Subsided Island Restoration Design in the Sacramento-San Joaquin Delta: A Solution for Levee Fragility and Water Supply Vulnerability in the Delta

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Executive Summary

The Sacramento-San Joaquin River Delta provides drinking water for two-thirds of California, irrigation water for an $18 billion agricultural industry, and habitat for many endangered and threatened species.

The Delta once encompassed over 350,000 acres of tidal marsh but beginning in the 19th century, humans constructed 1,100 miles of levees converting the tidal wetlands to agricultural land. This diking and draining of the Delta historic wetlands has resulted in oxidation and subsequent subsidence of the organic soils, creating large, basin-like islands as deep as 20 feet below sea level. These islands continue to subside at an annual average rate of 0.3-0.7 inches.

Levees in the Delta sit atop fragile, saturated foundations that will liquefy during moderate seismic events, leading to levee failure and island inundation. CALFED estimates that a magnitude 6.0 earthquake, with a peak acceleration of 0.20 g will cause 8-26 levee failures. This event has a one in four chance of occurring in the next 50 years.

If a levee breaks and an island floods, especially during a dry season or drought when the Sacramento and San Joaquin rivers provide little inflow, salt water from Suisun Bay will rush into the Delta to fill the draft. The extent and distribution of salinity intrusion is a function of the size, location, and duration of the breach, and the quantity of inflows into the Delta.

If un-repaired, a levee breach and accompanying flooded island will cause chronic water quality degradation as the tidal fluctuation transport salt water into the Delta. DWR has modeled the long-term salinity impacts of un-repaired levee breaches in the Delta. A levee breach on Sherman Island, left un-repaired, can double salinity levels at key water intake locations. Elevated salinity levels will shut down water exports for the 22 million Californians and the $18 billion agricultural industry dependent on the Delta. Exports can recommence when salinity levels have returned to acceptable levels. This is contingent on repairing the levee, flushing the Delta with freshwater releases from reservoirs, and pumping out unwanted salt water in the south Delta. This can conceivably take more than a year.

This study evaluates several options to reduce the water supply impacts of levee failure in the Delta. We evaluated these options based on their technical, economic, and political feasibility, and on their contribution to CALFED's major goals of improving ecological health, water quality, water supply reliability, and levee system integrity.

Strategically rebuilding subsided islands emerges as the strategy that best meets all feasibility constraints and contributes the most to CALFED's goals. Methods of rebuilding subsided islands include: reusing dredge spoils for cross levees and cut-off levees built across bands of mineral soil; creating non-tidal tule ponds to arrest further subsidence and accumulate organic matter to slowly rebuild island surface levels; importing rice straw fill material to expedite the rebuilding process, and breaching levees to restore tidal influence to island surfaces that are close to sea level.

Sherman Island is the best site to begin subsided island restoration activities. It is the largest and most deeply subsided island in the western Delta with 142 million cubic yards of subsided volume. It's western location and poor levee foundations make it highly susceptible to levee failure in the event of an earthquake. A levee failure on Sherman Island can lead to a 41% increase in salinity levels through out the Delta with localized increases much higher. Eighty-four percent of the island is owned by CALFED constituent agencies and it is adjacent to existing tidal marsh.

We detail a thirty-year partial restoration plan. The plan assumes full restoration in fifty years but does not project that far into the future because much of the restoration activities will be based on knowledge acquired in the first thirty years of experimentation.

The five-year plan proposes three new levees constructed on mineral soils. These levees create compartments that reduce the potential amount of flooding due to a single breach and reduce the length of un-engineered levee protecting the interior of the island by 40%. It also allows for 200 acres of tidal marsh restoration where the island surface is close enough to sea level. It provides another large compartment to begin experimenting with rice fill techniques. Finally, the five-year plan establishes over 1,000 acres of non-tidal tule marsh on the deepest portions of the island to immediately arrest subsidence and begin rebuilding the surface elevation.

The ten-year plan proposes two new levees constructed on mineral soils to further compartmentalize the island and restore tidal influence to another 220 acres of land. It also plans for the creation of 1,200 acres of tidal wetlands on the rice fill demonstration site begun in the first planning period. Finally, the non-tidal tule ponds expand to over 1,800 acres.

The thirty-year plan includes two new levees constructed on mineral soils to further compartmentalize the island and restore tidal influence to another 2,000 acres of land. The non-tidal tule ponds expand to over 4,100 acres.

The first thirty years of the plan create 3,600 acres of tidal wetlands, 4,100 acres of non-tidal tule ponds, and reduce the largest flood volume to 18 thousand acre-feet. The estimated cost for 64,000 feet of new levees, all the fill materials for subsided areas, and 4,100 acres of non-tidal tule ponds is $274 million.

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List of Acronyms

BCDC	Bay Conservation and Development Commission
CALFED	CALFED Bay Delta Program
CRWQCB	California Regional Water Quality Control Board
CWC	California Water Clearinghouse
DEM	U.S. Geologic Survey Digital Elevation Model
DOCs	Dissolved Organic Carbons
DWR	California Department of Water Resources
EIR	Environmental Impact Report
GIS	Geographic Information System
LTMS	Long Term Management Strategy
MHHW	Mean Higher High Water
MLLW	Mean Lower Low Water
NHI	Natural Heritage Institute
NRCS	Natural Resource Conservation Service
PL84-99	Public Law 84-99 establishing standards for levee rehabilitation in California
PWA	Phil Williams & Associates, Inc.
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geologic Survey

1 Introduction

This study evaluates alternatives to reduce the risk of levee failure and salinity intrusion in the event of an earthquake in the Sacramento-San Joaquin River Delta and applies the results to a site-specific subsided island restoration plan. Feasible alternatives satisfy material availability constraints, reasonable cost constraints, and contribute to CALFED's primary goals of increasing ecosystem quality, water quality, water supply reliability, and levee system integrity.

1.1 Problem Statement

The Sacramento-San Joaquin River Delta provides drinking water for two-thirds of California, irrigation water for an $18 billion agricultural industry, and habitat for many endangered and threatened species. The Delta is the physical and political heart of water resources in California.

However, less than 5% of the historical tidal and freshwater wetlands still exist in the Delta (PWA, 2000). Eleven hundred miles of levees built in the past 150 years have prevented seasonal, shallow inundation of Delta islands necessary to maintain wetlands. Consequently, the organic-rich soils of the Delta have oxidized and subsided, creating large, basin-like islands (Figure 1.1). In some places, islands have subsided more than 20 feet below sea level (Figure 1.2). Islands continue to subside at an annual average rate of 0.3-0.7 inches (Deverel, 1998). The volume of subsidence on eight western Delta islands is approximately 600 million cubic yards.

Levees in the Delta are built upon fragile, saturated foundations that will liquefy during moderate seismic events, leading to levee failure and island inundation. If a levee breaks and an island floods, especially during a dry season or drought when the Sacramento and San Joaquin rivers provide little inflow, salt water from Suisun Bay will rush into the Delta to fill the draft. The extent and distribution of salinity intrusion is a function of the size, location, timing, and duration of the breach, and the quantity of inflows into the Delta (DWR, 1990). When a 500-foot section of the Andrus Island levee collapsed in the summer of 1972, 164,000 acre feet of water flooded the island, drawing salt water into the Delta from the bay and shutting down water exports from the Delta for two months (DWR, 1982).

In addition to the acute salinity intrusion, levee breaches and flooded islands also create chronic salinity problems. A permanent levee breach on a Delta island will elevate salinity levels indefinitely (DWR, 1999).

Reducing increased salinity levels hinges on repairing the levee breaks, flushing the Delta with upstream reservoir releases, and pumping out salt water in the south Delta (DWR, 1982). Failure to repair the levees in a timely manner not only perpetuates elevated salinity levels in the Delta but also increases the damage to remaining portions of the levee systems. While the islands are inundated, the interior face of the levee is subject to wave erosion. The combination of several large levee breaches and waves rapidly eroding the levees from the interior increases the amount of time and material necessary to repair the levees, and subsequently, the amount of time to reduce salinity levels to acceptable levels. If emergency response teams are unable to patch all the levee breaches and pump water off the islands, it is conceivable that salinity levels will remain elevated and shut off an entire year or more of water exports. Similarly, it is conceivable that given enough time a flooded island will destroy its own levee system beyond repair (R. Seed, University of California, personal communication, 2001).

