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Coastal and Hydraulics Laboratory

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Sediment Analysis and Modeling for the South San Francisco Bay Shoreline Study

Gary L. Brown

Draft

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Sediment Analysis and Modeling for the South San Francisco Bay Shoreline Study

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Draft report

Approved for review

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Under South San Francisco Bay Shoreline Study

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Abstract: This report describes sediment transport analysis and modeling work done in support of the South San Francisco Bay Shoreline Study. This work was done for the purpose of generating a predicted morphology associated with YEAR-50 (2067) without project conditions in far South Bay. This morphology was provided to the long wave and short wave modeling teams, for the purposes of including the impacts of these morphologic changes on the flooding potential associated with long and short wave propagation across the far South Bay domain. The analysis contained herein consists of South Bay estimated sediment budget analyses for existing, YEAR-0 (2017), and YEAR-50 conditions. Sediment transport modeling results are also used in support of the sediment budget analyses, to help define some of the qualitative and quantitative processes that impact morphological evolution in Far South Bay.

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Preface

The South San Francisco Bay Shoreline Study sediment transport modeling was performed in support of the U. S. Army Engineer District, San Francisco. The purpose was to generate estimates of morphologic change to support the long and short wave modeling components of the shoreline study. This report summarizes the sediment transport analysis and modeling component of the study.

This report was prepared by Gary L Brown, Estuarine Engineering Branch of ERDC-CHL, under the supervision of Dr. Robert McAdory, Chief of the Estuarine Engineering Branch, Mr. Bruce Ebersole, Chief of Flood and Storm Protection Division, Dr. Rose Kress, Deputy Director of CHL, and Dr. William Martin, Director of CHL. COL Gary E. Johnston was Commander and Executive Director of ERDC, and Dr. James R. Houston was ERDC Director.

Unit Conversion Factors, Non-SI to SI Units of Measurement

Multiply	By	To Obtain
cubic feet	0.02831	cubic meters
cubic yards	0.7645549	cubic meters
feet	0.3048	meters
inches	0.0254	meters
miles (nautical)	1,852	meters
miles (U.S. statute)	1,609.347	meters
square miles (U.S. statute)	2.59	square kilometers
mbar	1.00	hPa

1 Introduction

The South San Francisco Bay Shoreline Study required estimates of future morphologic change for the Far South Bay portion of South San Francisco Bay for use in long and short wave modeling. This report documents the methods used to evaluate the expected future morphologic change in South San Francisco Bay. Chapter 2 gives an overview of general circulation patterns in the Bay, and studies of morphologic change within the Bay. Chapter 3 gives a sediment budget analysis, including expected changes to the budget associated with the Year 0 and Year 50 conditions. Chapter 4 gives the results of a numerical modeling analysis of the trends associated with pond breaching. Chapter 5 gives the justification for the selection of the morphologic changes associated with Year-50. Chapter 6 is a summary of the report.

2 Sediment Dynamics and Morphologic Change in San Francisco Bay

Sediment Transport Pathways

The general circulation pattern of sediment within San Francisco Bay has been well described by several researchers (e.g., Ogden Beeman & Associates, 1992). Quantification of these various transport mechanisms is very problematic, but a qualitative description of the dominant processes can be given for general guidance.

Sediment supplied to the Bay via the Sacramento/ San Joaquin Delta tends to settle in the upper bays. Some large flow events can carry suspended sediment all the way to Central and South Bay, but most of the annual sediment load is deposited further upstream.

Most of this sediment inflow occurs during the winter and spring. In the summer, daily winds tend to resuspend the sediment in the shallows via wind-wave action. The sediment is then slowly transported though the bay system to Central Bay.

When the sediment reaches Central Bay, it either resettles in Central Bay, travels through the Golden Gate and out of the system, or is transported into South Bay.

Once in South Bay, the sediment is either deposited within the bay, or passes through Dumbarton Bridge into Far South Bay.

Wind wave resuspension tends to mobilize the sediment in the mudflats of South Bay and Far South Bay. Residual circulation induced by these summer winds tends to be toward Far South Bay in the shallows, and towards Central Bay in the deeper tidal channel. Hence, as wind waves resuspend sediment in the shallows, the sediment is driven by residual circulation into Far South Bay.

In addition, wave heights in Far South Bay are mitigated by their passage though the gap at Dumbarton Bridge (Smith, 2009). This can create a suspended sediment concentration gradient across the Dumbarton Bridge opening, and drive a net tidal dispersive transport towards Far South Bay.

Sediment deposits in Far South Bay until an equilibrium is achieved between sediment supply and wind wave erosion. The excess sediment is then transported towards Central Bay via the main tidal channel, and recirculates through the system.

Locally derived sediment from tributaries is a significant fraction of the total available sediment in the system. These sediments are transported together with the sediments derived from the Delta.

Recent History of Morphologic Evolution

Several studies of morphologic evolution have been conducted in the Bay. Krone (1979) analyzed baywide bathymetric change from 1870 to 1950, and noted the slow migration of excess sediment resulting from historic hydraulic mining practices. This migration took place over decadal time scales. This study provided strong evidence of the temporal lag between sediment supply from the delta and sediment availability to the Central and South Bay systems.

The analysis by Ogden Beeman & Associates (1992) includes a baywide evaluation of morphologic change from 1955-1990. Of note in this study is the pattern of persistent erosion in South Bay north of Dumbarton Bridge, and persistent deposition in Far South Bay (south of Dumbarton Bridge). This deposition persisted in spite of dramatic subsidence in Far South bay associated with drought and groundwater withdrawal.

More recently, Jaffe and Foxgrover (2006) investigated the morphologic change associated with mudflats in South Bay and Far South Bay, for the years 1858-2005. This analysis exhibits similar trends to those observed in the Beeman study: i.e. mudflat erosion in North of Dumbarton Bridge, and mudflat stability or deposition South of Dumbarton Bridge.

3 Sediment Budget Analysis of South Bay

Several researchers have developed sediment budget analyses of San Francisco Bay. Of note are recent analyses of the entire Bay from Ogden, Beeman and Associates (1992) and an analysis of South Bay conducted by Philip Williams and Associates (2006).

For the purposes of this study, and estimate of the South Bay sediment budget for recent historical, year 0, and year 50 conditions was developed. Year 0 is taken to be the year 2017, and year 50 is taken to be the year 2067. This analysis was used to determine the sediment supply required to maintain an equilibrium planform in Far South Bay.

This analysis was developed under the assumption (corroborated by several lines of indirect evidence) that Far South Bay currently receives surplus sediment, which is either stored as net deposition, or exported from Far South Bay via ebb currents in the main tidal channel. (Shoelhammer, 1996) Therefore, the crucial threshold for disruption of the recent historical morphologic trend towards net deposition in Far South Bay is the threshold sediment demand, where the system switches from a sediment rich system to a sediment starved system. This analysis was designed to develop quantitative estimates of that threshold sediment demand, and to determine the likelihood that it will be exceeded.

Sediment Sources and Sinks

The primary sources of sediment to South Bay are the local tributary inflows, and the sediment supplied by exchange with Central Bay, which in turn is supplied by sediment outflow from the Sacramento/San Joaquin Delta.

Several researchers have provided estimates of the sediment yield associated with the local tributary inflows in South Bay (north of Dumbarton Bridge) and Far South Bay (South of Dumbarton Bridge). (Porterfield 1980, Philip Williams and Associates, 2006), These analyses rely on observed USGS stream gage data, as well as sediment yield estimates associated with watershed parameters.

As part of this study, Scott (2009) has developed a new analysis of these local tributary inflows. This analysis utilizes these same data sources, as

well as 1D HEC-6 numerical modeling results. The analysis indicates a significantly lower sediment yield to the Bay than is predicted by the previous methods, especially with respect to tributary inflows to Far South Bay. This is likely due to the fact that the previous analyses assume that a large fraction of sediment load in the river reaches the Bay. Scott's analysis accounts for the fact that most of the coarse grained sediments are not transported to the Bay, due to the sharp decrease in the hydraulic gradient in the tributaries as they approach the Bay. These coarse grained sediments settle in the channel and riparian floodplain, and they either remain in situ, or are dredged or mined. Therefore, Scott's analysis only accounts for the fraction of sediment that reaches the Bay, which yields a smaller estimate of these tributary inflows. Table 1 gives Scott's estimates, together with the estimates of other researchers.

Table 1
Local Tributary Sediment Inflow Estimates

Study	South Bay (mkg/yr)	Far South Bay (mkg/yr)	Total (mkg/yr)
Porterfield (1980)	--	--	300
PWA (2006)	91	181	272
Scott (2009)	73	26	99

The other primary sediment source to Far South Bay is the sediment inflow from Central Bay. Sediment can be exchanged with Central Bay via any of 4 primary transport pathways:

- Advective transport associated with tidal residual currents
- Advective transport associated with wind driven circulation
- Advective transport associated with baroclinic residual circulation
- Dispersive transport associated with tidal oscillation coupled with horizontal gradients in sediment concentration

The sediment exchange between South and Central Bay is governed by the relative strength of each of these pathways, together with the available suspended sediment supply associated with each of the bays. This complicated exchange is difficult to quantify. Reliable long-term measurements of these exchanges do not exist, and estimating the

quantity of sediment passing through the Golden Gate (and hence bypassing this exchange pathway) is problematic.

