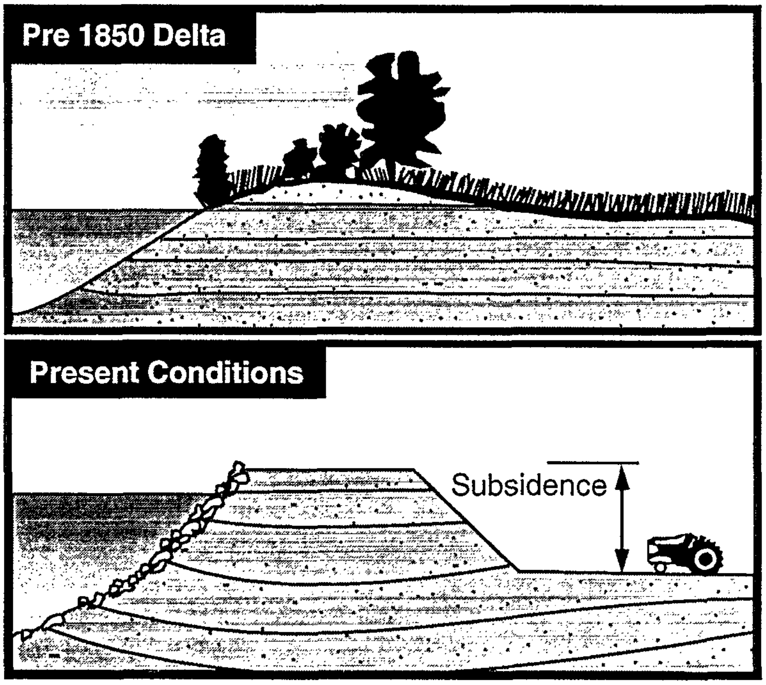
DELTA LEVEE AND CHANNEL MANAGEMENT ISSUES

GENERAL ISSUES RELATED TO THE PHYSICAL INTEGRITY OF DELTA LEVEES

Prepared by: Curtis Schmutte, Chief, and
Reynold Porterfield, Senior Engineer,
Special Projects Branch, Planing Division,
Department of Water Resources

Assisted by: William Forsythe, Junior Civil Engineer
Scott Yomogida, Junior Civil Engineer
Frederick Brovold, Roger Foot Associates,
Consulting Engineer

DELTA LEVEES



DEPARTMENT OF WATER RESOURCES
DIVISION OF PLANNING
Delta Planning Branch

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DIVISION OF PLANNING
Edward Huntley, Chief

Delta Planning Branch
Karl Winkler, Chief

This report was prepared under the direction of

Curt Schmutte........Supervising Engineer, Water Resources

Reynold Porterfield........Senior Engineer, Water Resources

by

William Forsythe........Junior Civil Engineer

Scott Yomogida........Junior Civil Engineer

Frederick Brovold, Roger Foott Associates........Consulting Civil Engineer

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EXECUTIVE SUMMARY

The Sacramento-San Joaquin Delta is one of California's most valuable, irreplaceable resources and without adequate levees, the Delta as we know it today will be lost. The levees serve many diverse needs. They protect valuable wildlife habitat, farms, homes, urban areas, recreational developments, highways and railroads, natural gas fields, utility lines, major aqueducts, and other public developments. The levees are also critical to protecting Delta water quality and serve a significant function in the State's water transfer system. In the Delta Flood Protection Act of 1988 (SB 34), the Legislature declared "...that the delta is endowed with many invaluable and unique resources and that these resources are of major statewide significance."

Since reclamation of the Delta began in the 1800's, the levees have increased from under 5 feet to over 25 feet in height. Due to subsidence of the island interiors, it was necessary to continually add material to hold back the adjoining rivers and sloughs. Since many of the levees were built piecemeal over many decades with little understanding of the engineering challenges posed by the Delta's geology and the impacts of long-term subsidence, there has been an ongoing concern over the performance of these levees.

Levee conditions in the Delta are quite different than those in many other locations, where land elevations are above normal water levels. Water forces then act on levees only during periods of high water or flooding. In the Delta, land elevations are generally much lower than waterway elevations. Because of this difference, the levees function more as earthen dams which act as continuous water barriers. This difference between many Delta levees and levees in other areas has important implications regarding levee design and reconstruction. For example, most of the Delta levees have to remain fully functional during any improvements or rehabilitation.

Levee failures continue to be one of the Delta's primary problems. Levee failures in the Delta are due to several factors which include: instability, overtopping, and seepage. To gain a better understanding of the problems facing the Delta, DWR has financed engineering investigations such as a recently completed seismic analysis of the Delta levees (see the adjoining report: *Review of Seismic Stability Issues for Sacramento-San Joaquin Delta Levees*). These investigations along with levee improvement projects performed under SB 34 have demonstrated that many difficult Delta levee problems are solvable. SB 34 has provided the necessary focus for coordinated levee engineering investigations and improvement projects that have advanced the state of the art of levee design. These efforts have demonstrated that levees can be engineered to alleviate the unfavorable conditions which continue to threaten this water hub of unique economic and natural value. SB 34 programs have also significantly advanced the understanding of Delta subsidence, its causes, and the importance of integrating subsidence control with levee improvements.

An important goal of SB 34 is the completion of levee improvements in a manner which is conscious of the habitat value of the levees. All levee improvement projects must be implemented in a way which allows no net long term loss of habitat. For example, levee upgrade work on Twitchell Island created a new 4 acre habitat to replace 3 acres of levee slope habitat that was disturbed while improvements were being made. Through the SB 34 program, over $3,000,000 has been provided to the Department of Fish and Game for habitat creation.

While maintenance and improvement work can affect habitat present on a levee, such work is vital to the protection of the island itself and the habitat existing on the island. The importance of the Delta as habitat can be seen in its increased use by waterfowl. With the dwindling wetland habitat throughout the state, the winter use by Delta waterfowl has increased from 0.5 million birds 20 years ago to about 1.5 million today.

With regard to Delta levee improvement costs, the United States Army Corps of Engineers (Corps) in 1982 estimated that almost $1 billion would be needed to rehabilitate levees on 53 Delta islands. Costs for some of the worst levees in the western Delta ranged from $2-4 million/mile. However, improvements made in 1992 and 1993 on extremely fragile levees in the western Delta have been completed using an innovative design for less than $1.5 million per mile. Even after accounting for recreation and maintenance, these costs are significantly less than the estimates made over 10 years ago to repair the same levees to essentially the same standards. Use of new designs, extensive monitoring, and economical borrow sources are all factors which need to be considered in developing realistic future costs.

Clearly, however, rehabilitation costs exceed the financial resources of most Delta landowners. Funding through SB 34 has provided for significant levee improvements, but is insufficient to properly rehabilitate all Delta levees. Therefore, a comprehensive cost sharing arrangement needs to be established which will address benefits and equitable cost sharing among all the beneficiaries. Cost sharing arrangements similar to those being forged with the Long Term Management Strategy (LTMS) program to provide economical sources of levee material will help to meet this objective.

Significant DWR activities focus on protecting the Delta both through emergency work and long term planning. SB 34 allows the Department to mobilize forces to take necessary immediate action for threatened levee sites as well as provide long term improvement projects. The long term improvement projects that DWR has sponsored address the specific problems of each levee system in a flexible manner. While this approach requires a larger investment for levee improvements, the long term benefits are well worth the cost.

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HISTORY OF DELTA LEVEES

The process of reclaiming the lands of the Delta began in the California gold rush era of the early 1850s. The population influx created a demand for food, which in combination with fertile Delta soils, convenient water supply, and shallow draft shipping to Central California markets created an incentive to reclaim and farm the Delta. The Federal Swamp and Overflow Act of 1850 provided for title transfer of wetlands from the Federal Government to the states and in 1861 the California Legislature passed the Reclamation District Act, allowing the formation of local government agencies for the purpose of providing mutual drainage and flood control benefits to the landowners within the District boundaries. However, it was not until 1868 when the state turned over responsibility for reclamation to the local agencies and landowners that large-scale reclamation was spurred.

Settlers first constructed low barriers of earth (see Figure 1) on the higher natural levees formed by deposits during previous floods. These low barriers, called "shoestring levees," were built primarily to keep tilled soil from washing away. Settlers rarely tried to prevent high tides from easing water over the lower portions of their land.