1.2 Objective

Given the conceptual model of levee failure and water quality impacts described above and in Figure 1.3, the Natural Heritage Institute has investigated alternatives to reduce the risk of salinity intrusion into the Delta. As CALFED's mission is to "develop a long-term, comprehensive plan that will restore the ecological health and improve water management for beneficial uses of the Bay-Delta system," we evaluated alternatives not only for their feasibility but also for their contribution to environmental quality and habitat (CALFED, 2000a). Based on this analysis, we outlined design considerations for acceptable mediation techniques and applied them to a strategic Delta island.

This report is a planning and design document intended not to scientifically prove theories, but rather to reason through possible events, anticipate likely outcomes, and explore preferred solutions. The results then inform the restoration design for subsided islands in the Delta.

1.3 Previous Work

The following three studies form the foundation of the conceptual model and many of the assumptions made in this report. Through its Seismic Vulnerability Sub-Team (the Sub-Team), CALFED has begun to examine the issue of seismic vulnerability of levees in the Delta. Separately, the Department of Water Resources (DWR) has modeled chronic water quality impacts in the Delta resulting from levee breaches. The Natural Heritage Institute has identified restoration opportunities in the Delta. No study has yet combined the issues of seismic vulnerability, salinity intrusion, and subsided island restoration into a single vision for improving ecological health, water quality, water supply reliability, and levee system integrity.

1.3.1 Seismic Vulnerability

CALFED's Seismic Vulnerability Sub-Team of the Levees and Channels Technical Team evaluated levee fragility and seismic vulnerability of the existing levee system (CALFED, 2000b). The study divided the Delta into four damage potential zones (Figure 1.4) based on proximity to known faults and the condition of levee foundations. Zone I is most susceptible to failure, Zone IV is the least susceptible. Sherman Island is the most susceptible to earthquake induced levee failure due to its liquefiable, cohesionless soils and proximity to known, active faults. The central Delta ranks second in susceptibility due to typically tall levees built on soft soils.

Based on earthquake modeling and levee conditions, the Sub-Team found that an earthquake with a magnitude of 6.0 and a peak acceleration of 0.20 g will cause 8 to 26 levee failures in the Delta. The Sub-Team predicted that such an earthquake has a 25% chance of occurring within the next fifty years (Figure 1.5).

The Sub-Team concluded that improving the entire levee system or even targeted sections of levees to reduce seismic vulnerability would be "extremely complex and expensive." Additionally, current levee upgrades underway in the Delta focused on defense against static pressures such flood flows in a river. The current upgrades would do almost nothing to prevent soil liquefaction.

The Sub-Team recommended increasing emergency response capacity in the Delta but did not quantify either the current response capacity or the recommended increase. The Sub-Team reported “the ability to respond to more than a few levee emergencies following a seismic event is limited. Response capability is limited by lack of suitable or available barges and equipment [and] limited availability of construction materials” (CALFED, 2000b). Dr. Ray Seed, a member of the Sub-Team estimated that emergency response teams could probably repair no more than ten levee breaches in a single season (R. Seed, University of California, personal communication, 2001).

1.3.2 Salinity Impacts

The Department of Water Resources modeled salinity impacts of levee breaches in the Delta with the DWR Delta Simulation Model 1 (DWRSIM1). In particular, DWR modeled the long-term impacts of un-repaired levees. DWRSIM1 accounted for Delta bathymetry, tidal fluctuations, facility configurations, water exports, breach size, and location. The model predicted altered salinity levels and compared them to historical salinity levels over four years at eight locations in the Delta (DWR, 1999).

DWR concluded that un-repaired levee breaches on Sherman Island would nearly double salinity near the Contra Costa Water District intakes (Figure 1.6). The model predicted similar patterns through out the Delta. DWRSIM1 also quantified the percent increase in salinity resulting from levee failures on five different islands (Table 1.1) (Enright, n.d.).

Table 1.1. Modeled Salinity Increase at Clifton Court Due to Levee Breaches

Island	**% Salinity Increase**
Holland Tract	12
Jersey Island	40
Sherman Island	41
Twitchell Island	19
Webb Tract	24

1.3.3 Restoration Opportunities

The Natural Heritage Institute developed a map of ecosystem lands and opportunities in the Delta (Figure 1.7). The map highlights low conflict restoration opportunities based on input from Delta landowners, water districts, and the Delta Protection Commission. The study identified several islands in the Delta where restoration could proceed. These are either public lands not managed for ecosystem values, or private lands with landowners willing to engage in restoration (NHI, 1998).

2 Methods

This study comprises four successive analyses that evaluate alternatives for seismic risk reduction and water impact reductions. The results of these analyses inform the mitigation decisions and restoration design detailed in the fourth chapter of this report. The successive analyses are:

- Seismic risk reduction approach analysis;
- Subsidence management and reversal technology analysis;
- Fill material availability analysis;
- Strategic island selection.

Some of these analyses are qualitative in nature and based on conversations with experts and managers in the Delta. Some are effectively a focused literature review. Others are quantitative in nature and rely on available data regarding Delta conditions.

2.1 Seismic Risk Reduction Approach Analysis

We qualitatively ranked ten strategies for reducing the risk of levee failure against environmental, technical, political, and economic criteria. The ten strategies represent the range of possible solutions. Environmental benefits generally relate to the consistency of an approach with increasing ecological health and creating tidal marsh, a major CALFED goal. Technical feasibility refers to the physical ability to implement the strategy given conditions in the Delta. Political feasibility is the likelihood of Delta residents and other stakeholders to support or accept the approach. Economic viability refers to the estimated cost of implementing a strategy relative to other strategies.

2.1.1 Water Infrastructure and Management Strategies Analysis

We reviewed specifications and cost estimates of an isolated conveyance facility (commonly called the peripheral canal) to draw conclusions regarding its environmental impact, technical feasibility, and economic feasibility (CWC, 2001). We reviewed NHI's Environmentally Optimal Alternative for the Bay-Delta (1998) to assess its political feasibility. The report discusses the political feasibility of an isolated conveyance facility based on NHI's work with Delta landowners and the Delta Protection Commission, as well as NHI's knowledge of California water politics.

We based our rankings of the emergency water storage strategy based on conversations with NHI staff familiar with water storage needs and opportunities in California.

We based our analysis of environmental impacts of inundating Delta islands with freshwater on work performed by DWR examining fauna in deep-water habitats in the Delta (Grimaldo et al., 2000) typical of that created by island inundation. We reviewed supporting documentation for the Delta Wetlands project (that proposes to inundate islands for water storage) to determine the technical and economic feasibility (Delta Wetlands, Inc., 2001). We based political feasibility on restoration opportunity maps created by NHI (1998).

2.1.2 Emergency Response Analysis

We reviewed CALFED's Delta Levee Emergency Management and Response Plan (2000e) and interviewed Ray Seed, member of the CALFED Seismic Vulnerability Sub-

Team to draw conclusions regarding the capacity, feasibility, cost, and environmental implications of an upgraded emergency response plan. We ranked political feasibility based on discussions with NHI staff familiar with Delta politics.

2.1.3 Levee Upgrades and Construction Analysis

We reviewed CALFED's Levee System Integrity Program Plan (2000b), DWR's Delta Levees Investigation (1982) and other technical documents (CALFED, 2000d; USACE, 1988) to rank the economic and technical feasibility and determine the environmental consequences of levee upgrades and construction. Ray Seed also contributed to the analysis of technical feasibility. We ranked political feasibility based on discussions with NHI staff familiar with Delta politics.

2.1.4 Subsidence Reversal and Mitigation Strategies Analysis

We reviewed studies on various island rebuilding techniques or processes that relate to island rebuilding in the Delta (Miller and Fujii, 2000; Shoellhamer, 2000; PWA, 2000, Deverel, 1998, Deverel, 2000). From the information on material availability and physical processes of island rebuilding, We ranked the technical feasibility. We based our economic viability ranking on unpublished NHI research regarding fill material and construction costs. NHI estimated unit costs based on interviews with engineers, state employees, and vendor quotes. We ranked political feasability based on the restoration opportunities map produced by NHI (1998) and conversations with NHI staff familiar with Delta politics.

2.2 Subsidence Management and Reversal Technology Analysis

The second analysis evaluated specific subsidence reversal strategies according to cost, fill density, fill availability, political feasibility, and compatibility with ecological restoration objectives. We evaluated compatibility of fill sources with restoration objectives based upon interim habitat values and the rate and extent to which any given method restored tidal marsh. Finally, We deemed strategies with prohibitive economic costs[1], major quality of life impacts, and potential threats to public health and safety as politically unfeasible.