Therefore, given the level of uncertainty associated with this exchange, the sediment budget proposed here was developed such that the sediment flux between South and Central bay is given as the residual of the sum of the other sediment sources and sinks to the system. This approach can be used to develop estimates of the amount of sediment required to satisfy certain threshold conditions within the system (e.g. the minimum sediment supply required to maintain an equilibrium planform in Far South Bay). These threshold values can be compared to estimates of available sediment supply to determine the likelihood that these quantities of sediment will be available to the system.

Sediment Budget Analyses

Recent History (1956-1990)

A sediment budget was first developed for the recent history of the Bay. This analysis utilized the bathymetric change calculations given in Ogden Beeman & Associates (1992) for the years 1956-1990. These bathymetric change calculations were needed to estimate the sediment sources and sinks associated with morphologic change. The results of the analysis are given in Table 2. The analysis includes results both with and without the impacts of subsidence on the net sediment deposition in Far South Bay. Historically, significant subsidence (on the order of 1-2 meters) occurred during the period of record in Far South Bay, due primarily to low rainfall and groundwater withdrawal (Ogden Beeman & Associates, 1992). The without subsidence values are given in parenthesis. Note that these analyses are performed with an assumed wet bulk density of bed sediment equal to 1300 kg/m^3.

Table 2
Sediment Budget for South Bay and Far South Bay, 1956-1990

Sediment Source/Sink Term	South Bay (mkg/yr)	Far South Bay (mkg/yr)	Total (mkg/yr)
Tributary Sediment Inflow	73	26	99
Net erosion/deposition of bed sediments (erosion is positive) (Ogden, Beeman & Associates, 1992) (Note: estimate accounts for sea level rise of 0.0011 m/yr)	158	-525 (-120)	-368 (38)
Sediment exchange from Central Bay (Flux from Central Bay to South Bay is positive)			269 (-61)

Note: values in parenthesis are calculations assuming no subsidence in Far South Bay.

YR-0 conditions

For an estimate of the sediment budget required for YR-0 conditions, the following assumptions were made.

- The sediment sources associated with local tributary inflows were assumed to be the same as the historic quantities.
- The sediment sinks associated with sea level rise were adjusted for the year 2017 by assuming an accelerated rate of sea level rise corresponding to the NRC I curve (National Resources Council, 1987).
- The sediment source associated with erosion in South Bay was assumed to be the same as the historic value. As a sensitivity test, the analysis was also done with zero erosion in South Bay. These results are given in parenthesis.
- The planform for Far South Bay was assumed to maintain equilibrium. This assumption is made such that the analysis yields the threshold value of sediment supply from Central Bay required to maintain this equilibrium planform in Far South Bay.
- The sediment sink associated with those projects designed to capture sediment (i.e. breaches in ponds A6 and A8, and the existing breaches in the Island Ponds, A19-A21) is included in the

budget. This demand is calculated by estimating the total volume of sediment expected to fill the ponds, and then prorating the rate of capture such that the highest rate is experienced in the first years of the project. This rate is likely to be an exponential function of the depth of the restored ponds, but for the purposes of this analysis it is assumed to be a linear rate.

Table 3
Sediment Budget for South Bay and Far South Bay, YR-0

Sediment Source/Sink Term	South Bay (mkg/yr)	Far South Bay (mkg/yr)	Total (mkg/yr)
Tributary Sediment Inflow	73	26	99
Net erosion/deposition of bed sediments (erosion is positive)	158 (0)	0	158 (0)
Net deposition associated with restored ponds: A6, A8, A19,A20, and A21.	0	-63	-63
Additional Deposition due to Accelerated Sea Level Rise (0.00293 m/yr)	0	-53	-53
Sediment exchange from Central Bay (Flux from Central Bay to South Bay is positive)			-141 (17)

YR-50 conditions

For an estimate of the sediment budget required for YR-50 conditions, the following assumptions were made.

- The sediment sources associated with local tributary inflows were assumed to be the same as the historic quantities.
- The sediment sinks associated with sea level rise were adjusted for the year 2067 by assuming an accelerated rate of sea level rise corresponding to the NRC I curve (National Resources Council, 1987).
- The sediment source associated with erosion in South Bay was assumed to be the same as the historic value. As a sensitivity test, the analysis was also done with zero erosion in South Bay. These results are given in parenthesis.
- The planform for Far South Bay was assumed to maintain equilibrium. This assumption is made such that the analysis yields the threshold value of sediment supply from Central Bay required to maintain this equilibrium planform in Far South Bay.
- The sediment sink associated with those projects designed to capture sediment (i.e. breaches in ponds A6 and A8, and the

existing breaches in the Island Ponds, A19-A21) is included in the budget. This demand calculated by estimating the total volume of sediment expected to fill the ponds, and then prorating the rate of capture such that the highest rate is experienced in the first years of the project. This rate is likely to be an exponential function of the depth of the restored ponds, but for the purposes of this analysis it is assumed to be a linear rate.

Table 4
Sediment Budget for South Bay and Far South Bay, YR-50

Sediment Source/Sink Term	South Bay (mkg/yr)	Far South Bay (mkg/yr)	Total (mkg/yr)
Tributary Sediment Inflow	73	26	99
Net erosion/deposition of bed sediments (erosion is positive)	158 (0)	0	158 (0)
Net deposition associated with restored ponds: A6, A8, and the Island Ponds	0	-21	-21
Sea Level Rise (0.00572 m/yr)	0	-136	-136
Sediment exchange from Central Bay (Flux from Central Bay to South Bay is positive)			-100 (58)

Discussion

These results show that the most significant sediment demand associated with maintaining the equilibrium planform in Far South Bay is the expected accelerated rate of sea level rise. The demand associated with the breached ponds is significant, but the peak demand associated with these breaches is in the earliest years of the project, whereas the demand associated with accelerated sea level rise increases as this rate continues to accelerate. Therefore, the uncertainty associated with the rate of sea level rise corresponds to the largest uncertainty in the sediment demand.

If the sediment demand for South Bay and Far South Bay exceeds the supply from local sediment sources, the residual requirement must be satisfied by sediment supply from exchanges with Central Bay. The

available sediment supply from the Sacramento/San Joaquin river system to San Francisco Bay is expected to decrease over time, due to sediment conservation practices, reservoir regulation, and water diversions (Wright and Shoelhammer, 2004). In order to examine the impacts of sediment supply on the availability of sediment for South Bay and Far South Bay, the sediment exchange values from Central to South Bay given in Tables 2-4 are plotted as a ratio of the 1990 sediment inflows from the Central Valley, as given by Ogden Beeman & Associates (1992). The inflows are given in Table 5, and the plot is given in Figure 1. Note that these inflows are approximations of the available sediment supply associated with Central Bay. They are leading indicators of the actual sediment supply, since sediment tends to migrate gradually though the upper Bays via settling and wind wave resuspension in the shallows.

The analysis indicates that the sediment demand through YR-50 does not exceed the supply of sediment from local sources (local tributary inflow and the erosion of South Bay sediment). For the sensitivity case of zero sediment erosion from South Bay, the demand does exceed the local supply, but the sediment required from the Central Bay source is much smaller than the sediment supply from Central Bay for the historic sediment budget. This is true even if one includes the reduction in the available sediment supply over time. For example, the expected sediment supply in 2035 is roughly half of the supply for the 1956-1990 period, whereas the maximum expected demand for YR-50 is less than a fourth of the historic sediment supply from Central Bay.

Table 5
Predicted Central Valley Sediment Load (Ogden Beeman & Associates, 1992)

Design years	Sediment Load (mkg/yr)
1956-1990	2380
1990	1590
2035	1430

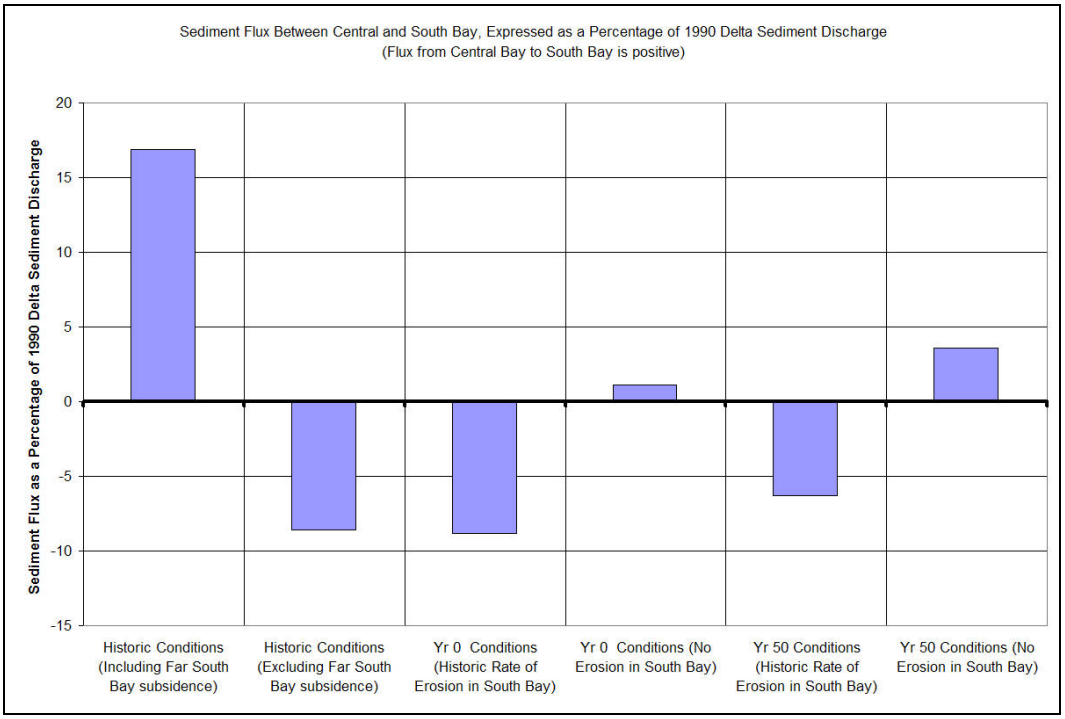

Figure 1. Sediment flux between Central Bay and South Bay expressed as a percentage of the estimated Central Valley sediment supply for 1990.

