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# Calibration of an estuarine sediment transport model to sediment fluxes as an intermediate step for simulation of geomorphic evolution

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**Abstract**

Modeling geomorphic evolution in estuaries is necessary to model the fate of legacy contaminants in the bed sediment and the effect of climate change, watershed alterations, sea level rise, construction projects, and restoration efforts. Coupled hydrodynamic and sediment transport models used for this purpose typically are calibrated to water level, currents, and/or suspended-sediment concentrations. However, small errors in these tidal-timescale models can accumulate to cause major errors in geomorphic evolution, which may not be obvious. Here we present an intermediate step towards simulating decadal-timescale geomorphic change: calibration to estimated sediment fluxes (mass/time) at two cross-sections within an estuary. Accurate representation of sediment fluxes gives confidence in representation of sediment supply to and from the estuary during those periods. Several years of sediment flux data are available for the landward and seaward boundaries of Suisun Bay, California, the landward-most embayment of San Francisco Bay. Sediment flux observations suggest that episodic freshwater flows export sediment from Suisun Bay, while gravitational circulation during the dry season imports sediment from seaward sources. The Regional Oceanic Modeling System (ROMS), a three-dimensional coupled hydrodynamic/sediment transport model, was adapted for Suisun Bay, for the purposes of hindcasting 19th and 20th century bathymetric change, and simulating geomorphic response to sea level rise and climatic variability in the 21st century. The sediment transport parameters were calibrated using the sediment flux data from 1997 (a relatively wet year) and 2004 (a relatively dry year). The remaining years of data (1998, 2002, 2003) were used for validation. The model represents the inter-annual and annual sediment flux variability, while net sediment import/export is accurately modeled for three of the five years. The use of sediment flux data for calibrating an estuarine geomorphic model guarantees that modeled geomorphic evolution will not exceed the actual supply of sediment from the watershed and seaward sources during the calibration period. Decadal trends in sediment supply (and therefore fluxes) can accumulate to alter decadal geomorphic change. Therefore, simulations of future geomorphic evolution are bolstered by this intermediate calibration step.
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*Keywords:* Sediment transport; Numerical modeling; Sediment fluxes; Geomorphic change; San Francisco Bay

## 1. Introduction

Modeling estuarine geomorphic evolution addresses concerns that include, but are not limited to, wetland restoration, legacy contaminant resuspension, and estuarine habitat distribution. In light of continued sea level rise and uncertainty of future temperature and precipitation changes, development of appropriate models may assist in preparing for future changes. Sea level rise may increase tidal prism and possibly inundate emergent marshes, thereby altering the sediment transport regime in both channels and fringe areas. Changes in temperature and precipitation will modulate watershed runoff and therefore sediment loads, possibly altering or threatening seaward habitats (Scavia et al., 2002; Pont et al., 2002). Anthropogenic effects on sediment loads have proven to be important (Cappiella et al., 1999); effects from climate

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change may easily be as large. Future water management practices, which may alter the hydrograph more than climate change, will also effect the timing and magnitude of sediment loads to estuaries.

Modeling estuarine sediment transport with a tidal-timescale model typically involves calibrating to the following hierarchy of data: tidal stage, velocity, salinity, and suspended-sediment concentration (SSC) (e.g., McDonald and Cheng, 1997; Lumborg and Pejrup, 2005). Prior efforts in geomorphic (or boundary flux) modeling of estuaries have used these calibrated tidal-timescale models to simulate bed evolution. Lumborg and Pejrup (2005) predict net fluxes over one year using a 20 d time-series of SSC as the validation parameter. Schoellhamer et al. (in press), however, show that calibration to these parameters does not guarantee accuracy in terms of modeling geomorphic evolution. Uncertainty in input parameters can cause bed evolution to adjust in response to erroneous values; this adjustment will not recognized as a ‘‘spin-up’’ effect, and the simulation of geomorphic evolution will be compromised. For example, Schoellhamer et al. (in press) show that a 10% error in tidal velocity can cause a bed adjustment that requires 10 years to equilibrate.

Some recent efforts to predict morphological development have used more robust approaches: Douillet et al. (2001) adjusted parameters in order to obtain best qualitative agreement between observations of percent mud on the seabed and simulated deposition; Ouillon et al. (2004) further calibrated the Douillet model using satellite-derived estimates of SSC. This two-step approach provides greater confidence than a single-step approach. Hibma et al. (2003) developed an approach for long-term geomorphic modeling, evaluating the results by comparing the development of morphological features within the model to measured morphological features from two estuaries. The lesson from prior and current efforts is clear: a model must be calibrated and validated to the type of data that will be the final product of the modeling effort.

Two types of data provide the most robust calibration information: frequent bathymetric surveys, and continuous cross-sectional sediment flux data. The former gives a snapshot of bathymetric change between survey dates, though the expense and difficulty of these surveys results in large temporal spacing between surveys (~10 years). This temporal spacing is adequate for decadal-scale geomorphic modeling, but the actual inter-annual and year-to-year mechanics of the sediment transport cannot be verified. In this regard, continuous cross-sectional sediment flux data satisfies multiple goals. The net sediment budget will be correct if the fluxes are modeled correctly, and the tidal and subtidal timescales of sediment transport can be modeled and evaluated. Decadal trends in sediment fluxes will accumulate to alter decadal trends in net erosion and deposition. Therefore, confidence in modeling sediment fluxes generates confidence in modeling net sediment budget trends. However, this is only an intermediate step; the spatial variability of erosion and deposition must still be evaluated using decadal-timescale bathymetric change data.

The two aforementioned data types are available for Suisun Bay, California (Figs. 1 and 2), though their temporal coverage does not overlap. Five bathymetric surveys were performed in Suisun Bay, spanning from 1867 to 1990 (Cappiella et al., 1999). These data show the influence of hydraulic mining on sediment deposition (1867–1887), while the subsequent reduced input of mining debris and decreased freshwater flows (1922–1942) results in net erosion. It would be possible to calibrate a model to these data alone, though the inter-annual and year-to-year sediment transport mechanics could not be evaluated.

