Sensitivity and spin up times of cohesive sediment transport models used to simulate bathymetric change

David H. Schoellhamer[1], Neil K. Ganju[1], Phillip R. Mineart[2], and Megan A. Lionberger[1]

[1]United States Geological Survey, Placer Hall, 6000 J Street, Sacramento, California, 95819, USA
[2]URS Corporation, 500 12th Street, Suite 200, Oakland, California, 94607, USA

ABSTRACT

Bathymetric change in tidal environments is modulated by watershed sediment yield, hydrodynamic processes, benthic composition, and anthropogenic activities. These multiple forcings combine to complicate simple prediction of bathymetric change, therefore numerical models are necessary to simulate sediment transport. Errors arise from these simulations, due to inaccurate initial conditions and model parameters. We investigated the response of bathymetric change to initial conditions and model parameters with a simplified zero-dimensional cohesive sediment transport model, a two-dimensional hydrodynamic/sediment transport model, and a tidally averaged box model. The zero-dimensional model consists of a well-mixed control volume subjected to a semidiurnal tide, with a cohesive sediment bed. Typical cohesive sediment parameters were utilized for both the bed and suspended sediment. The model was run until equilibrium in terms of bathymetric change was reached, where equilibrium is defined as less than the rate of sea level rise in San Francisco Bay (2.17 mm/yr). Using this state as the initial condition, model parameters were perturbed 10% to favor deposition, and the model was resumed. Perturbed parameters included, but were not limited to, maximum tidal current, erosion rate constant, and critical shear stress for erosion. Bathymetric change was most sensitive to maximum tidal current, with a 10% perturbation resulting in an additional 1.4 m of deposition over 10 y. Reestablishing equilibrium in this model required 14 y. The next most sensitive parameter was the critical shear stress for erosion; when increased 10%, an additional 0.56 m were deposited and 13 y were required to reestablish equilibrium. The two-dimensional hydrodynamic/sediment transport model was calibrated to suspended-sediment concentration, and despite robust solution of hydrodynamic conditions it was unable to accurately hindcast bathymetric change. The tidally averaged box model was calibrated to bathymetric change data and shows rapidly evolving bathymetry in the first 10-20 y, though sediment supply and hydrodynamic forcing did not vary greatly. This initial burst of bathymetric change is believed to be model adjustment to initial conditions, and suggests a spin-up time of greater than 10 y. These three diverse modeling approaches reinforce the sensitivity of cohesive sediment transport models to initial conditions and model parameters, and highlight the importance of appropriate calibration data. Adequate spin-up time on the order of years is required to initialize models, otherwise the solution will contain bathymetric change that is not due to environmental forcings, but rather improper specification of initial conditions and model parameters. Temporally intensive bathymetric change data can assist in determining initial conditions and parameters, provided they are available. Computational effort may be reduced by selectively updating hydrodynamics and bathymetry, thereby allowing time for spin-up periods.

INTRODUCTION

Bathymetric change induced by anthropogenic alterations can occur decades to centuries after the alteration. Diking of wetlands reduced tidal prism and caused adjacent tidal channels to fill with sediment (Hood 2004). Wolanski et al. (2001) found that a reservoir eliminated high flows that would scour sediment from an estuary, resulting in increased deposition. Freshwater withdrawals which reduce flow to an estuary can cause deposition to shift landward (Jay and Simenstad 1996). Gilbert (1917) found that mining practices in the watershed of San Francisco Bay in the second half of the 19th century greatly increased sediment load and estuarine deposition. The resulting pulse of riverine sediment has affected bathymetry for over a century (Jaffe et al. in press). In the Medway Estuary dikes that enclosed marsh breached in the late 1880s, increasing tidal prism and eroding salt marsh creeks, cliffs, and tidal flats (Kirby 1990). The sedimentation rate in Chesapeake Bay has increased by a factor of 2-3 since European settlement (Zimmerman and Canuel 2002). Increasing sea level rise may also be a factor in this increase (Donoghue 1990).

Erosion and deposition that significantly alter estuarine bathymetry affects resource management issues. Bottom sediments are a reservoir of contaminants in many estuaries (Ridgway and Shimmield 2002, Taylor et al. 2004). Erosion can remobilize contaminants previously buried in bottom sediment (Arzayus et al. 2002, Hornberger et al.