2.3 Material Availability Analysis

We estimated material available from a) dredge spoils in the Delta; b) future dredging; and c) imported materials.

We quantified and located available dredge spoils in the Delta based on interviews with local experts involved in dredging and storage activities (C. Schmutte, DWR; R. Yeadon, DWR; I. Tavana, USACE) and based on published documents and reports regarding past dredging (USACE, 1988; CRWQCB, 1988; Betchart, 1998).

Future dredging fell into two categories: dredging planned for the near-future and dredging necessary in the long term due to sediment import into the Delta. We estimated

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[1] The potential economic and ecological costs of levee failure have not been calculated, but the water supply impacts alone could cost several billion dollars. We considered any subsidence reversal or risk reduction technology cost effective if it could prevent the consequences of levee failure for less than the cost of those consequences or less than the $1.5 billion cost of an isolated conveyance facility (Peripheral Canal).

quantities for near future activities based on environmental impact reports pertaining to proposed dredging in the next ten years (BCDC, 1999; Port of Oakland, 2000). We determined long-term sediment availability from published sediment budget studies (Bay Institute, 1998; Krone, 1996; Beeman, 1992).

We estimated the availability of additional fill material based on estimates of nearby stored non-dredge spoil sediments (e.g. Montezuma Hills) and other out-of-Delta fill material sources (e.g. rice straw).

2.4 Strategic Island Selection

The Delta Flood Protection Act identified eight predominantly western islands that are critical to preserving water quality in the Delta (DWR, 1999). We ranked these eight islands according to multiple criteria including subsided volume, risk of levee failure, percent salinity increase in the event of levee failure, public ownership, political feasibility, and proximity to existing tidal marsh.

We calculated subsided volumes using a Geographic Information System (GIS)-based spreadsheet model that calculated the volume below sea level based on the digital elevation model (DEM) topographic data available from the USGS (1978). We ranked the risk of levee failure according to estimates reported in the CALFED Seismic Vulnerability Sub-Team’s report (CALFED, 2000b) and the water supply consequences of failure from previous DWR analysis (DWR, 1999; DWR; 1990). We ranked each island according to ownership, prioritizing islands owned by CALFED agencies, followed by other public agencies. We determined land ownership through parcel ownership maps available from the Contra Costa and Sacramento counties tax assessor’s offices.

We evaluated political feasibility based on a map of low-conflict restoration opportunities developed by NHI, local Delta agencies, and landowners (NHI, 1998). Since restoration of tidal marsh is a major objective of the CALFED program, We also considered proximity to existing tidal marsh habitat and favored sites that provide opportunities for improving habitat connectivity or increasing habitat patch size.

2.5 Restoration Design Approach

Once we selected the highest priority islands for initiating subsidence reversal efforts, we performed a site-specific GIS spatial overlay analysis to evaluate physical opportunities and constraints for applying a combination of appropriate seismic risk reduction, subsidence reversal, and tidal marsh restoration techniques.

We used a digital DWR (1998) soils map (originally created from NRCS digital soil maps) to identify mineral soils suitable for levee construction and organic soils that warrant immediate subsidence management treatments.

To determine the volume of fill necessary to rebuild Delta islands we modified the GIS-based spreadsheet model used in the subsided volume analysis to calculated the volume beneath the island-specific target restoration elevation based on the digital elevation model (DEM) topographic data available from the USGS. We relied upon the preliminary results of a CALFED-funded study on tidal marsh establishment to determine elevations necessary to restore tidal marsh. The study reports that an established tule stand (the dominant plant in Delta tidal wetlands) can colonize to as low as one foot below mean lower low water (MLLW) (PWA, 2000). The Delta Atlas provides MLLW elevations throughout the Delta (DWR, 1995).

2.5.1 Levee Building Opportunities

To locate levee-building opportunities (a preferred strategy identified by the above analysis) we searched for sites that matched the criteria of high mineral content properties and high elevations[2]. We ranked the relative consolidation of underlying soils resulting from the increased overburden weight of a new levee. Calculating ultimate consolidation of Delta soils requires core samples and empirically measured soil property parameters not available within the scope of this study. Therefore we simplified the ranking to four ordinal categories. The rank is based on the calculations of a predictive model relating organic content of soils and increase in effective stress with ultimate consolidation. The model serves only as a scalar to appropriately weigh the influence of levee height (and subsequently weight) against the influence of soil properties. The calculations described below make some coarse assumptions appropriate only for ordinal ranking of consolidation.

Gunaratne et al. (1998) predict ultimate settlement of organic soils as a function of percent organic content and change in effective stress.

Specifically:

$$\varepsilon_{ultimate} = \int_A^B \left[a(\omega) + b(\omega)\right] d\omega$$

$$a = \frac{\dfrac{97.79}{(1.27\omega + 97.79)^2} + \dfrac{23.13oc}{(0.16\omega + 23.13)^2}}{F(oc,\omega)}$$

$$b = \frac{\dfrac{360.17}{(1.86\omega + 360.17)^2} + \dfrac{40.61oc}{(0.52\omega + 40.61)^2}}{F(oc,\omega)}$$

$$F(oc,\omega) = \left(2.79 - \frac{\omega}{0.78\omega + 74.28}\right) + oc\left(9.72 - \frac{\omega}{0.12\omega + 15.33}\right)$$

where :

$\varepsilon_{ultimate}$ = ultimate consolidation (%)
B = final effective stress (kPa)
A = initial effective stress (kPa)

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[2] The intent of this analysis was to find the best places to build levees on Sherman Island, based on elevation below sea level and soil content. Though much of this analysis is quantitative, the end result is merely an ordinal ranking of suitability for levee construction and should be considered merely a screening exercise, not a predictor of soil consolidation.

oc = organic content (%)
ω# = effective stress (kPa)
a = primary consolidation coefficient
b = secondary consolidation coefficient

We simplified change in effective stress to the vertical stress applied to the top layer of soils, or the weight of the overlying levee. We assumed initial stress to be zero. We grouped values into four ordinal categories based on their suitability for levee construction: high suitability, medium high suitability, medium suitability, low suitability.

We derived percent organic content from the DWR digital soils map. Using ArcView GIS and the Xtools extension, we intersected the organic content data coverage with elevation data (serving to indicate levee height), creating a new coverage with polygons of unique elevation/organic content combinations. To simplify calculation, we placed levees into 10, 15, 20, and 25 foot height categories.

2.5.2 Levee Material Requirements

To determine the quantity of material necessary for levee construction, we developed a GIS-based spreadsheet model that calculated the volume of the levees based on the height of the levee (the difference between the surface elevation and the necessary levee height to defend against a 100 year flood). We based these calculations on the USGS digital elevation model and DWR levee construction standards. We increased this “neat” fill calculation by 100% for levee sections constructed above soils ranked high or medium-high suitability. A 100% increase accounts for losses typical in levee construction in the Delta. We increased “neat” fill calculation by 150% for levee sections constructed above soils ranked medium high or high consolidation. A 150% accounts for losses typical in levee construction on highly organic soils in the Delta (CALFED, 2000c).

2.5.3 Fill Material Opportunities

The fill material opportunities analysis is identical to the levee location analysis except that change in effective stress is defined as the weight of overlying fill materials, which will be lower in density than engineered levee sections. The ordinal ranking and map of resulting fill material placement opportunities is the same.

2.5.4 Non-tidal Tule Pond Opportunities

We identified tule pond opportunities in basin-like areas of the islands. The extent of tule ponds is constrained by a maximum depth of two feet and an assumed accretion rate of 2 inches per year (Miller and Fujii, 2000).

2.5.5 Levee Breaching/Restoring Fluvial Processes Opportunities

We identified compartmentalized sections of the islands that are high enough in elevation to restore tidal processes immediately or after minimal restoration. Subsided islands tend to slope inward so levee breaching cannot occur until an entire compartment is at or above the target elevation. Otherwise, water would rush inward and fill the void creating deep-water habitat rather than shallow, tidal wetland habitat.

3 Results and Discussion

3.1 Seismic Risk Reduction Approach Analysis

The results of the seismic risk reduction analysis, depicted in Table 3.1, show that rebuilding key Delta islands to sea level is the only approach that simultaneously achieves all of CALFED's primary goals; enhancing ecosystem quality, water quality, water supply reliability, and levee system integrity. Other approaches provide substantial interim progress toward one or more CALFED goals and some still warrant inclusion in the restoration design. We discuss the strengths and limitations of various seismic risk reduction strategies below.

