

NUMERICAL MODELING OF SEDIMENT DISPERSAL FOLLOWING DREDGE MATERIAL PLACEMENTS TO EXAMINE POSSIBLE AUGMENTATION OF THE SEDIMENT SUPPLY TO MARSHES AND MUDFLATS, SAN FRANCISCO BAY, USA

by

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ABSTRACT

Recent studies of sea level rise in San Francisco Bay have indicated that the majority of tidal marshes surrounding the Bay are likely to lose marsh plant communities by 2100 because natural sediment accretion rates will not keep pace with sea level rise. This potential loss of tidal marsh habitat, coupled with the requirement that 40% of the material dredged from San Francisco Bay be put to beneficial reuse, suggests that dredged material may provide a valuable resource to augment sediment supply to mudflats and marshes in the Bay. However, little information currently exists on where waves and currents transport sediment within San Francisco Bay following an in-Bay dredged material placement. A three-dimensional hydrodynamic, wave, and sediment transport model was applied to examine sediment dispersal throughout the San Francisco Bay and the Sacramento-San Joaquin Delta. One focus of the sediment transport modeling effort was to examine the sediment dispersal following dredged material placements. The model was applied to evaluate sediment dispersal away from two currently designated in-Bay sediment placement sites and two nearby sites adjacent to marsh areas. Model results indicated that placements at these sites which are in a highly dispersive region were not effective at supplying sediment to the nearby mudflats and marshes. The model was also applied to evaluate whether shallow-water dredged material placements in less dispersive areas adjacent to existing marshes or breached salt ponds would result in an increase in deposition rates within these areas through natural dispersal of the placed sediment. Comparison of these results with the dispersive location highlights the site specific nature of sediment dispersal in the Bay. At some locations within the Bay, dredged material placements were effective at supplying sediment to the surrounding mudflats and breached salt ponds and resulted in increased accretion rates. These model results highlight the usefulness of three-dimensional sediment transport modeling for managing dredged material placements and suggest that dredged material placements in strategic locations may be used in a nature-based strategy to augment sediment supply to mudflats, marshes, and breached salt ponds surrounding San Francisco Bay.

1. INTRODUCTION

The San Francisco Estuary encompasses South Bay, Central Bay, San Pablo Bay, and Suisun Bay (referred to collectively as San Francisco Bay), and the Sacramento-San Joaquin Delta (Figure 1). San Francisco Bay includes multiple federally-authorized navigation channels which undergo periodic maintenance dredging. From these navigation channels and other dredging projects, approximately 2,293,000 m³ (3,000,000 yd³) of sediment are dredged annually (DMMO 2013). Disposal of this dredged material is both costly and time consuming, as only 20% of this material is permitted to be placed at open-water in-Bay placements, with the remaining material transported to the San Francisco Deep Ocean Disposal Site (SF-DODS) in the Pacific Ocean or moved to regions on land. Additionally, 40% of the dredged material is required to be put toward beneficial reuse such as mudflat and marsh augmentation or wetland creation. Recent studies have predicted that about 96% of the marshes surrounding San Francisco Bay will not keep pace with sea level rise and will transition to open water mudflats by 2100 (Takekawa et al. 2013). Sea level rise, coupled with a reduction in sediment supply from the Sacramento-San Joaquin Delta (Schoellhamer 2011), suggests that augmenting the natural sediment supply to fringing mudflats and marshes could be important for maintaining the marsh habitats surrounding San Francisco Bay. As previously diked and possibly subsided areas are breached and returned to tidal action, which is planned for previous salt ponds as part of the South San Francisco Bay Salt Pond Project (SBSPRP 2012), more sediment will also be needed to raise

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these subsided areas to tidal marsh elevations. The natural dispersal of dredged material from open-water in-Bay placements to mudflats, marshes and breached ponds has the potential to be incorporated into nature-based strategies that help to alleviate some of the detrimental effects of increased sea level on the fringing shallows and infill newly breached regions, while limiting the costs associated with directly adding sediment to these sites. The primary objectives of this modeling study were to: 1) Investigate and better understand sediment dispersal following dredged material placements; 2) Determine if sediment from in-Bay placements can be naturally dispersed to beneficial regions, specifically mudflats, marshes and breached salt ponds; and 3) Compare the rate of dredged material dispersal in the relatively non-dispersive regions evaluated in this study to previously conducted simulations of dredged material dispersal at Environmental Protection Agency (EPA) designated in-Bay placement sites, which are typically more dispersive.

2. METHODS

The UnTRIM Bay-Delta model (MacWilliams et al. 2008, 2009; MacWilliams et al. in review) was applied together with the SWAN (SWAN Team 2009a) wave model and the SediMorph sediment transport and seabed morphology model (BAW 2005; Weilbeer 2005), as a fully-coupled hydrodynamic-wave-sediment transport model. A detailed description of the coupling of the Unstructured Tidal Residual and Intertidal Mudflat (UnTRIM) hydrodynamic, Simulating WAVes Nearshore (SWAN) wave, and SediMorph sediment transport models is presented in Bever and MacWilliams (2013). The UnTRIM, SWAN and SediMorph models run concurrently and pass information between one another as a fully three-dimensional coupled modeling system. In the coupled modeling system UnTRIM calculates the hydrodynamics, mixing, sediment advection and sediment settling, SWAN calculates the temporally and spatially varying wave properties, and SediMorph calculates the seabed shear stress, sediment erosion and deposition, morphologic change of the seabed and keeps track of the properties of multiple seabed layers. Validation of the hydrodynamics of the UnTRIM Bay-Delta model is presented in MacWilliams et al. (in review) and an initial validation of the waves and sediment transport as applied to San Francisco Bay is presented in Bever and MacWilliams (2013). The model has also been validated for predicted deposition and erosion thicknesses following the breaching of Salt Pond A6 (see Figure 5) in the South Bay (Bever and MacWilliams 2014).

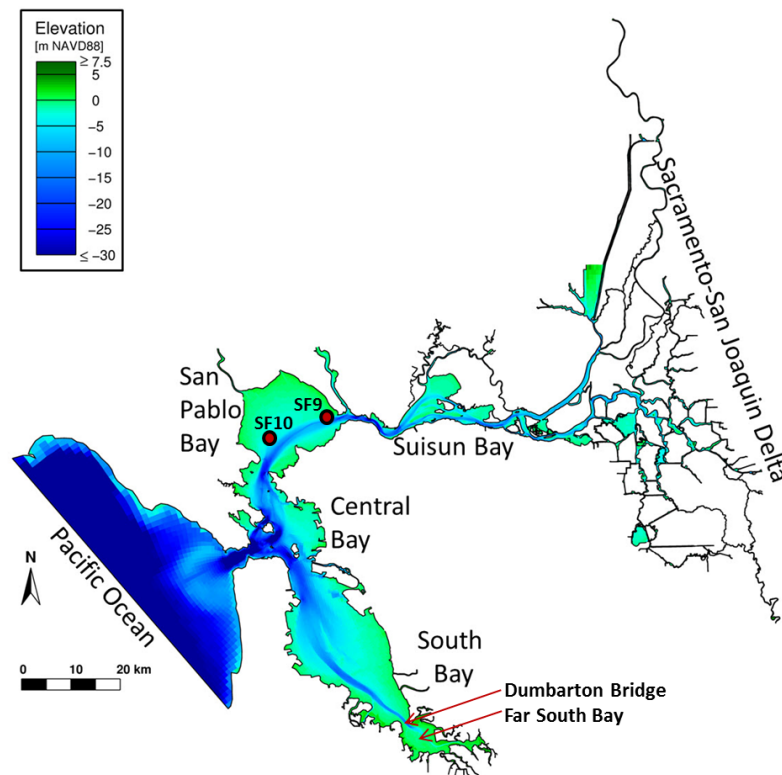


Figure 1. The UnTRIM Bay-Delta model domain with the sub-embayments of San Francisco Bay labeled. EPA designated dredged material placement sites SF10 and SF9 are shown with red circles.

2.1 UnTRIM Bay-Delta Model

The hydrodynamic model used in this study is the three-dimensional hydrodynamic model UnTRIM (Casulli and Zanolli 2002). A complete description of the governing equations, numerical discretization, and numerical properties of UnTRIM are described in Casulli and Zanolli (2002, 2005), Casulli (1999), and Casulli and Walters (2000).