The first levees were built with two purposes in mind. Levees built around the islands of the central Delta were intended primarily to exclude tidal water from the tracts underlain by peat; those built along the sedimentary banks of the rivers were also expected to protect the reclaimed land from high flood stages. These levees, built by immigrant Chinese laborers, were constructed by piling material on the river banks when high water threatened to overtop the levee. This produced levees that were narrow and steep-sloped with minimal freeboard. These practices resulted in levees that had to be maintained continually to combat settling and subsidence.

As reclamation continued, owners of the new land found that as more and more land was leveed off, flood stages rose, thus necessitating higher levees in order to have the same protection. As land was developed through levee construction in the Valley, the gold mining industry was developing hydraulic mining technology in the foothills and mountains to the east of the Sacramento Valley. Hydraulic mining generated a tremendous volume of debris which was washed downstream and settled in Valley streambeds. This tremendous load of new sediment exacerbated flood control problems due to

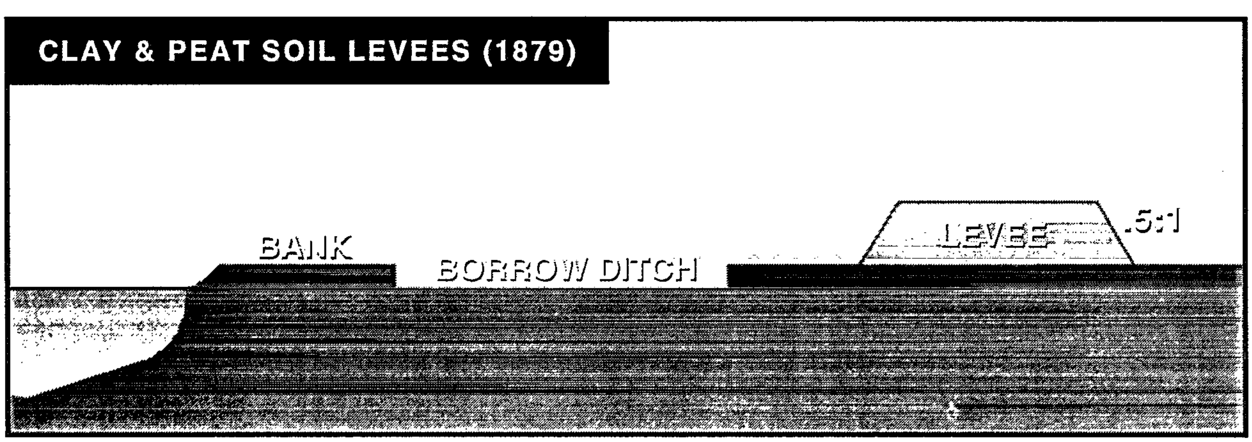

Figure 1: Cross-section of levees on sedimentary banks, 1879 (from Thompson, 1982)

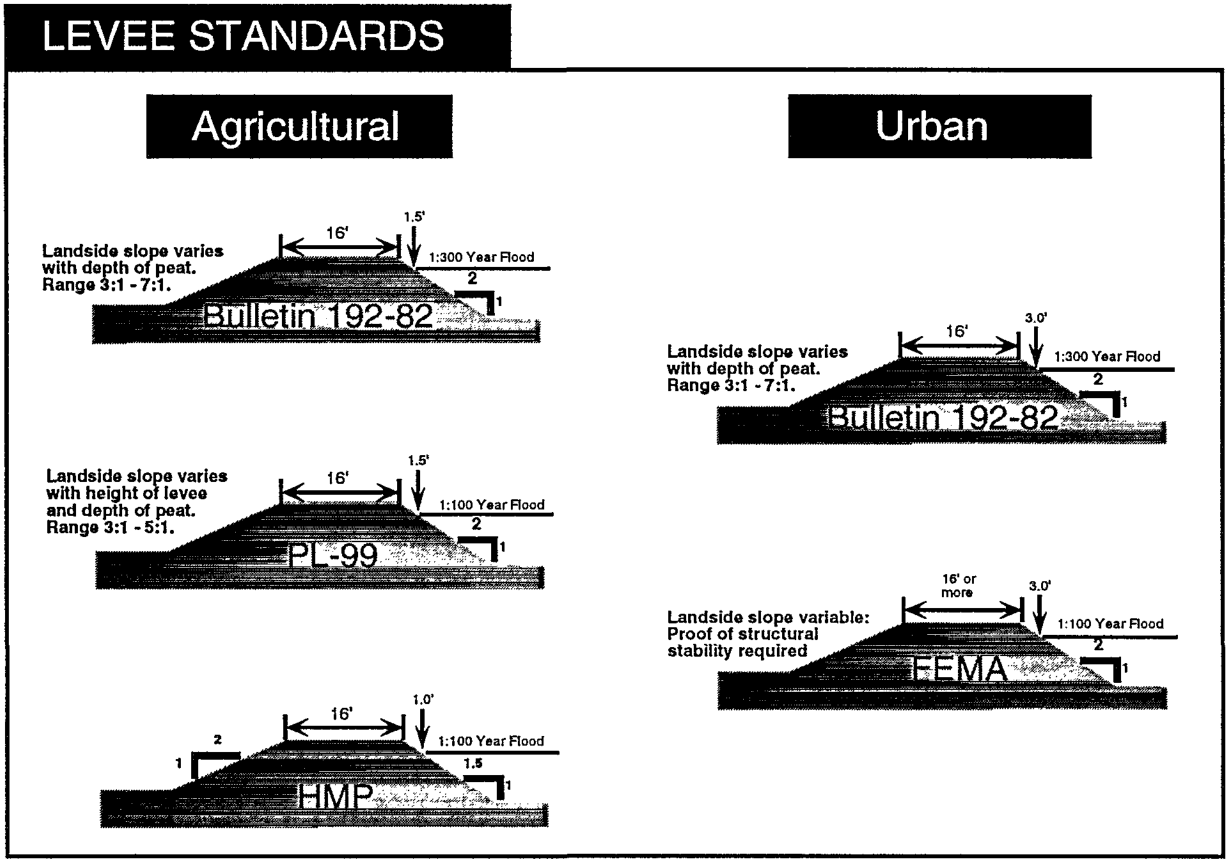

Figure 2: Levee standards (from DWR, 1990)

reduced channel capacities and also interfered with navigation.

Although hydraulic mining was stopped by court decree in 1884, the existing sediment load was still an ongoing problem. Individual landowners and local reclamation districts found themselves in competition, not only with the river, but with each other, in a battle to build higher levees so that when the inevitable flood came, it would destroy someone else's land. Clearly, a more coordinated approach to flood control was necessary.

This coordination was ultimately provided by the Corps. Beginning in 1893, with the Caminetti Act, the Corps began an involvement in flood control and navigation improvement which continues today. A major outcome of federal involvement in Sacramento Valley flood control problems is the Sacramento River Flood Control Project (SRFCP) in which a comprehensive program for levee improvement was undertaken.

Those levees that are part of the SRFCP are known as "project levees." Mostly found along the Sacramento and San Joaquin rivers, they are maintained to Corps standards and generally provide dependable protection. Nonproject or local levees (75 percent of Delta levees) are those constructed and maintained to varying degrees by island landowners or local reclamation districts. Most of these levees have not been brought up to federal project standards and are less stable, increasing their vulnerability to failure. The continuing precarious condition of local levees has been demonstrated several times since 1980. In particular, severe flooding in the Delta in each season from 1980 through 1983 and again in 1986 caused an estimated $100,000,000 in damage to the levee system. The federal disaster assistance program, administered by the Federal Emergency Management Agency (FEMA), provided reimbursement of approximately $65,000,000 for levee damage.

Because of the large federal contribution during this period and the prevalence of inadequate local levees that would still be at risk during high water, FEMA required that local levees be maintained and improved to a minimum standard as a condition of future disaster assistance. The criteria for the standard are defined in the State's Hazard Mitigation Plan.

The HMP was prepared after the flooding in 1983 and subsequently updated with essentially the same 1983 plan elements after the flooding in 1986. Continued financial assistance to local Delta levee districts and the setting up of an annual inspection program were primary state responsibilities listed in the latest HMP. Local districts' responsibilities included the adoption of the short-term HMP standard (see Figure 2) and the timely upgrading of their levees to that standard. As a prerequisite for receiving disaster aid after the 1986 flood, and in order to be eligible for future federal disaster assistance, the local districts agreed to complete upgrading their levees to the short-term HMP by September 1991. Passage of the Delta Protection Act of 1988 (SB34), committed the State to make funding available to local districts for completion of levee maintenance and rehabilitation objectives outlined in the HMP. The state also set up an annual local levee inspection program so that results of local districts' progress toward completion of the HMP could be reported to FEMA.