Figure 1 demonstrates that the recent historic sediment supply from Central Bay approached 17% of the total available sediment inflow. This does not necessarily indicate that 17% of the available sediment was diverted, however, since the sediment supply available at Central Bay can lag the sediment inflow from the central valley by decades (Krone, 1979). In addition, a much larger fraction of the sediment may be diverted, but this excess sediment supply is retuned to the central Bay via the main tidal channel in South Bay.

The analysis given here indicates that the sediment demand associated with year 50 is unlikely to exceed the recent maximum historic demand associated with significant Far South Bay subsidence. The predicted sediment demand for Yr-50 conditions is governed largely by the accelerated rate of sea level rise, which in turn is bounded by significant uncertainty.

4 Sediment Transport Modeling and Results

AdH hydrodynamics and sediment transport

In order to gain further insight into the sediment dynamics of the South Bay system, a numerical sediment transport model was developed. The hydrodynamic model used to drive the sediment transport model is the Adaptive Hydraulics model (ADH). ADH is an unstructured finite-element modeling package capable of simulating multiple physics, including shallow water flows, Navier-Stokes flows and groundwater flows. It has the capacity to dynamically refine and relax mesh resolution, such that gradients within the computational domain are accurately resolved. For a complete description and references, see http://adh.usace.army.mil.

The sediment transport module is multiple grain sized, mixed sediment transport algorithm attached to the AdH hydrodynamic model. At the time of this study, the sediment transport module was considered developmental. Hence the results are intended to be used only for analysis of trends and processes, and to be used as supplemental information for the overall analysis of the system.

For this application, the model was run in 2-dimensional depth-averaged mode. This assumption implies that 3-dimemsional forcings, such as salinity stratification, are not significant factors in understanding the dynamics of the system. This assumption is clearly not valid for North and Central Bays, but for South Bay many of the dominant processes can be investigated effectively with a depth-averaged model. However, for certain conditions and at certain scales, the 3-dimensional effects become important, and this possibility should not be neglected when evaluating the results.

Model Domain

The model domain and bathymetry were taken from the long wave modeling effort of Letter and Sturm (2009). Hence the model domain includes the entire Bay. As with the long wave effort, model resolution is focused heavily on the study area of the model, with coarse resolution given in the upstream reaches of the domain. Figure 2 depicts the entire model mesh.

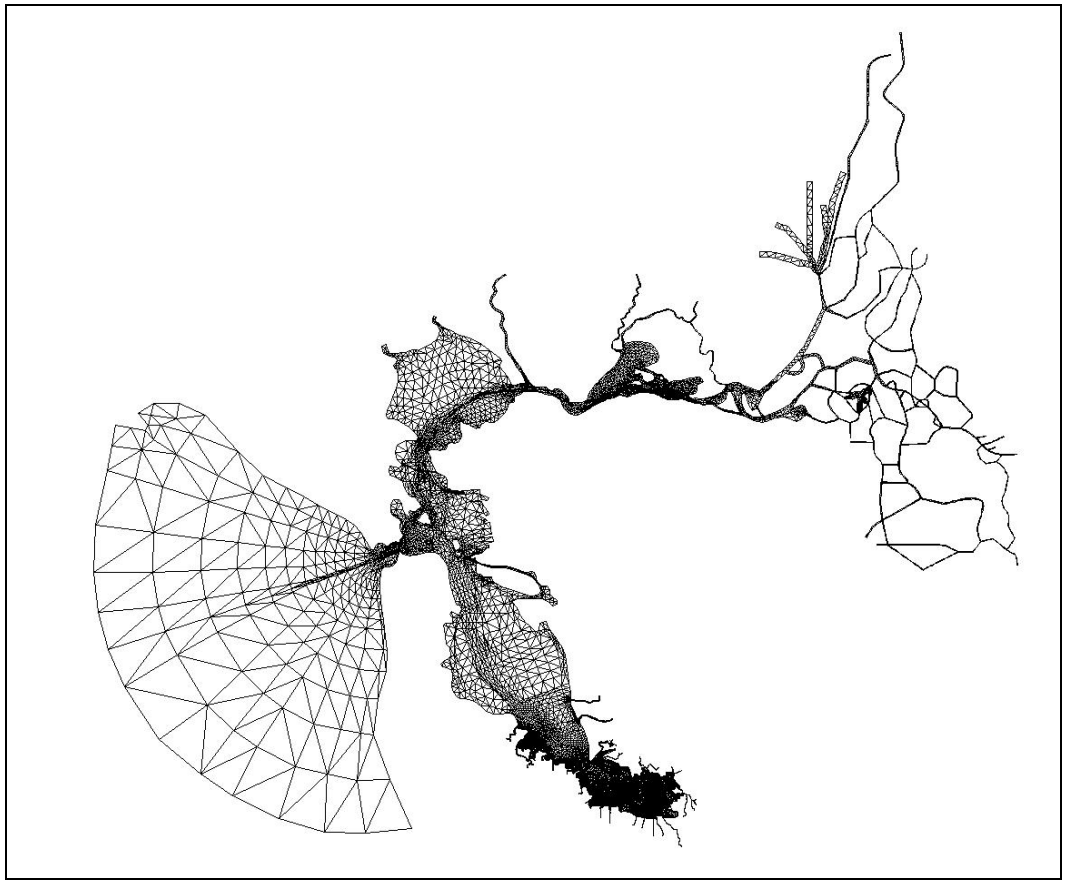

Figure 2. The model mesh.

Applied boundary conditions

The hydrodynamic boundary conditions used to drive the model were taken from the long wave modeling effort of Letter and Sturm (2009). These include the tidal boundary conditions and the wind speed and direction.

Note that wind wave resuspension was calculated by the method of Teeter (2001), which uses wind speed as a proxy for shallow water wave conditions. Since it is known that the wave energy in Far South Bay is dissipated as waves pass through Dumbarton Bridge, it was necessary to reduce the wind speed by some factor for Far South Bay. The factor chosen for this reduction in Far South Bay was 0.9.

The sediment inflow boundary conditions for the Sacramento and Jan Joaquin Rivers were taken from USGS streamflow data at Freeport and

Stockton. The sediment inflows for the local tributaries in South bay were provided by Scott (2009), using the methods developed for the fluvial sediment analysis for this project.

Applied sediment characteristics

Sediment in South San Francisco Bay tends to consist primarily of cohesive particles being transported as discrete flocs. There flocs tend to exhibit spatially consistent behavior, due to the homogeneity of the sediment in the system (Gangu, et al, 2006).

The bed sediment in South Bay consists of sediment sizes ranging between clay sizes and fine sand, with the majority of the sediment consisting of clay and silt particles. Most of the sand found in the surficial sediment is found in the tidal channel, especially in the proximity of the local tributary mouths. Fining of the bed sediment occurs with lateral distance from the main tidal channel, which is evidence of depositional sorting. Figure 3 depicts the results of a coulter-counter analysis of surficial bed sediment collected in Far South Bay for this study. Note that the sediment in the mudflat consists exclusively of clay and silt classes, whereas fine sand is present in the tidal channel sample.