1999, Lee and Cundy 2001). Geomorphic evolution of estuarine habitats and landscapes over decadal timescales (greater than 10 years) is sensitive to sediment supply from the watershed as well as estuarine hydrodynamics. Future climate change, land use change, and sea level rise are some of the many factors that may alter sediment supply and threaten ecologically beneficial estuarine habitats (Scavia et al. 2002, Pont et al. 2002).

Numerical models of cohesive sediment transport can be used to predict bathymetric change in an estuary. A model imperfectly simulates estuarine hydrodynamics and sediment transport. Model output is compared to measurements and coefficients are calibrated to achieve the best possible fit. Often the primary objective of numerical models is simulation of suspended-sediment concentration, but in this work our focus is on simulation of bathymetric change. Simulated bathymetric change will be sensitive to the simulated boundary conditions, hydrodynamics, and selected sediment coefficients. The model initial conditions will imperfectly represent the actual conditions of the estuary at the start of the simulation, so the model must be initialized, or spun up, such that the bathymetric change for the desired simulation period is not affected by the initial conditions.

In this work we investigate the sensitivity and required spin up time of a simple cohesive sediment transport model used to simulate bathymetric change. A zero-dimensional model, representing a well-mixed control volume, will be applied to a hypothetical estuary to simulate bathymetric change over many decades. The model will be run until a dynamic equilibrium is achieved. Then basic boundary condition, hydrodynamic, and cohesive sediment transport parameters will be perturbed to represent their imperfect specification. The time needed for the model to reestablish dynamic equilibrium (spin up time) and the resulting change in bed elevation (error) will be determined for each parameter. Two case studies of bathymetric change simulation from San Francisco Bay are presented. A two-dimensional model was successfully calibrated to suspended-sediment concentration but was unable to accurately hindcast bathymetric change. A tidally averaged box model was found to require about one decade of spin up time, about the same as found with the zero-dimensional model.

METHODS

Zero-dimensional model of a hypothetical estuary

The model domain is a well-mixed control volume (fig. 1). A semidiurnal tide is imposed on the control volume. Water surface elevation is assumed to be constant and as the bed elevation changes the maximum tidal current speed is adjusted such that the water flux through the control volume at any time in the tidal cycle is constant. Tidal velocity is

$$u = u_o \frac{h}{h_o} \sin \omega t \qquad (1)$$

in which u_o is the initial maximum tidal current speed, h_o is the initial water depth, h is the water depth that changes as deposition or erosion occurs, ω is the angular frequency of the tide equal to $2\pi/12$ hour^{-1}, and t is time. Bottom shear stress is calculated with a quadratic shear stress formula

$$\tau = \rho C_D u^2 \qquad (2)$$

in which ρ is the fluid density and C_D is a drag coefficient.

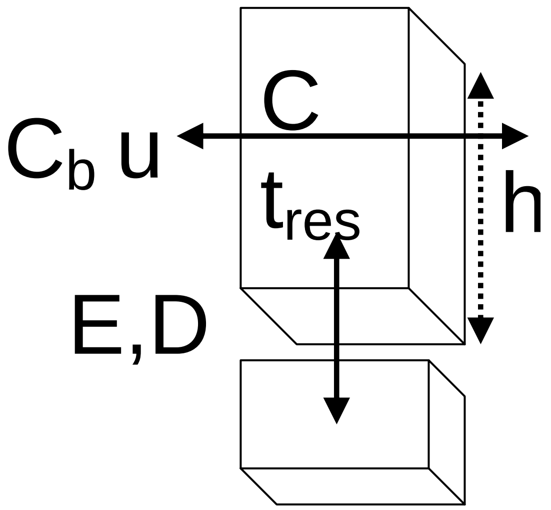

Figure 1. Zero-dimensional model. The upper box is the control volume and the lower box represents the sediment bed. Solid arrows indicate water or sediment fluxes and the dashed arrow indicates depth h of the control volume.