An additional data set of cross-sectional sediment flux data, however, is available at the landward and seaward boundaries of Suisun Bay, Mallard Island and Carquinez Strait, respectively (Figs. 1 and 2). These data are available for water years 1997–1998, and 2002–2004. McKee et al. (2006) estimated advective and dispersive loads between

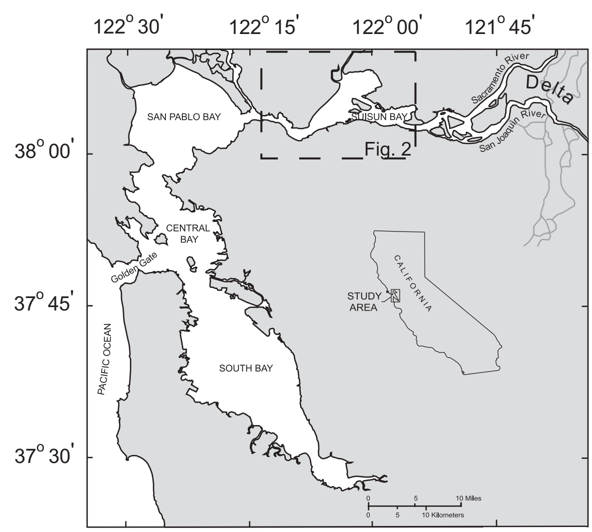


Fig. 1. Area map of San Francisco Bay; Suisun Bay is the landward-most embayment, positioned between the Sacramento/San Joaquin Delta and San Pablo Bay.

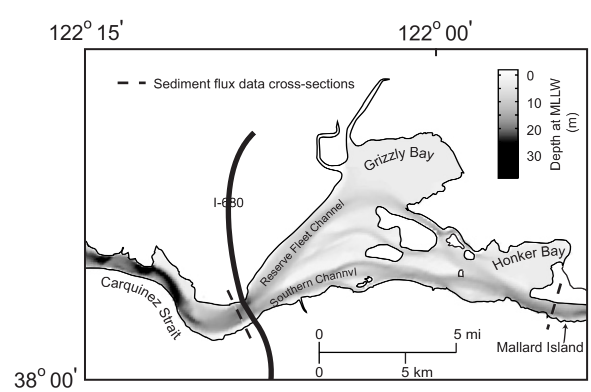


Fig. 2. Detailed map of Suisun Bay; Mallard Island is the landward boundary of Suisun Bay, while Carquinez Strait is the seaward boundary. The model seaward boundary is the left edge of this figure.

the Sacramento/San Joaquin Delta and Suisun Bay at Mallard Island, using continuous SSC data and freshwater flow measurements. Advective loads were estimated as the product of daily averaged point SSC (at the edge of the channel) and daily freshwater flow; the relationship between dispersive and advective flux was determined using point flux data from multiple periods. An error analysis yielded an average uncertainty of $\pm 25\%$ for daily sediment fluxes. Further details can be found in McKee et al. (2006). Ganju and Schoellhamer (2006) developed estimates of advective, dispersive, and Stokes drift flux between Suisun Bay and Carquinez Strait, based on measurements of SSC, longitudinal salinity gradient, and freshwater flow. Continuous point measurements were collected over a two-month period, while cross-sectional measurements were collected over two tidal cycles. The cross-sectional measurements were used to establish the point measurements as surrogates for cross-sectional sediment fluxes; the estimated cross-sectional fluxes were then used to establish long-term continuous data as surrogates for cross-sectional sediment fluxes. Errors in this method ranged from $\pm 22\%$ for Stokes drift flux to $\pm 48\%$ for dispersive flux. Further details of these methods can be found in Ganju and Schoellhamer (2006). The data for both boundaries overlap for five water years which span extremes of freshwater flow and sediment load, and are within the domain of the model.

Our goal for this study is to calibrate the model at the intermediate annual-timescale. We have already calibrated and applied the model at the tidal-timescale, for the simulation of estuarine turbidity maximum (ETM) dynamics (Ganju and Schoellhamer, in press). Tidal-timescale features, such as gravitational circulation, can accumulate to modulate annual-timescale features, such as prolonged landward transport during the dry season. Decadal trends in these features, such as prolonged drought, then accumulate to alter decadal geomorphic trends. Simulating annual sediment fluxes is the intermediate step, before simulating historical decadal bathymetric change, that builds confidence in modeling future scenarios of geomorphic change.

## 2. Methods

### 2.1. Site description

Our study area is Suisun Bay, the most landward subembayment of northern San Francisco Bay (Figs. 1 and 2). The Sacramento and San Joaquin Rivers deliver freshwater to Suisun Bay, during the winter and spring, due to rain, snowmelt, and reservoir releases. Precipitation is negligible during late spring and summer. Suisun Bay is a partially mixed estuary that has extensive areas of shallow water that are less than 2 m deep at mean lower-low water. Shallow estuarine environments such as Suisun Bay are ecologically significant because a large fraction of the biota depends on these areas for shelter and nourishment (Cloern et al., 1985; Caffrey et al., 1998). Wetlands, which usually form on shallow fringes of the Bay, provide habitat for species and communities not found elsewhere within the Bay (Goals Project, 1999). Channels in Suisun Bay are about 10–20 m deep. Carquinez Strait is a narrow channel about 18 m deep that connects Suisun Bay to San Pablo Bay, to the rest of San Francisco Bay, and to the Pacific Ocean. Tides are mixed diurnal and semidiurnal, with a maximum tidal range of about 2 m and maximum velocities of 2 m/s during the strongest spring tides. Freshwater inflow typically encounters saltwater in the lower rivers, Suisun Bay, and Carquinez Strait. The salinity range in this area is about 0–25 and depends on freshwater inflow.