3.1.1 Water Infrastructure and Management Strategies

Numerous water infrastructure and management alternatives could mitigate the water supply impacts of levee failure, but would not safeguard the Delta ecosystem and are limited by economic and political weaknesses. The politically unpopular peripheral canal would secure water supply and potable export water, but would not reduce the risk of levee failure to the Delta ecosystem and not protect Delta water quality. An isolated conveyance facility similar to the peripheral canal would cost an estimated $1.5 billion (CWC, 2001).

Constructing water storage facilities south of the Delta would mitigate the impacts of acute water quality degradation from levee failure during periods of low inflow, but would not address the chronic degradation to water quality in the Delta predicted by DWR modeling analyses (DWR, 1990). Surface water storage facilities for non-emergency use are expensive and unpopular among politically powerful environmental

Table 3.1. Seismic Risk Reduction Analysis

CRITERIA	Environmental							Financial	Tech-nical	Political
	Reduce Seismic Vulnerability of Levees	Manage / Reverse Subsidence	Reduce Salinity Impacts in the Delta	Attenuate Floods	Self-Sustaining / Self-Reinforcing Method	Increase Tidal Marsh Acreage	Increase Habitat Connectivity	Economically Viable	Technically Possible	Politically Feasible
Water Infrastructure and Management Strategies										
Bypass Delta with Peripheral Canal	●	○	○	○	○	○	○	●	●	○
Maintain Emergency Water Storage South of Delta	◑	○	○	○	○	○	○	◔	●	◔
Inundate Strategic Delta Islands with Freshwater	●	●	○	○	○	○	○	◔	●	◔
Emergency Response Upgrade										
Improve Emergency Response to Levee Failure	○	○	◑	○	○	○	○	●	◑	◑
Levee Upgrades and Construction										
Maintain & Upgrade Levees to Current PL-84 99 Standards	○	○	○	○	○	○	○	◑	●	●
Maintain & Seismically Upgrade Current Levees by Densifying Levees Above PL-84 99 Standards	◕	○	◕	○	○	○	○	○	◕	●
Maintain & Seismically Upgrade Current Levees by Significantly Increasing Cross Sectional Area Above PL-84 99 Standard	◕	○	◕	○	○	○	○	◑	○	●
Build New Seismically Sound Setback Levees and Widen the Floodplain	◕	○	◑	◕	◑	◑	●	○	○	○
Compartmentalize Islands with Cross Levees	●	○	●	○	○	○	○	●	●	●
Subsidence Reversal and Mitigation Strategies										
Rebuild Delta Islands to Sea Level in Fifty Years and Restore Tidal Marsh Habitat	●	●	●	●	●	●	●	◑	●	●

● Highest ranking ○ Lowest ranking

groups. Off-stream storage involves high pumping costs to convey water from the Delta to the reservoir. Reserving large amounts of surface storage for probable, but infrequent, seismic disasters would be extremely expensive and politically difficult to enforce. Large amounts of water would evaporate or remain unused in emergency storage for years and the political temptation to divert emergency reserves to California's insatiable demand for water may be irresistible. South of Delta groundwater storage is more sensible with lower capital costs, minimum evaporative losses and less up front pumping costs, but would probably be more susceptible to early withdrawal during dry periods instead of acute emergencies associated with levee failure.

3.1.2 Controlled Non-Tidal Inundation of Delta Islands

The non-tidal inundation of Delta islands substitutes freshwater for solid fill material to reduce the risk and consequences of levee failure. Flooding also arrests the oxidation of peat soils and therefore provides subsidence management. Before flooding, the interior faces of the levees would have to be rock-lined to prevent wave erosion. This comes at a significant cost.

Flooded islands mostly provide deep-water habitat for invasive centrarchids and shad. Chinook salmon, a desirable and threatened native species, prefers the inter-tidal zones of tidal wetlands (Grimaldo et al., 2000). Deep-water habitat exposes salmon to predation by invasive species. To create tidal marsh and achieve complete subsidence reversal requires the addition of solid fill material (PWA, 2000).

3.1.3 Emergency Response Measures

Improving emergency response measures is necessary but it will not significantly reduce the risk of catastrophic failure. Emergency response measures include stockpiling rocks, plastic sheeting, sandbags and other fill material nearby, and maintaining additional barges and work crews in the Delta. Rock for levee breaks in the Delta comes from a single quarry in Marin County that has threatened to cease operations in the near future. Emergency response measures would include either continued operation or outright purchase of this quarry (R. Seed, University of California, personal communication, 2001). The CALFED Seismic Vulnerability Sub-Team concluded that increased investment in emergency response capability would significantly decrease risks associated with smaller earthquakes (events resulting in less than 5 simultaneous levee breaches) (CALFED, 2000b), but consultation with Ray Seed, a Sub-Team member, suggests that even the best emergency response program would be overwhelmed by more than 10 simultaneous levee breaches (R. Seed, University of California, personal communication, 2001).

If an earthquake occurred, it would likely originate from the west along known fault lines. This means that it would also seriously impact the urban centers around the San Francisco Bay area. In the event of a smaller earthquake, Delta levees may sustain damage while urban centers may experience very little damage. In a large earthquake, resources for responding to levee failure in the Delta would be constrained by competing emergency response needs further west.

3.1.4 Levee Upgrades and Construction

The CALFED panel concluded that levee retrofitting strategies including densifying loose levee embankment and foundation soils or making major geometric improvements in levee cross-sections would be “extremely complex and expensive”. More important, they found that CALFED’s plan to spend a billion dollars for “simply making minor modifications”(along the lines of PL84-99 criteria) would not significantly reduce seismic vulnerability. “Simple levee upgrades currently being considered to improve static (non-seismic) stability are largely ineffective at reducing seismic fragility. These types of ‘static’ upgrades will do very little to reduce the risk of levee failures associated with soil liquefaction” (CALFED, 2000b). Even the best seismically engineered levees in the Delta sit atop older, un-engineered and compacted levees and saturated foundations prone to liquefy.

3.1.5 Compartmentalize Islands with Set-back and Cross Levees

Strategically placed set-back and cross levees are a potentially promising strategy for decreasing the length of levees vulnerable to failure, reducing the consequences of levee failure, and creating large areas of tidal marsh. New engineered cross levees that “cut-off” peninsulas with a high circumference to area ratio can significantly reduce the length of un-engineered levee and associated maintenance costs particularly when the cut-off peninsula is converted to tidal marsh.

Cross levees that compartmentalize an island reduce the potential area and volume that could flood should a levee fail. Since the economic and water quality impacts of levee breaches are proportional to the area and volume of island flooded (DWR, 1990), compartmentalizing islands reduces the costs associated with levee failure by reducing the area flooded by any given levee breach.

The foundations of cross levees through the island interior are not saturated, as are those of river levees. Since 85% of the threat of failure is due to liquefaction of saturated foundations, cross levees are less likely to fail during an earthquake (R. Seed, University of California, personal communication, 2001). More importantly, the Delta’s levees are almost totally un-engineered. New cross levees would be engineered and hence, stronger.

Levee setbacks that expose lands higher than one foot below MLLW to tidal inundation create tidal marsh (PWA, 2000). Areas deeper than one foot below MLLW require additional fill material before breaching peripheral levees and creating tidal marsh.

CALFED has largely dismissed the potential for expanding habitat by building new set-back levees because of the difficulty associated with constructing levees on compactable peat soils. However, not all Delta soils are compactable peat soils. The DWR (1998) soils maps indicate that there are bands of mineral soils associated with historical channels throughout the Delta (Figure 3.1)[3]. In many cases, these bands are significantly higher in elevation than the adjacent peat soils because they have subsided less since the Delta wetlands were reclaimed for agriculture. The ability of these mineral

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[3] The existing database only applies to the upper seven feet of soil material. It does not indicate soil characteristics below that depth. Since these inorganic bands are generally higher than surrounding organic soils, we assume that they are inorganic at significant depth as well.

soils to bear relatively heavy loads combined with their typically higher elevations creates opportunities for constructing cross levees.

