A TIDALLY AVERAGED SEDIMENT-TRANSPORT MODEL OF SAN FRANCISCO BAY, CALIFORNIA

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Abstract: A tidally averaged sediment-transport model of San Francisco Bay was incorporated into a tidally averaged salinity box model previously developed and calibrated using salinity, a conservative tracer (Uncles and Peterson 1995). The Bay is represented in the model by 50 segments composed of 2 layers, one representing the channel (>5-meter depth) and the other the shallows (0 to 5-meter depth). Calculations are made using a daily time step and simulations can be made on the decadal time scale.

The new sediment-transport model includes an erosion-deposition algorithm, a bed sediment algorithm, and sediment boundary conditions. Erosion and deposition of bed sediments are calculated explicitly, and suspended sediment is transported by solving the advection-dispersion equation implicitly. The bed sediment model simulates the increase in bed strength with depth owing to consolidation of fine sediments that make up San Francisco Bay mud. The model is calibrated to either net bathymetric change or suspended-sediment concentration. Specified boundary conditions are the tributary fluxes of suspended sediment and suspended-sediment concentration in the Pacific Ocean.

The purpose of developing a tidally averaged sediment transport model is to create a tool to simulate sediment transport and bathymetric change in San Francisco Bay on a decadal time scale. The model has been applied to three resource management issues: 1) to estimate sediment outflow and change in storage on the bed as part of a new sediment budget for the Bay, 2) to evaluate restoration scenarios of the South San Francisco Bay salt ponds, and 3) to better understand the long-term fate of Polychlorinated Biphenyls (PCBs) in San Francisco Bay.

Introduction: Knowledge about long-term sediment movement within San Francisco Bay (Bay) is required to develop sediment budgets for the Bay and various subareas within the Bay (Schoellhamer et al, 2005). Reliable sediment budgets, in turn, are useful for evaluating the long-term fate of various contaminants associated with sediment particles (Leatherbarrow et al. 2005) and proposed wetland restoration projects (PWA in progress).

Accordingly, a model for simulating sediment transport in the Bay was developed. The sediment-transport model was incorporated as a subroutine in a tidally averaged, salinity model previously developed by Uncles and Peterson (1995). The Uncles-Peterson (UP) model uses residual-current, hydrodynamic calculations applied to adjacent segment layers, an approach that also is applicable to sediment transport. The UP model has been calibrated, widely distributed, and used to simulate the long-term effects of global warming on salinity (Knowles and Cayan 2004). This report describes the sediment-transport model and its application to three resource-management issues in the Bay.

<u>Description of the Study Area:</u> The Bay is made up of multiple broad, shallow bays connected by deep, narrow channels. The average depth in the Bay is less than 6 m, with a maximum depth of 100 m at the Golden Gate (Conomos 1979). The Bay receives 90 percent of its mean annual freshwater inflow from the Sacramento-San Joaquin Delta (Delta), which drains 40 percent of California including the agriculturally rich Central Valley. The remaining 10 percent of freshwater inflow comes from local tributaries and waste-water treatment plant effluent. North San Francisco Bay (North Bay) is a partially-mixed estuary with estuarine circulation maintained by the density difference between freshwater river inflow from the Delta and Pacific Ocean seawater (Conomos and Peterson 1977). South San Francisco Bay (South Bay) is typically well-mixed because of small freshwater inflows.

Sediment supply to the Bay varies seasonally with 80 percent of the average annual supply entering the Bay during the winter (Conomos and Peterson 1977). During high winter flows, sediment enters into the slower waters of Suisun and San Pablo Bays and begins to deposit. Coarse-grained and aggregated fine-grained sediments deposit, while the finest particles are exported out the Golden Gate. During the summer, sediment supply to the Bay is drastically reduced. Sediment undergoes a cycle of resuspension by tidal currents and wind waves, transport by tidal currents, and deposition at slack tide.

<u>UP Salinity Model:</u> The UP salinity model (Uncles and Peterson 1995) uses a box-model approach where each segment layer is well mixed. The Bay is represented by 50 width-averaged segments (boxes) (Figure 1) each composed of 2 layers (Figure 2). The upper layer of each segment represents the shallows (0 to 5-meter depth) and the lower layer represents the channel (> 5-meter depth). The two layers allow for density stratification. Tidally averaged residual currents advect water, and theoretical mixing rates constrain the dispersive exchanges of water between segments. A tidally averaged salinity field is solved implicitly using a one-day time step to enable the model to run over a decadal time scale in a relatively short period of time. The model has been calibrated to tidally averaged salinity (Uncles and Peterson 1995).