The UnTRIM model solves the three-dimensional Navier-Stokes equations on an unstructured grid in the horizontal plane. The boundaries between vertical layers are at fixed elevations, and cell heights can be varied vertically to provide increased resolution near the surface or other vertical locations. Volume conservation is satisfied by a volume integration of the incompressible continuity equation, and the free-surface is calculated by integrating the continuity equation over the depth, and using a kinematic condition at the free-surface as described in Casulli (1990). The numerical method allows full wetting and drying of cells in the vertical and horizontal directions. The governing equations are discretized using a finite difference – finite volume algorithm. Discretization of the governing equations and model boundary conditions are presented in detail by Casulli and Zanolli (2002).

The UnTRIM San Francisco Bay-Delta model (UnTRIM Bay-Delta model) is a three-dimensional hydrodynamic model of San Francisco Bay and the Sacramento-San Joaquin Delta, which has been developed using the UnTRIM hydrodynamic model (MacWilliams et al. 2007, 2008, 2009; MacWilliams et al. in review). The UnTRIM Bay-Delta model extends from the Pacific Ocean through the entire Sacramento-San Joaquin Delta (Figure 1). The UnTRIM Bay-Delta model takes advantage of the grid flexibility allowed in an unstructured mesh by gradually varying grid cell sizes, beginning with large grid cells in the Pacific Ocean and gradually transitioning to finer grid resolution in the smaller channels of the Sacramento-San Joaquin Delta. This approach offers significant advantages both in terms of numerical efficiency and accuracy, and allows for local grid refinement for detailed analysis of local hydrodynamics, while still incorporating the overall hydrodynamics of the larger

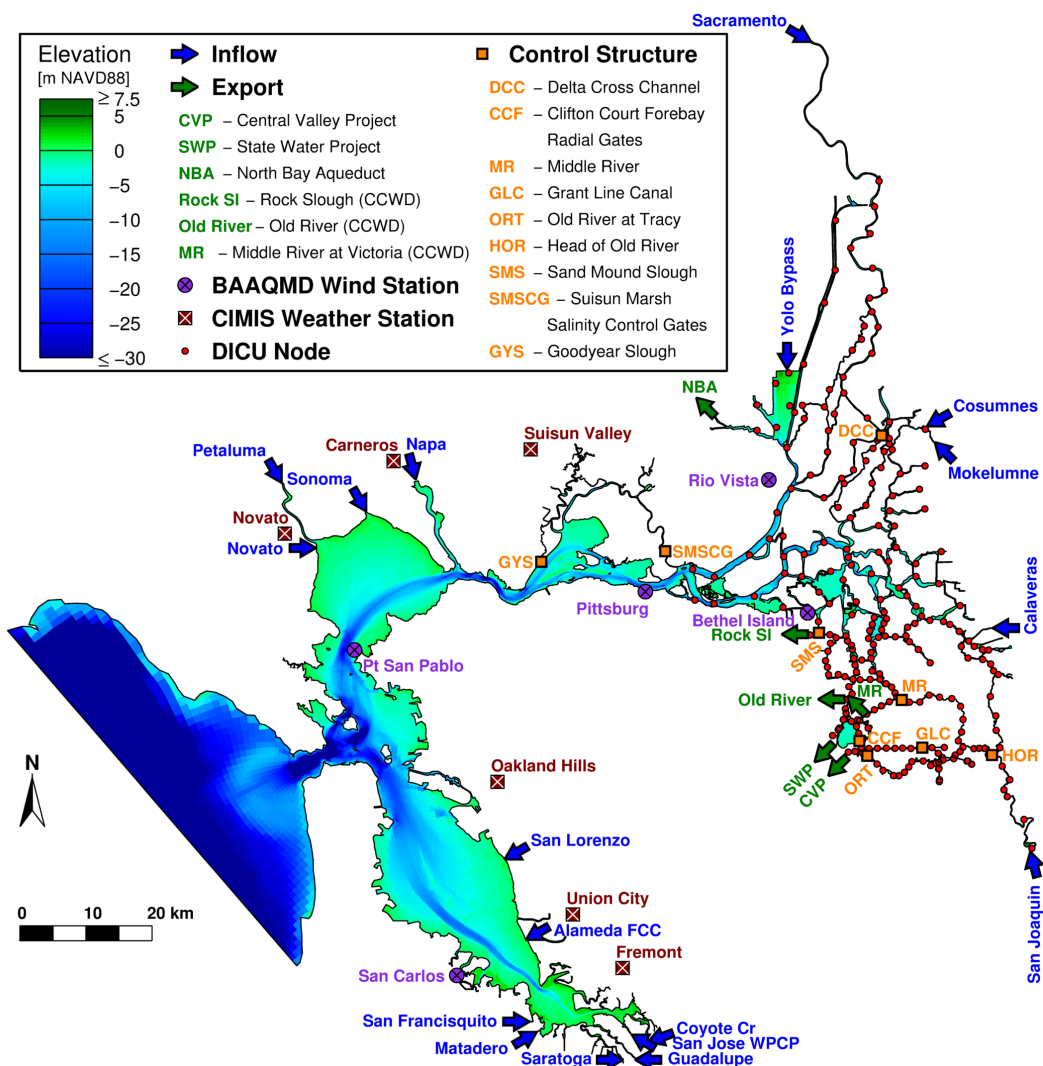


Figure 2: UnTRIM Bay-Delta model domain and forcing used for this study.

estuary in a single model. The vertical grid resolution is 1 m to a depth of 20 m below zero NAVD88 and between 20 m and 105 m below zero NAVD88 the vertical spacing gradually increases from 2 m to 5 m. The UnTRIM Bay-Delta model has been calibrated using water level, water flow, and salinity data collected in San Francisco Bay and the Sacramento-San Joaquin Delta (MacWilliams et al. 2008, 2009; MacWilliams et al. in review).

This application of the UnTRIM Bay-Delta Model uses a high resolution South Bay model grid to accurately represent the mudflats, channels, and salt ponds south of Dumbarton Bridge (MacWilliams et al. 2012a). Forcing conditions for the UnTRIM Bay-Delta model include observed wind, evaporation and precipitation from the area surrounding San Francisco Bay (MacWilliams et al. in review). Tributary inflows, water export from pumping plants and Delta Island Consumptive Use (agricultural diversions) are specified as boundary conditions (Figure 2). The oceanic open boundary is forced using observed water level data from San Francisco, shifted to account for the phase difference between San Francisco and the ocean boundary, and salinity data collected at the Farallon Islands. The model also includes operable gates and seasonal barriers located throughout the Sacramento-San Joaquin Delta (Figure 2).

2.2 SWAN Wave Model

The SWAN wave model was used to estimate the temporally and spatially varying waves that are necessary for accurate sediment transport modeling. The SWAN model (SWAN Team 2009a) is widely used for predicting wind wave properties in coastal areas (e.g., Funakoshi et al. 2008). SWAN “represents the effects of spatial propagation, refraction, shoaling, generation, dissipation and nonlinear wave-wave interactions” (SWAN Team 2009b) on wind waves. Therefore, SWAN can estimate the wind waves in coastal regions with variable bathymetry and ambient currents. SWAN can also accommodate spatial variability in bottom friction parameters and wind velocity.

The SWAN options used for this simulation were in most cases the default values. As such the model included wind generated waves, whitecapping, wave refraction, quadruplet wave-wave interactions, and wave breaking. A Madsen et al. (1988) bottom friction formulation was used. SWAN also included the influence of the UnTRIM current velocities in the wave calculations. Directional space was divided into 36 sections and frequency space was divided into 47 bins, from 0.0521 s^{-1} to 4.1447 s^{-1} with logarithmic spacing. SWAN waves were computed hourly for input to the sediment transport calculations.

A method from Rogers et al. (2003) to reduce the artificial reduction of lower frequencies by dissipation was included so the wave period would better match observations. A functionality to limit the wave turning from refraction based on the Courant-Friedrichs-Lewy (CFL) condition was included based on Dietrich et al. (2013), which helps prevent unreasonably large wave periods near steep bathymetry.