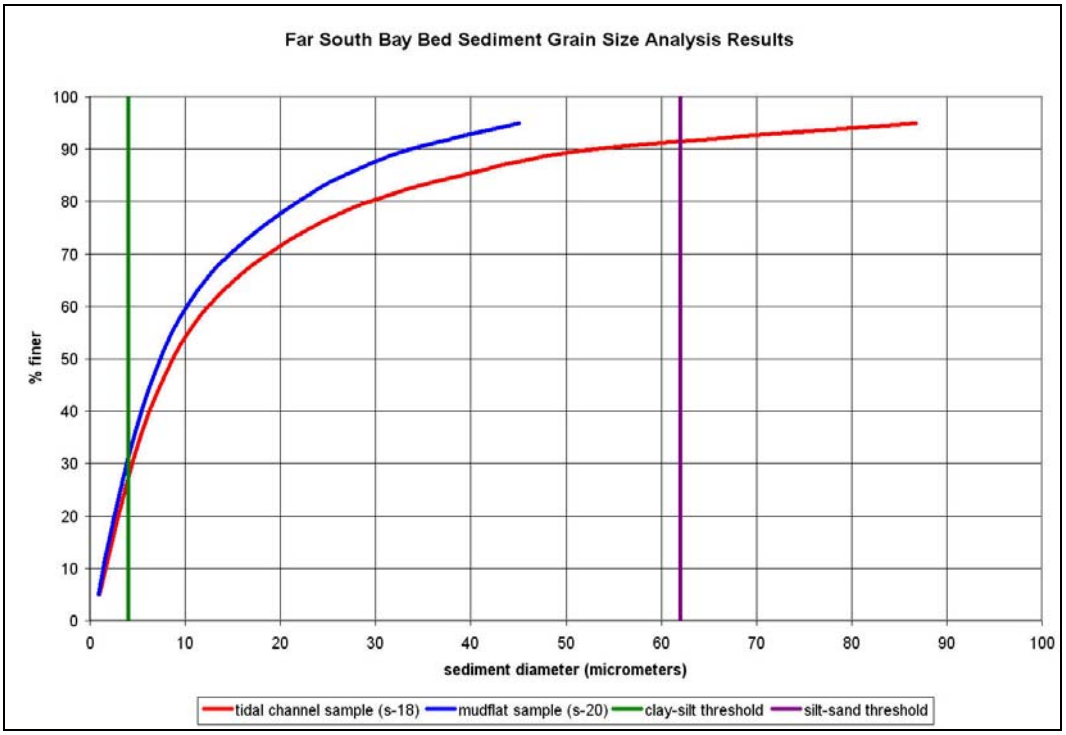

Figure 3. Sediment bed samples in Far South Bay

For the purposes of modeling the sediment in the bay, 6 sediment classes were chosen. These range in size from clay to fine sand. Each clay and silt class was assigned a discrete, constant settling velocity (the fine sand settling velocity is calculated using semi-empirical methods within the model). These settling velocities vary between 0.05 mm/s for the clay particles, to 0.9 mm/s for the coarse silt particles.

The erosion properties of the bed sediment were derived from SEDFLUME core data that was developed and analysed by Sea Engineering (2005). These SEDFLUME core data were fit to a power law relationship for erosion given by Alishahi and Krone(1964)

$$E_s = M\left(\frac{\tau}{\tau_{ce}} - 1\right)^n \qquad (1)$$

Where, M is the erosion rate constant for the grain class, τ is the applied shear stress, τ_{ce} is the critical shear stress for erosion and n is an exponent.

The SEDFLUME core data was used to generate 2 separate values of bed sediment coefficients used in this formulation: 1 set for surficial sediments, and 1 set for compacted sediments. A third set of values were assigned to new sediment deposit. This new deposit is allowed to consolidate within the model, such that the sediment parameters are identical to the surficial parameters within 28 days. This consolidation process ensures that sediment bed strength is correlated to the frequency of applied shear stress on the bed. The values used in the model are given in Table 6.

Table 6
Erosion Coefficients for South Bay Sediment

Bed sediment type	Bulk density (kg/m^3)	Critical erosion shear (Pa)	Erosion rate constant ($kg/m^2/s$)	Erosion rate exponent
New sediment deposit	1200	0.05	.00001	1
Surficial sediment	1300	0.26	.0025	1
Compacted sediment	1350	0..56	.01	2

Model validation

The sediment transport model was validated against observed data taken by the USGS (http://ca.water.usgs.gov/abstract/sfbay/). These data consist of optical backscatter data that have been field verified against periodic suspended sediment samples. The simulation period for comparison to field data was January through April of 2003.

Four observation locations were selected for comparison. These locations are given in Figure 4. The comparisons between model and field data are given in Figures 5-8.

Note that both the model and field data consist of both surface (or mid-depth) and bottom observations. Although the model is simulated in

depth-averaged mode, a theoretical sediment profile associated with the solution, and hence the modeled sediment can be obtained at any location in the profile, given the depth averaged concentration and the local profile properties.

The modeled suspended sediment values at Mallard Island are consistently low, indicating that the modeled sediment supply to the Bay system is underrepresented. If the model were used to make long term predictions of change, this deficiency would impact the accuracy of the results. However, for the short term trends analyses used here, this deficiency is unlikely to affect the results.

The modeled and observed suspended sediment values at the other gages are highly correlated. Suspended sediment movement in South Bay and Far South Bay is dominated by tidal currents and winds, and the surficial bed sediment properties are relatively homogeneous. Therefore, matching observed values only requires that these few parameters are well represented in the model.

This validation against suspended sediment data is sufficient to investigate general trends of sediment circulation, and initial changes to planform morphology. However, long term investigations of morphologic change require a more comprehensive validation process, including validation of erosion and deposition quantities.

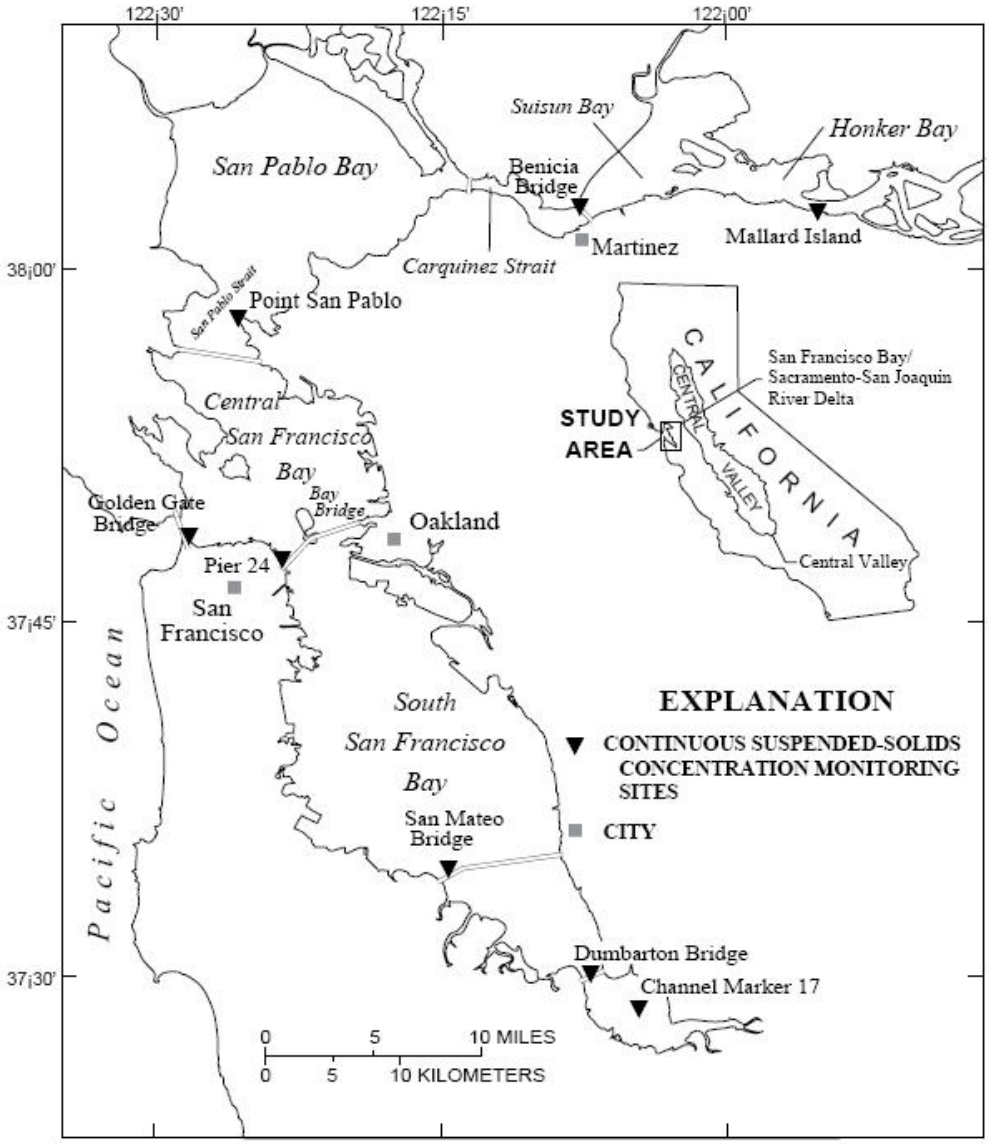

Figure 4. Suspended Sediment Observation Locations (source: USGS)