Suspended and bed sediment in Suisun Bay is predominately fine and cohesive, except for sandy bed sediment in some of the deeper channels (Conomos and Peterson, 1977). The typical SSC range in northern San Francisco Bay is about 10–300 mg/L and sometimes over 1000 mg/L in an ETM. Several ETMs exist in San Francisco Bay, with notable ETMs in Suisun Bay (Schoellhamer and Burau, 1998), and within channels tributary to San Pablo Bay (Ganju et al., 2004).

The annual cycle of sediment delivery and redistribution begins with large, episodic freshwater flows during winter, which are mostly controlled by reservoir releases. A portion of the watershed sediment load deposits within the Delta (Wright and Schoellhamer, 2005), and the remainder is delivered to the estuary during this period (McKee et al., 2006). Suisun Bay tends to export sediment during this period (Ganju and Schoellhamer, 2006), due to high residual outflow combined with high SSC. San Pablo Bay is the recipient of this exported sediment. Diurnal winds during spring and summer cause wind-wave resuspension of bottom sediment in the shallow waters of Suisun and San Pablo Bays, increasing SSC (Ruhl and Schoellhamer, 2004). Gravitational circulation in the deeper channels of the estuary transports sediment from seaward (San Pablo Bay) to landward (Suisun Bay) subembayments (Ganju and Schoellhamer, 2006), especially in the spring and summer months. Thus, tides and wind redistribute the annual pulse of new sediment throughout the Bay. Since 1850, alterations in the watershed and estuary have changed the sediment loads and bathymetry of Suisun Bay (Gilbert, 1917; Porterfield, 1980; Cappiella et al., 1999). These changes, which have continued to modulate current sediment fluxes, are a major impetus for modeling both sediment fluxes and geomorphic change in Suisun Bay.

### 2.2. Model development

The Regional Oceanic Modeling System (ROMS) (Shchepetkin and McWilliams, 2005) is a public-domain hydrodynamic model with an optional sediment transport module. There are several advantages that ROMS has over other available models: (1) it is free, public-domain software; (2) it is improved and expanded amongst hundreds of researchers continuously; and (3) it is part of a community-based sediment transport initiative sponsored by the US Geological Survey.

ROMS is a split-mode model: the barotropic, depth-integrated equations are solved on a shorter (fast) time step (due to barotropic propagation speed) while the baroclinic terms are solved at a longer (slow) time step. The grid features of ROMS are: an Arakawa "C" grid, orthogonal curvilinear horizontal coordinates (Fig. 3), and stretched, terrain-following vertical coordinate. Boundary conditions for momentum/tracers on the four edges of the grid can be clamped (fixed), gradient (zero-derivative), radiation (allow disturbances to propagate away), or wall (zero-flux). In all cases, ROMS has adaptive capabilities, in order to switch from active conditions for inward fluxes and passive conditions for outward fluxes. Discretization options for momentum/tracers range from the 2nd order to 4th order (in space). With regards to turbulence, at least four common two-equation closures ($k$–$\varepsilon$, $k$–$kl$, $k$–omega, and gen) can be specified with the generic length scale implementation provided in the model.

Full details of the sediment transport module are given in Warner et al. (in press). ROMS has the capability to represent multiple size classes, each size class is treated as an independent quantity. The sediment source term, bed erosion, is given by Ariathurai and Arulanandan (1978) as

$$c_{\text{source}} = \varepsilon_s(1-n)\left(\frac{\tau_w}{\tau_c}-1\right) \quad \text{for } \tau_w > \tau_c, \tag{1}$$

where $\varepsilon_s$ is the erosion rate constant, $n$ is the porosity, $\tau_w$ is the shear stress exerted on the bed, and $\tau_c$ is the critical erosion shear stress of the sediment bed. The sediment sink term, deposition, is given by

$$c_{\text{sink}} = \frac{\partial w_s c}{\partial s}, \tag{2}$$

where $w_s$ is the bulk settling velocity of the size class. Flocculation processes are not considered, and must be parameterized using a bulk settling velocity.

Multiple bed layers may be specified, with each layer composed of a user-specified mixture of sediment classes. The properties of the mixed class bed, such as critical

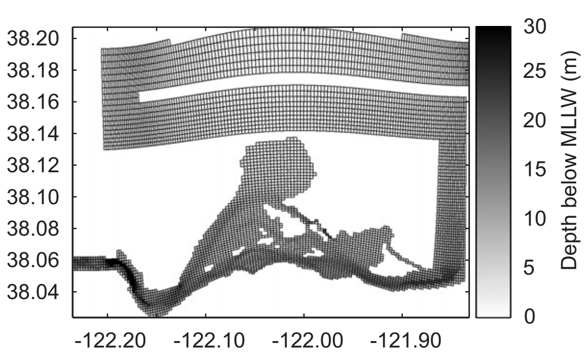


Fig. 3. ROMS modeling domain of Suisun Bay; landward boundary is the head of idealized Sacramento/San Joaquin Delta, seaward boundary is the western end of Carquinez Strait.

erosion shear stress, are weighted using the average mass fractions of the classes. The details of the bed layer model are given by Warner et al. (in press). Consolidation is not yet implemented in the ROMS model, but should not have a major affect on the annual timescale.

Bed stresses in bottom-boundary layer can be parameterized using multiple options: linear stress formulation, quadratic stress formulation, logarithmic stress formulation, or options that include wave–current interaction (Madsen, 1994; Styles and Glenn, 2000). Warner et al. (in press) detail the bottom-boundary layer module and the various modes available. Two bedload transport formulations, Meyer-Peter and Mueller (1948) and Soulsby and Damgaard (2005) are also available (but not implemented for this study). ROMS also has the capability of continuous bed-updating and morphological acceleration, but these were in a developmental stage at the time of this study, and not used here.