2.3 SediMorph Seabed Morphology Model

The primary purpose of the SediMorph module is to compute the sedimentological processes at the seabed of a free-surface flow (BAW 2005; Weilbeer 2005). Within the sediment bed, SediMorph incorporates multiple seabed layers that facilitate both bed armoring and the preservation of fine easily erodible sediment near the surface where it can be resuspended. SediMorph calculates erosion of the seabed according to Partheniades (1965) and Ariathuria and Arulandan (1978). Sediment deposition from the water column is simply the sum of the nearbed suspended sediment concentration and the sediment settling velocity. Bedload transport is calculated according to Meyer-Peter and Müller (1948).

SediMorph allows for the use of multiple sediment classes, and these classes are considered well mixed within any single seabed layer. With the use of multiple seabed layers, sediment is eroded or deposited into layers at the sediment water interface that have a set maximum thickness of 1 cm. These layers can be winnowed of fine sediment creating an armored sediment bed, or they can store easily erodible fine sediment that was deposited for later resuspension. A single porosity value was specified for the entire seabed within the model. All sediment classes were used in their relative proportions within a layer in the calculation of bulk seabed properties, such as determining the average grain size. For sediment deposition and erosion, however, all the sediment classes were treated individually within a seabed layer. If the shear stress is above the critical shear stress of any given sediment class then that class can be eroded from the surface exchange layer. The thickness of the surface exchange layer was set as five times the maximum seabed grain size within a model grid cell, similar to Wiberg et al. (1994). The sediment density of each sediment class was used with

the single porosity value to determine the deposition and erosion thickness (from the calculated deposited or eroded sediment mass) of each sediment class individually. These thicknesses were summed to give the net seabed deposition or erosion, dependent on each sediment class eroded from the layer or deposited from the overlying water column. The bathymetry and morphology of the seabed was updated at each hydrodynamic and sediment transport time step (90 s) to account for net erosion or deposition.

2.4 Sediment Grain Sizes, Initial Sediment Bed and Tributary Sediment Input

To limit the number of grain classes within the model, the continuously varying grain size distribution within the real world was simplified to represent the most dominant constituents, as has previously been done in three-dimensional sediment transport modeling in San Francisco Bay (Ganju and Schoellhamer 2009; van der Wegen et al. 2011; Bever and MacWilliams 2013). The dominant sediment classifications (classes) within San Francisco Bay are single particle silts, flocculated silts and clays (flocs), sand and gravel and their physical characteristics for the model were based on data within San Francisco Bay (Table 1) as described in Bever and MacWilliams (2013; 2014). The gravel sediment class was specified to be transported only as bedload.

Over 1300 observed surface grain size distributions were used to generate a realistic one-meter-thick initial sediment bed for the entire San Francisco Bay-Delta system. Grain size distribution data were from a USACE LTMS report (Pratt et al. 1994), the dbSEABED west coast surface grain size distribution database (Jenkins 2010), the United States Geological Survey (USGS) sand provenance study (Barnard et al. 2013) and the Delta sediment grain size study (S. Wright, USGS Pers. Comm. 2012). Interpolation of data to the model grid and the development of a one meter thick initial sediment bed was performed as detailed in Bever and MacWilliams (2013) (Figure 3). A porosity of 85% was specified for any deposited sediment. This porosity is at the high end of values reported for the San Francisco Bay in Caffrey (1995), because both the sediment supplied by tributaries and recently reworked sediment should be relatively unconsolidated.

Sediment Class	Settling Velocity (mm s ⁻¹)	Critical Shear Stress (Pa)	Diameter	Density (kg m ⁻³)	Erosion Rate Parameter (kg m ⁻² s ⁻¹)
Silt	0.0774	0.0379	11 µm	2650	2.5x10 ⁻⁵
Flocculated Silt and Clay	2.25	0.15	200 µm	1300	5x10 ⁻⁵
Sand	23	0.19	250 µm	2650	5x10 ⁻⁵
Gravel	n/a	n/a	8 mm	2650	n/a

Table 1: Sediment grain class parameters.

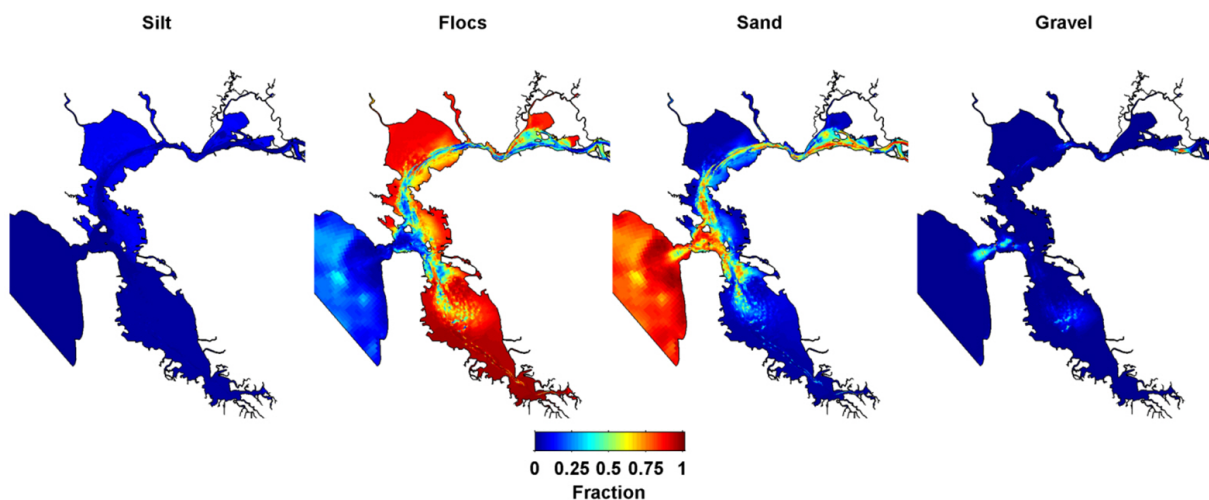


Figure 3: The fraction of each sediment class making up the initial sediment bed. The Delta is not shown, since the focus of this study was on San Francisco Bay.

Suspended sediment was supplied through tributary input to the Sacramento-San Joaquin Delta and the South Bay. Sediment was supplied to the Delta by the Sacramento, San Joaquin, Cosumnes, and Mokelumne Rivers and the Yolo Bypass, representing nearly 100% of the sediment inflow to the Delta (Wright and Schoellhamer 2005). Sediment was supplied to the South Bay by Alameda Creek, San Lorenzo Creek, Coyote Creek, and the Guadalupe River. The suspended sediment concentration of incoming freshwater for each of these sediment sources was specified using field data provided by T. Morgan (USGS Pers. Comm. 2012) and downloaded from the USGS National Water Information System website. Rating curves were used when field data were not available. The total incoming suspended sediment concentration from each tributary was partitioned into the three suspended sediment grain classes. Within the Delta, the silt, flocs, and sand classes composed 35%, 55%, and 10% of the total suspended sediment concentration, respectively. For the South Bay tributaries, the incoming suspended sediment concentration was set to 80% silt, 19% flocs and 1% sand.

2.5 Dredged Material Placement Methods

Dredged material was added to the three-dimensional hydrodynamic, wave and sediment transport simulation as a series of discrete placement events during each simulation period. For each placement event the date and time of the placement, the placement location, scow size, and sediment fractions being placed in suspension or deposited on the seabed were specified. Placement events were modeled including an initial sediment bed and ambient suspended sediment concentrations. The sediment was initialized within the model simulation assuming some amount of minutes had elapsed since the actual placement event, such that the suspended dredged material was well mixed within the water column and some of the material was deposited on the seabed. The physics of the actual descent of the sediment from a barge to the seabed were not modeled by the coupled hydrodynamic, wave and sediment transport models. Instead, simulations using the STFATE model (Johnson and Fong 1995) were used to determine the amounts of dredged material stripped into the water column and deposited on the seabed during the descent from the scow.