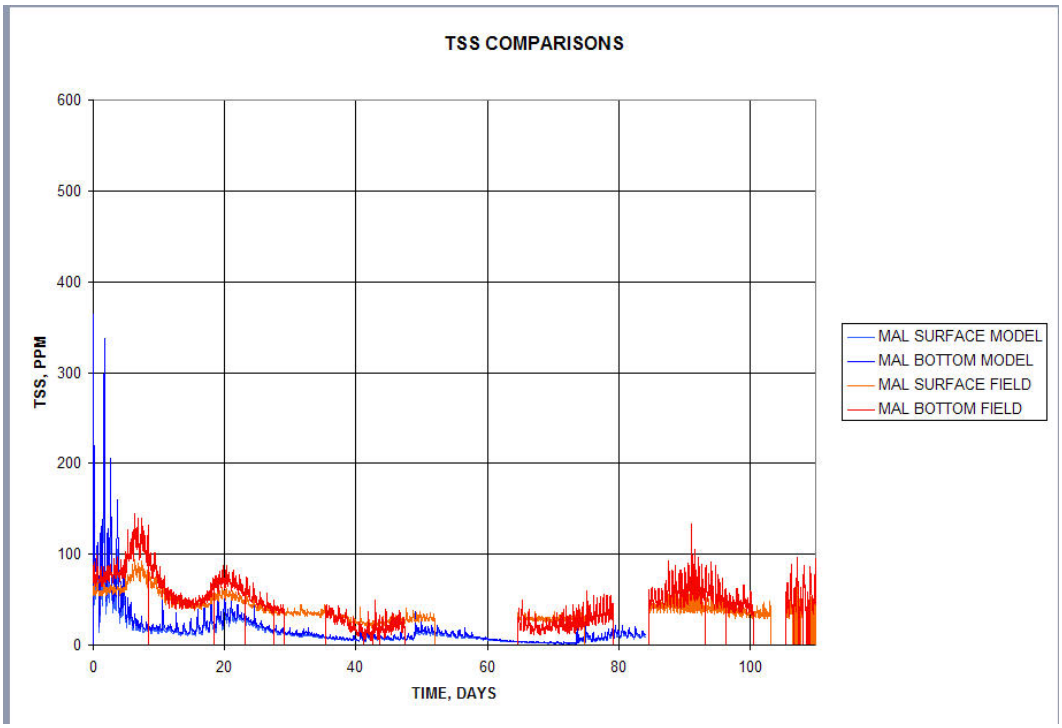

Figure 5. Observed and Modeled TSS at Mallard Island (Observed data from USGS)

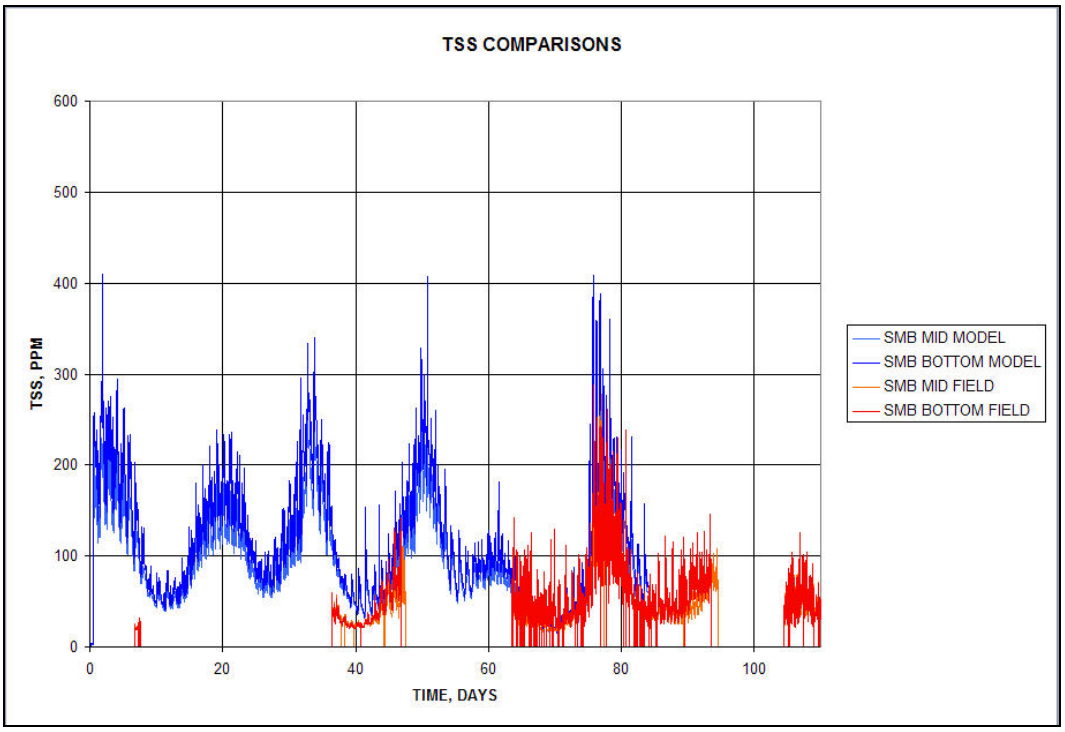

Figure 6. Observed and Modeled TSS at San Mateo Bridge (Observed data from USGS)

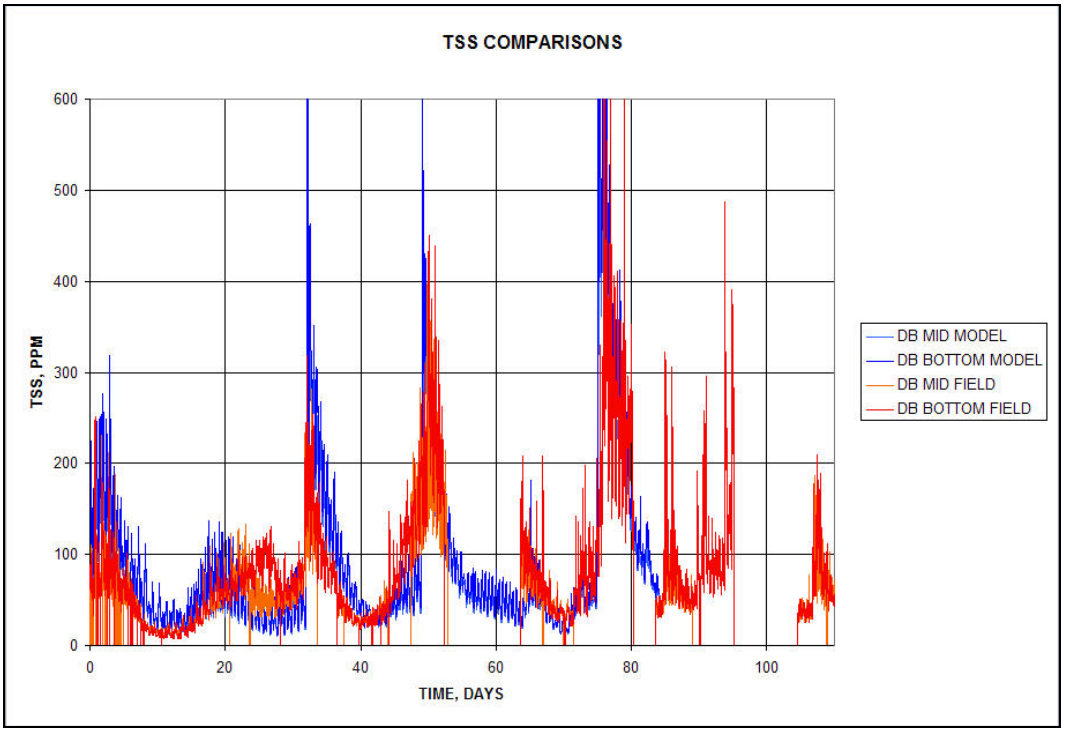

Figure 7. Observed and Modeled TSS at Dumbarton Bridge (Observed data from USGS)

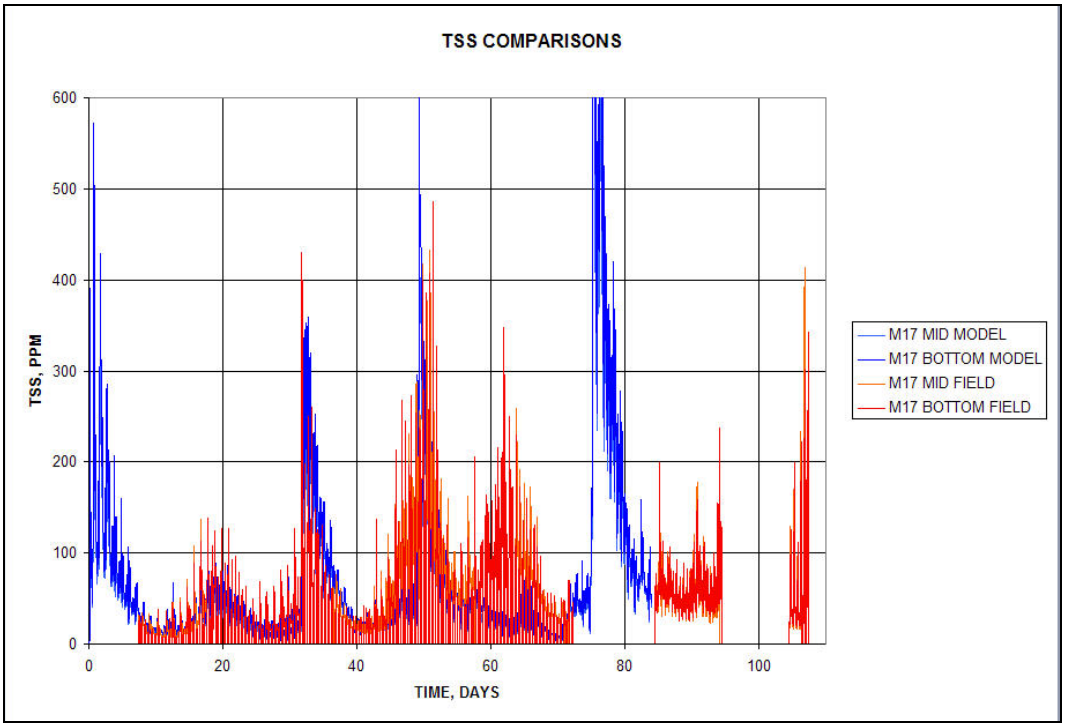

Figure 8. Observed and Modeled TSS at Channel Marker 17 (Observed data from USGS)

Model results in support of morphologic trends analysis

The model was used to investigate the trends associated with the proposed breaching of ponds A6 and A8. To this end, 3 separate model runs were conducted.