The traditional cohesive sediment formulae for erosion and deposition are applied to a hypothetical estuary here because of their familiarity and simplicity. Erosion rate E and deposition rate D are

$$E = M\frac{\tau - \tau_{ce}}{\tau_{ce}} \quad \text{for } \tau > \tau_{ce} \tag{3}$$

$$D = w_s C\frac{\tau_{cd} - \tau}{\tau_{cd}} \quad \text{for } \tau < \tau_{cd} \tag{4}$$

in which M is an erosion coefficient, τ_{ce} is the critical shear stress for erosion, w_s is the settling velocity, C is the suspended-sediment concentration, and τ_{cd} is the critical shear stress for deposition which is less than τ_{ce}.

The change in suspended sediment concentration during a simulated time step is

$$\Delta C = \frac{(E - D)\Delta t}{h} - \frac{(C_b - C_{old})\Delta t}{t_{res} + \Delta t} \tag{5}$$

in which C_b is the boundary suspended-sediment concentration, C_{old} is the suspended-sediment concentration at the previous time step, and t_{res} is the residence time of the control volume. Residence time of the control volume represents the rate of exchange of water in the control volume with adjacent water. Residence time varies from zero, such that the control volume represents a small area like a cell in a larger model, to 150 days such that the control volume represents an entire estuary.

The change in bottom elevation during a simulated time step is

$$\Delta h = -\frac{(E - D)\Delta t}{\rho_b} \tag{6}$$

in which ρ_b is the bulk density of the bottom sediment.

The time step was 6 minutes and a boundary condition of c_b=0.1 kg/m^3 (100 mg/L) represented the concentration of waters surrounding the control volume and was used for the initial concentration. Typical values of cohesive sediment transport coefficients were assigned (table 1, MacDonald and Cheng 1997).

Table 1. Model parameters. Typical values of cohesive sediment transport parameters were used (MacDonald and Cheng 1997)

Parameter	Value
Tidal angular frequency ω	2π/12 hours^{-1}
Fluid density ρ	1000 kg/m^3
Drag coefficient C_D	0.003
Erosion coefficient M	0.0001 kg/m^2/s
Critical shear stress for erosion τ_{ce}	0.2 N/m^2
Settling velocity w_s	0.001 m/s
Critical shear stress for deposition τ_{cd}	0.1 N/m^2
Simulation time step Δt	6 minutes
Boundary suspended-sediment concentration C_b	0.1 kg/m^3
Bulk density of bottom sediment ρ_b	1000 kg/m^3

The model was run with u_o=0.5 m/s and h_0=10 m until equilibrium was reached, defined as when the rate of bed elevation change (computed at the end of a tidal cycle) became less than the rate of sea level rise (2.17 mm/yr in San Francisco Bay, Flick et al. 2003). Equilibrium depths and tidal velocity magnitudes varied slightly with residence time (table 2). This equilibrium condition was assumed to be the actual condition of the estuary and the initial condition for the model. To represent the imperfect simulation of an estuary by a model and to test model sensitivity, C_b, u_0, M, w_s, τ_{ce}, and τ_{cd} were changed by 10% to cause deposition. The model was run until a new equilibrium was achieved.

Table 2. Equilibrium depths and maximum tidal current speeds

Residence time t_{res} (days)	Equilibrium depth h_o (m)	Equilibrium maximum tidal current speed u_o (m/s)
0	14.498	0.345
0.5	14.515	0.344
5	14.445	0.346
50	14.089	0.355
150	13.386	0.374

Two dimensional model of San Francisco Bay

A two-dimensional hydrodynamic and sediment transport model of San Francisco Bay was developed using the Danish Hydraulic Institutes (DHI) MIKE 21 model (DHI 1997,1998). This model solves the time-dependent, vertically integrated equations of continuity and conservation of momentum in two horizontal dimensions by a finite difference method. This model was used to evaluate the erosion, transport, and deposition of cohesive sediments under the action of currents and wind generated waves. The hydrodynamic model was calibrated using data collected during 1978, 1979, and 1980 (Cheng and Gartner 1984) supplemented by data collected from 1981 to 1983 (Gartner and Walters 1986). These data sets contained 20 water-level and 31 current meter stations.