At the time of each dredged material placement event, both suspended sediment and a sediment deposit on the seabed were instantaneously initialized within a single horizontal grid cell (Figure 4). Each sediment class represented different fractions of the total placement sediment mass and different fractions of the suspended and deposited sediment. The suspended portion of the placement sediment was set to have a vertically uniform concentration that depended on the amount of each sediment class stripped into the water column during a placement event, as determined using STFATE. The deposited portion of the placement sediment was initialized as a sediment deposit having a thickness dependent on the added mass and density of each sediment class (Figure 4). The dredged material deposited on the seabed filled up multiple seabed layers at the sediment water interface, such that the placement sediment remained on the surface of the seabed where it could be eroded, and was not assumed to be mixed within the initial sediment bed or with previous dredged material placements. However, following the initial placement of dredged material on the bed, sediment eroded from the surrounding sediment bed could deposit on top of the placement sediment as the simulation progressed.

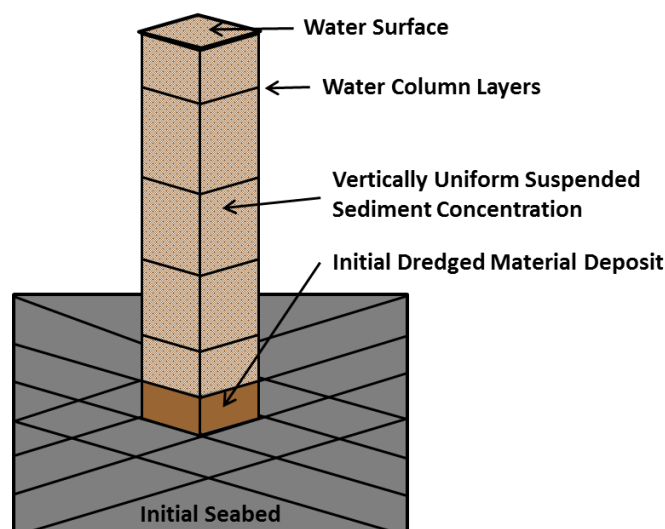


Figure 4: Schematic of the single horizontal grid cell immediately following a dredged material placement event.

Following the addition of the sediment to a model grid cell, the sediment in suspension settled toward the seabed and the initial dredged material deposit was eroded if the bed shear stress exceeded the critical shear stress of the sediment. The erosion, deposition, and transport of the initially suspended and deposited portions of the placement were then modeled by the hydrodynamic-wave-sediment transport models.

2.6 Dredged Material Placement Simulations

Dredged material dispersal was simulated at four placement regions in the far South Bay, South of Dumbarton Bridge (Figure 1), to evaluate how much of the sediment would be naturally dispersed to adjacent mudflats and marshes (Figure 5). Three of the four scenarios presented here were used to determine how the location of the placement influences the amount of sediment retained south of Dumbarton Bridge and transported either onto mudflats or into breached salt ponds (Table 2). Each of these simulations spanned five months. The three placement regions progressed from the north to south and are referred to as the North, Middle, and South placements. The fourth scenario investigated the sediment dispersal following the placement of a much larger volume of dredged material. This scenario was developed to represent the total dredged material volume, sediment properties, scow sizes, and placement timing typical of that from a dredging episode of the Redwood City Harbor Channel, the closest federally-authorized navigation channel to the study region. This simulation spanned one year to allow for a longer period of sediment dispersal following the dredged material placements. Because these dredged material dispersal scenarios were used to investigate the possible future transport of dredged material into breached salt ponds, the Island Ponds, Pond A6, and Pond A17 were all breached in the simulations (Figure 5). Identical time periods without dredged material placements were also simulated as Base Case scenarios. Comparison of each dredged placement scenario to the Base Case allowed for an assessment of whether the dredged material transported into a specific region was additive or in place of sediment that would have been transported there in the absence of the dredged material placement.

All the simulations assumed sediment properties representative of the sediment that is typically dredged from the Redwood City Harbor Channel. Each scow volume was converted into sediment volume assuming a dry bulk density of 800 kg m^{-3} , as in MacWilliams et al. (2012b). The sediment was partitioned into the modeled sediment classes using 28, 70, 2, and 0% for the silt, flocs, sand, and gravel, respectively, based on grain size distribution observations within the Redwood City Harbor Channel. The model grid cells in the far South Bay were small enough that the dredged material needed spread out in space in order to prevent the total sediment deposit from reaching the water surface. To accomplish this, the placements were partitioned within regions of between 9 to 60 grid cells. The area of these placement regions varied between about 0.05 and about 1 km^2 (~10 to ~250 acres).

Scenario	Placement Location	Motivation	Placement Region Area, km^2	Placement Sediment Volume	Scenario Duration
1	Dumbarton Bridge (North)	Placement Location Testing	0.15 km^2 (179398 yd^2)	36698 m^3 (48000 yd^3)	May-Oct 2009
2	Middle SB (Middle)		0.11 km^2 (131558 yd^2)	36698 m^3 (48000 yd^3)	May-Oct 2009
3	Near Pond A6 (South)		0.05 km^2 (59799 yd^2)	36698 m^3 (48000 yd^3)	May-Oct 2009
4	Near Dumbarton Bridge	Larger Placement Volume	0.98 km^2 (117207024 yd^2)	267594 m^3 (350000 yd^3)	Sep 2009 – Sep 2010

Table 2: Brief descriptions of each dredged material placement simulation.

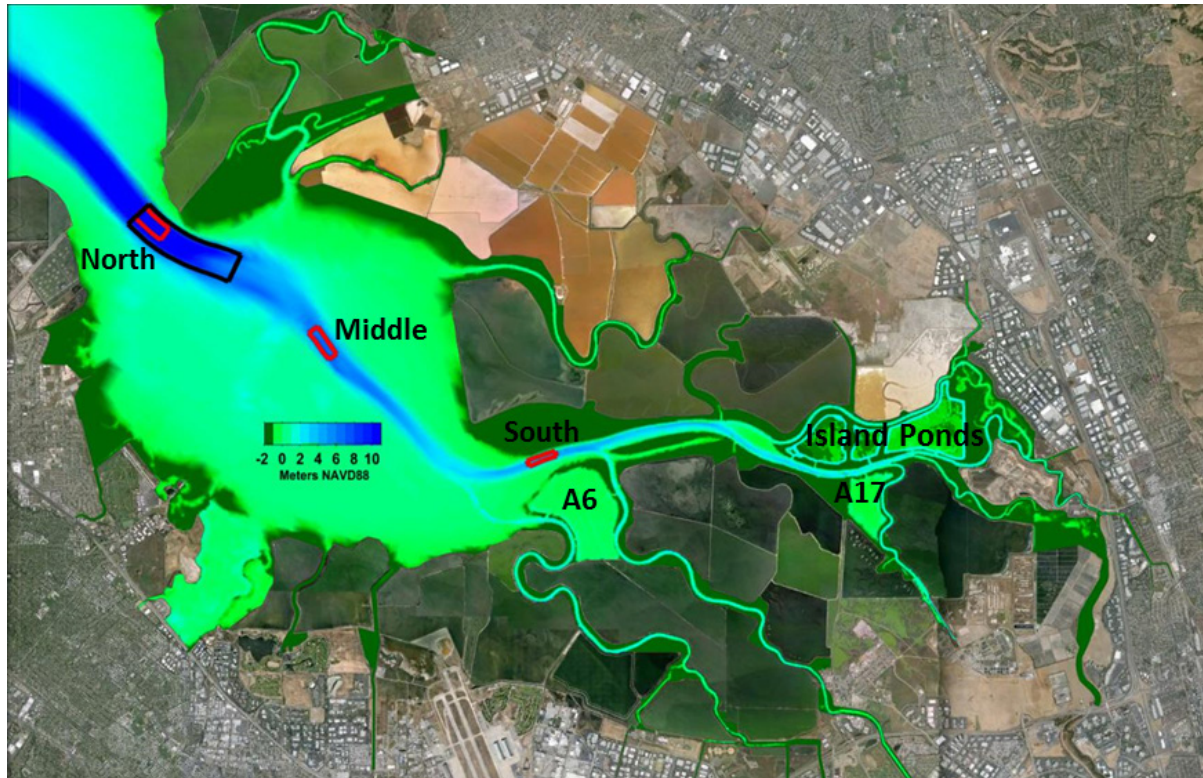


Figure 5: Model bathymetry and the locations of the North, Middle and South placement regions (red boxes, Scenarios 1-3) and the larger placement volume placement region (black box, Scenario 4). Model bathymetry is shown as meters below zero NAVD88.

