibers composed of rootlets and green plant parts.
5.0	7.0	Peat; brown (5YR 2/1); 80-90 percent organic fibers; slightly sticky.
7.0	9.0	Peat; dusky yellowish brown (10 yr 2/2); 80-90 percent organic fibers; slightly sticky.
9.0	12.5	Peat; brownish black (5YR 2/1); 70-80 percent organic fibers; sticky.
12.5	14.0	Clay; medium dark gray (N4); 20 percent organic fibers; soft and sticky.
14.0	15.0	Clay; medium gray (N4); trace fine sand; 5 percent organic fibers; sticky.
15.0	20.0	Clay; medium gray (N5); trace fine sand; 2-5 percent organic fibers
20.0	27.0	Clay; medium bluish gray (5B 5/1); fine to medium sand; 1-5 percent organic fibers; very soft; fast drilling.
27.0	60.0	Clay; medium bluish gray (5B 5/1); fine to medium sand; very sticky.
60.0	70.0	Clay; dark yellowish brown (10YR 4/2; fine sand; very sticky; slow drilling.
70.0	75.0	Clay; medium bluish gray (5B 5/1); medium sand; sticky.
75.0	78.0	Sand (medium to coarse); rounded quartz grains.
78.0	80.0	Clay; medium bluish gray (5B 5/1)trace sand; sticky.
80.0	110.0	Clay; greenish gray (5G 6/1) to medium bluish gray (5B 5/1); sticky to fairly hard.
110.0	118.0	Clay; medium bluish gray (5B 5/1); fine sand; moderately plastic.
118.0	120.0	Sand (medium) with some mica flakes.
120.0	130.0	Clay; medium dark gray (N4) to dark greenish gray (5G 4/1) interbedded with medium bluish gray (5B 5/1) clay; sticky.
130.0	142.0	Clay; dark greenish gray (5G 4/1); fine to medium sand and mica flakes; sticky.
142.0	160.0	Sand (medium to coarse); some clay; moderate yellowish brown (10YR 5/4); composed of quartz grains and mica flakes.
160.0	200.0	Sand (medium to coarse); trace clay; olive gray (5Y 4/1).

Table E-1 (continued)
GEOLOGIC LOG OF BACON ISLAND EXTENSOMETER

Depth (ft) From	To	Description
200.0	250.0	Clay; olive gray (5Y 4/1) to dark greenish gray (5GY 4/1); fine to medium sand and trace silt; sticky; moderately soft; slow drilling.
250.0	260.0	Sand (coarse); trace clay; moderate yellowish brown (10YR 5/4).
260.0	270.0	No sample.
270.0	280.0	Clay; olive gray (5Y 4/1); medium sand.
280.0	290.0	Clay; dark greenish gray (5GY 4/1) to medium bluish gray (5B 5/1); medium to coarse sand.
290.0	310.0	Sand (coarse); some clay; greenish black (5G 2/1) to dark greenish gray (5GY 4/1); moderately soft.
310.0	320.0	Clay; dusky brown (5YR 2/2); fairly hard.
320.0	330.0	Clay; dark gray (N3) with streaks of olive gray (5YR 3/2) clay; fine sand and silt; easy drilling.
330.0	340.0	Sand (medium to coarse); some clay; dusky brown (5YR 3/2) to medium dark gray (N4); soft.
340.0	350.0	Sand (fine to medium); some silty clay; medium dark gray (N4); soft.
350.0	360.0	Clay; moderate yellowish brown (10YR 4/2); medium to coarse sand; fairly hard; slow drilling.
360.0	370.0	Clay; dark greenish gray (5YR 4/1) to medium gray (N5); trace very fine sand; soft.
370.0	380.0	Clay; brownish gray (5YR 4/1); medium sand; sticky.
380.0	400.0	Clay; dark yellowish orange (10YR 6/6) to dark greenish gray (5GY 4/1) to medium dark gray (N4); trace cobbles; stiff; sticky; slow drilling.
400.0	410.0	Sand (coarse); some clay; dusky yellowish brown (10YR 2/2).
410.0	420.0	Clay; medium dark gray (N4); some coarse sand; sticky; massive clay.
420.0	428.0*	Clay; massive
428.0	433.0*	Clay; some sand.
433.0	435.5*	Clay.
435.5	438.0*	Clay; some sand.
438.0	444.0*	Sand.