- No breaches in A6 or A8 (existing conditions)
- Initial breaching of A6 and A8 (initial breach)
- Breaching of A6 and A8 with expected sediment infilling (long-term breach)

The modeled results demonstrated little morphological change at A8, other than some erosion of the breach itself and the gradual infilling of the pond. The initial trends associated with breaching of A6 are given in Figure 9. This figure shows the bed displacement difference between the initial breach simulation and the existing condition simulation. Note that a negative displacement difference does not necessarily indicate erosion; it indicates a change in displacement. So, for example, if a particular location is depositing, it could merely indicate a decrease in the deposition rate. So, for the purpose of clarity, the terms erosion and deposition are discarded in favor of negative displacement difference and positive displacement difference.

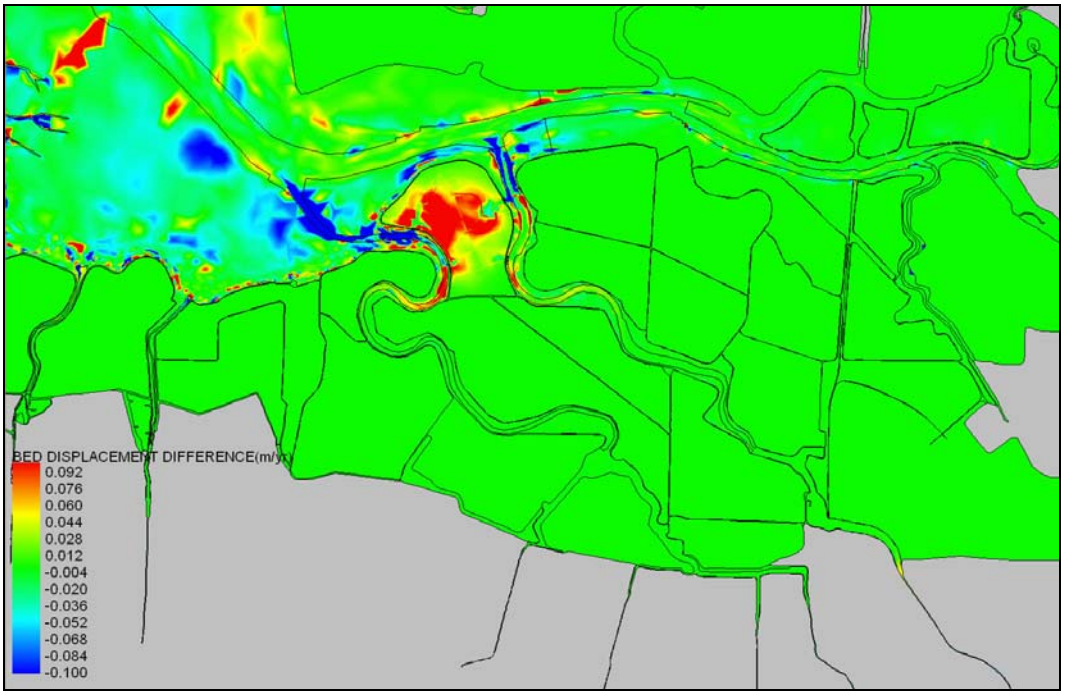

Figure 9. Displacement difference associated with initial breaching at A6

Several trends are noteworthy. Each of the breaches experiences significant negative displacement difference, especially those on the north end of A6. Also, there is negative displacement difference observed in the Guadalupe Slough and Alviso Slough tidal channels, seaward of these 2 northern breaches, and also in the channel and mudflats west-northwest of A6. Landward of the breaches, there is some positive displacement difference.

These differences represent the initial response to the breaching of A6. Figure 10 gives the initial model response to opening the breached ponds, with sediment infilling added to the ponds.

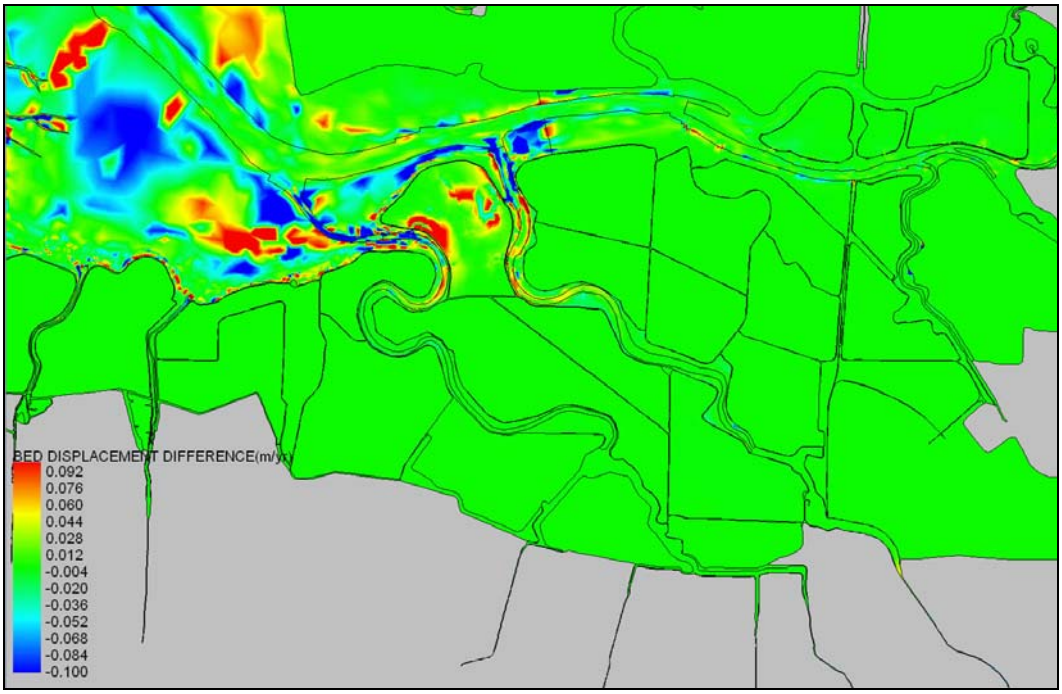

Figure 9. Displacement difference associated with initial breaching at A6, with sediment infilling in the ponds

The model still exhibits both positive and negative displacement differences, but the distribution is different than the initial breach case. The negative displacement differences are less pronounced in the channels, and sediment redistribution can be observed in the offshort mudflats.

These morphological changes are likely in response to either, or both, of two primary forcing mechanisms.

- Changes in the bed shear stress distribution associated with the opening of the breaches.

- Redistribution of sediment from the mudflats and sloughs to the ponds.

In order to address this issue, a sediment flux analysis was conducted. The modeled sediment flux at Dumbarton Bridge was observed for a resuspension event (a storm) and the subsequent tidal transport. The sediment flux was recorded for all three test configurations. The results are given in Figure 10.

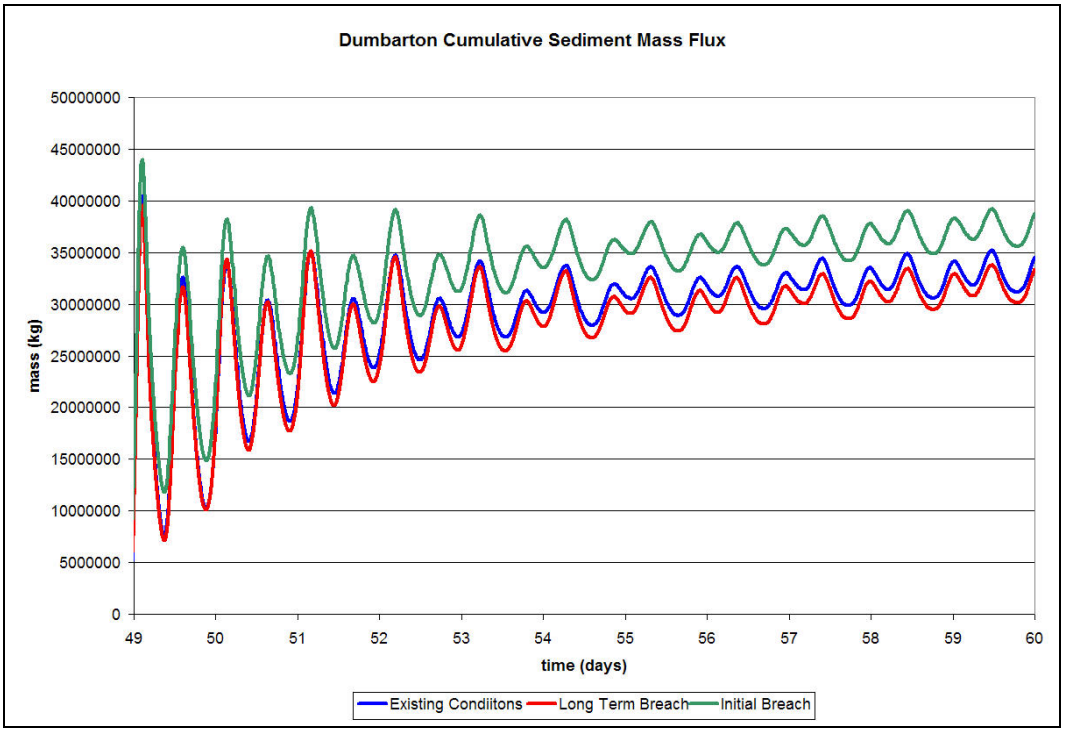

Figure 10. Sediment mass flux for a storm event and subsequent tidal forcing at Dumbarton Bridge

This analysis indicates that a significant increase in the sediment mass flux at Dumbarton Bridge is evident for the case where the sediment demand is highest (initially breached ponds). Hence, the sediment that is supplying the ponds is not primarily derived from local erosion, but is imported through Dumbarton Bridge. The increased tidal prism and decreased suspended sediment concentrations within Far South Bay are sufficient to allow advective and dispersive transport at Dumbarton bridge to resupply the sediment demand of the ponds.