The sediment at the North and Middle placement sites (Scenarios 1 and 2) was placed using sixteen 2293 m³ (3000 yd³) scows. At the South placement site (Scenario 3), the same volume of sediment was placed, however one hundred and twenty 305 m³ (400 yd³) dredged material placements were used because of channel depth and width limitations on possible scow sizes. The 2293 m³ dredged material placements were spaced to occur once every four hours in the North and Middle placement regions. The 305 m³ placements occurred once every 33 minutes in the South placement region, so the 2293 and 305 m³ placements ended at nearly the same time after the start of the simulations. For the simulation using a larger placement volume (Scenario 4) the total scow volume was 267,594 m³ (350,000 yd³), based on the average sediment volume dredged from the Redwood City Harbor Channel over the last three dredging episodes. Sediment was placed at a rate of 2675 m³/day (3500 yd³/day) using two 917 m³ (1200 yd³) and one 841 m³ (1100 yd³) placements at 6:00, 12:00, and 18:00 each day, leading to a total of 300 placements spread over 100 days. The simulation started on 1 September 2009 to correspond to a typical time period when dredging of the navigation channel has occurred. The placements were conducted such that each placement occurred in a single model grid cell. Each cell within a placement region received a placement, and then the placements repeated beginning again at the first cell. The cycle was repeated until the required number of placements was completed.

3. RESULTS: SEDIMENT DISPERSAL FOLLOWING IN-BAY PLACEMENTS IN THE SOUTH BAY

Analysis of the scenarios focused on the percentage of the dredged material that was predicted to be transported to different regions within the South Bay, such as onto mudflats and into breached salt ponds. For this analysis, mean lower low water (MLLW, about 0.37 m below zero NAVD88 in Figure 5) was considered the delineation between the intertidal and subtidal areas of the far South Bay. Any region with a seabed elevation above MLLW was considered to be either mudflat or marsh, and sediment deposition in these regions was considered likely to be beneficial to the system. The predicted depositional patterns of the dredged material following redistribution by the currents and waves were also highlighted in the analysis.

3.1 Dredged Material Placement Dispersal

During the dredged material placements in the North placement region (Scenario 1) an average thickness of approximately 0.5 m of sediment, about 57% of the total amount of dredged material, was deposited on the seabed near Dumbarton Bridge over the course of 2.5 days (Figure 6). Erosion of the placement deposit occurred during and following the placement period, such that about 0.4 m of sediment above the initial bed elevation was left after 5 months of simulation. However, some of this sediment was initial seabed sediment that deposited on top of the dredged material during the simulation. The dredged material was transported throughout the South Bay (Figure 7), with about 83% of the sediment remaining south of Dumbarton Bridge (Figure 8A). Sediment was transported onto the mudflats and into Salt Pond A6, Salt Pond A17 and the Island Ponds over the duration of the simulation (Figures 7 through 9). At the end of the simulation this scenario predicted about 18% and 2% of the dredged material to be supplied to the mudflats and the breached salt ponds, respectively (Figure 8A). The silt class was preferentially transported out of the channel and across the mudflats to deposit above mean tide level, while the flocs and sand classes were more confined to the channel region than the silt class (Figure 7).

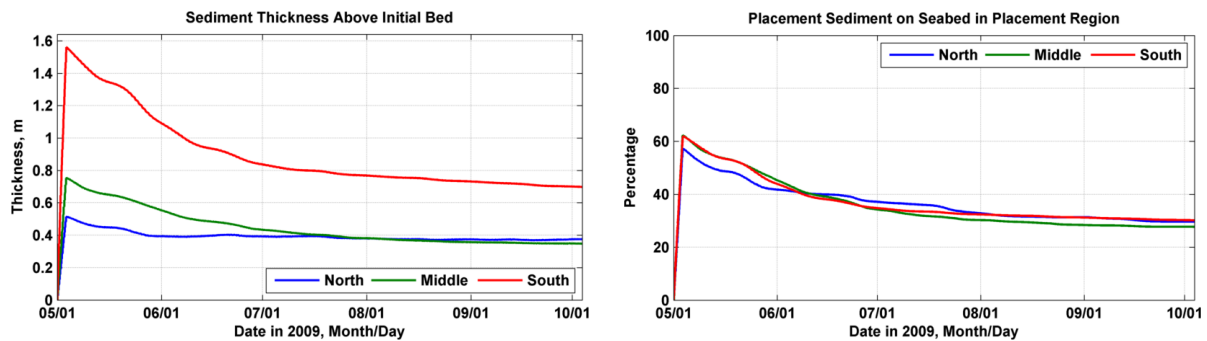


Figure 6: The average seabed sediment thickness above the initial sediment bed in the placement region (left) and the percent of the placement sediment remaining in the placement region (right) for the North, Middle, and South placement scenarios.

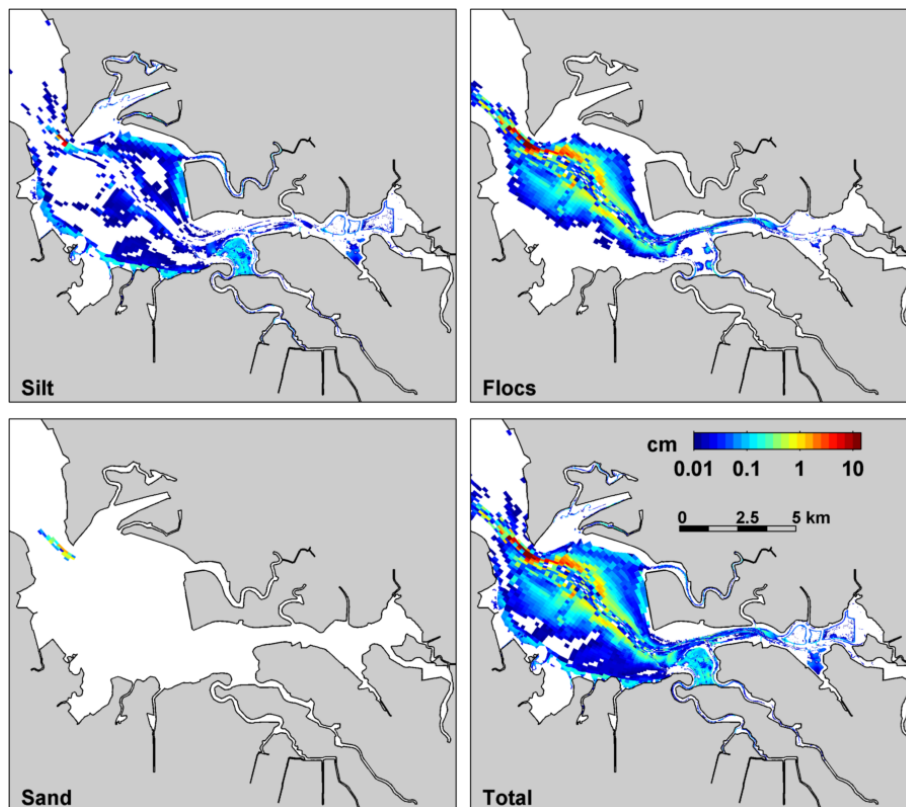


Figure 7: Dredged material deposition thickness at the end of the simulation for the North placement scenario. Deposition is shown for silt (upper left), flocs (upper right), sand (lower left), and the total of all three classes (lower right). Deposition is shown on a log scale in centimeters.