Input data used in the salinity mass-balance calculations include root-mean-square coastal sea level elevation at the Golden Gate to represent tides, near-bed coastal salinity, precipitation, evaporation, and freshwater outflow from the Delta. Delta outflow is calculated by DAYFLOW (California Department of Water Resources, 1986). Errors are thought to be relatively small (<10%) on a monthly time-scale, except for extreme low, or perhaps, high flows (Uncles and Peterson, 1996).

Salinity boundary conditions are set at the Pacific Ocean (box 46) and the Delta (box 45), and a zero flux boundary condition is applied at the most southern point of South Bay (box 1) to ensure conservation of mass. The lower-layer segment salinity at box 46 is set to coastal salinity, while the upper-layer segment salinity is variable since it is affected more by buoyant freshwater inputs from upstream sources. Delta outflow entering the Bay is relatively fresh water; therefore, salinity is set to zero in both layers of box 45. Additionally, local tributary flows also are relatively fresh and are set to zero salinity.

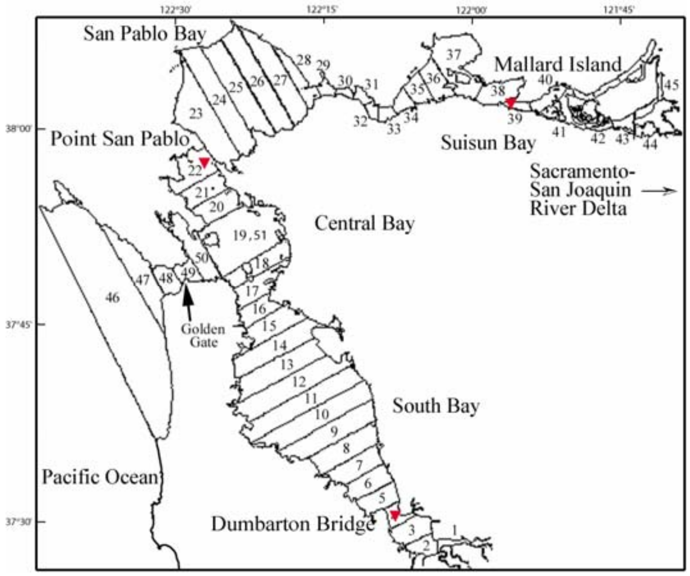

Figure 1 UP model segmentation of the San Francisco Bay (Uncles and Peterson 1995).

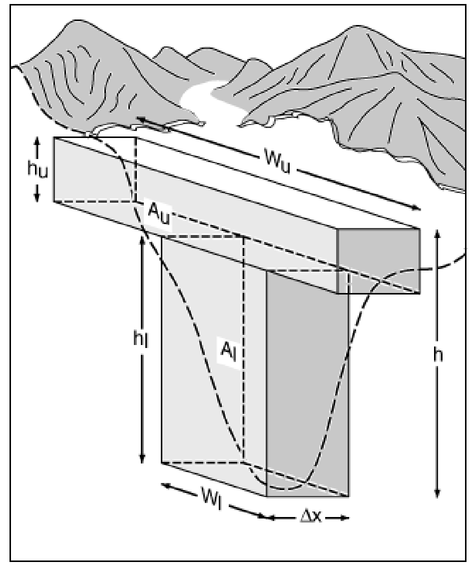

Figure 2 2-layer box composition of the UP box segments (Uncles and Peterson 1995).

Sediment Transport: The sediment-transport model was incorporated as a subroutine into the existing UP salinity model to simulate sediment transport in the Bay on a decadal time scale (1940 – 2004). A daily time step is used to compute daily-average suspended-sediment concentration (SSC) and net sedimentation. Mixing and advection rates calculated by the salinity model are used to simulate suspended sediment exchange between models segments. Exchange between bed sediments and suspended sediments are calculated explicitly with the aid of a simplified bed model.