These observations are consistent with both the historical observations of the response of Far South Bay to subsidence, as well as the generally observed rapid infilling of sediment observed in Far South Bay.

These modeled results indicate that the morphological changes observed in the vicinity of the ponds are primarily associated with the redistribution of sediment associated with changes to the shear stress profile, and hence to the equilibrium erosional planform. These changes can be expected to evolve over time as the sediment infilling takes place.

5 Year 50 Bathymetry

Rate of Sea Level Rise and Far South Bay Morphology

The predicted morphology of Far South Bay for the year 50 conditions is largely dependent on the rate of sea level rise. At lower rates of sea level rise, the sediment supply to Far South Bay exceeds the demand imposed by the rate of rise, and the morphology maintains an equilibrium planform relative to the water surface. As sea level rise accelerates, at some point a threshold is reached where the sediment supply to Far South Bay can no longer keep pace with the rate of rise, and Far South Bay becomes sediment starved. At that point, it is expected that the significant changes in the mudflat planform will occur, the mudflats begin to erode, and sediment redistributed to the most efficient sinks within the system.

For the purposes of this study, we investigated the impacts of 2 different sea level rise scenarios: NRC I and NRC III (National Resources Council 1987). These rates are derived using the following equation:

$$\eta(t)=(0.0012+M)t+bt^2 \qquad (2)$$

Where η(t) is the sea level rise for year t (meters), t is the elapsed time since the basline year of 1986 (years), M is the rate of local subsidence (+) or uplift (-), (meters/year), and b is the acceleration of the eustatic sea levels rise (meters/year^2)

For San Francisco Bay, the local subsidence/uplift was assumed equal to 0. The acceleration rate (b) was taken from the following table.

Table 7
National Resources Council (1987) Rates of Sea Level Rise

NRC Curve	Acceleration of sea level rise b (m/yr^2)	Rate of Sea Level rise @ Yr-0 (2067) (m/yr)	Rate of Sea Level rise @ Yr-50 (2067) (m/yr)	Total SLR @ Yr-50 (meters)	Total SLR between Yr-0 and Yr-50 (meters)
I	2.79E-5	0.0029	.0057	0.28	0.22
III	1.05E-4	0..0077	.018	0.80	0.65

Bathymetry associated with NRC I Rate of Sea Level Rise

The sediment budget analysis has shown that, for the NRC I sea level rise conditions, the expected sediment demand for the Far South Bay in Year 50 is not expected to exceed the estimated historic sediment supply to South Bay from Central Bay. The numerical modeling analysis shows that, for the limited increase in sediment demand due to the proposed pond breaching projects associated with the Year 0 conditions, the sediment needed to supply these ponds will likely be derived from outside the Far South Bay system.

These lines of evidence indicate that the Far South Bay system is likely to maintain an equilibrium with the sediment supply and wind wave climate, and hence most of the morphologic change should be associated with the breached ponds themselves, with some adjustment of the bathymetry in the immediate vicinity of the ponds associated with changes in shear stress.

Figure 11 is a color contour plot of the expected Yr-50 bathymetry for the NRC I rate of sea level rise. The overall platform elevation has increased by 0.22 m over the Yr-0 planform elevation, to account for the total sea level rise over the project life. This maintains the same average depth in Far South Bay, indicating that the planform is in equilibrium. Pond A-6 is filled completely, and Pond A-8 is partially filled.

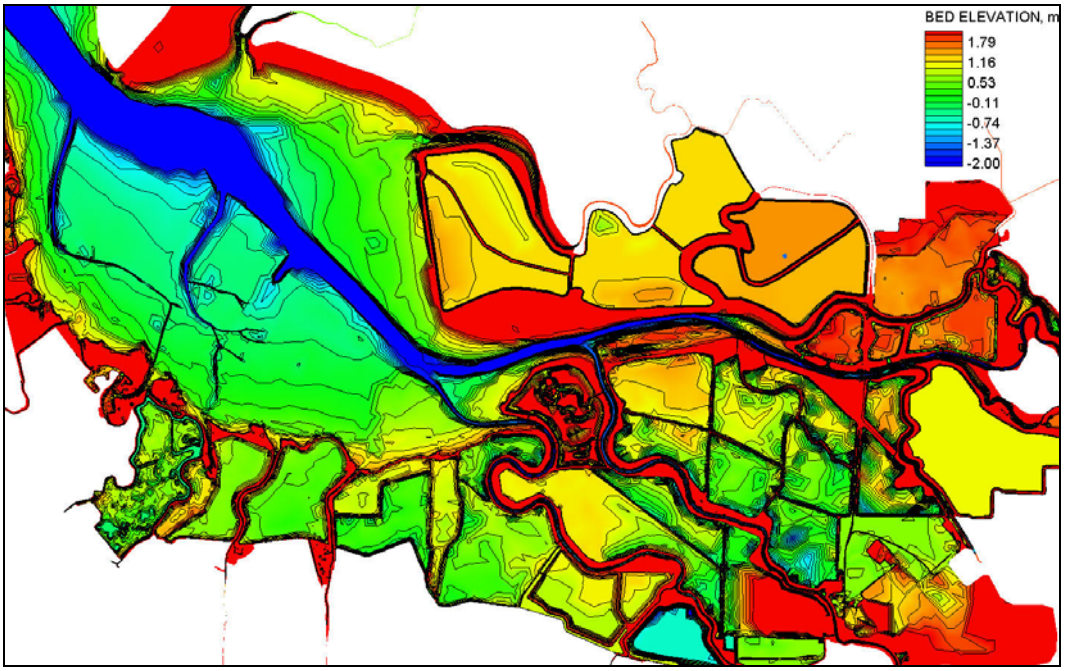

Figure 11. Yr-50 Bathymetry for the NRC I Sea Level Rise Scenario

Bathymetry associated with NRC III Rate of Sea Level Rise

For the higher rate of sea level rise given by NRC III, the critical threshold for the equilibrium planform is reached shortly after Yr-0 . Figure 12 shows the increase in the average depth in Far South Bay over the preject life, as a consequence of the accelerating sea level rise.

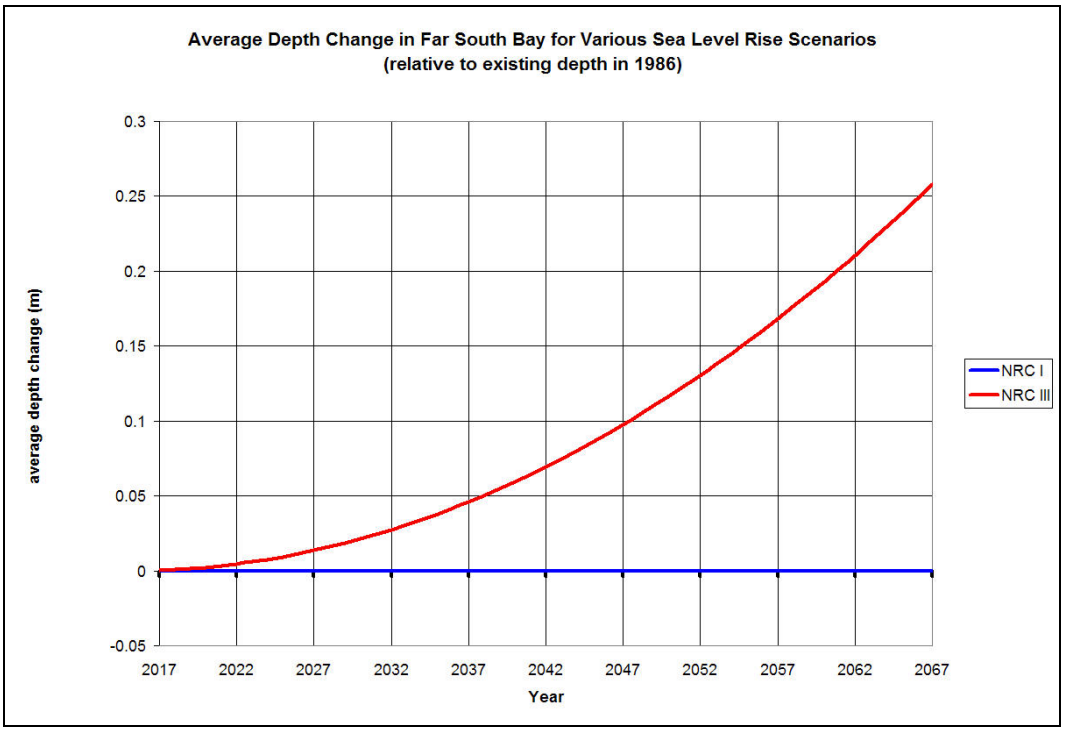

Figure 12. Average Depth Change in Far South Bay for Various Sea Level Rise Scenarios

Since the sediment supply no longer keeps pace with sea level rise, the morphology is expected to adjust to a sediment starved condition. The average depth should increase by approximately 0.25 m in Far South Bay (see Figure 12). The spatial distribution of this average depth adjustment should correlate with the spatial distribution of the erosion potential of the sediment: i.e. regions experiencing the highest erosion potential should erode the most.