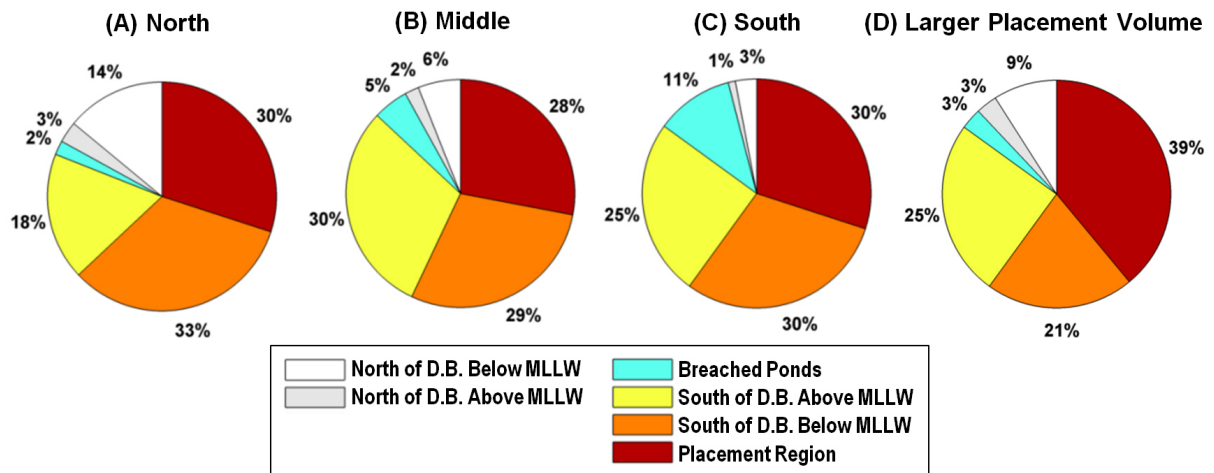


Figure 8: The percentage of the dredged material within different regions at the end of the dredged material placement simulations. Sediment deposited above MLLW is considered to be on the mudflats or marshes. D.B. stands for Dumbarton Bridge.

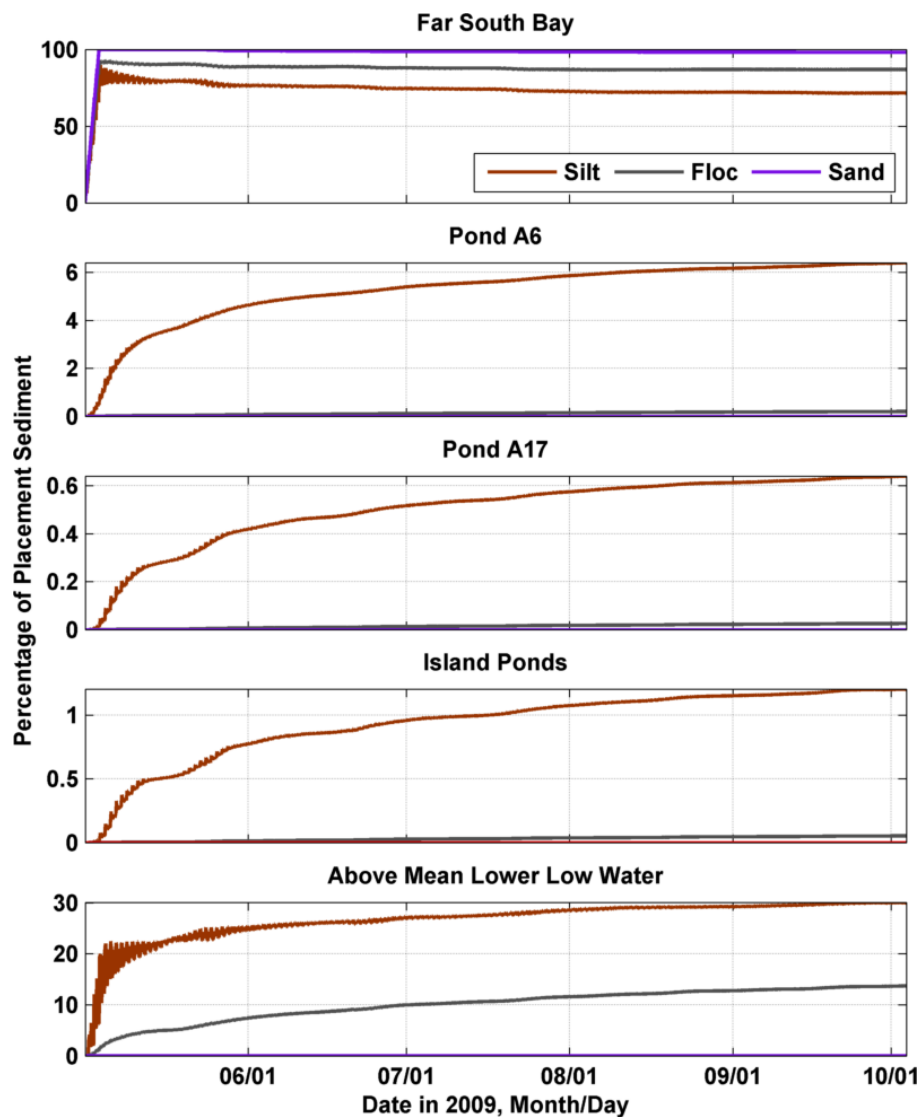


Figure 9: The percentage of the dredged material within different regions for the North placement scenario over the duration of the simulation.

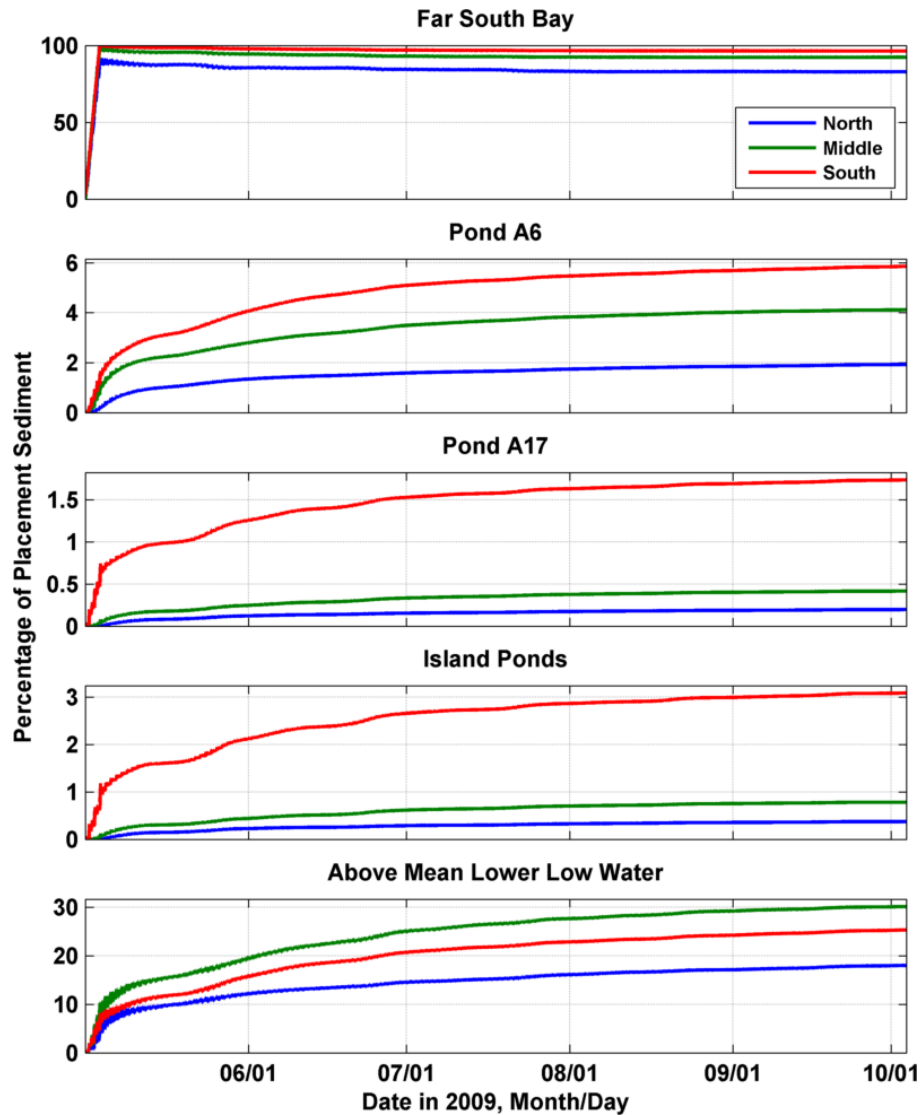


Figure 11: The percentage of the dredged material that is deposited within different regions over the duration of the simulations for the North, Middle and South placement scenarios.