Two formulations are used in the model to represent erosion. For sediment that undergoes deposition and resuspension on each tide cycle erosion of the top unconsolidated layer can occur spontaneously and is given by (Parchure and Mehta 1985):

$$E = \varepsilon \exp [\alpha (\tau - \tau_{ce})^{1/2}] \quad (7)$$

in which ε is an erosion rate constant (g/m^2/s), and α is an empirical coefficient based on comparison with measurements. The underlying weakly to highly consolidated sediments that are resuspended by more severe conditions are simulated using Equation 3. The equation prescribing deposition rate is shown in Equation 4.

Continuous SSC data are collected at 15-minute intervals at seven sites in San Francisco Bay (Buchanan and Ruhl 2001). Two different periods from these data sets were used to calibrate and validate the suspended sediment model.

The calibration and verification of SSCs showed that the model could capture the short time-scale processes. Long-term sedimentation is a consequence of the short time-scale sediment transport processes but is also influenced by the bed processes such as consolidation and fluidization as well as the global supply of sediments. Therefore, the model calibrated for SSCs does not necessarily ensure that the long-term bathymetric evolution of the Estuary can be reproduced. To verify how well the model performs in long-term sedimentation prediction, simulations were set up to hindcast the historic bathymetric changes observed in the Bay.

The sedimentation pattern in the South San Francisco Bay in the early part of the 20th century was distinctly different from that in the later period (Foxgrover et al. 2004). Therefore, the analysis focused on the period between 1955 and 1980 for hindcasting. Given that the two endpoints are almost 30 years apart with no data in between, different assumptions can be made regarding the pathways to progress from the starting to the ending bathymetry. Since the SSC data is more informative in terms of the natural variability than the historic bathymetric surveys, the hindcasting simulation incorporated all the short time scale processes with a simplistic feedback loop for updating the bathymetry. That is, no presumption is made on the bathymetric changes, and the credibility of the model is reliant on the interrelationship between SSC and the rate of sedimentation. An alternative approach would be to assume an average rate of sedimentation and erosion based on the historic bathymetry and calibrate the model to reproduce this rate. This approach would provide a better fit for hindcasting but would be unlikely to represent historic variability.

It is not possible to simulate 25 years of sediment transport on a short time scale due to the long computer run this requires, the limitations in model technology, and the propagation of errors. This necessitates making some simplifying assumptions. Average year hydrologic and meteorological conditions were assumed for model inputs. The 25-year period was divided into two time blocks Therefore, the predicted annual sedimentation using the 1950s bathymetry and normal year hydrology was multiplied by 13 to obtain the total sedimentation between 1955 and 1968. The bathymetry was then adjusted based on the model prediction, and other known anthropomorphic changes such as borrow pits and shoreline changes were added to serve as the starting bathymetry of the next simulation. The model was then rerun with average hydrologic conditions and the results multiplied by 12 to obtain the 1980 bathymetry.

Tidally averaged box model of San Francisco Bay

A tidally averaged sediment-transport model of San Francisco Bay was incorporated as a subroutine in a tidally averaged salinity box model (the UP model) previously developed by Uncles and Peterson (1995) (Lionberger et al. in press). 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). 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 for developing sediment budgets on a decadal time scale.

The 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 Bay is represented by 50 width-averaged segments each composed of 2 layers, representing the shallows (0 to 5-meter depth) and the channel (> 5-meter depth). The simulation period was 1940 – 2004. Model coefficients were adjusted to simulate bathymetric change measurements in subembayments (Jaffe et al. 1998, Cappiella et al. 1999, Foxgrover et al. 2004). 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.

RESULTS

Zero-dimensional model of a hypothetical estuary

Deposition rates were initially large and then decreased as equilibrium was approached (fig. 2). The model was most sensitive to maximum tidal current speed. Decreasing maximum tidal current speed 10% deposited 1.4 m after 10 years for a residence time of 0 days (table 3). The next most sensitive coefficient was the critical shear stress for erosion, which when increased 10% deposited 0.56 m after 10 years for a residence time of 0 days. Deposition rate decreased as residence time increased because the response of the bed was slower. For a residence time of 150 days, equilibrium was reestablished after only a few tidal cycles. Results were least sensitive to τ_{cd}, which when increased 10% deposited 0.096 m after 10 years for a residence time of 0 days.