3.2 Subsidence Management and Reversal Technology Analysis

Subsidence management techniques arrest or reduce future subsidence: subsidence reversal techniques entail importing or growing fill material to physically rebuild subsided islands to sea level. Because of large uncertainties about cost, transportation, and environmental impacts, we did not evaluate several approaches including sanitary landfill, aggregate disposal, and greenwaste disposal. Rather, we concentrated our analysis on the following techniques, which we discuss in greater detail below:

- Cultivation of non-tidal tule ponds to gradually accrete island surface elevations;
- Utilization of rice straw bales;
- Beneficial use of current and historical dredge spoils for levee construction and upgrades;
- Island capture of bedload and suspended sediment currently moving through the Delta;
- Importation of soil from upland sites.

The potential use of each of the above fill materials is constrained either by cost, availability, time, geotechnical, or transportation infrastructure requirements. These constraints were the primary considerations. Table 3.2 depicts the estimated cost per cubic yard for each of these fill materials based on research done by NHI. We did not evaluate the suitability of fill material as a substrate for tidal marsh establishment, but assumed that all the fill approaches itemized above would be suitable for supporting tidal marsh.

Table 3.2. Fill Cost Estimates

Source	**Average cost per cubic yard ($)**	**Cost range per cubic yard ($)**
Bay Dredge Spoil (Beyond 10 mile radius)	15.00	10.00-41.00
In-Delta Dredge Spoil (within 10 mile radius)	8.00	5.00-10.00
Dredge Spoil Re-Use from Delta Islands	5.00	1.50-12.00
Bedload capture	5.00	5.00
Suspended Sediment Capture	5.00	5.0
Rice Straw	0.70	0.55-0.87
Fresh Water	0.10	0.06
Tule Cultivation[1]	7.00	6.00-7.00

[1] Includes sediment augmentation, water level management, and levees

3.2.1 Tule Cultivation

Tule cultivation is the most straightforward approach for halting ongoing subsidence on a broad scale over time. Shallow flooding associated with tule ponds prohibits aerobic degradation. The rapid growth and slow decay of plant matter creates a net accumulation of organic material. Tule ponds mimic the processes that built Delta islands; the accretion of organic material in response to frequent flooding (PWA, 2000).

The high productivity of the system leads to rapid growth of tule reed (*Scirpus acutus*) and cattails (*Typha spp*.). The yearly cycle of growth and decay deposits an abundant litter. In this manner, tule marshes can aggrade as much as four vertical inches in a year. Net vertical growth over several years is more likely between 0.5 and 2 inches per year due to compression of organic matter under its own weight (Miller and Fujii, 2000).

Because tule cultivation requires perennially inundated conditions, it is most feasible on the lowest areas of any given Delta island – areas that often correspond with the highest rates of ongoing subsidence. The slow but persistent rate of vertical accumulation makes it most useful in arresting high rates of subsidence but the process of actually raising the elevation of these deeply subsided areas (20 feet below sea level) is slow and could take more than 100 years to rebuild to sea level. Although tule cultivation will gradually and incrementally reduce the consequences of levee failure (by filling the island), it does not act quick enough to significantly reduce the risk of levee failure over the next several decades.

Because tule cultivation is most effective at halting continued subsidence but relatively slow at rebuilding islands, other, more expedient approaches should be instituted to reduce the risk of seismically induced levee failure in coordination with tule cultivation.

3.2.2 Rice Straw Bale Fill

Rice grows on four hundred thousand acres a year in the Sacramento Valley. After harvest, two to three tons of straw remain on each acre of land or approximately a million tons of straw a year (Bainbridge et al., 2000). Rice straw used for construction is baled at a density of seven pounds per cubic foot (State of California, 1994). Assuming this density, one million tons of rice straw creates over 10 million cubic yards of rice straw.

Because a surplus of rice straw bale material now exists due to laws restricting disposal by burning, the use of rice straw provides a significant opportunity for synergistic use of a waste material. Currently, farmers either use scarce water to break down rice straw in winter months or they simply stockpile excess rice straw bales.

The greatest advantages of rice straw relative to other fill materials are its relatively low density, low cost, and abundance. Further, rice straw approximates the character of decomposed tules that originally formed the Delta’s peat soil more than any other fill material we considered. Unlike dredge spoils and other mineral soils, relatively large volumes of rice straw can be deposited on the Delta’s organic soils without causing large amounts of soil compaction. Table 3.2 suggests that rice straw costs are less than $1 per cubic yard delivered to the site compared to more $5-$20 per cubic yard for dredge spoils).

Anaerobic decomposition of rice straw under inundated conditions could create negative water quality problems. Decomposing organic matter creates dissolved organic carbons (DOCs). Drinking water treatment processes react with DOCs to form harmful disinfectant by-products such as trihalomethane. Currently, about 40-45% of DOCs in the Delta comes from agricultural island drainage; the rest comes from rivers, upland runoff, wetlands, and microbial production (Bergamaschi et al., 2000).

DOCs themselves do not pose a threat to ecosystem health in the Delta. Degrading rice straw may produce fewer DOCs than the agricultural practices it replaces. The possibility that it may impact drinking water mandates caution when applying this strategy to islands close to the Delta Pumps and the Contra Costa water intakes in the south Delta.

3.2.3 Dredge Spoil Re-Use

Beneficially reusing dredge spoils is a promising approach for simultaneously addressing the Delta subsidence problem and the dredge spoil disposal problem. Dredge spoils can be used to strengthen existing levees, build new cross levees, and raise small areas to near sea level for tidal marsh restoration.

The relatively small volume of total dredge spoils limits its application for broad scale subsidence reversal. The limited availability of dredge spoils is further aggravated by the tendency of organic soils to compact appreciably when overlain by dredge spoils. For this reason, dredge spoils should be used primarily to repair existing levees, construct new levees on mineral soil, and in combine with less dense fill material such as rice straw bales and tule cultivation for subsidence reversal efforts.

3.2.3.1 Quantity and Location of Dredge Spoils

The largest quantities of dredge spoils in the Delta are located at sites associated with the Sacramento or the Stockton shipping channels. Smaller scale dredging may provide valuable material for local restoration, but provides negligible quantities relative to the scale of island subsidence reversal. For example, all marina-related dredging in the South Delta in the next four years will generate only 97,000 cubic yards of material (DWR, 2000). This is less than one hundredth of one percent of the total volume of islands below sea level.

Figure 3.2 shows the location of dredge spoil deposits in the Delta. Table 3.3 lists the quantity available at each site. In total, approximately 42 million cubic yards (mcy) of dredge spoils are stored in the Delta, concentrated around the Sacramento and Stockton shipping channels.

Table 3.3. Quantity and Location of Available Dredge Spoils

Site	**Owner**	**Existing Quantity (cubic yards)**
Augusta	Port of Sacramento	1,000,000[1]
Brannan Island State Park	State of California, Department of Parks and Recreation	9,300,000[2]
Bradford Island	-	1,000,000[1]
Decker Island	DWR, Mega Sands, Port of Sacramento	20,000,000[1]
Grand Island	US Army Corps of Engineers	N/A[1]
Los Ulpinos	US Army Corps of Engineers	2,300,000[2]
McCormmack Tract	-	N/A[1]
Old Scour Pond	DWR	N/A[1]
Roberts Island #1	Port of Stockton	N/A[3]
Roberts Island #2	Port of Stockton	N/A[3]
S-12 (Prospect Island)	Port of Sacramento	1,710,000[4]
S-16 (Rio Vista)	US Army Corps of Engineers	3,000,000[5]
S-35 (Collinsville)	DOW Chemical Company	890,000[4]
Sacramento North Shore (across from Sherman Lake)	US Army Corps of Engineers	3,000,000[2]
Spud Island	Port of Stockton	N/A[3]

Webb Tract	-	N/A[1]
Total		**42,200,000**

N/A- Quantity estimate not available.
[1] C. Schmutte, DWR, personal communication, 2000.
[2] Betchart, 1998.
[3] USACE, 1988.
[4] CRWQCB, 1988.
[5] I. Tavana, USACE, personal communication, 2000.

In addition to currently sited dredge spoils, government agencies have estimated future quantities from dredging activities. Table 3.4 lists these activities and quantities. In total, these amount to nearly 10 mcy of additional dredge spoils available in the next ten years.

Table 3.4. Near Future Dredging Activities and Quantities

Location	**Quantity (cubic yards)**
Mokelumne River	6,500,000[1]
South Delta	3,000,000[2]
Total	**9,500,000**

[1] CALFED, 2000a
[2] S. Roberts, DWR, personal communication 2000

Krone (1996) projects an average of 500,000 cubic yards of annual Delta sediment deposition from now until 2035. This translates to an additional 17 million cubic yards of dredge material possibly available in the next 34 years.