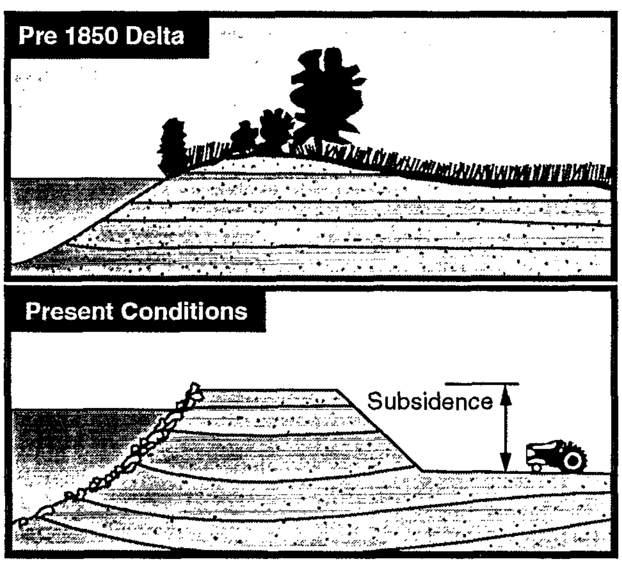

Figure 3: To offset subsidence, some of today's levees stand over 30 feet high.

Based on a November 1991 inspection, FEMA and the State Office of Emergency Services (OES) personnel asserted that although substantial progress had been made by most districts, only four of the forty-seven districts inspected complied with the minimum HMP criteria. Many districts have cited financial difficulties caused by delayed reimbursement of 1980's federal and state disaster assistance claims and lower than expected average levels of annual Subventions Program dollars as contributing factors for not meeting the September 1991 deadline.

Another reason cited for project delays was the policy instituted by the Department of Fish and Game to enforce streambed alteration agreements for work performed on the waterside of nonproject levees. Discussions between Local Districts, DWR, FEMA, and OES have begun to implement a proposed amendment to the FEMA/State HMP Agreement allowing districts more time to complete HMP requirements. In these discussions, FEMA has informed the districts that the September 1991 deadline will not be applied and that instead, with implementation of a proposed amendment to the FEMA/State Agreement, progress will be evaluated district by district.

In an effort to achieve better stewardship of wildlife resources on the Delta levees, DWR has developed an appendix to the proposed amendment to the FEMA/State HMP Agreement. The purpose of the appendix is to provide Delta reclamation districts, whose responsibility includes maintenance of local levees, with flexible guidance for levee vegetation management consistent with the requirements of the State's HMP.

SUBSIDENCE

Subsidence has a significant impact on Delta levees because the hydraulic gradient through the landside toe of the levee increases as the toe elevation decreases. Prior to land reclamation in the late 1800's and early 1900's, the Delta (see Figure 3) was a freshwater tule and reed marsh. The Delta developed throughout a time of rising sea level due to melting ice sheets as the earth warmed from the last ice age. Over

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the years, ground elevations in the Delta rose with the sea level through deposition of decayed plant material. The result was a layer of peat soil over a large part of the Delta. In some areas, this peat was more than 50 feet deep.

When this peat land was drained for farming, it dried out, warmed up, and began to oxidize. The loss of soil through oxidation has led to subsidence of the ground surface at a rate of up to 3 inches per year. In the central Delta, the land surface has subsided as much as 21 feet over time and is now more than 15 feet below sea level. The Sacramento San Joaquin Delta has historical rates of subsidence that are among the highest observed in the world.

Since the water levels in Delta channels have changed relatively little in the last century, the levees that started out 2 or 3 feet above ground elevation must now be maintained, in many cases, over 20 feet high. Today, peat soil, subsidence and levees constructed of sands still remain the primary causes of levee distress.

FLOOD CONTROL BENEFITS

The Sacramento-San Joaquin Delta is irreplaceable, and without adequate levees the Delta as we know it today will be lost. The levees serve many diverse needs. They protect valuable wildlife habitat, farms, homes, urban areas, recreational developments, highways and railroads, natural gas fields, utility lines, major aqueducts, and other public developments. The levees are also critical to protecting Delta water quality and serve a significant function in the State's water transfer system.

FISH AND WILDLIFE

The Delta levees protect important wildlife habitat for numerous species of waterfowl and other wildlife. The diversity of Delta habitat supports:

- 230 species of birds,
- 45 species of mammals,
- 52 species of fish,
- 25 species of reptiles and amphibians,
- 150 species of flowering plants.

If the islands flood, the habitat on the island that supports many animal and plant species would be replaced by open water habitat to fish and other aquatic life. The land subsidence experienced throughout the Delta would create flooded areas that would be deep. These deep areas would not have the high phytoplankton production of older flooded regions, and would thus be of lower value to the fisheries. The net result of flooded islands would be the loss of significant habitat for land based species in exchange for marginal habitat for water based species.

A limiting factor for waterfowl on the Pacific Coast is the availability of wintering habitat in California. That habitat has dwindled from over 5 million acres of wetlands to about 450,000 acres. Winter use of the Delta by waterfowl has increased from about 0.5 million birds 20 years ago to about 1.5 million today. This is a substantial portion of the Pacific Flyway fall flight and is thought to result from two food factors: the salt-tolerant plants of the Suisun Marsh and the waste grain left after harvesting corn on the Delta islands. Subsequent flooding of these areas due to a levee failure would eliminate these food sources and, consequently, have damaging effects on waterfowl, birds, mammals reptiles, amphibians, and plants.

DELTA AGRICULTURE

The predominant land use in the Delta is agriculture. Of 738,000 acres, more than 70 percent is in cultivation. Delta soils are good for many crops, and the channels between tracts provide a ready source of irrigation water. The annual gross income of agricultural activities exceeds $500 million. The Delta levees provide protection for both the cultivated land and the quality of the irrigation water.

In addition to crops grown in the Delta, an even larger area of cropland is irrigated with water diverted from the Delta by the Central Valley Project (CVP) and the State Water Project (SWP). Most of this diverted irrigation water is used in the San Joaquin Valley to grow nearly every type of crop produced in California. The average annual area irrigated with CVP and SWP water in the San Joaquin Valley was about 2.2 million acres in 1980, requiring about 4.5 million acre-feet of water from the Delta. The estimated value of these crops was $1.8 billion in 1980, not including the value of any crops grown outside the San Joaquin Valley.

WATER QUALITY

The Delta is a vital link in the State's water supply. Degradation of the water supply by saline water (see Figure 4) could result from the failure of one or more Delta levees, making water unsuitable for use by about two-thirds of

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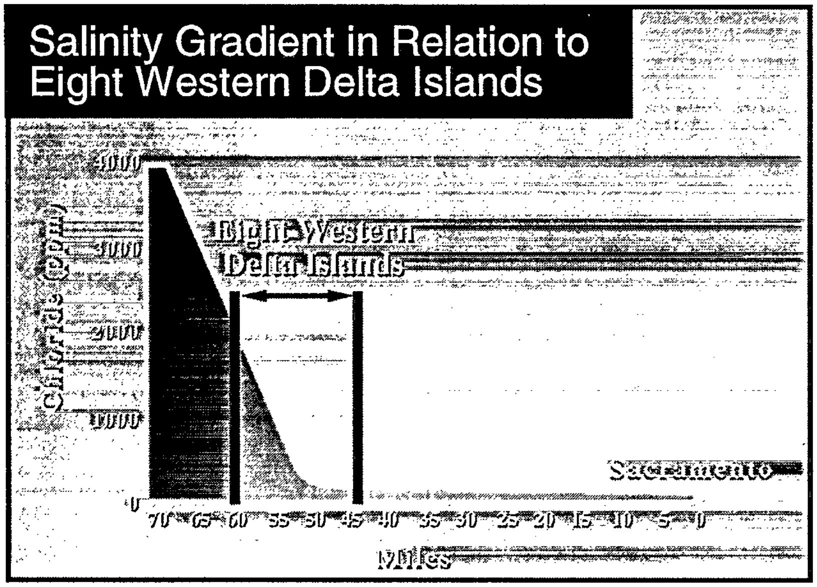

Figure 4: Salinity gradient in relation to the Western Delta Islands (from DWR, 1990)

California's residents. If a levee on one of the western Delta islands fails and the island floods and is not reclaimed, the following long-term problems exist:

- The area of the mixing zone increases;
- the rate of fresh and salt water mixing increases;
- the path for ocean salt water intrusion into the Delta decreases; and
- the amount of evaporation losses increases.