* Based on digital data collected on a cassette tape during borehole geophysical logging of the 12-1/4-inch diameter hole.

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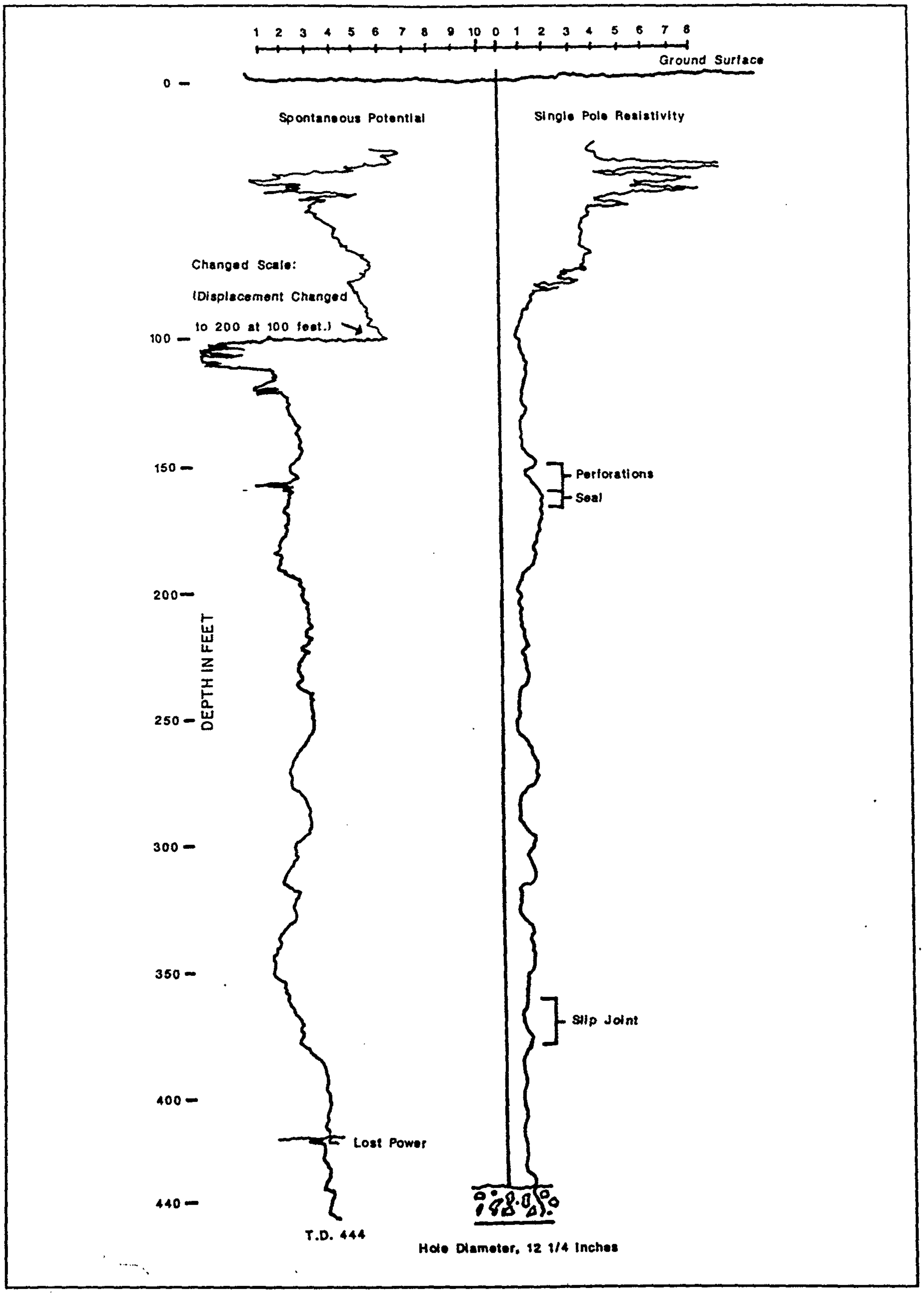
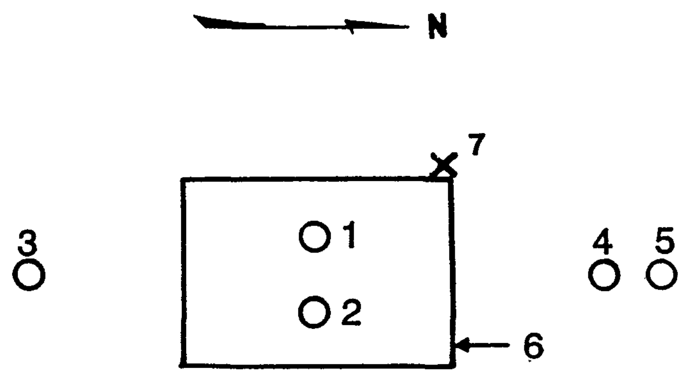