For these simulations, we use a $k$–$\varepsilon$ turbulence closure, eight vertical layers, 40 s time step (hydrodynamics and sediment transport), and average grid spacing of about 200 m in both directions. Spatial discretization in the horizontal was determined to be fine enough to resolve major channels within Suisun Bay, while vertical discretization was fine enough to represent the vertical velocity and salinity structure. Increased resolution would have resulted in unreasonable computational expense. Sediment parameters are given in Table 1. Each year is run separately, starting with the same initial bathymetry.

### 2.2.1. Modeling domain

Though Mallard Island is the geographic landward boundary of Suisun Bay, specifying boundary conditions at this location for historical and future multi-decadal simulations is difficult, due to tidal variation in stage, salinity, and SSC. Bidirectional flow is observed more than 50 km landward of Mallard Island. Prescribing stage, salinity, and SSC at the Mallard Island boundary is possible for simulating recent periods, but data do not exist for periods prior to the late 20th century. Therefore, extending the boundary to the bidirectional flow limit simplifies specification of boundary conditions. For instance, unidirectional freshwater flow measurements exist from 1929 onwards, and prior flows can be estimated using various proxies. Salinity can be specified as zero, and sediment loads can be estimated with rating curves for the Sacramento and San Joaquin Rivers.

However, the Sacramento/San Joaquin Delta represents a complex domain with multiple channels, open-water areas, flow gates, and export pumps. Including the Delta would more than double the modeling domain, and require further parameterization for in-Delta hydrodynamic processes. Due to the constraints mentioned above, we simplify the Delta in this study, as a single, continuous channel. The channel has the same water surface area as the Delta (and therefore tidal prism), and length equivalent to the distance from Mallard Island to Freeport (on the

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Table 1
Selected parameters and sensitivity analysis results for 2004

| Parameter | Initial value | Perturbed value | Change in flux at seaward boundary (Mt) | Change in flux at landward boundary (Mt) | Change in net sediment budget (Mt) |
|---|---|---|---|---|---|
| Critical erosion shear stress (Pa) | 0.10/1.0 | 0.11/1.1 | 0.40 | 0.00 | 0.40 |
| Settling velocity (mm/s) | 0.10/0.25 | 0.11/0.275 | 0.50 | 0.03 | 0.47 |
| Erosion rate ($kg/m^2/s$) | $2\times10^{-5}$ | $1.8\times10^{-5}$ | 0.39 | 0.00 | 0.39 |
| Seaward SSC ($kg/m^3$) | Variable | Increased by 10% | 0.48 | 0.00 | 0.48 |
| Landward SSC ($kg/m^3$) | Variable | Increased by 10% | 0.00 | 0.00 | 0.00 |
| Tidal velocity (m/s) | Variable | Decreased by 10%[a] | 0.41 | −0.07 | 0.48 |
| Freshwater flow ($m^3/s$) | Variable | Decreased by 10%[a] | 0.44 | 0.16 | 0.28 |
| Wave period (s) | 1.6 | 1.44 | 1.09 | −0.13 | 1.22 |

Positive change in sediment budget indicates increased deposition in Suisun Bay. Two values for sediment parameters refer to two sediment classes. Base 2004 seaward fluxes are 0.46 Mt (seaward), base landward fluxes are −0.26 Mt (seaward), for a base sediment budget of −0.20 Mt (export).
[a] *Note*: SSC was increased for these cases to keep sediment load constant.

Sacramento River), where sediment load measurements are available. Calibration of stage and salinity within the domain of Suisun Bay is unaffected by this idealization (Ganju and Schoellhamer, in press), though sediment transport processes through the Delta to Suisun Bay must be independently verified by this study. This idealized Delta can only be used for modern simulations, as the Delta has been modified greatly since the 19th century.

Carquinez Strait, immediately landward of the Napa River, was chosen as the seaward boundary of the domain (Fig. 1). Eastern Carquinez Strait is subject to complex circulation dynamics due to geometry of the Strait as well as baroclinic effects, and should be included within the model domain. Suspended-sediment dynamics near the I-680 Bridge are sensitive to the formation of an ETM on the north side of the Strait (Schoellhamer and Burau, 1998). Inclusion of the Napa River was ruled out due to a lack of long-term sediment load data; therefore the logical seaward boundary was landward of the Napa River but seaward of the I-680 Bridge. The sediment flux cross-sections (Fig. 2) are within the domain of the numerical model. The initial bathymetry reflects the most recent survey, performed in 1990 (Cappiella et al., 1999).

*2.2.2. Idealization of landward boundary conditions: flow, salt, sediment*

Net freshwater flow into Suisun Bay is a combination of flows through the Sacramento River, San Joaquin River, the seasonally flooded Yolo Bypass, minor tributaries, and exports by the federal and state water projects. Because these separate inputs and outputs are not explicitly modeled, the net flow is the parameter of interest. The DAYFLOW program (California Department of Water Resources, 2006) balances these inputs and outputs, to yield a daily value of flow past Mallard Island. This value is imposed at the landward boundary of the domain. Conceptually, this ignores the within-Delta transfer of water (and therefore sediment). However, the model will be calibrated to fluxes at the Mallard Island cross-section, so actual sediment retention within the Delta system will be accurately represented (though possible sediment exports by the water projects will be ignored). Salinity at the landward boundary is specified as zero.

Daily sediment loads past Freeport on the Sacramento River and Vernalis on the San Joaquin River were obtained from the US Geological Survey (http://water.usgs.gov). For modeling purposes, the SSC is specified as a boundary condition, therefore the loads are divided by the DAYFLOW value to yield the appropriate landward boundary SSC. A single sediment class was selected to represent incoming suspended sediment. While this ignores the grain size distribution observed in riverine flows, the simplification is necessary due to limited historical data. All boundary conditions are spread equally across the cells on the landward boundary, both vertically and laterally.