All these factors contribute to increased salinity intrusion and subsequent degradation of the water quality for all beneficial uses of Delta water.

As demonstrated in past flood events, significant short-term water quality impacts can occur even if a flooded island is reclaimed. California's recommended salt level for drinking water is 250 parts per million (ppm) chloride. However, during a previous island flooding under low-flow conditions, chloride levels reached 440 ppm at the Contra Costa Canal Intake, and several tons of additional salts were exported to users of water diverted from the Delta. Protecting the Delta's water quality is essential, not only because the Delta is the source of drinking water for more than 20 million people, but also because the estuary is a unique and valuable resource.

RECREATION

The Delta, because of its proximity to several large population centers, has become one of California's major recreational areas. The meandering and interwoven waterways provide 50,000 acres of protected waters for recreational activities that amount to over 12 million user days annually. Opportunities exist for fishing, boating, picnicking, camping, water sports, and sight-seeing. In the Delta there are:

- 82,000 registered pleasure boats,
- 120 commercial recreation facilities,
- 20 public recreation facilities,
- 20 private recreation associations,
- 8500 berths, 120 docks, and
- 30 launch facilities.

The Delta would lose many of its attractive qualities if levees were to fail, creating inland seas.

FLOOD PROTECTION

Flooding has been a major problem in the Delta since the first levees were constructed in the early 1850's. Approximately 100 levee failures have occurred in the Delta since 1900. About 35 of these failures have occurred since 1930. Before 1950 most of the failures were due to levee overtopping. The construction of upstream dams has now reduced the threat of this failure mechanism. However, failures due to levee instability and seepage are becoming more prevalent.

In the future if levees that fail are not repaired, large areas in the Delta could become open water surfaces like Franks Tract, Big Break, and Lower Sherman Island. In these cases, portions of the levees have mostly washed away, causing the flooded islands to become part of the open water estuary. Much of the destruction of

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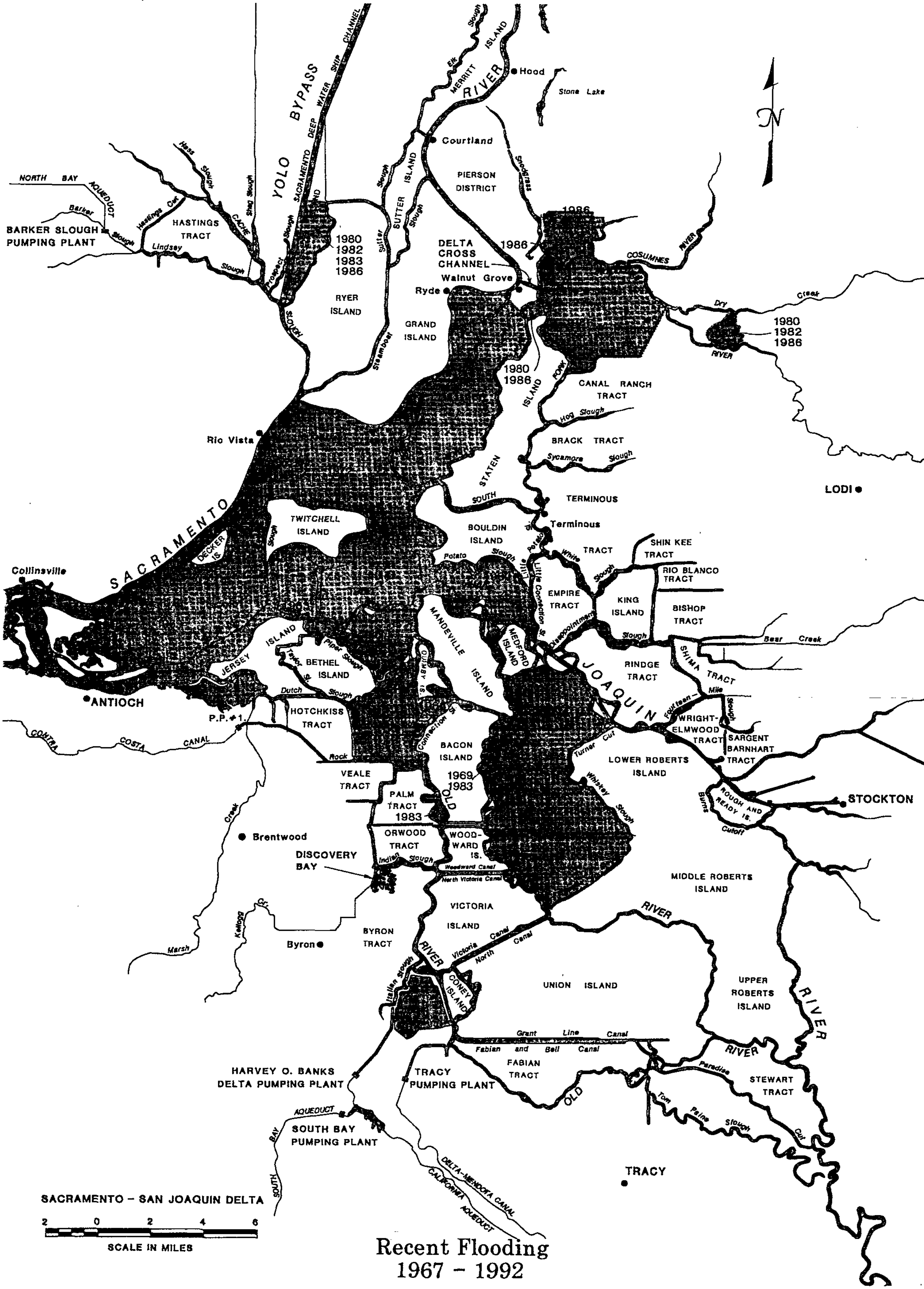

Recent Flooding
1967 - 1992

Figure 5: Recent Flooding
Delta Levees

these former levees was caused by wind-wave action on the unprotected interior levee slopes. Depending on the islands that flooded, there could be increased erosion from wind-driven waves and increased seepage on islands adjacent to these large open water areas. By letting flooded islands become part of the open water surfaces, adjacent islands could be placed at a higher risk of levee failure.

LEVEE FAILURE MECHANISMS

Levee failures continue to be one of the Delta's primary problems. Levee failures in the Delta are due to several factors, including: instability, overtopping, and seepage. When a levee fails, the beneficial uses of the island and waterway are jeopardized as well as the lives of the people inhabiting the island. Major costs are also incurred to reinstate the levee and pump out the island. To understand what measures need to be taken to remedy levee problems, it is first necessary to understand the mechanisms that drive these levee failures.

FAILURE CATEGORIES

Failures can be identified principally by the major category of failure (stability, overtopping or subsurface seepage erosion), then more specifically by contributing factors (subsidence, cracks and fractures, encroachments, erosion, deformation, seepage, sink holes, rodent burrows, and poor foundation conditions). One characteristic that aggravates failures is the contribution of subsidence or decrease in land-surface elevation.

Subsidence

Subsidence is a significant factor in many of the central and western Delta levee failures, since it has caused many of the islands' interiors to lie substantially below sea level. Subsidence is due primarily to the loss of organic soil such as peat, a soil that contains more than 50 percent organic matter. Exposing peat to oxygen causes aerobic decomposition, a process whereby microbial organisms convert organic carbon solids to carbon dioxide and other gases. Activities which raise the soil temperature and reduce soil moisture greatly accelerate this process. This reaction occurs within the first few feet of soil and is referred to as shallow subsidence. Recent studies indicate as much as 50 pounds of carbon per acre are being lost to the atmosphere each day. This carbon loss has a measured effect of lowering the land surface approximately 0.05 mm per day. Deep subsidence, shown by preliminary analysis to have little effect when compared to shallow subsidence, is caused by ground water withdrawal and a decline of natural gas pressure.

Land subsidence research for the Delta is continuing under a cooperative agreement between the United States Geological Survey and DWR. Currently the USGS is conducting a study on Twitchell Island to determine the rate at which the soil is losing carbon (carbon flux) under various land and water management practices. The working hypothesis of this research is that flooding and vegetative cover will cause the rate of oxidation to slow. Results of evaluating historical subsidence indicate the 1) subsidence is slowing over time and, 2) areal variability of subsidence rates are related to varying soil organic matter.

Continuing subsidence poses a major threat to the stability of the west Delta levees. Results of an analysis by the Corps indicates that there is likely to be two to three times the number of levee failures as a result of subsidence during the next 30 years, compared to the last 30 years. Efforts to control subsidence should be a significant part of any Delta flood control plan.