Figure E-3
ELECTRIC LOG, BACON ISLAND EXTENSOMETER

The table that supports the recorder is founded in inorganic soil about 14 feet below the ground surface. The peat thickness at that point is about 12 feet. A pressure transducer, DRWCK Incorporated Model PDCR-830, will be installed along with the deep extensometer to measure water level change in the aquifer. These measurements will furnish data to equate ground water level change with sediment compaction.

The entire apparatus on the surface is enclosed in a steel shed that sits on a concrete pad lying on the peat. A shallow extensometer and two piezometers are located outside the shed (Figure E-4).



EXPLANATION:

1	Deep Extensometer
2	Shallow Extensometer
3	Shallow Extensometer
4	Piezometer, 11.5 feet deep
5	Piezometer, 27.5 feet deep
6	Steel Shed
7	Bench Mark

Not Drawn to Scale

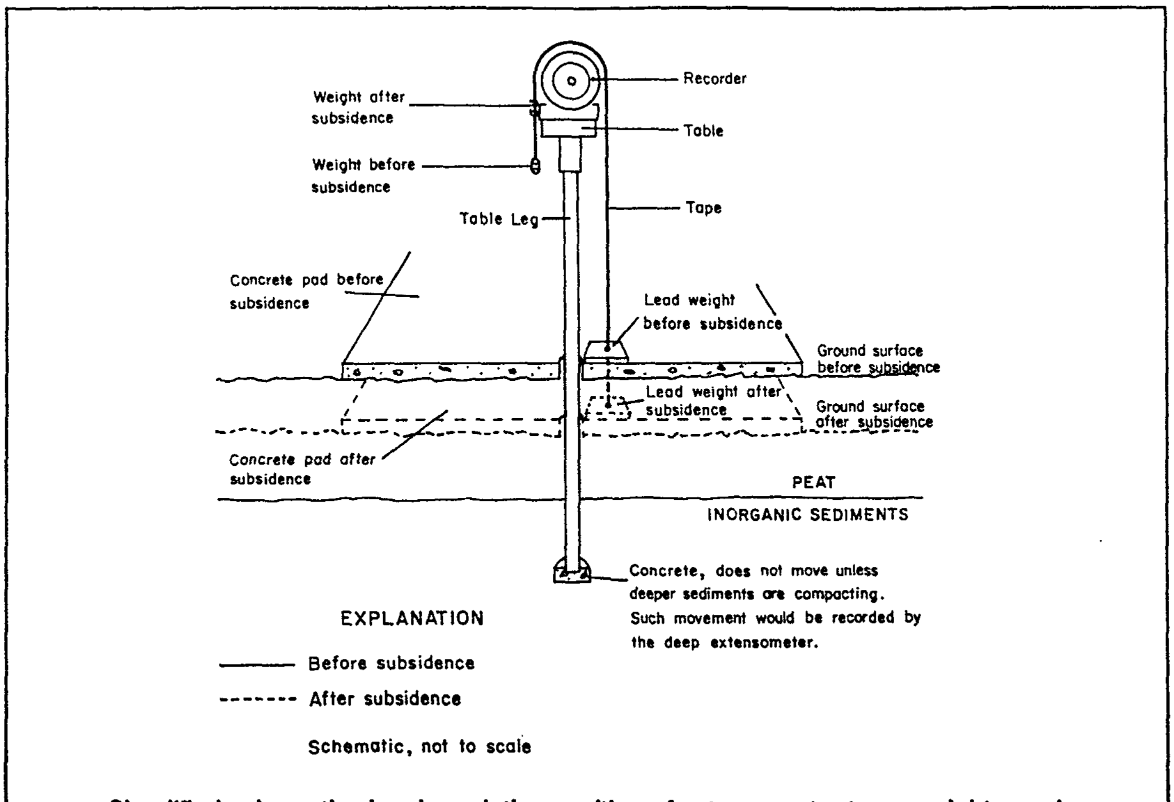
Figure E-4
SCHEMATIC, BACON ISLAND EXTENSOMETER STATION