Additional input data required for the sediment model include daily estimates of average wind velocity, suspended-sediment flux from the Delta, and local tributary sediment loads. Wind-velocity and tide data are used to calculate tidally averaged bed shear ($\overline{\tau_b}$),

$$\overline{\tau_b} = \frac{\rho g \overline{u}^2}{C_z^2} + c_w \frac{1}{2} \rho f \frac{\overline{u_w^2}}{\cosh kh} \qquad (1)$$

Where ρ = density (kg/m3); g = gravity (m/s2); $\overline{u}$ = tidally averaged current speed (m/s); C_z = Chezy coefficient, ($m^{1/2}$/s); c_w = calibration coefficient, f = friction factor, 0.1; $\overline{u_w}$ = daily average wind velocity (m/s); k = wave number, (m^{-1}); and h = average water depth (m). Daily suspended-sediment flux from the Delta is estimated for water years 1995 – 2003 by McKee et al. (2002). For all other simulation periods, a rating curve was developed (not shown) relating SSC at Freeport, Sacramento (station 11447500) and Delta Outflow (DAYFLOW) to suspended-sediment flux from the Delta. Tributary sediment load is simulated for major tributaries in the Bay including Napa River, Walnut Creek, Alameda Creek, San Francisquito Creek, and Guadalupe River (Porterfield 1980).

Sediment boundary conditions are specified at the Delta (box 39) and at the Pacific Ocean (box 46). The suspended-sediment flux at Mallard Island represents the Delta boundary condition and SSC in the lower layer of box 46 is held constant at 5.7 mg/L, the long-term mean concentration from monthly water quality sampling by the USGS (http://sfbay.wr.usgs.gov/access/wqdata). The upper layer of box 46 is left free to vary, as it is affected more by buoyant freshwater inputs from upstream sources. Mass conservation in segment 1, the Southern end of South Bay, is maintained by a no-flux boundary condition.

The daily mass balance sediment algorithm begins by adding tributary sediment load to specific boxes throughout the UP model grid. The tributary loads are mixed within the estuary by implicitly solving the advection-dispersion transport equation using mixing parameters calculated by the salinity model. Mass exchange with the sediment bed (C_n) is simulated by explicit calculation at the end of each time step (n) as

$$C_n = C_o + \left(Fc_E R_E - c_D R_D\right)\frac{\Delta t}{H} \qquad (2)$$

where C_o = SSC at the beginning of the time step (mg/L); F = erodibility factor described below; c_E = calibration coefficient; R_E = rate of erosion (g/m^2/s); c_D = calibration coefficient; R_D = rate of deposition (g/m^2/s); Δt = time step (s); and H = total water depth (m).

The rate of erosion is affected by shear strength properties of the sediment bed, which vary with depth and time (Krone 1999). A simplified method was developed to simulate the effect of consolidation of the sediment bed by reducing the erodibility of the bed as a function of depth of sediment and time since deposition. A summary of previous sediment bed studies (Hayter 1984), showed that sediments consolidated over time have properties that vary in the top 4 cm of the bed, but that are essentially uniform below this depth with a critical shear stress roughly four times the critical shear stress at the bed surface. To account for freshly deposited sediments that are still easily eroded, a representation of bed profile incorporating three layers was developed. The top layer is composed of freshly deposited, easily erodible sediment that was deposited to the bed during the present or the previous time steps. The middle layer represents the partially consolidated sediments that become harder to erode with increasing depth. The lowest layer represents consolidated sediments where the erodibility is constant and about four times less than at the bed surface. The erosion rate calculated by the model is multiplied by the erodibility factor, F, whose value depends on the sediment layer and the elevation of the sediment bed surface relative to a vertical datum. The erodability factor, F, varies from 1.0 to 0.25 and is given as

$$F = \begin{cases} 1.0 & z > 0 \\ 1.0e^{34.7z} & 0 \geq z > -0.04\text{ m} \\ 0.25 & -0.04\text{ m} \geq z \geq -\infty \end{cases} \qquad (3)$$

where z is the sediment bed surface elevation referenced to the bed datum. Sediment remaining in the top layer after one full time step is incorporated into either the middle or lower layers depending on the current bed elevation below the datum and assumes the F value at that depth. If deposition raises the bed surface elevation above the datum, the datum is reset to the current bed surface elevation.

The model is calibrated by adjusting c_w, c_E, and c_D. The model can be calibrated to either net bathymetric change or SSC, but results show the model cannot simulate both simultaneously.

The sediment transport model was calibrated to SSC by adjusting model coefficients until modeled SSC most closely matched simulated daily-averaged continuously-measured SSC during water year 1999 at two locations in the bay, Point San Pablo in North Bay and Dumbarton Bridge in South Bay (Buchanan and Ruhl 2001). Water year 1999 is classified as having an average annual Sacramento-San Joaquin River basin outflow. Separate sets of calibration parameters were determined for North Bay and for South Bay. Results of the calibration at Dumbarton Bridge (figure 3) show that a tidally averaged sediment transport model can be used to predict the general trends in SSC associated with tidal fluctuations, residual velocity, and wind stress.