In summary, approximately 60 mcy of dredge spoils will be available for use over the life time of this project. This is about one tenth of the total subsided volume of western Delta islands.

3.2.3.2 Out-of-Delta Sources and Quantity of Dredge Spoils

In 1998 alone, 5 million cubic yards of materials were dredged from the San Francisco Bay. Forty-three percent of this material was deposited at a deep ocean disposal site, fifty miles from the Golden Gate. A smaller percentage (<16%) made its way to upland disposal sites, including some to Winter Island, just west of Sherman Island (BCDC, 1999). The Port of Oakland estimates that its own dredging will create another 15 million cubic yards of material in the next four years (Port of Oakland, 2000).

Rather than dispose of this material in ocean dumping grounds, it could be used to reconstruct islands in the Delta. Some of this material already goes to upland restoration sites such as the Hamilton Wetland site and the Montezuma Wetlands for similar activities (BCDC, 1999).

Both the Long Term Management Strategy (LTMS) and the environmental impact report (EIR) for Oakland Harbor dredging considered Delta Island disposal. The LTMS evaluated the possibility of using the Sherman Island scour pond site but expressed concerns regarding the salinity impacts of Bay dredge spoils (BCDC, 1999). The Oakland Harbor Dredging EIR rejected the proposal on the grounds that the cost of transport is too high. The Corps expressed interest in receiving dredged materials on Delta islands but the Department of Water Resources denied their request due to the uncertainty surrounding impacts of saline dredge spoils (Port of Oakland, 2000).

Given the potential benefits, the use of saline dredge spoils in the Delta must be further examined. The prospect of using saline dredge materials benefits both Bay ports in need of disposal sites and Delta islands in need of material.

3.2.4 Fluvial Sediment Capture

Strategies that capture sediment suspended in the river and moving along the bed of the channel attempt to mimic historical sediment deposition processes and could reduce the need to dredge future accumulations of sediment from navigation and flood conveyance channels. Although promising, strategies to capture suspended and bedload sediment are limited by the same constraints as dredge spoil re-use. The supply of sediment transported to the Delta is very small relative to the area of subsided lands, and placement of captured sediment on organic soils will result in significant compaction.

3.2.4.1 Delta Sediment Budget

Ninety percent of the Delta's fluvial sediment supply is from the Sacramento River (Bay Institute, 1998). Much of the sediment in the San Joaquin reaches of the Delta is of Sacramento River origin (Dinehart, 2000).

The system of artificial levees (essentially complete by 1930) isolates 97% of historical marshland in the Delta (Bay Institute, 1998). Waters that historically spread out across the deltaic plain to deposit their sediment loads are now confined to narrow channels and carry their loads out to the Bay.

At the same time, modifications in the upper watershed have greatly decreased available sediment sources. Large, lowland dams control 73% of the Sacramento and San Joaquin river basins. These dams trap 90% of all incoming sediment including 20.4 million cubic yards of suspended load (Bay Institute, 1998). In an undammed system some of this would still deposit in sediment sinks upstream but fine clays and sands would travel all the way to the Delta.

Table 3.5. Delta Sediment Budget

	Pre 1985 (mcy)[1]	**1849-1914 average (mcy)[1]**	**1955-1990 average (mcy)[2]**	**1990 (mcy)[2,3]**	**2035 (mcy)[2,3]**
Inflow	2.0	22.9	7.7	6.1	6.0
Deposition	0.4	4.5	0.0	0.0	0.0
Dredging	-	-	0.5	0.5	0.5
Water withdrawals		0.0	1.3	1.6	2.0
Outflow to Bay	1.6	18.4	5.9	3.9	3.5

[1] Gilbert, 1917
[2] Krone, 1996
[3] Beeman, 1992

In 1990, an estimated 6.1 million cubic yards of sediment entered the Delta. Water exports removed 1.6 million cubic yards (in the form of suspended sediments) from the Delta, dredging removed another 0.5 million cubic yards, and the remaining sediment passed through the Delta to the Bay (Beeman, 1992). This leaves approximately 4 million cubic yards of uncaptured sediment each year; 95% of which is suspended load (D. Shoellhamer, USGS, personal communication, 2000). Forty-five percent of this suspended load is carried in the winter months (Shoellhamer, 2000).

3.2.4.2 Methods of Suspended Sediment Capture

Sediment transport in rivers is a function of particle characteristics and stream characteristics. Particle characteristics include diameter, shape, specific gravity, and settling velocity. Stream characteristics include flow velocity, velocity pulsation, water density, kinematic viscosity, depth of flow, and surface slope (Stelczer, 1981).

To induce deposition in the Delta, channels could be widened to decrease flow velocity and depth, or to direct flow across shallow, rough terraces, enhanced with subsurface features (e.g. fences, recycled Christmas trees) that reduce velocity and induce sediment deposition (USGS, 2000).

One approach for capturing a small amount of bedload and suspended sediment is to construct setback levees that widen the floodplain to encourage deposition of sediment on re-exposed historic point bars. Over many decades, this approach would take advantage of the existing hydrologic regime to rebuild island surfaces, provide flood attenuation benefits, reduce shear stress on existing peripheral levees in the event of high water, and slightly reduce the inflow of unwanted sediment into San Francisco Bay.

3.2.4.3 Methods of Bedload Capture

Bedload consists of less than 5% of the total sediments transported through the Delta; approximately 200,000 cubic yards a year (Shoelhamer, 2000). Relative to the total subsidence volume of 600 mcy in the western Delta, this quantity is insignificant.

However, shoaling of bed materials in the Delta does offer an untapped, local source of fill materials in the Delta. In the same way that dredge spoils from aggraded channels provide fill material, shoals of sand that deposit after high flow events could provide fill material for restoration.

The USGS is just beginning to investigate the processes of bedload transport in the Delta. A comprehensive mapping of shoaling is still many years away. Studies in Threemile Slough provide anecdotal insight into this restoration opportunity (Oltmann et al., 1999).

Threemile Slough connects the Sacramento River with the San Joaquin river along the eastern end of Sherman Island. After high flow events, the river creates wave-like bedforms in the southern end of the slough that migrate towards the Sacramento River. These migrate at a rate of 100 tonnes a day. Assuming a specific weight for migrating sand of 1900kg/cubic meter, this equals approximately 70 cubic yards of sand a day moving through and out of Threemile Slough.

The USGS has also located similar shoaling phenomena in the Mokelumne River and alongside Decker Island, suggesting that there may be many sites throughout the Delta with fluvial sediment available for use in restoration.

3.2.5 Other Imported Fill

The Montezuma Hills, immediately north of the Sacramento River, offer an nearly limitless supply of rock and soil. Examination of USGS 7.5 minute quad maps reveals 11.5 million cubic yards of sediment deposits between the Sacramento River and the hills. The hills themselves offer thousands of acres of rock and fill material should it become necessary to extract for use in the Delta.

3.3 Strategic Island Selection

Of the eight islands listed in the Delta Flood Protection Act as critical to preserving water quality in the Delta, Sherman Island is clearly the principal strategic island for restoration (Table 3.6).

Table 3.6. Strategic Island Selection

	Sherman Island	Jersey Island	Webb Tract	Twitchell Island	Holland Island	Bradford Island	Bethel Island	Hotchkiss Tract
Importance of Island								
Subsided Volume (mcy)	142	34	97	57	46	27	30	10
Risk of Levee Failure[1]	High	Medium	Medium	Medium	Medium	Medium	Medium	Medium
Percent Salinity Increase[2]	41	40	24	19	12	NA	NA	NA
Miles to Water Diversion Points [3]	9	3	5	10	<1	6	2	<1
Restoration Feasibility								
Percent owned by CALFED agencies	84	-	-	83	-	-	-	-
Percent Publicly Owned (non-CALFED)[4]	2	95	5	-	<10	11	<10	<10
Near Existing Tidal Marsh	Yes	No	Yes	No	No	No	No	No

[1] CALFED, 2000b.

[2] Enright, n.d. Percent Salinity Increase refers to DWRSIM1 model results that estimate the percent increase in salinity due to a levee breach and flooding on the island of interest.

3 Shortest distance (river miles) to either Clifton Court (south Delta pumps) or Rock Slough (Contra Costa Water District intakes).