The erosion potential can be estimated with ADH model output of the shear stress distribution in Far South Bay, and with the critical shear stress for erosion for the surficial muds in Far South Bay. Using this information, the spatial distribution of the morphology adjustment for the sediment starved condition is approximated by the following equation.

$$\Delta z_b = \lambda \frac{\Delta h_{avg} A_S}{\int_{A_s} \lambda dA}$$

$$\lambda = \sum_{i=1}^{i=3} \left(p_{\tau.i} \frac{\tau_i - \tau_c}{\tau_c} \right) \qquad (3)$$

$$\tau_c = 0.26$$

$$\tau_1 = 0.3$$

$$\tau_2 = 0.4$$

$$\tau_3 = 0.5$$

Where Δz_b is the bed elevation adjustment (meters), $p_{\tau.i}$ is the percent exceedance (for the ADH simulation) of the shear stress τ_i (Pa), τ_c is the critical shear stress for the surficial muds in Far South Bay (also from the ADH simulations) (Pa), A_S is the surface area of Far South Bay (meters^2), and Δh_{avg} is the average depth adjustment for Far South Bay (from Figure 12) (meters).

The resulting bed elevation change is depicted in Figure 13. Note that, although the elevation changes are all negative, this does not indicate that erosion is occurring throughout the Bay. Erosion is only occurring in areas where the change in bed elevation exceeds the increase in depth due to the accelerated sea level rise. In the areas where this is not true, the modified condition is still depositional, but at a slower rate than in the equilibrium condition.

The maximum elevation change is set equal to the total depth change for NRC III over the 50 year project life (-0.8 m, see Table 7). This was done to account for the increased resistance to erosion in the channels, due to armoring and consolidation.

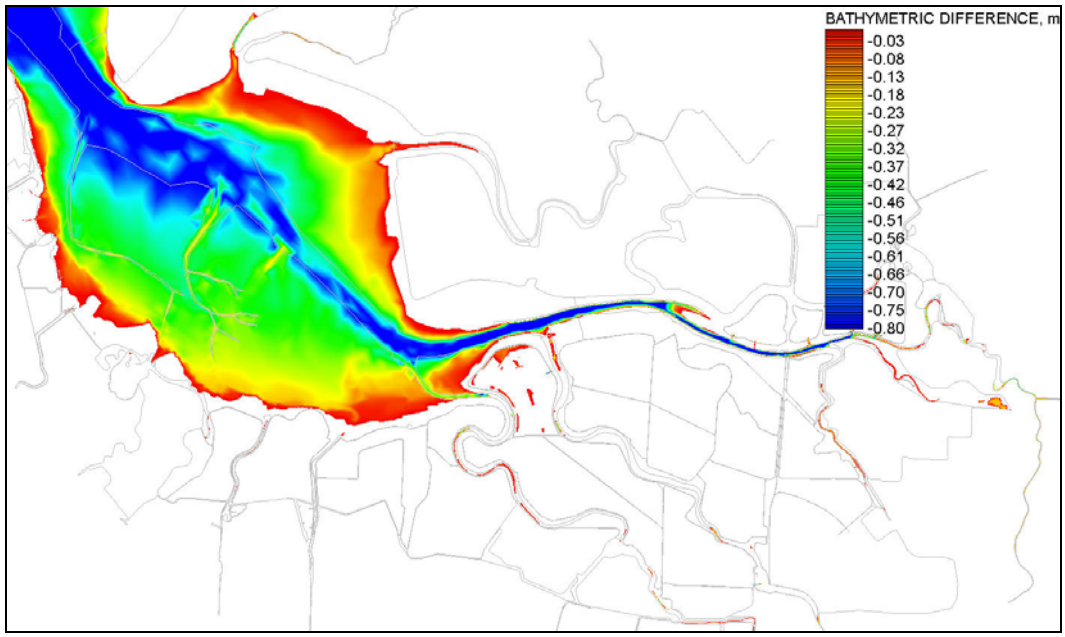

Figure 13. Bathymetric Adjustment in Far South Bay Associated with NRC III Rate of Sea Level Rise

Figure 14 is a color contour plot of the expected Yr-50 bathymetry for the NRC III rate of sea level rise. The overall platform elevation has increased by 0.65 m over the Yr-0 planform elevation, to account for the total sea level rise over the project life. The bathymetric change data given in Figure 13 is then added to the elevations, to adjust the bathymetry to the expected nonequilibrium conditions. Pond A-6 is filled completely, and Pond A-8 is partially filled.

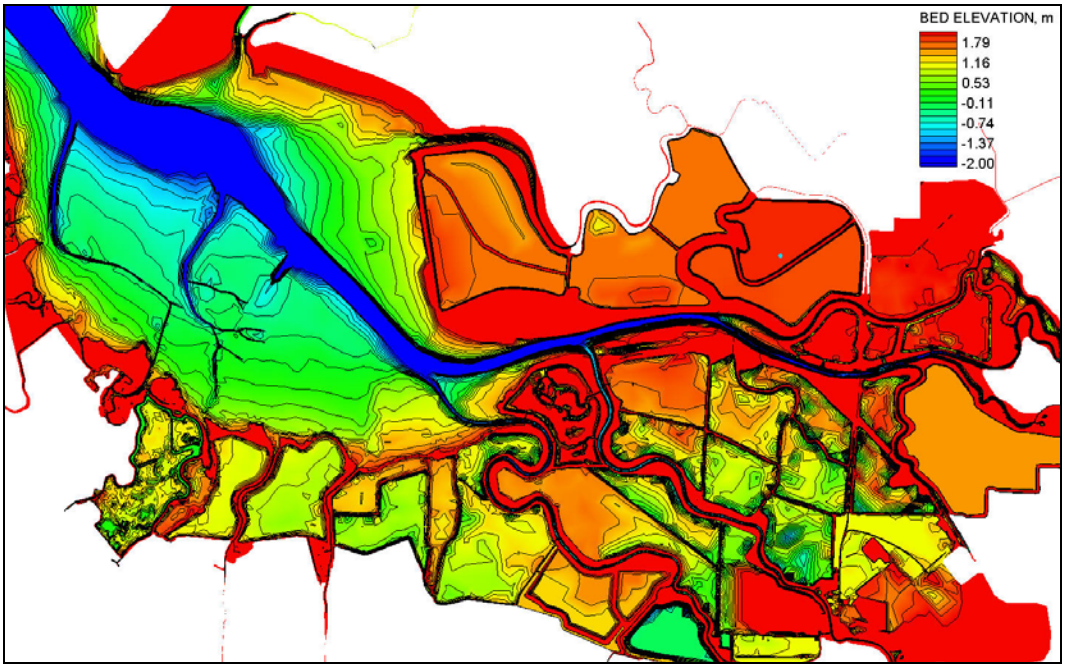

Figure 14. Yr-50 Bathymetry for the NRC III Sea Level Rise Scenario

6 Summary

- Far South Bay currently receives surplus sediment, which is either stored as net deposition, or exported from Far South Bay via ebb currents in the main tidal channel.

- The crucial threshold for disruption of the recent historical morphologic trend towards net deposition in Far South Bay is the threshold sediment demand, where the system switches from a sediment rich system to a sediment starved system.

- The sediment budget analysis indicates that the maximum sediment demand for the year-50 conditions is not expected to exceed the recent historic demand (including subsidence).

- The numerical modeling analysis shows that, for the limited increase in sediment demand due to the proposed pond breaching projects associated with the Year 0 conditions, the sediment needed to supply these ponds will likely be derived from outside the Far South Bay system.

- These lines of evidence indicate that , for the NRC I sea level rise scenario, the Far South Bay system is likely to maintain an equilibrium with the sediment supply and wind wave climate, and hence most of the morphologic change should be associated with the breached ponds themselves, with some adjustment of the bathymetry in the immediate vicinity of the ponds associated with changes in shear stress.

- For the NRC III sea level rise scenario, the increased sediment demand resulting from the increased rate of sea level rise exceeds the critical threshold for the equilibrium planform . This threshold is exceeded shortly after Yr-0. This results in a nonequilibrium planform, with an increased average depth in Far South Bay of approximately 0.25m by the end of the project life (Yr-50). This increased average depth is spatially distributed according to the erosional potential at each point in the Bay, and the resulting changes are applied to the bathymetry to generate an expected nonequilibrium bathymetry for the Yr-50, NRC III condition.

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