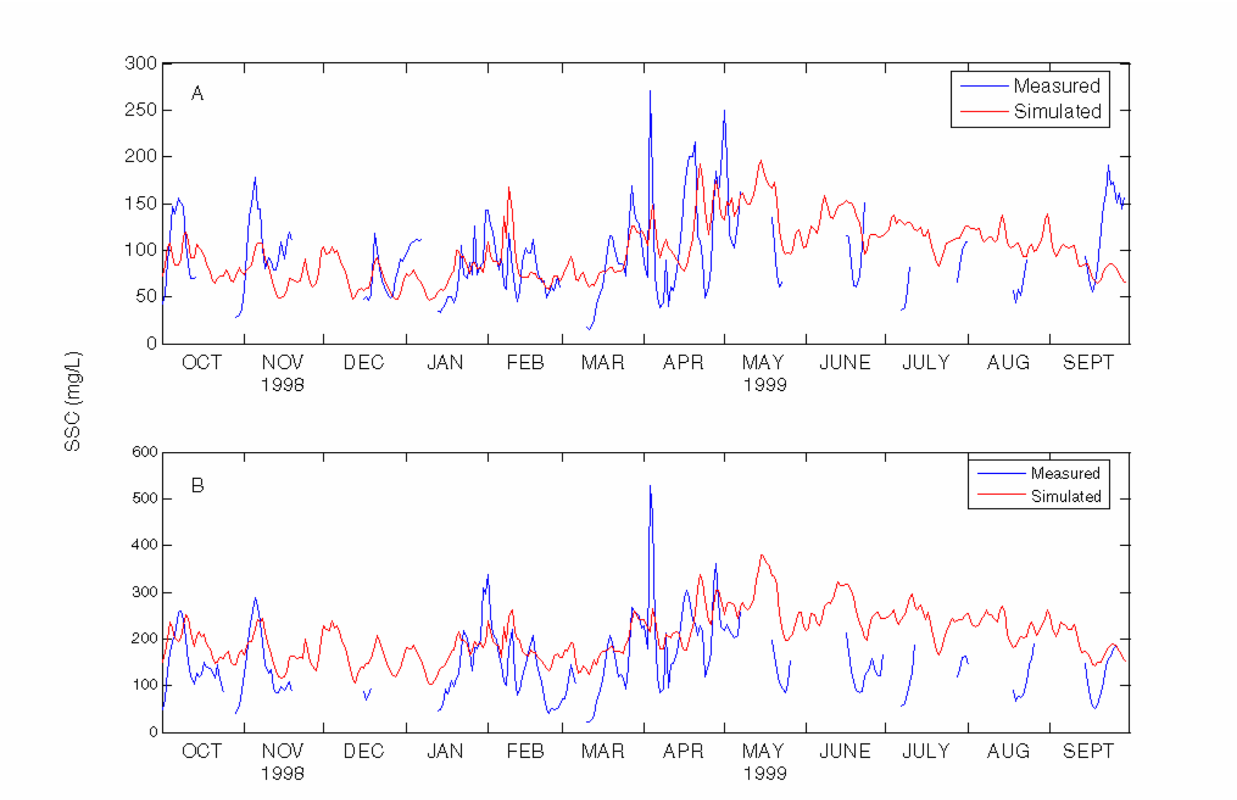

Figure 3 Simulated SSC for water year 1999 at Dumbarton Bridge (A) at mid depth (22 ft below MLLW) and (B) at near bottom (41 ft below MLLW).

Estimates of net bathymetric change are available for Suisun Bay, San Pablo Bay, and South Bay (Jaffe et al. 1998, Cappiella et al. 1999, Foxgrover et al. 2004) for periods ranging from 28 to 49 years. No survey data exists for Central Bay. Regional sediment density data from sediment cores were used to convert net mass change to net volumetric change in order to compare estimated bathymetric change to simulated net sedimentation from the model calibrated to SSC.

Results of the comparisons (Table 1) indicate that the model calibrated to SSC is not able to hindcast bathymetry change accurately. This is most likely the result of small errors compounding over longer simulation periods.

Table 1 Comparison of simulated net sedimentation to estimated bathymetric change for the model calibrated to SSC and for the model calibrated to net sedimentation.