[4] Sacramento and Contra Costa counties Tax Assessor Parcel Maps.

Sherman Island is the most logical Delta island on which to begin the implementation of a full-scale subsidence reversal effort. Relative to the seven other islands, it is important because it is:

- At the greatest risk of inundation during a seismic event;
- Large and deep; and thus more likely to cause degradation of water quality if it is inundated.

Relative to the other seven islands, Sherman Island is most feasible because it is:

- Publicly owned, identified as a low-conflict restoration opportunity by local Delta interests (NHI, 1998);
- near existing tidal marsh.

Jersey Island is not as large as Sherman Island nor as deeply subsided, but DWR estimates that salinity impacts due to levee failure are similar. A single, public owner, the Iron House Sanitation District owns most of Jersey Island. This makes Jersey Island an attractive island to restore either after or concurrent with Sherman Island.

Webb Tract is large and deeply subsided and will have a significant impact on salinity levels in the event of failure. This makes it an important island to restore. It is under mostly private ownership and restoration may not be as feasible. Twitchell Island is not as large as Webb, but would have a similar impact on salinity. Since 83% of the island is owned by a CALFED constituent agency, restoration is much more feasible. Holland Island, Bradford Island, Bethel Island, and Hotchkiss Tract are smaller and less subsided, and would have less impact on salinity levels in the event of levee failure. These four islands are mostly private and restoration would not be as feasible.

The prioritization of islands for restoration can be adjusted based on an expanded suitability analysis that includes a comparison of relative opportunities and constraints for restoration based on natural factors, such as availability of mineral soil for levee construction, and access for fill material delivery. Prioritization can be further refined by an analysis of currently funded restoration and levee improvement projects for individual islands that can be combined with a comprehensive rebuilding plan

4 Restoration Design

Below we present our phased approach for rebuilding Sherman Island based on our analysis of techniques and strategies presented above. The design takes advantage of the unique opportunities and accommodates the constraints posed by the natural conditions of Sherman Island. Long-term uncertainties in restoration strategies require constant experimentation, monitoring, and adjustment. Sherman Island could serve as an adaptive management laboratory to study the restoration of subsided islands. The plan offers opportunities to apply different methods, refine techniques, and monitor impacts of restoration.

Due to these uncertainties, the plan only projects out thirty years. It is assumed that what is learned in the first thirty years will inform restoration in the following decades. The plan will restore approximately 3,600 acres of tidal marsh habitat over the next thirty years with the intent of full restoration in fifty years.

4.1 Site Analysis

Sherman Island encompasses 11,300 acres of land, surrounded by 19.5 miles of levee. Ten miles of levee are un-engineered and extremely vulnerable (CALFED, 2000b). Although portions of the island are as deep as 19 feet below sea level, the average elevation of the island is only 11 feet below sea level (Figure 4.1). The total volume below sea level is 142 million cubic yards. The total volume below the target elevation of –3.2 feet (1 foot below MLLW) is 93 million cubic yards.

Sherman Island is adjacent to two ecologically managed lands; the Sherman Lakes Waterfowl Management Area to the west, and the northern tip of Decker Island to the north (Figure 4.2). Tidal wetland restoration on Sherman Island will establish connectivity with and between these two existing areas.

Figure 4.3, derived from NRCS soils data, depicts the organic content of Sherman Island soils. Although the majority of Sherman Island consists of peat soil that is greater than 11% median organic, there are bands of mineral soil on Sherman Island that are less than 6% median organic. Favorable opportunities for constructing levees exist where these areas of mineral soil correspond with high elevations. Figure 4.4 depicts levee-building opportunities as the weighted combination of mineral content and elevation according to the Gunaratne method described previously.

4.2 Levee Design Criteria

For the purposes of estimating fill requirements and cost, we make the following assumptions regarding the levee construction specifications: trapezoidal shape; 3:1 slopes; 16 feet crown width; 1.5 feet above 100-year flood freeboard elevation; $15.00 per cubic yard of engineered levee. For levees constructed on high or medium high suitable soils, we increased fill estimates by 100% to account for losses due to consolidation. For levees constructed on medium or low suitable soils, we increased fill estimates by 150% to account for losses due to consolidation. Levee cap fill estimates come from CALFED Levee Rehabilitation Study (CALFED, 2000d).

4.3 5-Year Plan

The purpose of the 5-year plan, outlined in Figure 4.5 and Table 4.1, is to obtain the most amount of benefit, for minimal expense, in the shortest timeframe. To do so, we include the following components:

- Northeast cut-off levee and tidal marsh restoration;
- Southwest cut-off levee and rice straw fill/saline dredge spoil demonstration site;
- North-South mid-island partitioning cross levee to reduce flood volume;
- Peripheral levee foundation caps;
- Subsidence management and reversal tule ponds.

Table 4.1. 5-Year Plan Components

Levees	**Material Source**	**5-Year Plan**	**Cumulative**
Northeast cutoff levee	Decker Island	110K yds^3	
Southwest cutoff levee	Decker Island	440K yds^3	
Mid-island north-south cross levee	Decker Island	840K yds^3	
Levee Caps	Old Scour Pond, McCormmack	160K yds^3	
Totals		*1550K* yds^3	*1550K* yds^3

Fill Areas	**Material Source**	**5-Year Plan**	**Cumulative**
Southwest scourpond (rice)	Sacramento Valley	4-10M yds^3	
Southwest scourpond (dredge spoils)	Bay/Decker Island	2M yds^3	
Totals		*6-12M* yds^3	*12-24M* yds^3

Non-tidal Tule Ponds	**Elevation**	**5-Year Plan**	**Cumulative**
Northeast (-16 feet)	-16 feet	46 acres	
East (-12 feet)	-12 feet	11 acres	
North central (-8 feet)	-8 feet	425 acres	
South central (-16 feet)	-16 feet	260 acres	
West (-12 feet)	-12 feet	280 acres	
Totals		*1022 acres*	*1022 acres*

Restored Tidal Wetlands	**5-Year Plan**	**Cumulative**
Northeast Tip	200 acres	200 acres

We propose to build short cut-off levees to create peninsulas in the northeast and southwest portion of the island, effectively reducing the length of peripheral levees on Sherman Island by approximately 20,000 feet or 20%.

The northeast peninsula is shallow, ranging from sea level to –2 feet elevation. Breaching the existing peripheral levee would allow for the immediate creation of 200 acres of tidal marsh without the addition of fill. We propose to fill the southwest peninsula with a combination of rice straw bale and saline and freshwater dredge spoil material**.** This area requires between 12 and 24 million cubic yards of material to reach its target elevation, depending on the mix and density of materials and the subsequent soil consolidation. Half of the total fill will occur during this first five-year period. The remaining volume will be filled during the next period. The southwest region of Sherman Island will be a demonstration site testing various combinations and densities of materials and monitoring for water quality, subsidence, and ecological impacts. The results of these experiments will inform further restoration strategies.

With these two peninsulas rebuilt to sea level, the resulting maximum volume vulnerable to flooding due to seismic failure is reduced by 19 %, from 88 to 72 TAF.

To reduce the potential for inundation of the rest of the island in the event of levee failure, we take advantage of the band of mineral soil that traverses the island north-south to build a cross levee to partition the remaining 72 TAF void into two sections of 16 and 56 TAF respectively.

To aggressively manage and reduce subsidence in the deepest and most quickly subsiding portions of the island (11-19 feet below sea level), we construct tule cultivation ponds. These areas are not suitable for immediate creation of tidal marsh because of their depth below sea level. The elevation that is gained by tule cultivation will reduce the supplemental fill volume requirements when such a treatment is employed.

We propose to cap existing peripheral levees along the San Joaquin River and the northern extent of Mayberry Slough where immediate improvements are necessary to strengthen levees adjacent to deeply subsided areas, and to prevent erosion from wave fetch in bordering tule cultivation ponds. CALFED has estimated that upgrading the 19.5 miles of Sherman Island levees will require 320,000 cubic yards of material. The 10 miles of levee we propose to upgrade will require roughly half that.

4.3.1 Benefits

This plan produces 200 acres of restored tidal wetlands in five years. It creates over 1,000 acres of non-tidal wetlands, arresting subsidence and benefiting waterfowl and other wildlife. It reduces the maximum single flood volume from 88 TAF to 56 TAF. Finally, it dedicates significant resources and space to experimenting with fill techniques that will guide restoration on all subsided islands in the Delta.