*2.2.3. Idealization of seaward boundary conditions: tides, velocities, salt, sediment*

Because the final geomorphic model will be used for simulations spanning the 19th, 20th, and 21st centuries, idealizations are necessary in terms of tidal height, velocity, salinity, and SSC. Tidal harmonics provide an appropriate initial estimate of historic tidal elevations and velocities. A tidal harmonic predictor was developed through instrument deployments (Jeff Gartner, writ. comm.), for locations throughout San Francisco Bay. The predictor provides tidal elevations and velocities at the west end of Carquinez Strait, which is the seaward boundary of the modeled domain. Meteorological forcings such as wind and barometric pressure are not represented in the tidal record. The tidal elevation and depth-averaged velocity are applied uniformly in a lateral sense at the seaward boundary. Three-dimensional velocities at the seaward boundary are solved with a gradient condition, which allows for the expected gravitational circulation in western Carquinez Strait (Burau et al., 1993).

For salinity, the method of Warner et al. (2005) is used, which utilizes a deterministic function based on near-bottom longitudinal salinity profiles as follows:

$$S(X) = (S_0/2)[1 + \tanh(\alpha - X/\beta)], \quad (3)$$

where $S$ is the salinity, $X$ is the longitudinal coordinate with origin at the mouth of the estuary, $S_0$ is the oceanic value of salinity, and $\alpha$, $\beta$ are empirical parameters. Parameter $\alpha$ is held constant as 2 following Warner et al. (2005). The parameter $\beta$ is related to freshwater flow ($Q$); for a given estuary this relationship can be established and used in the expression. Data from 358 longitudinal cruises between 1969 and 2005 of the US Geological Survey's R/V *Polaris* were processed to determine this relationship, as follows:

$$\beta = \exp[4.25 - 0.22 \log Q]. \quad (4)$$

Within the model code, the salinity gradient is calculated as a function of freshwater flow. This salinity gradient is applied on flood tides, at the first interior point of the domain, to calculate the flood tide salinity.

Sediment boundary conditions are substantially more difficult, as SSC at the seaward boundary responds to antecedent watershed sediment loads, tidal energy, and wind-wave resuspension in San Pablo Bay. Because flood-tide SSC is the parameter of interest, the measured flood-tide SSC at Carquinez Bridge (Buchanan and Ganju, 2005) was averaged on a daily basis. The pattern for water years 1998–2003 showed a similar pattern: inter-annual signals related to freshwater flow and wind-wave resuspension were superimposed on a spring–neap pattern that had greatest variability during spring tide periods and the least variability at the beginning and end of the water year (when sediment input is at a minimum). Therefore, three signals were superimposed to recreate a synthetic time-series of SSC: a flow signal that peaks in the early spring, an inter-annual wind-wave signal that peaks in the summer, and a spring–neap signal that is a function of tidal energy (obtained from tidal harmonics). The time-series is then modulated by a mean yearly SSC which is linearly related to total sediment input from the Delta during the water year. A random fluctuation of 10% of the SSC value is also included to represent noise. The final time-series essentially represents a tidally averaged SSC signal, which peaks during periods of high wave and tidal energy (Fig. 4). The SSC value was assigned equally to two sediment classes: a weaker fraction and a stronger fraction (in terms of critical erosion shear stress), with the same properties as assigned to the bed fractions in Suisun Bay and the Delta (discussed below).

### 2.2.4. Bed parameters

The major foreseen modification to the sediment transport model is the inclusion of two fine sediment classes, with varying fractions in the bed, based on location. Wright and Schoellhamer (2005) demonstrate that the Delta is a net depositional environment during high flow events, while Ganju and Schoellhamer (2006) show that Suisun Bay was net erosional during high flow events. Therefore, it is necessary to "armor" the Delta and allow for a net depositional environment, while Suisun Bay should be relatively weak and erosional during high flow events. This parameterization is congruent with observed bed characteristics (Regional Monitoring Program, 2006): channels of the Delta are sand-dominated (80% sand in lower Sacramento River), while most of the Suisun Bay bed is dominated by clays and silts (90% clay/silt in Honker and Grizzly Bays). The inclusion of two sediment classes (one weak, one strong, in terms of critical erosion shear stress) with varying bed fractions based on geographic location will allow for proper representation of the depositional and erosional nature of the Delta and Suisun Bay. The fractions are initialized as 40% weak/60% strong in Suisun Bay, and 12% weak/88% strong in the Delta at the beginning of the simulation. The parameters for each

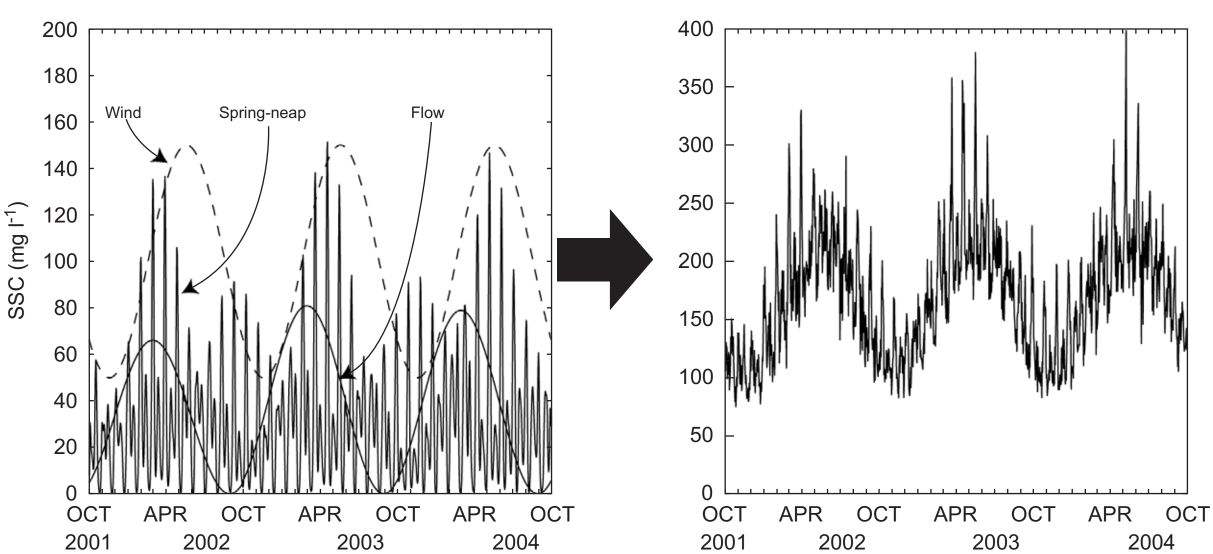


Fig. 4. Formulation of idealized seaward SSC boundary condition for three water years, as the sum of a wind, spring–neap, and flow signal, plus a noise component (not shown).