Embayment and Survey Period	UP boxes	USGS Bathymetric Change Estimates (million cubic meters)	UP Net Sedimentation calibrated to SSC (million cubic meters)	UP Net Sedimentation calibrated to net sedimentation (million cubic meters)
Suisun Bay (1942-1990)	29-39	-35	-12	-35
San Pablo Bay (1951-1983)	23-28	-11	-131	-11
South Bay (1956-1983)	1-14	-47	-25	-47
Central Bay (1956-1983)	15-22, 46-50	NA	-185	0

The model also was calibrated to net sedimentation. Model calibration coefficients were adjusted within various bays until the simulated net sedimentation matched estimated bathymetric change in Suisun Bay, San Pablo Bay, and South Bay (Table 1). Because no survey data exists for Central Bay, an assumption of no net change was used. Determining the effectiveness of the model calibrated to long-term net sedimentation requires a validation data set for comparison. Validation data are currently unavailable pending new bathymetric surveys and analyses to determine recent net bathymetric change.

Other Model Applications: Because the model can simulate long periods, it has become a valuable tool for evaluating sediment transport in the San Francisco Bay system. Applications include 1) development of a sediment budget, 2) a landscape-scale analysis of potential sediment change in South Bay resulting from the planned restoration of salt ponds to tidal action and 3) estimation of the time period required for recovery of water quality impairment by polychlorinated biphenyls (PCBs) in bottom sediment.

The UP sediment model was used to estimate the Bay sediment budget for the period of 1995 – 2002 when change in storage of the system and sediment outflow through the Golden Gate is unknown (Schoellhamer et al. 2005). The model was first calibrated for the period 1955 – 1990, when the only unknown is sediment outflow, and then applied to the 1995 – 2002 period, assuming the same calibration coefficients were applicable, to obtain a sediment budget that estimates the two unknown terms.

The South Bay Salt Pond Restoration Project plans to restore over 15,000 acres of former salt ponds, some of which are deeply subsided, to a mosaic of tidal wetland and managed environments to provide habitat for a host of avian, fish, and other endangered and indigenous species. However, a restoration project this large has the potential to significantly alter existing habitats. Therefore, prior to performing restoration actions, it is essential to develop an understanding of the potential long-term system response to restoration actions, such as how the restoration may affect South Bay sediment dynamics, morphology, and ultimately the extent of tidal marsh, mudflat and shallow-water habitats within South Bay and the restored ponds. The use of a sediment budget tool is desirable because it accounts for conservation of mass – sediment that is captured and deposited in the restored ponds is no longer available for deposition and/or redistribution within South Bay (Philip Williams and Associates, PWA, in progress).

The UP Model was chosen as the sediment budget tool for the project, and the model was calibrated to past geomorphic change as determined by Foxgrover et al. (2004). In order to assess the restoration alternatives, the ponds to be restored were divided into clusters associated with each UP model box, and the total area and mean depth of each pond cluster was added to the model to represent a new sediment sink. The model was run forward 50 years and the model outputs were evaluated using a suite of empirical and analytic tools in order to determine the potential year-50 morphology and habitat distribution of the South Bay (PWA in progress).

An ongoing effort jointly funded by the Clean Estuary Partnership and the Regional Monitoring Program further builds on the salinity and sediment transport models to simulate long-term trends in total PCB concentrations in the water column and bedded sediment. A primary objective of this effort is to estimate timescales of recovery with respect to water quality impairment by PCBs as part of a Total Maximum Daily Load allocation.

The PCB model accounts for external inputs of PCBs to the Bay from the Central Valley via the Sacramento-San Joaquin River Delta, local tributaries, atmospheric deposition (wet and dry), and municipal wastewater effluent in a spatially explicit manor (Leatherbarrow et al. 2005). The model includes a post-depositional vertical mixing model that explicitly accounts for storage of PCBs in bed sediment. Along with physical processes that determine PCB transport, this study incorporates the influence of chemical-specific traits of PCBs that govern partitioning between particulate and dissolved fractions, degradation in water and sediment, and volatilization into the atmosphere. The primary application of this model is to develop scenarios of decadal trends in PCB contamination in major segments of the Bay for various reductions in PCB loading.

Conclusions: A tidally averaged sediment transport model was developed that uses the hydrodynamics of the UP model calibrated to salinity, a conservative tracer. The model uses a daily time step and is able to perform simulations on the decadal time scale. The UP sediment model can be calibrated to either SSC or net bathymetric change, but not to both simultaneously, because small errors in the model compound over time. The model is currently being used to simulate changes in sediment dynamics and morphology as a result of the South Bay salt pond restoration project and to forecast decadal trends in PCB contamination.

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