The shallow extensometer was constructed by drilling a 12-inch-diameter well to a depth of 27 feet. A 2-inch-diameter steel pipe was embedded into a 10-foot concrete plug at the bottom of the well. This plug is seated in inorganic soil (mineral soil) below the peat.

Another shallow extensometer, inside the steel shed, was constructed by placing a Stevens A35 drum recorder on the same table that supports the recorder for the deep extensometer. One end of a steel tape is attached to a heavy weight, which rests on the concrete floor of the shed. The tape passes up and over the pulley wheel of the Stevens recorder, and a small weight is suspended from the other end of the tape. As the concrete floor and heavy weight move downward due to subsidence of the shallow organic soil, the small suspended weight will move upward, thus rotating the recorder drum. The table that supports the recorders is founded in inorganic soil below the organic soil and will not move in relation to the concrete pad (Figure E-5).

The two piezometers installed near the shed provide shallow ground water level measurements. These were built by driving 3-foot-long well points into the peat. The tip of one well point is at a depth of 11.5 feet; the other is at 27.5 feet. Three-inch-diameter PVC pipe extends from the well points to the ground surface (Figure E-6).

A bench mark consisting of a brass cap was embedded in the concrete foundation of the steel shed and was surveyed into the Global Positioning System network by the National Mapping Division, U.S. Geological Survey using conventional surveying methods.



Simplified schematic showing relative position of extensometer tape, weights, and concrete pad before and after shallow subsidence of peat. Not to scale.
SOURCE: Modified after U.S. Geological Survey, 1987.