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size class are given in Table 1. Each fraction is eroded and deposited separately at each time step, but bulk bed properties are calculated as a geometric mean of the multiple sediment class properties. More complex characteristics of mixed-sediment beds are not considered here, and the properties of the mixed bed are assumed to be a linear combination of the individual sediment class properties.

#### *2.2.5. Atmospheric forcing*

The effect of wind-waves on sediment resuspension in San Francisco Bay can be substantial during episodic winter storm events and the diurnal winds during the summer. Wind data from Suisun Bay were used to calculate wave height and period using the Shore Protection Manual equation for fetch and depth-limited waves (Coastal Engineering Research Center, 1984). Though fetch within Suisun Bay depends on wind direction and location, a uniform fetch of 20 km was assumed. This is the mean distance between the mouth of Suisun Bay and the shallows of Grizzly and Honker Bays, where wind-wave resuspension is most relevant. Diurnal wind events in Suisun Bay tend from a westerly direction, so wave direction was held constant at 270°. Ultimately, wave period was also held constant, for simplicity. Though there are modern data available for implementing wind-waves in the model, there is still a need to construct a generic wind-wave time-series for historical simulations where data are not available, and therefore simplification of wave period and direction is appropriate.

#### *2.2.6. Selection of calibration/validation years and calibration/validation goals*

Because there are five water years of data available, it is possible to calibrate and validate with subsets of these data. We have chosen 1997 and 2004 for calibration years for several reasons: 2004 data were used to generate the regressions that led to the sediment flux predictions at the I-680 Bridge cross-section (Ganju and Schoellhamer, 2006), therefore these are the most reliable data; net freshwater flow in 2004 is the closest of the five years to the average flow condition over the modern (1930–2004) period; 1997 is the second-most extreme year in terms of peak freshwater flow during the modern period; and 1997 represents the only wet year with significant landward dispersive fluxes during the summer (1998 had seaward dispersive fluxes during the unusually high-flow summer). The remaining water years represent years with the largest estimated sediment export (1998) and the largest estimated sediment import (2002). These extremes provide a suitable test of the model formulation and setup.

The goals in this modeling effort are, in order of decreasing importance: (1) represent the inter-annual variability of cross-sectional sediment fluxes, (2) model relative year-to-year variability (i.e. more export in 1998 than 1997, more import in 2002 than 2003 and 2004), (3) model the net sediment budgets within the error of the estimates, and (4) model the magnitude of episodic and inter-annual events within the error bounds of the estimates. The main parameters which are varied are critical erosion shear stress, settling velocity, wave period, and sediment fractions between the Delta and Suisun Bay. Parameters are varied to meet goals 3 and 4 within the error of the estimates of McKee et al. (2006) and Ganju and Schoellhamer (2006).

#### *2.2.7. Sensitivity analysis*

The sensitivity of the calibrated model to several of the parameterizations and idealizations is explored to ensure that net fluxes are not significantly affected by parameter specification. These parameters include, but are not limited to: critical erosion shear stress, settling velocity, erosion rate, seaward boundary SSC, landward boundary SSC, tidal velocity, freshwater flow magnitude, and wave period (Table 1). Parameters will be adjusted by 10% to favor deposition: an increase in critical erosion shear stress, settling velocity, seaward and landward boundary SSC, and a decrease in erosion rate, tidal velocity, freshwater flow magnitude, and wave period. While the uncertainty of some parameters may be greater than 10% (e.g. critical erosion shear stress), the uncertainty of others may be less (e.g. freshwater flow). We choose 10% as an intermediate value, which should highlight the sensitivity of the model to different parameters. The initial result and the perturbed result will demonstrate the sensitivity of the model for each parameter, without the need of a third simulation favoring erosion. Each parameter will be varied separately while the remaining parameters are held at the initial calibration value. The effect on landward and seaward boundary fluxes will be observed for each of these eight perturbations, using 2004 as the modeled water year. This year is selected as it represents the water year with a net sediment budget closest to zero.

## 3. Results

### *3.1. Calibration and validation*

Model performance was varied with respect to the four goals of: (1) representing the inter-annual variability of cross-sectional sediment fluxes, (2) modeling relative year-to-year variability, (3) modeling the net sediment budgets within the error of the estimates, and (4) modeling the magnitude of episodic and inter-annual events as closely as possible. For the calibration years, 1997 and 2004, all goals were met, except for goal 4 in 1997 (matching of peak events). For the validation years, goals 1 and 2 were met, while goal 3 was only met for 2003. Goal 4 was met for 2002 and 2003, but not for 1998.