Analysis of dredged material dispersal in the South Bay showed that the farther sediment is barged south of Dumbarton Bridge the larger the percentage of the dredged material will remain south of the bridge and the larger the percentage of the dredged material will be deposited within the breached salt ponds (Figure 8). For all three scenarios, the model predicted about 30% of the dredged material would remain on the seabed within the placement region after five months. For the North placement scenario a combined 20% of the dredged material was predicted to be deposited south of Dumbarton Bridge on the mudflats and within the breached salt ponds at the end of the 5 month simulation, with another 3% of the dredged material on the mudflats north of Dumbarton Bridge. When including sediment on mudflats north of Dumbarton Bridge, the model predicted that the South and Middle placements each supplied about 37% of the placement sediment to mudflats and breached salt ponds (Figure 8), making them about 1.6 times more efficient at supplying sediment to these regions than the North placement scenario.

The fourth scenario (Scenario 4) was designed to be representative of a dredging episode from the Redwood City Harbor Channel, in terms of the total sediment volume, the placement region, the scow size and frequency, and the dates of the placements. As with the smaller North placement, this larger placement volume scenario predicted increased sediment deposition throughout the far South Bay and erosion of the sides of the channel and the mudflat near the placement relative to the no placement Base Case (Figure 10D). The majority of the sediment deposition from the larger placement volume scenario was predicted to occur along the channel sides, with the silt sediment class most likely to be transported to the fringing shallows and the breached salt ponds (Figure 12). As a result of the larger placement region used in this scenario, the average thickness over the

placement region reached only about 0.6 m of dredged material (Figure 13). The average seabed thickness was predicted to increase following the completion of the dredged material placements (Figure 13) as a result of reworking of the sediment bed and deposition within the placement region.

The larger placement volume scenario near Dumbarton Bridge was predicted to supply sediment to all the previously examined regions (Figure 8D). Over the one year simulation 25% and 3% of the dredged material was predicted to be supplied to the mudflats and to the breached salt ponds, respectively. Much of the sediment was predicted to be supplied to these regions during the first third of the simulation and was likely initially assumed to be stripped into the water column during the placements and added to the simulation as suspended sediment. This implies the larger the percentage of sediment that is initially in suspension, the larger the net benefit from the placement over the one year simulation period. The placement location near Dumbarton Bridge, however, made this scenario relatively less effective at supplying sediment to the breached salt ponds than the Middle or South placement locations.

Although 39% of the dredged material was predicted to remain in the placement region at the end of the simulation, the placement thickness was predicted to erode to less than 1 cm of dredged material in about 25% of the placement region. The more erosional portions of the placement region were situated along the sides of the channel and on the shallowing southern portion of the placement region, where the average current-induced bed shear stress was generally higher (Figure 14). This indicates that if the placements were targeted to specific portions of an overall larger region, it may be possible to increase the rate of sediment dispersal from the placement region relative to the scenario which assumed a uniform placement distribution within the placement region. This also suggests that the model may be suitable for fine tuning the exact placement locations to maximize sediment dispersal, or fine tune placements within existing designated in-Bay placement sites.

Although none of the simulations predicted drastic channel infilling at the end of the simulations, much of the sediment was still contained within the channel and all of the deposition maps show sediment preferentially deposited on the margins of the channel (Figures 7, 10, and 12). This implies that with recurring episodes of multiple placements there is the potential for channel infilling, either through a reduction in channel depth or through channel narrowing from deposition on the flanks of the channel.

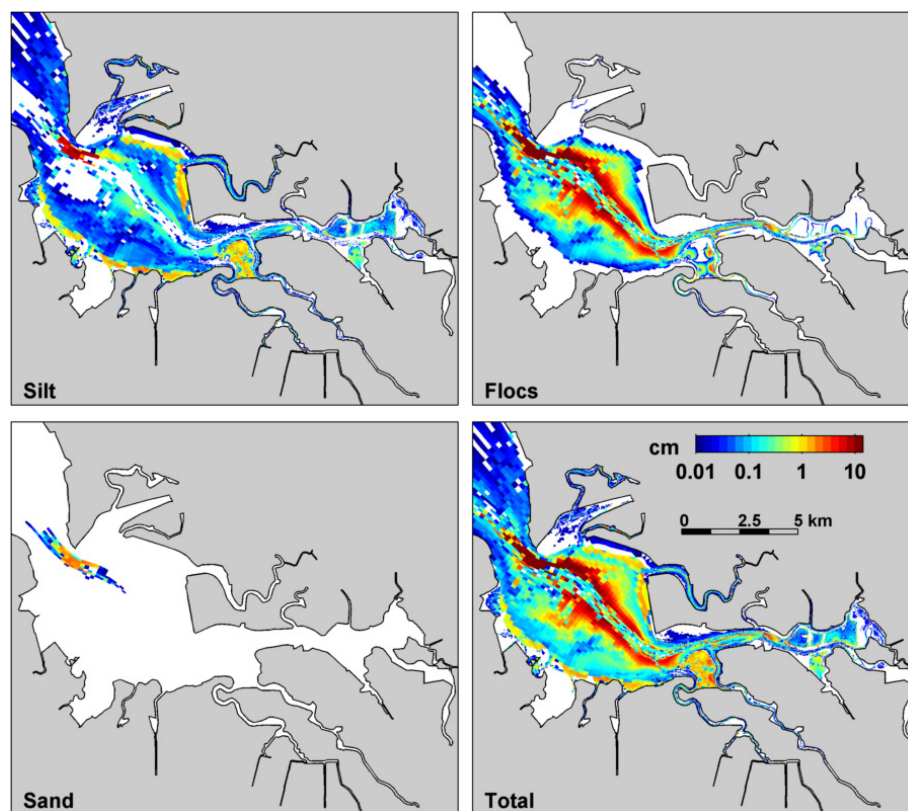


Figure 12: Dredged material deposition thickness at the end of the larger placement volume scenario (Scenario 4). Deposition is shown for the silt (upper left), flocs (upper right), sand (lower left), and the total of all three classes (lower right). Deposition is shown on a log scale in centimeters.

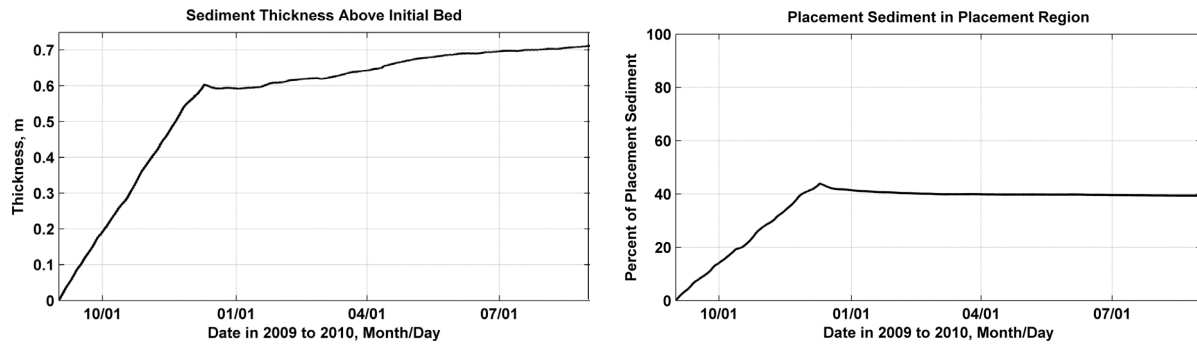


Figure 13: The average seabed sediment thickness in the placement region (left) and the percent of the placement sediment remaining in the placement region (right) for the larger placement volume scenario.