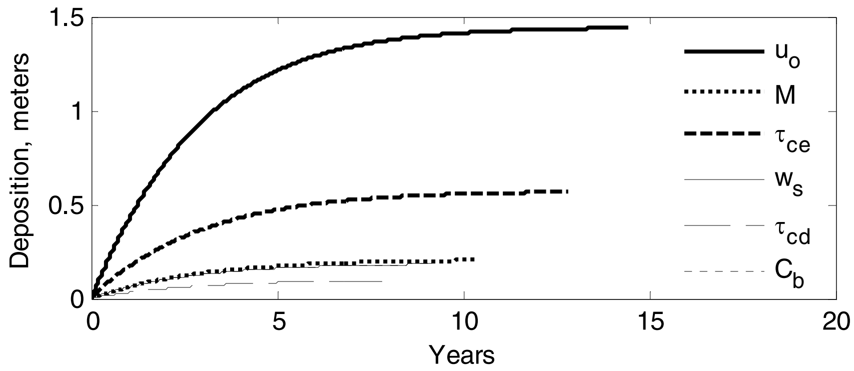

Figure 2. Deposition for a residence time of 0 days for the perturbed parameters.

Table 3. Deposition after ten years, in meters, for various residence times caused by perturbing a parameter 10% to favor deposition. The initial condition is equilibrium for the unperturbed parameters. [1]Equilibrium was reestablished within ten years and the value shown is deposition when equilibrium was reestablished.

Residence time t_{res} (days)	u_o	M	τ_{ce}	w_s	τ_{cd}	C_b
0	1.4	0.20	0.56	0.18[1]	0.096[1]	0.18[1]
0.5	1.3	0.18	0.50	0.16	0.083	0.16
5	0.45	0.060	0.19	0.052	0.0096[1]	0.056
50	0.046	~0[1]	~0[1]	~0[1]	~0[1]	~0[1]
150	~0[1]	~0[1]	~0[1]	~0[1]	~0[1]	~0[1]

For short residence times the time required for the model to reestablish equilibrium after perturbation was on the order of one decade or greater and for long residence times equilibrium was reestablished in much less than one year (table 4). As residence time increased, the rate of bed elevation change decreased but eventually nearly the same bed elevation was achieved. For long residence times the rate of deposition quickly became less than the rate of sea level rise, which was used to define equilibrium. For example, perturbation of u_o and a residence time of 150 days resulted in a deposition rate that was less than the rate of sea level rise after only 4.5 days. When the simulation was allowed to continue, deposition continued and reached 1.00 m after 1268 years.

Table 4. Time needed to reestablish equilibrium after perturbing a parameter 10% to favor deposition, in years, for various residence times.

Residence time t_{res} (days)	u_o	M	τ_{ce}	w_s	τ_{cd}	C_b
0	14	10	13	9	8	9
0.5	23	15	19	13	11	13
5	78	28	54	25	4	25
50	179	<1	<1	<1	<1	<1
150	<1	<1	<1	<1	<1	<1

Two dimensional model of San Francisco Bay

Predicted sedimentation was compared to measured sedimentation that occurred between the 1950s and 1980s on a point-to-point basis, where each point represents an area of 200 by 200 meters. The comparison is illustrated on Figure 3. The largest discrepancies were found in the northern part of the South San Francisco Bay, where excessive erosion was predicted for the main channel, which led to excessive accretion to the south. Although the two dimensional hydrodynamic and sediment transport model calibrated to suspended-sediment concentration in San Francisco Bay could not accurately hindcast bathymetric change the difference in bathymetry between model simulations with and without a large construction project appeared reasonable, indicating that the same errors were present in both simulations and canceled when differenced (Federal Aviation Administration 2003).