With respect to Goal 1, the model simulates inter-annual variability well: high freshwater flows consistently result in net export from Suisun Bay, while sediment is imported from Carquinez Strait to Suisun Bay and the Delta during low freshwater flow periods (Fig. 5). Goal 2 is also met, as

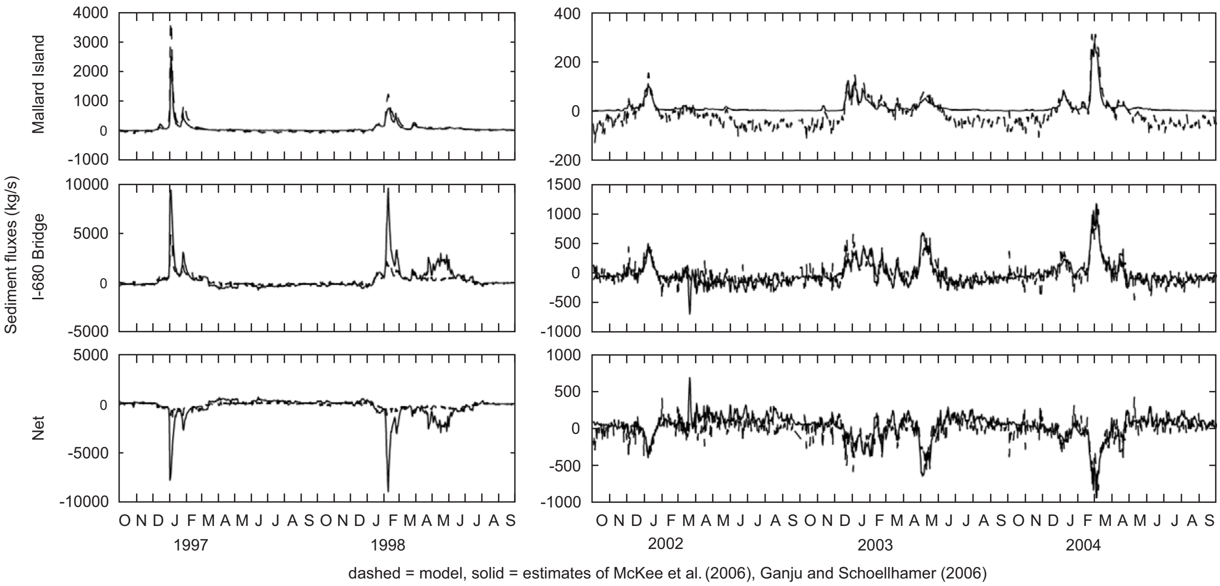


Fig. 5. Time-series of sediment fluxes at Mallard Island, I-680 Bridge, and the net budget for Suisun Bay. Dashed lines indicate model results, solid line are estimates of McKee et al. (2006) and Ganju and Schoellhamer (2006).

the model predicts greater erosion in 1998 than 1997, and more deposition in 2002 than 2003 and 2004 (which the model predicts as erosional) (Fig. 6). However, the variability between 2003 and 2004 is not represented correctly. Goal 3 is met for three out of five years (Fig. 6), though the relative performance varies from year-to-year. Goal 4 is met for water years 2002, 2003, and 2004, while the episodic events in 1997 and 1998 are overestimated at Mallard Island and underestimated at Carquinez Strait. Nonetheless, they are close to the upper and lower bounds of the estimates of McKee et al. (2006) and Ganju and Schoellhamer (2006). The net magnitude of the inter-annual landward fluxes observed in the summer is modeled well, though spring–neap variability will not match due to the use of tidal harmonics and synthetic SSC as seaward boundary conditions. Overall, poor agreement is observed during low-flow periods at Mallard Island, and during episodic events in 1997 and 1998. The discrepancies are discussed in detail (see Discussion).

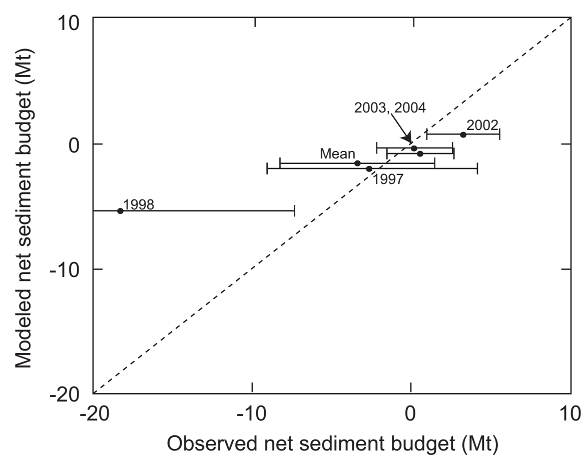


Fig. 6. Net observed and modeled sediment budgets in Suisun Bay for five water years. Poor agreement in 1998 is due to error in the extrapolation of dry season relations (see Fig. 7).

### 3.2. *Sensitivity analysis*

Model sensitivity of sediment fluxes to model parameters (Table 1) varies depending on the parameter of choice. Perturbations of the sediment characteristics (critical erosion shear stress, settling velocity, erosion rate, seaward SSC), favoring deposition, led to expected increases in deposition. The least sensitive parameter is SSC at the landward boundary. Despite a 10% increase in sediment load at the landward boundary, net fluxes at Mallard Island remained constant (peak loads were increased slightly). Decreases in tidal velocity led to increased deposition, due to reduced shear stresses in Suisun Bay. A decrease in freshwater flow resulted in increased Delta trapping and reduced fluxes into Suisun Bay. The most sensitive parameter was wave period. This arises from the highly non-linear relationship between wave energy and shear stress, and suggests that correct parameterization of waves is necessary for accurate simulations. All of the deviations are within the error bounds of the measurements.

## 4. Discussion

### 4.1. *Model response to forcings*

#### 4.1.1. *Delivery phase*

The delivery of suspended sediment from the Central Valley to the Delta and Suisun Bay occurs during freshwater flow pulses in the winter and spring. The Delta's depositional capacity is an important feature which must be captured to adequately simulate loads between the Delta and Suisun Bay. The use of an idealized Delta is validated by correct simulation of the episodic sediment delivery phase past Mallard Island, though modeled sediment load past Mallard Island is biased high for the two wetter years (1997, 1998) presented here. This discrepancy may be caused by a few factors: (1) greater hydraulic efficiency of the idealized Delta, as opposed to the real Delta; (2) misrepresentation of coarse sediment as fine sediment, during peak flows; and/or (3) neglect of effects caused by sediment transport through the Yolo Bypass. The Yolo Bypass is a 100 km$^2$ flood-control channel that diverts Sacramento River flows above 2000 m$^3$/s. A relative lack of data precludes specifying the time-varying concentration of a coarser size class in freshwater flows, or including the Yolo Bypass within the model. It should be noted that the peak flow event of 1997 is extreme, having been exceeded only once in the modern era (1930-present).