For example, construction of a trench in the western Delta provided a glimpse of future problems if subsidence is not controlled. Removing the peat soil caused numerous sand boils to develop in the bottom of a shallow trench. Boils like these, which can internally erode a levee, could become more common on the western islands if subsidence is not controlled.

Stability

Factors which affect levee stability include size, shape, strength, deformability, and water pressure. For example, on Twitchell Island, high, narrow levees made of weak soils over deformable peat foundations were among some of the most unstable levees in the Delta prior to improvement.

Levee foundation materials in the Delta vary. They include clay, silt, and sand in the east Delta and peat with some alluvial clay, bay mud, sand, and silt deposits in the west Delta. In general, the inorganic materials provide adequate foundation conditions, but uncompressed peat has an extremely low density and is highly deformable. Water pressure against and within the levees and the weight of the levee can cause this foundation material to compress and to displace laterally, resulting in a levee failure.

Differential foundation settlement may be another cause of stability failures, particularly where levees are founded on peat that abuts old, historic river channels that have been filled, or sloughs filled with clay and sand. The clay, silt, and sand-filled channels do not consolidate very much compared to the surrounding peat. Cracks may develop in the levee above the old channel sediment-peat contacts, encouraging subsurface seepage erosion called "piping". Although the actual causes of the levee failures have not been determined, both the 1980 failure of the Santa Fe Railroad embankment that separated Upper and Lower Jones Tracts and the 1982 failure of McDonald Island levee were near such old channels.

Levee failures are often preceded by a localized partial failure involving 200 to 1,000 feet of levee. Partial failure includes settlement of the levee and the formation of cracks and sinkholes in the landward levee slope. Unless repair is immediate, the condition may become worse until the levee fails completely.

Overtopping

Overtopping failure occurs when the crest of a levee is lower than the water level. The combination of high tides, wind, and high discharges into the Delta contribute to overtopping and subsequent levee failure. While construction of upstream reservoirs since the middle 1940's has reduced the frequency of levee overtopping, overtopping remains a threat to the Delta islands, and especially to islands of the North Delta..

On December 3, 1983, a section of levee on Bradford Island failed as a result of overtopping. On that day, many levees were suffering some overtopping and the chances of other levee failures throughout the Delta were imminent. Abnormally high tides coupled with high river discharges and high winds produced a dangerous situation. The threat could have been prevented by maintaining adequate levee freeboard by raising levees that had settled below critical elevations.

Soil logs from exploratory drill holes along the alignment of some levees show that peat in the foundations is now only about 60 percent of its original thickness. Efforts to control consolidation and deformation of these thick peat foundations can also successfully reduce the probability of future overtopping.

Subsurface Seepage Erosion

Water seeping through or beneath levees may result in critical conditions as the soil erodes through the levee, creating large voids (pipes). These voids continue to grow and work their way backwards from the seepage discharge point. If piping is not properly controlled, levee failure may occur because the levee simply washes away from the inside out. The Thornton levee failure represents these types of failures and are characteristic of the sandy eastern Delta levees. Piping may be caused by any one of the following:

- burrowing rodents,
- loosely consolidated or sandy levee material,
- decaying tree roots,
- old pipes buried in the levee,
- settlement cracks,
- high water, or
- a narrow levee.

Vegetation allowed to grow uncontrolled and dense may become particularly hazardous. It can shield the true condition of a levee, preventing levee inspectors from spotting potential problems and correcting them in time. Also, during times of high water, vegetation can impede flood fighters from effectively combating leaks.

FAILURE MODES

To provide adequate protection for the Delta islands, it is necessary to understand the characteristics and causes of levee failures. Engineering investigations for work on threatened levees have been instrumental in gaining this understanding. The failure modes can either be identified as continuous or transient in nature.

Cracks and Fractures

Cracks and fractures in levees are often a common sign of levee distress, especially on deep peat islands found in the western Delta. The cracking phenomenon can be explained by considering the highly deformable nature of the peat soils present beneath and to the landside of levee embankments. The peat typically deforms considerably at loads significantly less than those required to cause a stability failure. This condition is most acute when fill is placed on peat that has not previously been loaded and which may be highly deformable. As the peat deforms and consolidates in response to the weight of the newly applied fill, it becomes less subject to deformation. For example, on Twitchell Island 4 feet of berm fill placed on virgin peat has settled to below the original ground elevation. Large settlements in the berm relative to the levee embankment caused 6-inch-wide cracks with almost a foot of vertical offset. While the cracks pose a stability problem, they pose a greater danger by providing shorter, unobstructed pathways for piping to occur.

Another explanation for cracking is the lateral movements of the underlying peat, particularly beneath the levee's berms. These movements may be related to a lowering of the water table on the land side of the levee, since removing buoyancy has a net result similar to adding levee load. Reports of cracking of the landside slope of levees after times of drought are not uncommon and probably are frequently due to this cause.

Once cracked, the levee fill may tend to act as a series of adjacent blocks of soil on a soft base, and relative movements (e.g., as a heavy block settles and heaves up a lighter adjacent block) could be expected. Additional external loading could also trigger relative movements, which might explain the occurrence of significant cracking following periods of high tides or the placement of additional fill on the levee crown.

Encroachments

Encroachments may reduce the level of protection provided by the levee system and also make levee maintenance and improvements more difficult. The performance of levees, which are critical during periods of high water, can be compromised by structural encroachments. Struc-

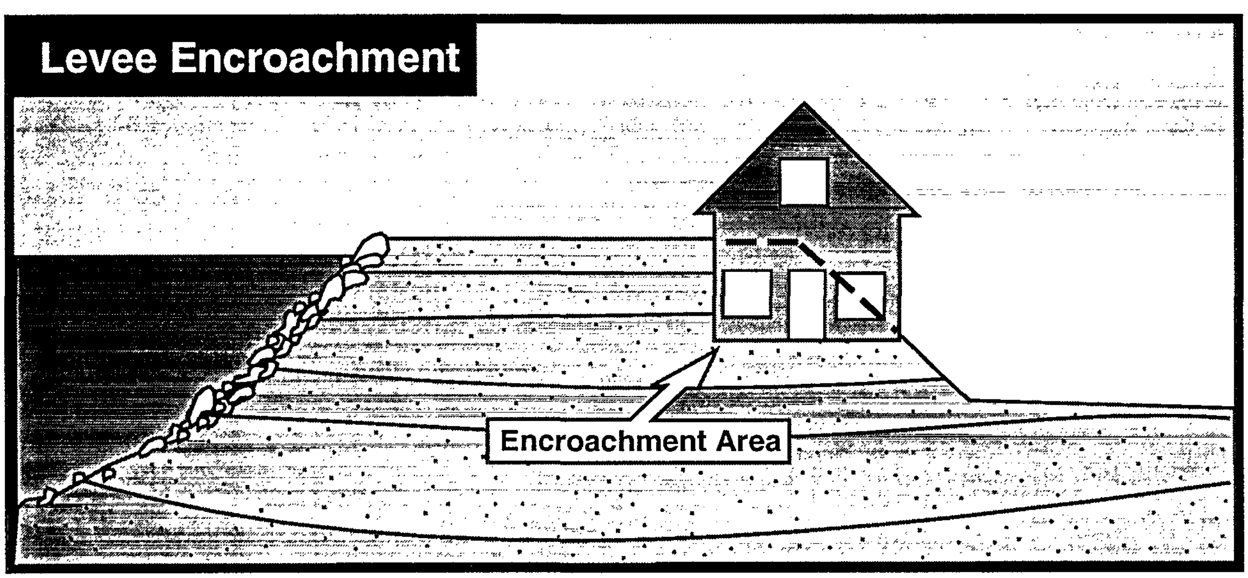

Figure 6: Levee encroachments (from DWR, 1990)

tures (houses, walls, boat docks, etc.) covering the levee slope may hinder inspection of seepage, boils, rodent burrows, sinkholes, sloughs, or cracks.

The problem of encroachments can be seen most clearly on Bethel Island and Hotchkiss Tract, which are the most urbanized areas in the western Delta. Many homes were built on the levee with retaining walls as foundations against the levee slope before the enactment of building setback regulations. Bethel Island Municipal Improvement District adopted an ordinance in June 1989 which established setback regulations. Efforts to identify all the encroachments on these two islands have been completed. Encroachment control plans are currently under development.