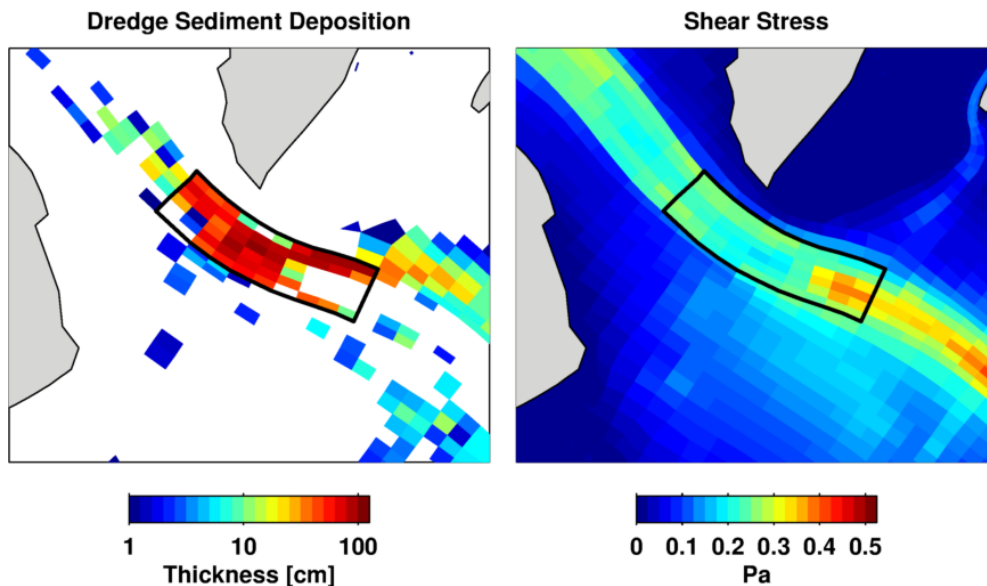


Figure 14: The ending dredged material depositional thickness (left) and time-averaged current-induced bed shear stress (right) near the larger placement volume scenario placement region. Dredged material depositional thicknesses of less than 1 cm are colored white. Shear stress is time averaged over the entire one year simulation.

4. DISCUSSION

4.1 Comparison of Dispersive Versus Non-dispersive Placement Regions

Similar dredged material placement simulations were conducted in San Pablo Bay at EPA designated in-Bay placement sites SF9 and SF10 (MacWilliams et al. 2012b) (Figure 1). Because the focus of the previous San Pablo Bay simulations was to develop a general understanding of sediment dispersal away from placement sites and investigate how the stage of the tide during a placement influences sediment dispersal, several simplifying assumptions were made relative to the South Bay simulations detailed in this manuscript. Most importantly, the simulations were conducted with no initial sediment bed such that the placements were conducted on a ridged seabed and the only sediment simulated was the sediment associated with the dredged material placement. The SF9 and SF10 dredged placement scenarios only considered a single dredged material placement, and were of shorter duration than the South San Francisco Bay dredged material placement simulations. Due to the absence of an initial sediment bed and the simulation of dredged material placements during a period of high outflow from the Sacramento-San Joaquin Delta, the predicted sediment dispersal for the SF9 and SF10 scenarios were considered to be the maximum dispersal away from these placement regions. While up to 46% of the dredged material remained within San Pablo Bay, only 3.5 to 6.8% of the dredged material was predicted to be supplied to the shallow shoals, with the remaining 40% retained in the deeper channel through San Pablo Bay. These simulations highlighted that sediment

placed at dispersive locations is transported throughout San Francisco Bay, with relatively little sediment being supplied to mudflats and marshes adjacent to the placement sites (MacWilliams et al. 2012b).

Simulations of sediment dispersal away from SF9 and SF10 (MacWilliams et al. 2012b) showed that the currently designated in-Bay placement sites in San Pablo Bay are not ideal locations for natural dispersal of dredged material onto mudflats and marshes. Placements at the far South San Francisco Bay locations evaluated in this study, however, were effective at supplying dredged material to mudflats, marshes and breached salt ponds through natural sediment redistribution following the placements. Comparing the San Pablo Bay (dispersive) to the South Bay (relatively non-dispersive) results suggests four main conclusions:

1. The far South Bay is much less dispersive than the EPA designated in-Bay placement sites, SF9 and SF10.
2. Dredged material placements in the far South Bay are predicted to be much more effective at supplying sediment to adjacent mudflats and marshes than dredged material placements at SF9 and SF10.
3. The far South Bay has a much greater potential to be used for the natural dispersal of dredged material from open-water in-Bay placements onto mudflats and marshes than the locations evaluated in San Pablo Bay.
4. A smaller percentage of the dredged material is predicted to be transported back into federal navigation channels from dredged material placements in the far South Bay than from placements at SF9 or SF10.

4.2 Dredged Material Placement Assumptions and Limitations

The interaction of tides, winds, waves, and sediments results in complex physical processes which need to be simplified and parameterized in order to be represented in a numerical model. The interpretation of the model results must therefore take into account how these assumptions influence both the model predictions and any conclusions drawn from the model predictions.

Within the present modeling system, the partitioning of the sediment between the four sediment classes is set as inputs to the model, and sediment mass cannot move between the different sediment classes through aggregation or disaggregation. As a result, the dredged material placement model predictions are sensitive to the initial partitioning between the silt and floccs sediment classes, because the silt class is dispersed much more widely than the floccs class. A larger initial silt fraction would likely result in higher percentages of the placement sediment above mean tide level or mean high water and more sediment transported into the breached ponds. By not allowing the flocculated particles to break into smaller constituent particles the model may also be overestimating the amount of sediment preserved within the channel or on the channel sides south of Dumbarton Bridge. If the floccs disaggregated into smaller particles on spring tides and reformed on neap tides the transport distance of the sediment would likely be greater, leading to a larger percentage of the placement sediment transported to higher tidal elevations and into the salt ponds.

The model does not account for the possibility of consolidation of the sediment bed over time. With bed consolidation, some sediment would consolidate during neap tide periods and be harder to erode the following spring tide. Dredged material on the seabed within the placement region may also consolidate and reduce the ability of the currents to resuspend the dredged material. Since bed consolidation is not currently represented within the model, the model may over-predict the transport distance of the sediment.

Because of these limitations the model is best suited for comparisons of predictions between different scenarios. That is, the model has greater skill in predicting the relative differences in sediment dispersal between different scenarios than predicting the exact sediment dispersal for a single scenario. In order to increase the confidence in the model predictions of individual dredged material placement scenarios, the model predictions should be validated using observations made during an actual in-Bay dredged material placement. This validation would allow for an assessment of how accurately the model predicts the rate of sediment erosion at the placement site and how accurately the model predicts deposition rates in adjacent breached ponds or mudflats following the placement. However, there is currently not any observation data available for conducting this type of model validation.

5. CONCLUSIONS

Dredged material placement simulations in far South San Francisco Bay demonstrated that the natural dispersal of sediment from open-water in-Bay placements has the potential to be used in a nature-based strategy to augment mudflat, marsh and salt pond sedimentation. Placement regions in the far South Bay were much more effective at supplying sediment to mudflats and marshes than dispersive regions in San Pablo Bay and supplied less sediment to federal navigation channels than the San Pablo Bay placement regions.

The investigation of sediment dispersal following dredged material placements south of Dumbarton Bridge showed that sediment was generally retained in the far South Bay and supplied to the mudflats and breached salt ponds. The model predicted that at least 80% of the dredged material placed at the North, Middle, and South placement regions was retained south of Dumbarton Bridge at the end of the simulations, with the most southern placement retaining the most sediment and supplying the most sediment to the breached salt ponds. These simulations showed that the farther south the placement occurred the larger percentage of the dredged material was transported into the breached salt ponds. When including shallow mudflat regions with seabed elevations above MLLW, the Middle and South placements performed equally well, with about 37% of the dredged material predicted to be deposited within the combined salt ponds and mudflats over the five month simulations. The Middle and South placement regions were predicted to be 1.6 times more efficient at supplying sediment to the breached ponds and the mudflats than the North placement region.

For the scenario with the larger placement volume, the model predicted that 28% of the placement sediment was supplied to the mudflats and breached ponds over the one year simulation. At the end of the simulation, 39% of the placement sediment was predicted to be still within the placement region. This resulted in part because the model predicted the channel near Dumbarton Bridge to be net depositional over the simulated time-period and in part due to the infilling of the deeper eastern side of the channel. Erosion of the placement sediment from the placement region was patchy and dependent on the current-induced bed shear stress. This implies the spatial distribution of the predicted bed shear stress may be used to further optimize individual placement sites within a larger placement region to attempt to maximize erosion and dispersal of placed dredged material.

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