Figure E-5
SIMPLIFIED SCHEMATIC OF A SHALLOW EXTENSOMETER

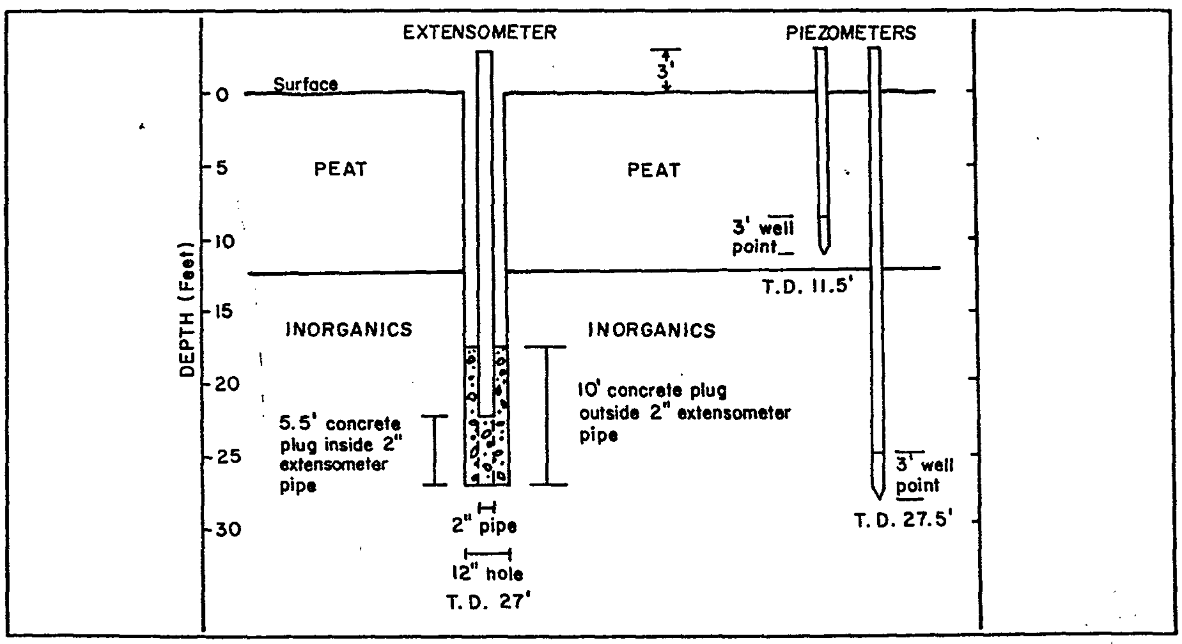


Figure E-6
CONSTRUCTION DETAILS, BACON ISLAND SHALLOW EXTENSOMETER AND PIEZOMETERS OUTSIDE STEEL SHED

Construction Procedures and Materials

Drilling procedures and materials used by the U.S. Geological Survey for construction of the Bacon Island deep extensometer, shallow extensometer outside the steel shed, and the two piezometers are shown in Table E-2.

Table E-2
BACON ISLAND EXTENSOMETER DRILLING AND MATERIALS

DRILLING

One well 436 feet deep with geophysical logs including SP, resistivity, caliper, and Gamma. Maintain plumbness by use of directional surveys. Install gravel pack, casing, and extensometer pipe.

One hole 27 feet deep and install extensometer pipe without casing.

Three holes 12 feet deep for instrument table legs; drilled by auger.

MATERIALS

Recorder, Stevens, Type F, 10:1 and accessories. 2 each
Data logger (Campbell Scientific CR-21x)
Tape reader
Cable to tape recorder
Tape recorder
Displacement transducer
Water level pressure transducer
Special collar for modification of recorder. 2 each
Boston gear, G-188 for recorder. 2 each
Compaction pipe, 2-inch dia., Sch. 80, Black Steel, 483 feet
Slip joint, 5 feet long closed, 8 feet long extended. 1 each
Pressure recorder, Bristol Range 0-100 with 30-day clock. 2 each
Airline, 150 feet, 1/4-inch copper, continuous with 1/4-inch galvanized section on bottom.
Nitrogen, 2 cylinders
Nitrogen regulator, 2-stage
Instrument table, steel, 3-legged, and fulcrum for compaction pipe
Instrument table legs, concrete, supplies
Concrete base, forms, ready mix, hardware
Building, 8 x 12 ft, steel, insulated
12-inch conductor casing
Volclay grout
6-5/8-inch casing
Shutter screen
Landing clamps
Centralizers
14-inch conductor casing
Drive points
Schedule 40 PVC, 3/4 inch ID
8x16 gravel pack and sand
Cement baskets
Threading and couplers
Schedule 40 black pipe, 2-inch
Concrete, pumped down hole