4.3.2 Considerations

Considerations requiring further inquiry include determining the water quality impacts from rice straw decomposition; water quality and ecological impacts of saline dredge spoils, and determining the suitability of areas for levee construction by assessing the depth of peat soil underlying mineral soil bands.

4.4 10-Year Plan

The 10-year plan, outlined in Figure 4.6 and Table 4.2, continues partitioning the island into smaller sections and rebuilding them with varied sources of fill. It also takes steps to protect the existing infrastructure. Components include:

- Cut-off levee, tidal restoration and sediment capture site;
- Raised highway cross levee;
- Expanded subsidence management and reversal tule ponds;
- Tidal marsh restoration in rice straw fill demonstration site.

Table 4.2. 10-Year Plan Components

Levees	**Material Source**	**10-Year Plan**	**Cumulative**
Second northern cutoff	Decker Island/Brannan Island	140K yds^3	
Mid-island east west levee	Decker Island,	1700K yds^3	

	Augusta		
Totals		*1840K yds^3*	*3390K yds^3*

Fill Areas	**Material Source**	**10-Year Plan**	**Cumulative**
Southwest scourpond (rice)	Sacramento Valley	4-10M yds^3	8-12M yds^3
Southwest scourpond (dredge spoils)	Bay/Decker Island	2M yds^3	4M yds^3
Totals		*6-12M yds^3*	*12-24M yds^3*

Non-tidal Tule Ponds	**Elevation**	**10-Year Plan**	**Cumulative**
Northeast	-15 feet	42 acres	88 acres
East	-11 feet	23 acres	34 acres
North central	-7 feet	400 acres	765 acres
South central	-15 feet	260 acres	520 acres
West	-11 feet	80 acres	360 acres
Totals		*805 acres*	*1827 acres*

Restored Tidal Wetlands	**10-Year Plan**	**Cumulative**
Northeast Tip	220 acres	420 acres
Rice fill demonstration site	1200 acres	
Totals	*1420 acres*	*1620 acres*

We divide the 56 TAF middle section of the island into two smaller sections of 32 and 24 TAF. We propose to elevate the existing highway atop this levee. In the northeast corner of the island, the highway will travel atop a second new levee, which will cutoff another shallow peninsula and create an additional 220 acres of immediate tidal marsh habitat. This 220 acres is adjacent to the Sacramento River and Horseshoe Bend and will be able to capture some of the bedload and suspended sediment that travel down these waterways in high flows.

4.4.1 Benefits

This planning period produces an additional 220 acres of restored tidal wetlands adjacent to 200 acres restored in the first five-year period. It also provides connectivity between the tidal wetlands on the northern tip of Sherman Island and those on Decker Island. Additionally, it produces 1,200 acres of new tidal wetlands on rice fill in the southwest corner. This connects with the Sherman Lakes Waterfowl Management Area currently managed for ecological purposes. The area provides feeding, rearing and cover habitat for salmon and other native species that is connected to existing habitat. It creates over 1,000 acres of non-tidal wetlands, arresting subsidence and benefiting waterfowl and other wildlife. The cross levee reduces the maximum single flood volume from 56 TAF to 32 TAF. Finally, it continues experimenting with fill techniques and ecological management strategies that will guide restoration on all subsided islands in the Delta.

4.4.2 Considerations

Considerations requiring further inquiry include determining methods for maintaining levees, and preventing erosion from wave fetch; supplementing the monoculture of tules with plantings to create diverse habitat; and determining long term impacts of DOCs created in tidal wetlands.

4.5 30-Year Plan

The 30-year plan, outlined in Figure 4.7 and Table 4.3, further partitions the island into smaller sections and rebuilds them with varied sources of fill. It also restores fluvial and tidal influence to rebuilt sections. Components include:

- Western north-south cross levee to partition the island;
- Eastern cut off levee, tidal wetland restoration and sediment capture site;
- Expanded subsidence management and reversal tule ponds, augmented by fill; techniques derived from rice straw fill demonstration site.

Table 4.3. 30-Year Plan Components

Levees	**Material Source**	**30-Year Plan**	**Cumulative**
Western north-south cross levee	Decker Island	1330K yds^3	
Eastern cut-off levee	Decker Island, Bradford Island	580K yds^3	
Totals		*1910K yds^3*	*5300K yds^3*

Fill Areas	**Material Source**	**30-Year Plan**	**Cumulative**
Eastern Island/San Joaquin (rice)	Sacramento Valley	12-24M yds^3	
Eastern Island/San Joaquin (dredge spoil)	Bay, Delta dredging, Decker Island, Bradford Island, sediment capture	4-8M yds^3	
Totals		*16-32M yds^3*	

Non-tidal Tule Ponds	**Elevation**	**30-Year Plan**	**Cumulative**
North central	-8 feet	1275 acres	1700 acres
South central	-11 feet	1240 acres	1500 acres
West	-8 feet	620 acres	900 acres
Totals		*3135 acres*	*4100 acres*

Restored Tidal Wetlands	**30-Year Plan**	**Cumulative**
Eastern Island/San Joaquin	2000 acres	
Totals	*2000 acres*	*3620 acres*

The most effective fill techniques to emerge from the demonstration projects in the first decade of restoration will be employed to expediently rebuild the remaining low lying sections of the island in the following decades. Thirty years from now (Figure 4.7) approximately 35% of the original Sherman Island will have been restored to tidal marsh using various methods of fill, with much of the remaining area under tule cultivation for continued subsidence management and reversal.

We propose to construct two more levees. One dissectes the island between the northern peripheral levee and the east-west cross levee. This will reduce the largest compartment volume from 32 TAF to 18 TAF. The second levee runs between the eastern peripheral levee and a cross levee. With fill augmentation strategies developed in the first decades of this plan, the compartment could be raised to the target elevation and create 2,000 acres tidal wetlands.

Creating three adjacent compartments parallel to the San Joaquin River also provides versatility for the breaching of peripheral levees to expand the floodplain for flood attenuation benefits and sediment capture, should that method of fill prove to be effective. Like the previous levees, this final east-west levee is constructed on a narrow band of mineral soil extending from the end of Mayberry slough.

4.6 50-Year Plan

Within the first 30 years, over 3,600 acres of Sherman Island are restored to tidal wetlands at or near sea level. By this time, we assume that fill and restoration techniques will have advanced so that the remaining 7,600 acres can be restored within the next twenty years. We restrain from detailing 50-year plan because it would be unreasonable to project restoration 50 years into the future based on existing knowledge and strategies.

4.7 Estimated Cost

Cumulative cost estimates for the first three phases (30 years) of the restoration plan are presented in Table 4.4. We have not estimated the cost for executing the 50-year plan because the fill techniques that will be used will be contingent upon those that have proven to be the most effective and economical during the preceding phases.

Table 4.4. Cost Estimates

Phase	**New Levees (ft)**	**Levee construction cost ($ millions)**	**Levee material cost ($ millions)**	**Fill cost ($ millions)**	**New Tidal Marsh (acres)**	**Total Tidal Marsh (acres)**	**Subtotal Cost ($ millions)**	**Total Cost ($ millions)**
5-year	20,000	$8	$29	$31	200	200	$67	$67
10-year	23,000	$9	$28	$28	1,420	1,620	$65	$132
30-year	21,000	$8	$28	$106	2,000	3,620	$142	$274
50-year	0	$0	$0	No estimate	7,700	11,320		
Total	*64,000*	*$24*	*$85*	*$165*		*11,320*		*$274*

$15/yd^3 constructed levee

Fill costs from Table 3.2

4.8 Conclusion

According to this plan, 35% of Sherman Island (3,620 acres) will be restored to tidal marsh in 30 years, at an approximate cost of $274 million (Table 4.4). The plan projects that within fifty years all of Sherman Island will be restored to tidal habitat at or near sea-level. This will fully eliminate reliance on levees and eliminate the seismic vulnerability of Sherman Island. It will better defend against salinity intrusion in the event of an earthquake than the existing levee system. It will create habitat connectivity from Suisun Marsh into the western Delta. It will do so on land that is already primarily owned by CALFED constituent agencies.

Strategies learned from the Sherman Island experience could be applied in the future to subsided island restoration through out the Delta even before the fifty-year plan is complete. Jersey Island, Webb Tract, and Twitchell Island all offer challenges and opportunities for subsided island restoration that need to be addressed to prevent levee failure and salinity intrusion in the Delta.

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