Erosion

Levee waterside slopes are subject to varying erosional effects from channel flows, tidal action, wind-generated waves, and boat wakes. The accelerated growth in recreational use in recent years by pleasure boaters, anglers, and water skiers has intensified this erosion.

The USGS found that about 20 percent of the annual energy dissipated against the levees could be attributed to boat-generated waves in a typical narrow channel subject to both winter flood flows and heavy boat traffic. In a channel relatively unaffected by winter flood flows, energy dissipation from boat-generated waves ranges from about 45 to 80 percent of the total, depending upon wind movement and other factors.

Erosion is often reduced by placing rock revetment (riprap) or a berm on the waterside levee slope. By absorbing the energy of wind-generated waves and boat wakes, berms and revetments provide a barrier that dissipates the water-borne energy. Many levees were originally constructed so as to provide a berm. In most cases, however, these buffers between the main channels and the levees were themselves unprotected from erosive forces and therefore have been lost. Consequently revetment is the primary source of erosion protection used today.

Vegetation is desirable in controlling erosion. However, the continual wave action at normal water levels frequently undercuts vegetation at the waterline, and progressive caving erodes the levee slope. In some places, dense stands of vegetation obstruct the view of levee inspectors and make it difficult or impossible to detect problem areas. In addition, high winds can topple large trees on the levee, exposing the levee to increased erosion and leaving large gaps in the levee.

Deformation

Levee foundations consisting of soft organic soils and peats are analogous to toothpaste; as the pressure on the tube increases, the toothpaste squeezes out. Similarly, when fill is placed over the soft foundation soils, the soil deforms and bulges, migrating to the path of least resistance. As these softer blocks of peat squeeze out, cracks, fractures, or sinkholes can develop which encourage seepage and may lead to piping. To prevent the deformations from leading to a levee failure, large berms placed at the landside toe have been effective in controlling deformation, thus effectively "capping" the soft peat.

Levee work performed on Twitchell and Sherman islands involved significant berm placement to control deformation and improve stability. These recent experiences clearly demonstrate the value of understanding deformation and how it can be controlled by thorough engineering design and construction.

Seepage

The constant elevation difference between the higher channel water surface and the lower ground surface of many Delta islands causes a continual seepage of water through and beneath the levees from the channels to the interior of the islands. Seepage tends to increase with time as land subsidence lowers the island ground surface. This seepage can result in levee instability, loss of agricultural production, and higher power costs for drainage pumps.

Levee instability can result from saturation and from removal of levee material by water seeping through the levee. In some instances, saturated soils extend 1,000 feet into the islands.

Visible flows occur in some places at the levee toe and in the toe drain ditches.

Sinkholes

Sinkholes are depressions in the landside of the levee that are typically wet or filled with water. These holes can range in depth from a few inches to many feet and are between 2 and 10 feet in diameter. Instances of the spontaneous development of sinkholes on levee back slopes are periodically reported on the deep peat islands. They are very disturbing, since they connote the existence of a void system and transport mechanism within the levee which can undermine levee integrity, giving no warning until surface collapse occurs. Further, the uncertainty regarding the process of sinkhole formation makes predicting sinkholes difficult.

An investigation was conducted on Sherman Island in 1991 to assess the causes of sinkholes. The study did not answer all questions regarding sinkholes and the results may not be applicable to other sinkhole situations. Nevertheless it did provide major insight into the sinkhole phenomenon at that particular location, and it provided useful background knowledge for assessing other sinkhole occurrences.

Potentially key characteristics identified at the Sherman Island sinkhole locations were:

- The presence of fissures in the peat below the levee fill.
- The existence of a relatively free flow of water through the levee from the river and into the sinkhole.
- The non-cohesive, easily erodible/transportable nature of the sandy levee fill.

The presence of fissures beneath the sinkholes is the most fundamental piece of new data. It means that a sinkhole can form by a relatively simple process of downward migration of material into and along the fissure. The fact that the levee is formed of easily eroded material is a further aid to sinkhole formation.

Corrective measures at Sherman Island to mend the sinkholes involved trying to fill the fissures by grouting, surface filling and compaction, and adding fill to the landside slope of the levee. Sinkholes on Twitchell Island have been successfully controlled by surface filling.

Rodent Burrows

The Delta provides abundant habitat, including marshlands, berms, and levees, for rodents. Properly managed vegetation can reduce rodent problems. Rodent burrows, particularly those of beaver, muskrat, and ground squirrels, can threaten the integrity of a levee. Burrows in levees can weaken the levee section and contribute to levee failure by increasing the potential for piping. Vegetation on levee slopes makes it difficult to detect rodent burrows. In some areas where excessive vegetation occurs (such as dense stands of bamboo or blackberry vines), it is impossible to detect burrows.

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LEVEE DESIGN

Levee design practices can be generally grouped into three periods. The first period is the longest, going from the mid 1800s to some time in the early 1900s when levees were not designed, but simply constructed with respect to water level heights. With the next period, which runs from the 1940s to the 1980s, came the evolution of the standard levee section, which used seepage and stability as levee design criteria, and defined standard levee slopes and widths. The third period began in the early 1980's and extends to the present, where levees are beginning to be designed for site specific conditions using the specialized knowledge and tools of soil mechanics and geotechnical engineering in order to reduce costs.

Levee conditions in the Delta are quite different from those in many other locations, (see Figure 6) where land elevations are above normal water levels. Water forces then act on the levees only during periods of high water or flooding. In the Delta (see Figure 7), land elevations are generally much lower than normal water levels. Because of this difference, the levees function more as earthen dams which act as continuous water barriers. This difference between many Delta levees and levees in other areas has important implications regarding levee design and reconstruction. For example, most of the Delta levees have to remain fully functional during any improvements or rehabilitation.

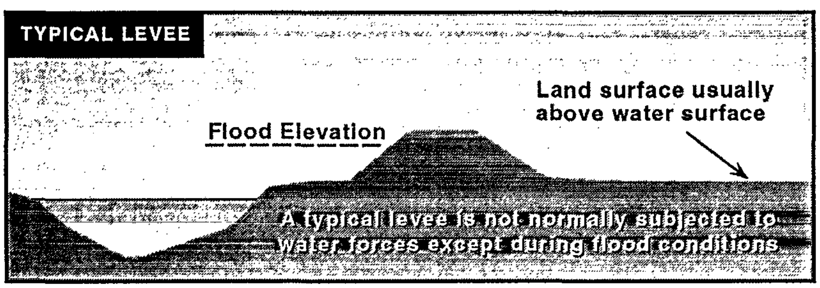

Figure 7: Typical levee

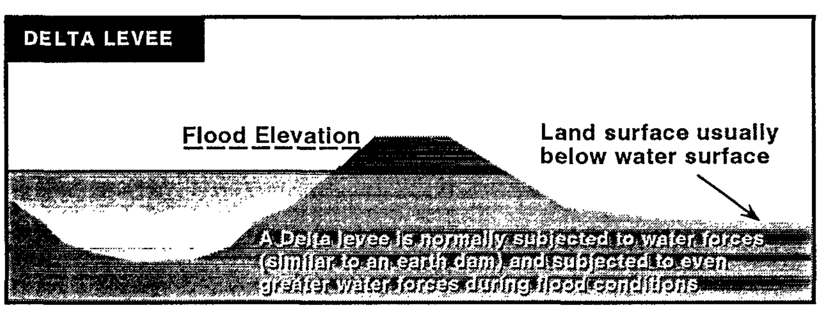

Figure 8: Delta levee

MAIN DESIGN AREAS

Levee failure mechanisms were previously discussed. All of these mechanisms can be placed in five main levee design areas: height, slope and foundation stability, deformation, seepage control, and erosion control.

<u>Levee Height</u> - The levee height must be greater than design flood elevations to protect the levee from overtopping and should provide some additional height to increase the margin of safety.

<u>Slope and Foundation Stability</u> - The levee slopes and foundations must be strong enough to prevent gross failure under design flood and seepage conditions. Design alternatives for improving levee stability are flattening the levee slopes and constructing levee toe berms. Flatter slopes improve stability by acting as a counterweight against destabilizing forces and by consolidating and strengthening soft foundation soils.

Seepage Control - Seepage through or beneath levees must be adequately controlled to prevent levee failure by seepage erosion. If seepage gradients and forces are too large, soil can be transported by the seeping water, creating voids in the levee or foundation materials. This process, called "piping", can lead to sudden and catastrophic levee or foundation failure.

Deformation - Movements, displacements, and settlements during the levee service life must be within a tolerable range. Many Delta levees experience relatively large deformations because of the widespread soft peat and clay foundation conditions.