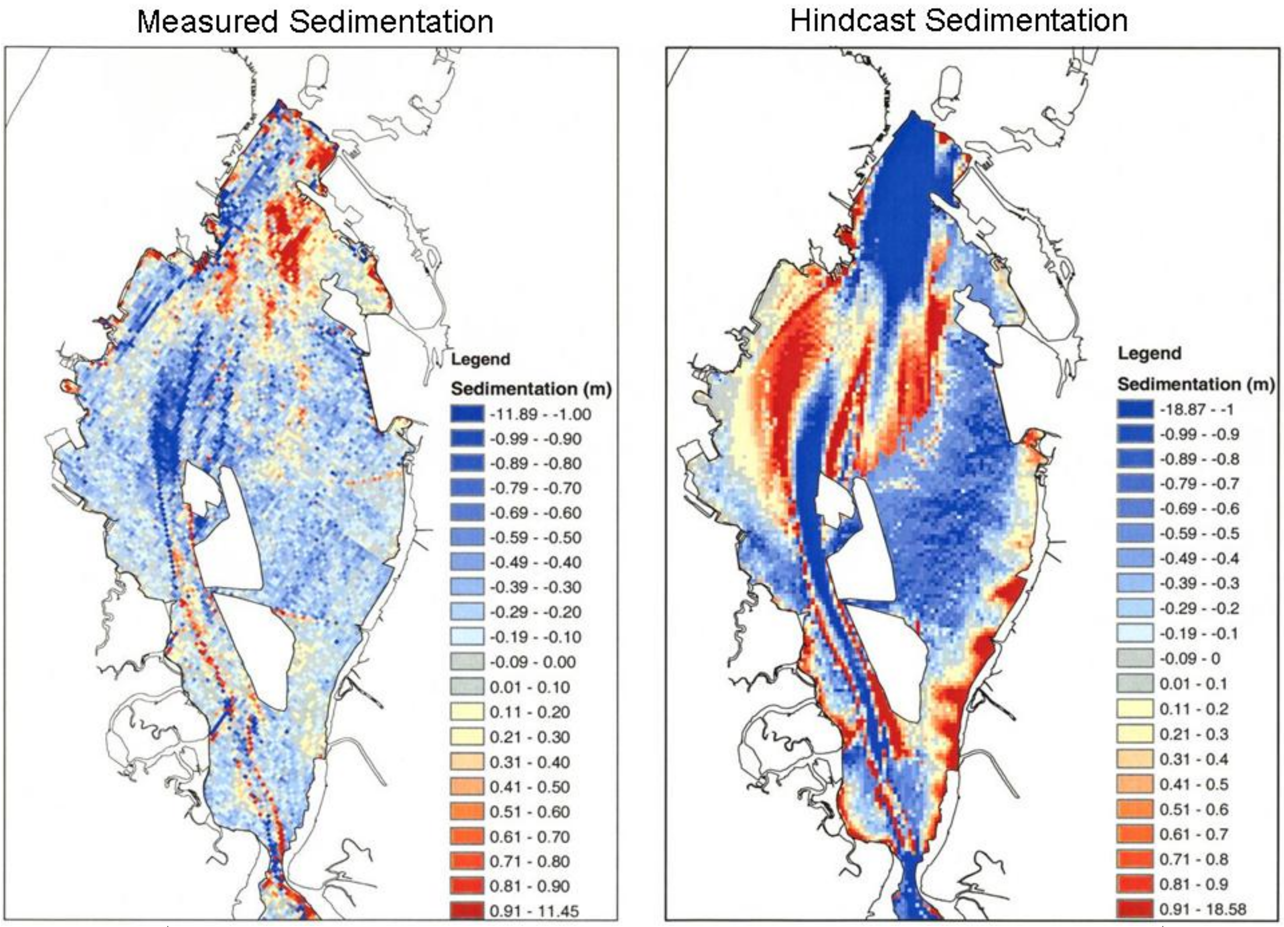

Figure 3. Measured and hindcast sedimentation with a two dimensional model, South San Francisco Bay (Federal Aviation Administration 2003).

Tidally averaged box model of San Francisco Bay

During the first 10-20 simulation years (1940-1960), bathymetry changed rapidly (fig. 4). Afterward, the rate of bathymetric change decreased considerably, although the tributary input of sediment and hydrodynamic forcing did not significantly change in the late 1950s or early 1960s. Thus, we believe that the initially large rate of bathymetric change is caused by model spin up. The model was calibrated with bathymetric change data from initial surveys from 1942-1956 (Jaffe et al. 1998, Cappiella et al. 1999, Foxgrover et al. 2004), which provides up to 16 years of model spin up.