During these same periods, the modeled sediment fluxes past the I-680 Bridge cross-section are underestimated. The relationships developed by Ganju and Schoellhamer (2006) are based on data collected during spring 2004, when freshwater flows never exceeded 1000 m$^3$/s. It is possible that the relationships, based on freshwater flow, salinity gradient, and point SSC, are erroneous when extrapolated to periods with higher freshwater flow, such as 1997 and 1998. To test this hypothesis, we use the simulated flow, salinity gradient, and point SSC to calculate sediment fluxes for all five water years, and compare those predictions to the actual modeled sediment fluxes. The residual error increases with flow (Fig. 7), suggesting that the relationships are more appropriate for low-flow periods.

#### 4.1.2. Wind-wave resuspension

The application of idealized wind-waves to the domain results in enhanced erosion in the shallower portions of the bay, which is consistent with previous field observations (Ruhl and Schoellhamer, 2004). The effect is minimal in deeper channels, where the shear stress induced by waves is

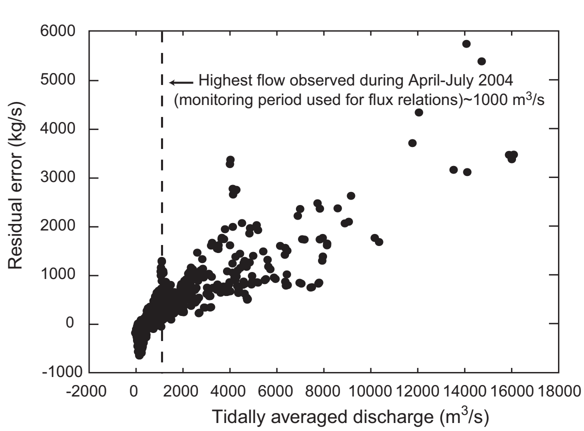


Fig. 7. Residual error generated by extrapolating dry period empirical relationships of Ganju and Schoellhamer (2006) to wetter periods.

minimized. Increased wave height results in increased erosion and sediment export from Suisun Bay, mainly during episodic wind events and the summer period. During the spring and summer, however, this is countered by increased sediment concentrations in San Pablo Bay, which is shallower and more susceptible to wind-wave resuspension (Ganju and Schoellhamer, 2006). The sediment supply from San Pablo Bay (represented by the wind signal in the synthetic SSC condition) is available to Suisun Bay through Carquinez Strait, which is a zone of increased gravitational circulation. In order to counter sediment export from Suisun Bay due to wind-wave resuspension, sediment import due to gravitational circulation must be properly represented as well.

#### 4.1.3. Gravitational circulation

Landward sediment transport due to gravitational circulation is common in partially mixed estuaries (Geyer et al., 2001), and several prior studies have identified strong gravitational circulation (Burau et al. 1993; Schoellhamer and Burau, 1998) and net landward sediment transport over prolonged periods in Carquinez Strait (Ganju and Schoellhamer, 2006). The mechanism is well-represented in the model, as net landward transport is observed through the summer months, with larger magnitudes near the bed, where greater SSC coincides with residual landward flow. The magnitude of the landward transport is dependent on the synthetic SSC and near-bottom residual flow; while the synthetic SSC is known a *priori*, the residual flow follows the expected pattern of seaward flows during high freshwater flow, and landward flows near the bed during low freshwater flow. This summertime sediment import to Suisun Bay counteracts erosion due to wind-waves within the shallower portions, resulting in net import during the summer periods for all water years except 1998 (when freshwater flow was elevated through the summer).

### 4.2. Landward sediment flux at Mallard Island

The flux calculation method at the Mallard Island cross-section (McKee et al., 2006) estimates daily advective flux, and uses an adjustment to correct for possible landward dispersive flux. The adjustment was based on the ratio of point dispersive to advective fluxes, at the southern end of the channel. The ratio was found to be mostly negative, i.e. dispersive fluxes were consistently in the landward direction; however, this formulation may underestimate landward dispersive flux. McKee et al. (2006) calculate landward dispersive flux to be 20% of the seaward advective flux over the nine-year study period. The modeling work here shows the percentage to be representative of high-flow years (e.g., 1997), but larger during low-flow years. Averaging the modeled sediment flux in the cross-section over the entire year shows net seaward flux in the upper water column, and net landward flux in the lower water column. The point measurements used for the McKee et al. (2006) relationships were collected at depths which the model identifies as neutral to seaward flux locations. Therefore, the modeled landward fluxes are realistic, and represent the landward redistribution of Suisun Bay sediments during low-flow periods.

## 5. Conclusions

Developing an estuarine geomorphic model requires appropriate calibration data beyond tidal stage, currents, salinity, and SSC. Optimally, frequent bathymetric surveys can be used for evaluating the capabilities of a model. However, the time and cost-intensive nature of these surveys dictates typical intervals of at least a decade. This is sufficient to evaluate the performance of a geomorphic model; however, decades of sediment transport must be modeled up-front. An accompanying data set of continuous sediment fluxes at the domain boundaries provides another metric by which to evaluate the model. The performance of the model can be evaluated relatively quickly, by simulating inter-annual and yearly transport cycles. Bathymetric change data ensure correct evaluation of spatial patterns of erosion and deposition, while sediment flux data ensure that the net sediment budget is correctly modeled. In this study, we calibrate and validate the sediment transport mechanisms of a model with sediment flux data, as an intermediate step. The idealized model successfully captures inter-annual and yearly sediment transport cycles, and simulates the net sediment budget correctly for three of five water years. This robust test of the model gives further confidence for hindcasting simulations of bathymetric change, and future simulations of geomorphic evolution in response to climate change and sea level rise.

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