The deformation of levees founded on soft soils can be controlled by constructing the levee improvements in stages. This provides time for the foundation soils to adjust to the new levels of stress with corresponding increases in strength. The reason that construction in stages controls deformations is that soft peats and clays usually display their lowest strengths immediately after loads are applied; then, with increasing time, the strengths gradually increase.

Erosion Control - Levee slope protection is a key element in rehabilitating and maintaining the integrity of the Delta levees. Potential methods of erosion control include riprap, articulating blocks, grouted rocks, interlocking concrete blocks, vegetation management, geosynthetics, and gabions. These slope protection methods vary widely in character and cost and are discussed in more detail at the end of this section.

DESIGN PROCEDURES AND METHODS

Available geotechnical design procedures and methods include:

- Field investigation and exploration by borings, cone penetration test soundings, and test pits.
- Laboratory soil testing to determine soil strength, permeability, compressibility, and compaction characteristics.
- Engineering analyses of slope stability, seepage, deformations, and settlement.
- Field instrumentation to measure levee and foundation deformations and piezometric (water) elevations and pressures.

EVOLVING DESIGN PRACTICE

Levee design practice continues to evolve based on experience accumulated from previous projects and the application of state-of-the-art soil mechanics and geotechnical engineering. A design practice that has worked successfully on several recent levee projects is to:

- Collect, review, and evaluate historical data, information, and aerial photography.
- Conduct geotechnical exploration and laboratory testing.
- Perform engineering analyses and develop feasible design alternatives.
- Consider alternatives which maximize habitat avoidance and perform necessary biological assessment to mitigate unavoidable impacts.
- Select a preferred alternative and do final design of levee improvements.
- Install field instrumentation to monitor levee and foundation behavior during construction.
- Construct levee improvements.
- Monitor and maintain the reconstructed levee.
- Evaluate effectiveness, costs, and results of the design and construction methods.

RECENT PROJECTS

A similar design practice to that described above was applied to recent projects for Sherman Island, Twitchell Island, and the Thornton levees.

Sherman Island - A section of the Sherman Island levee had experienced extensive cracking. The levee section was improved by constructing an underdrain to collect seepage and by constructing a levee toe berm on the land side.

Twitchell Island - A 4-mile section of the Twitchell Island levees was in poor condition and in need of upgrading. A program was designed to include installing a landside underdrain, placing toe berms in stages (see Figure 8), increasing the levee crown width, and flattening the levee backslope. Much of the project has been constructed at a lower cost than had been previously estimated for such an extensive upgrading.

Thornton Levees - The Thornton levees had experienced dangerous seepage conditions during previous high water periods. In many sections, the levees are constructed of moderately permeable sands. A design utilizing internal drains (see figure 9) constructed in the levee landside slope was developed to control and collect seepage during high water. The project is scheduled for construction in the near future.

EROSION CONTROL

The waterside levee slopes are subject to continuing attack by wind, waves, soil movement, and burrowing animals. Slope protection designs attempt to dissipate wave energy without allowing erosion of the slope protection or the soil beneath it.

A number of special problems are involved in providing slope protection for Delta levees:

- Foremost is the fact that many Delta levees constantly have water against them. Therefore they are always under attack and are difficult to maintain.
- Delta levees can provide valuable habitat, recreational opportunities, and aesthetic value.
- Tidal action can cause the water levels in some channels to vary as much as 4 feet daily.
- Existing levee slopes are often steep and irregular, which makes placement of slope protection materials difficult.
- Because many levees are continually settling and require periodic additions of material to maintain freeboard, the slope protection method employed must easily accommodate raising the levee crown.
- Many Delta rivers and sloughs have water velocities strong enough to scour their channels and undermine the levee slope protection.
- Some Delta sloughs and rivers have levees overgrown with trees and other large vegetation. These plants sometimes aid in resisting wave-induced erosion, but they also conceal any weakness and instability that may have developed in a levee. Furthermore, high winds can topple these trees, whose

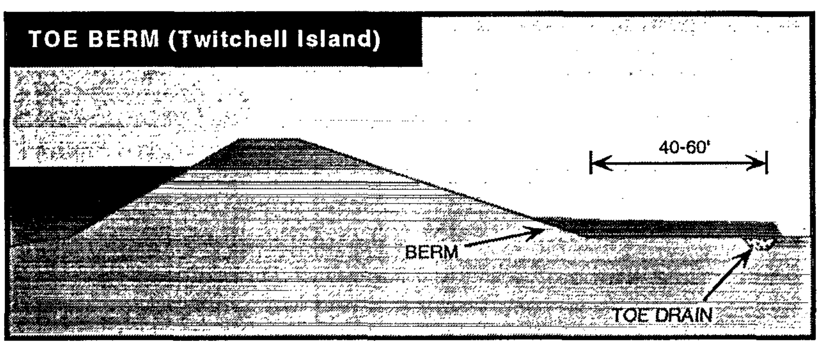

Figure 9: Toe berm and drain for Twitchell Island levee improvement project

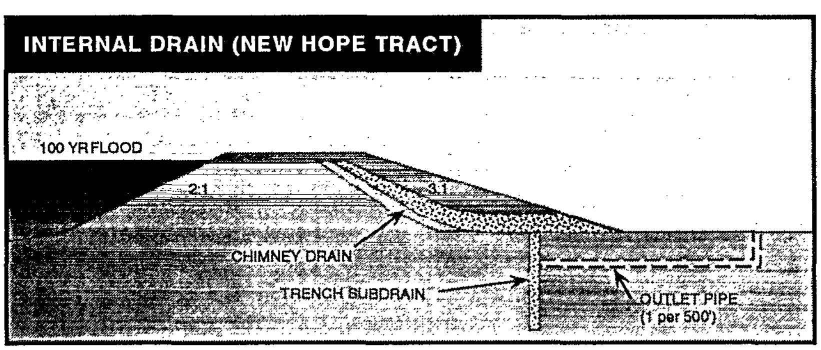

Figure 10: Internal drain design for New Hope levee improvement project

root systems pull away and expose large gaps in the levee.

EROSION CONTROL ALTERNATIVES

Riprap, which is loose, broken rock, has been widely used in the Delta to protect levee slopes from erosion. Quarry rock is the principal type of riprap used, although other materials such as broken concrete has been substituted on occasion. Riprap has been a fairly cost effective means of slope protection. Rock is readily available near the periphery of the Delta and the cost is relatively low. Labor cost in placing the riprap is also relatively low. However, wave action can cause pumping of water through the gaps between rocks and eroding the underlying levee material. The use of a geotextile underneath the riprap layer may greatly improve its long term effectiveness.

Armorflex, a proprietary system, is a type of slope protection in which cellular concrete blocks, either open or closed, are cabled together without fabric encapsulation. The main disadvantage of the Armorflex system is the high labor cost involved in assembling the blocks. Each block must be individually strung onto the cable by hand. The slope on which Armorflex is to be placed must be prepared to a smooth surface, and a geotextile must be placed beneath the blocks. The top of the Armorflex mat must be anchored and the toe of the levee must be protected from scour, either by extending the lengths of Armorflex or placing extra rock.

Vegetation on levee slopes is important for environmental and aesthetic reasons. Vegetation also helps protect levees from erosion caused by precipitation and wavewash. The roots of plants help to hold the soil in place, and the leaves and stems help dissipate wave energy. Vegetation alone, however, has not proven to be an effective slope protection in many reaches in the Delta. Because vegetation does not usually extend below the mean water level, the levees are exposed to wave energy during low tides. In places of average to steep slopes, large waves commonly erode the soil and dislodge vegetation. Further, vegetation shelters burrowing animals and conceals animal dens and tunnels which may have detrimental effects on levee stability.

Controlled or managed vegetation on slopes and waterside berms used in conjunction with riprap or interconnected concrete blocks provides a combination of benefits. Many of the cabled or interlocking systems could be constructed to allow openings for trees or large brush, provided they are not located on steep slopes or near the levee crown. Alternatively, a small waterside berm could be built to support the growth of trees and other vegetation. The slopes above and below the berm could be protected economically and effectively with riprap, leaving the top of the berm to provide the aesthetics and wildlife habitat. A 1992 demonstration project on Staten Island has shown that waterside berms can be quickly and economically constructed and vegetated.