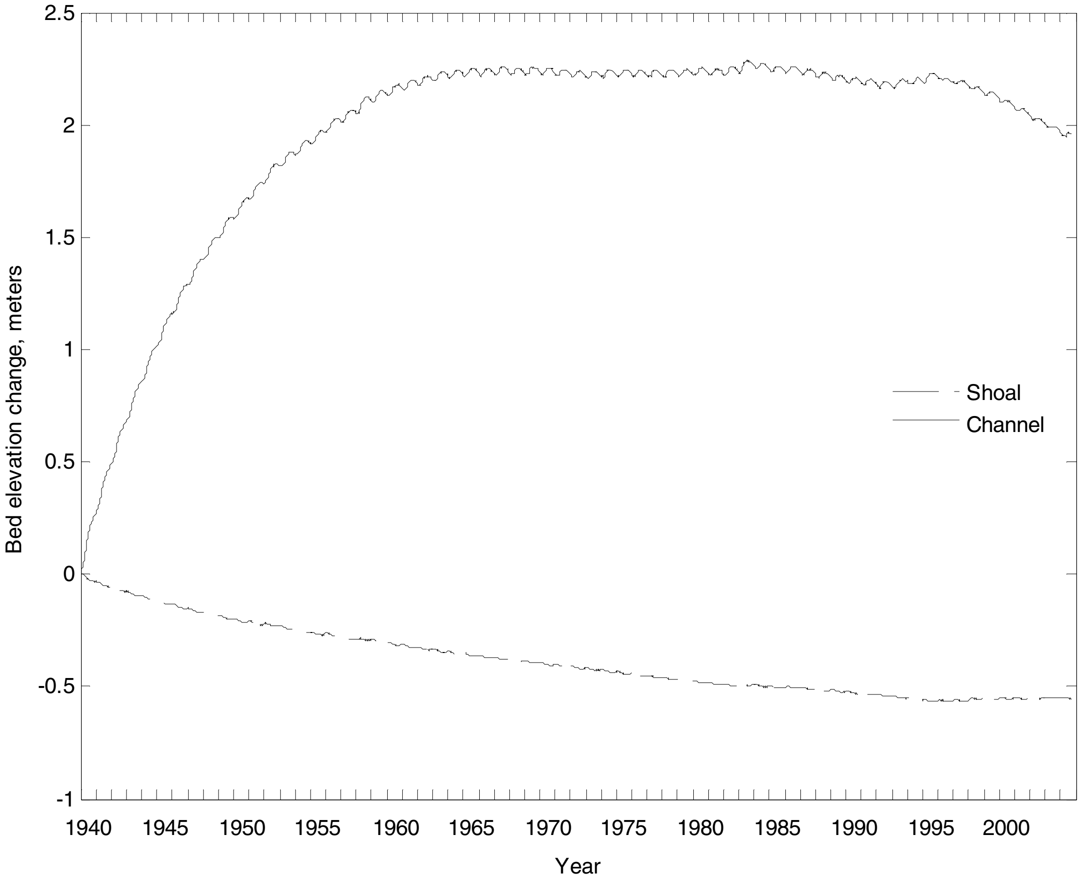

Figure 4. Example bed elevation change from a tidally averaged box model of San Francisco Bay (segment 7, see Lionberger et al. in press or Uncles and Peterson 1995).

DISCUSSION

Small errors in a cohesive sediment transport model can lead to erroneous simulated bathymetry changes that are significant to resource managers. Small perturbations of boundary conditions, hydrodynamic forcing, and cohesive sediment transport parameters resulted in significant changes in bathymetry (water depth) of a hypothetical estuary initially in equilibrium. For example, the model was most sensitive to a 10% perturbation, or error, in maximum tidal current speed. Thus, if the only error of a cohesive sediment model is a 10% error in the tidal currents, significant disequilibrium will be simulated in an estuary that should be in equilibrium. The next most sensitive parameter was critical shear stress for erosion, which is more difficult to estimate. The effect of model imperfections on simulated bathymetric change would be more pronounced for applications to real estuaries.