In reality, no single slope protection alternative accomplishes all the aims listed above (see Table 1). Except for riprap and natural vegetation, none of these alternatives has ever been adequately tested in the Delta. Therefore DWR and DFG have implemented levee demonstration projects which maximize fish and wildlife habitat values without using riprap. Alternative demonstration projects were performed in the fall of 1992 using Tri-lock interlocking blocks, Armorflex cabled blocks, and riprap. The results of these projects will help determine the most beneficial alternative. To date, however, nothing has been found to be more cost effective than riprap.

Slope Protection Alternative	System Cost per Sq. Ft. 1,4	Description	Flexibility for Levee Settlement	Ease of Extension in Levee Raising	Relieves Hydrostatic Pressure 5	Deters Burrowing Animals	Possibility of Revegitation	Performance History in the Delta	Ease of Installation	Durability
Riprap	1.75	Broadly graded rocks	Excellent	Excellent	Yes	Fair	Poor	Excellent	Excellent	Excellent
Grouted-rock Soil-cement		Cemented masses or layers	Poor	Poor	No	Excellent	Poor	Unknown	Poor	Excellent
Articulating Block	5.25-5.75	Nylon fabric connecting & forming concrete blocks	Fair	Poor	Yes	Fair	Poor	Unknown	Fair	Good
Armorflex 3	5.00-5.50	Preformed concrete blocks joined by cables	Excellent	Fair	Yes	Fair	Good	Unknown	Good	Excellent
Tri-Lock, Armorloc 3, & Monoslab	5.00 4.25-4.50 4.00	Interlocking preformed concrete blocks	Good	Poor	Yes	Fair	Good	Unknown	Fair	Excellent
Vegitation (Co-Composting) 2	1.50	Plants growing on slope	Excellent	Excellent	Yes	None	Excellent	Poor	Excellent	Poor
Geosynthetic	0.30	Porous synthetic covering	Excellent	Excellent	Yes	Fair	Good	Poor	Fair	Poor
Reno Matress	2.25-3.00	Rectangular wire	Fair	Fair	Yes	Fair	Poor	Unknown	Good	Excellent

1 Cost of material and installation only. Cost of slop preparation will vary with slope protection method and condition of slope.
2 Co-composting may be used to help establish vegetation on the slopes. However, the existing and surrounding peat soil is as good a growth medium.
3 Requires geosynthetic or graded filter beneath rocks.
4 Cost may vary with quantity. Area to be covered for pricing ranged from 50 feet x 20 feet to 5 miles x 20 feet
5 Slope protection must be permeable enough to allow water collected behind the protection to equalize with the water in the channel.

Table 1: Slope protection alternatives (From DWR, Feb 1990)

LEVEE MATERIAL

On the basis of typical levee sections, the Corps determined that about 55 million cubic yards of material would be required for construction to rehabilitate substandard Delta levees. It was also determined that because of a general scarcity of soils suitable for levee construction within the Delta, a significant portion of the construction material would have to be imported at a higher cost.

An economical, easily accessible nearby source of fill material for Delta levees is sediment deposited in adjoining Delta waterways and ship channels. These adjoining channels have historically been the source of most of the Delta levee material. However, removing material near the waterside toe of levees causes stability and seepage concerns. Borrowing channel material is also becoming more difficult due to Endangered Species Act restrictions. Dredging of the Sacramento and San Joaquin River ship channels should continue to provide significant quantities of sandy material, and through increased coordination of dredging and levee repairs, this material could become an even more valuable resource.

Land acquired for the purpose of creating wildlife habitat typically requires moving large amounts of earth to create the desired habitat conditions. Material excavated from these areas can be an economical source of levee fill material. For example, habitat plans under development for 500 acres of DWR land in the north Delta may provide several hundred thousand cubic yards of material to rehabilitate New Hope Tract levees.

Another source of levee material is the natural sand deposits that exist on some islands. Recent levee improvement projects on Webb, Holland, and Bouldin Islands effectively utilized sand mounds on the islands as economical sources of fill. Roughly 2 million cubic yards was placed at an average cost of $5.00/cy whereas on Twitchell Island, 500,000 cy's was imported at costs exceeding $10/cy.

LONG-TERM MANAGEMENT STRATEGY

A program for use of materials dredged from ship channels and harbors for levee rehabilitation could greatly reduce these costs. The Long-Term Management Strategy (LTMS) is a multi-participant program established and run by the U. S. Environmental Protection Agency, the Corps, the San Francisco Regional Water Quality Control Board, and the San Francisco Bay Conservation and Development Commission to provide information and prepare plans to designate and manage dredging and disposal from the San Francisco Bay over the next 50 years. Potential disposal options to meet the region's dredging requirements include ocean site(s), in-Bay sites, and reuse/nonaquatic alternatives, including marshland creation projects. Dredging in the San Francisco Bay area creates an annual disposal requirement of approximately 8 million cubic yards (mcy) of dredged material. Moreover, there are proposals to deepen existing projects that total approximately 19 mcy.

Given the continuing need for levee fill material due to the depletion of local borrow sources, sediment dredged from Bay channels is a potentially valuable resource for levee repair. A potential barrier to utilization is the impact on water quality since the dredged sediment originates from a saline environment. Therefore, future reuse plans must recognize that imported fill material must be carefully managed to prevent degradation of Delta water quality.

The Department, in coordination with the Corps and the Regional Water Quality Control Board, has been conducting demonstration projects to determine the viability of relocating Bay material to the Delta. In 1990, a demonstration project on Sherman Island utilized 1,600 cy of dredge sediments from Suisun Slough to construct a landside berm. An extensive monitoring program over a 2-year period showed no soil contamination or any adverse impact on water quality resulting from the placement of these marine sediments. Following the successful Sherman Island Project, 50,000 cy of sandy material dredged from Suisun Bay Channel and stored on Simmons Island was transported to Twitchell Island and incorporated into the levee on Twitchell Island. Water quality monitoring to date has not identified any significant impacts due to increased salinity.

These projects have demonstrated an environmentally sound solution for dredge disposal as well as for levee maintenance and improvement. Building on the success of these reuse projects, future plans include another beneficial reuse project for levee improvements on Jersey Island.

LEVEE FUNDING

Besides the local land owners, Federal Disaster Relief Funds, administered by the Federal Emergency Management Agency, have historically been a significant source of revenue to repair the levees. Severe flooding, causing an estimated $100 million in damage, occurred in the Sacramento-San Joaquin Delta between 1980 and 1986. Eighteen islands were inundated during this period, prompting five Presidential disaster declarations and one State emergency declaration. During this period, FEMA authorized reimbursement of approximately $65 million for emergency repair work.

As an alternate means to assist the local agencies, Senate Bill 541 (Way), was enacted in 1973. This bill provided State reimbursement of a portion of the maintenance costs for nonproject levees. Today, nonproject levees are funded through the Delta Flood Protection Act of 1988 (Senate Bill 34). The bill created the Delta Flood Protection Fund and declared legislative intent to appropriate $12,000,000 each year to the fund through fiscal year 1998-99. This appropriation is divided as follows: $6,000,000 for the Delta Levee Subventions Program, which provides local assistance to agencies in the Delta for the maintenance and improvement of Delta levees, and $6,000,000 for Special Projects, which implements levee improvement measures on the eight western Delta islands and the communities of Walnut Grove and Thornton. Due to State funding priorities, appropriations made to the Delta Flood Protection Fund in the past 2 years have been substantially less than anticipated. Funding this fiscal year has been restored to the intended appropriation of the Act.

On August 19, 1991, the Corps, DWR and The Reclamation Board signed an agreement to begin a special study on 57 islands in the Delta, which are protected by non-project levees. Potentially, this six year study could lead to federal involvement in projects that will improve flood protection, environmental restoration, and correct navigation related problems in the Delta.

With regard to future costs, the Corps in 1982 estimated that almost $1 billion would be needed to rehabilitate levees on 53 Delta islands. Costs for some of the worst levees in the western Delta ranged from $2-4 million/mile. However, improvements made in 1992 and 1993 on extremely fragile levees in the western Delta have been completed using an innovative design for less than $1.5 million per mile. Even after accounting for recreation and maintenance, these costs are less than the estimates made over 10 years ago to repair the same levees. Use of new designs, extensive monitoring, and economical borrow sources are all factors which need to be considered in developing realistic future costs.

Clearly, however, rehabilitation costs exceed the ability of most Delta landowners to rehabilitate their levees. Funding through SB 34 has provided for significant levee improvements, but is insufficient to properly rehabilitate all Delta levees. Therefore, a comprehensive cost sharing arrangement needs to be established which will address all the beneficiaries. Cost sharing arrangements similar to those being forged with the LTMS program will help to meet this objective.

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