A model typically is calibrated to SSC rather than equilibrium and tidal cycle variability, wind waves, watershed pulses increase variability compared to the simple zero-dimensional model presented here. An example is the two dimensional hydrodynamic and sediment transport model calibrated to suspended-sediment concentration in San Francisco Bay. Calibration and validation with time series of suspended sediment concentration was successful yet the model could not accurately hindcast bathymetric change (Fig. 3). The difference in bathymetry between model simulations with and without a large construction project, however, appeared reasonable, indicating that the same errors were present in both simulations and canceled when differenced. Thus, predicting bathymetric change is more difficult than predicting the change in bathymetry caused by a perturbation in the estuary.

For typical or even minor imperfections in a model, a spin up time of one decade or more appears to be needed to insure that bathymetric change during the desired simulation period is not affected by the initial conditions. Spin up times needed for the zero-dimensional model to reestablish equilibrium and for the tidally averaged box model were both typically about one decade. If the spin up time is not sufficient, model results showing bathymetric change would be caused by the model adjusting bathymetry in response to the initial conditions and not be representative of future bathymetric change.

A simplifying assumption implicit in this analysis and most if not all cohesive sediment transport models is that the cohesive sediment parameters are stationary in time. For decadal simulations of bathymetric change, this may not necessarily be the case. Changes in benthos, fishing, trawling, riverine sediment load, and invasive species which may occur over decades all have the potential to alter cohesive sediment transport parameters. For example, Widows et al. (2000) found that erosion rate changed by a factor of greater than 100 as the composition of the benthic community changed and parallel changes in benthic community and sediment erosion may be climate driven. In South San Francisco Bay, sedimentation patterns were not persistent during the last century (Foxgrover et al. 2004). Therefore, if the two-dimensional model parameters were adjusted to simply match what happened between the 1950s and 1980s (fig. 3), no assurance exists that the correct sedimentation trend would be predicted for the future.

The spin up times in table 4 are dependent on the definition of equilibrium used. We adopted a rate of bathymetric change less than the rate of sea level rise as our definition of equilibrium. If the goal of a numerical model were to determine how an estuary responds to sea level rise, model spin up times would have to be greater to insure that bathymetric change caused by the imperfect initial conditions was much smaller than bathymetric change caused by sea level rise. Equilibrium in this study merely indicates that the rate of bathymetric change is less than a threshold, not that bathymetric change equals zero. True equilibrium was not achieved.

Accurate simulation of bathymetric change is difficult because of parameter sensitivity and spin up times exceeding 10 years. If the end product of a model is bathymetric change, then calibration to bathymetric change would be more appropriate than calibration to SSC, but bathymetry data typically are available only every few years or decades and care must be taken to insure that the surveys reference identical datums. Calibration of a model to the rate of bathymetric change would reduce spin up time, but determining an appropriate calibration period would be difficult especially if bathymetric data are temporally sparse. One possible solution to the spin up problem is to use simple models that can easily simulate decades, but the simplifying assumptions reduce accuracy and resolution. Some noncohesive morphodynamic models selectively update bathymetry and hydrodynamics to reduce computational effort (Hibma et al. 2003). This procedure could allow complex cohesive sediment transport models to simulate decades, providing for sufficient spin up time and calibration to bathymetric data.

CONCLUSIONS

Modeling future bathymetric change has become necessary due to concerns over habitat restoration, water quality, and navigation in estuarine and coastal environments. Accurately predicting future bathymetry requires considering model adjustment to initial conditions and model parameters. Modeled bathymetry will respond and adjust to these conditions and parameters, though the adjustment may take more than 10 y. Therefore a spin-up time must be allowed for, and bathymetric change during this period should not be considered part of the solution. Calibration to bathymetric change may assist in determining the correct parameters, though spatial and temporal variability of cohesive sediment bed parameters may confound efforts. If temporally intensive bathymetric data are available, spin-up time may be reduced by calibrating to short-term bathymetric change, but bathymetric surveys are usually temporally sparse. Simplification of models in terms of domain, inputs, or time-stepping allow for decreased computational effort and therefore more computational time may be devoted to model spin-up.

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