Key Points:

- The timing of wind events relative to the tidal cycle most strongly dictates bed evolution in a shallow estuary
- Settling velocity controls system-wide sediment accumulation
- Windy periods are better represented by faster settling particles

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Cohesive Sediment Modeling in a Shallow Estuary: Model and Environmental Implications of Sediment Parameter Variation

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Abstract Numerical models of sediment transport in estuarine systems rely on parameter values that are often poorly constrained and can vary on timescales relevant to model processes. The selection of parameter values can affect the accuracy of model predictions, while environmental variation of these parameters can impact the temporal and spatial ranges of sediment fluxes, erosion, and deposition in the real world. We implemented a numerical model of San Pablo Bay, an embayment within San Francisco Bay, California, for November–December 2014, and compared model outputs to observations of water level, velocity, wave parameters, salinity, and suspended sediment concentration (SSC) in the shallow regions. Idealized model runs show that wind timing relative to the phase of the tides is the strongest control on sediment fluxes and bed erosion. We varied sediment erodibility in the outflow of the Petaluma River; while this causes erosion and deposition to vary strongly through the shallows system, total export from the shallows does not change. Model runs with realistic winds show that wind likely resuspends faster settling particles or allows for more particle flocculation; particle settling velocity controls system-wide sediment accumulation. At the margins of the system, the magnitude of SSC is closely tied to wind direction when winds occur during flood tide, but sediment deposition is less connected: Both bed evolution and SSC need to be considered in the prediction of marsh fate. Spatial patterns of light attenuation due to SSC is strongly tied to assumed settling velocity.

Plain Language Summary Numerical models rely on a number of input values, or parameters, to make predictions about sediment movement and accumulation through estuarine systems, yet often the values are poorly known. Selection of parameter values can impact the effectiveness of numerical models; meanwhile, real-world variation in the parameters also impacts sediment transport. We implemented a three-dimensional numerical model in San Pablo Bay, part of San Francisco Bay, California, to predict water level, water velocity, waves, salinity, and suspended sediment concentration to explore these two questions. Our modeling reveals that the timing of winds relative to tidal phase has the strongest impact on spatial patterns of bed erosion and deposition, stronger than wind direction, sediment settling velocity, spring-neap cycle, or spatial variation in bed erosion parameters. When winds are known, settling velocity, coupled with the erosion rate parameter, can impact the spatial distribution of light attenuation, which is important for protecting estuarine systems from phytoplankton blooms. Under our model, a near-shore region will attenuate more light than a near-channel region under low winds only when settling velocity is smaller; that is, model parameter values impact our interpretation of model outputs.

1. Introduction

By modeling sediment transport, we can predict whether coastal marshes will accrete and keep up with sea level rise, or erode; whether dredged channels will need to be re-dredged in 1 year, 10 years, or 100 years; and whether and where estuaries have enough sediment in the water column to prevent sunlight penetration and phytoplankton production. Numerical models typically consider two kinds of sediments: cohesive and non-cohesive. Non-cohesive sediments are frequently larger (sands, pebbles, etc.), and their physical properties are generally good predictors of their response to flow and turbulence. Cohesive sediments are composed of fine silts and clays, and their physical properties are impacted by physical and biological

processes that are not yet fully understood (Borsje et al., 2008). These uncertainties make cohesive sediment transport models challenging to implement; currently, models rely on empirical and semi-empirical parameterizations of the pertinent processes (Chou et al., 2018; Fringer et al., 2019).

Two important properties controlling cohesive sediment concentration and transport are suspended particle size and bed erodibility. Fine sediments can aggregate in the water column, yielding flocculated particles (flocs) that are larger, and less dense, than the primary particles. Flocs are fractal structures, and their size can be impacted by the fractal dimension of flocculation, aggregation and breakup rates, sediment concentration, and the turbulent shear rate (Winterwerp et al., 2006). Biological processes, such as the production of extracellular polymeric substances (EPS), can also impact floc size and durability (Fettweis & Baeye, 2015). Temporal variations in sediment flocculation on tidal timescales can impact sediment transport (Livsey et al., 2020a). Sediment particle size drives its settling velocity (w_s): larger particles settle faster (Ferguson & Church, 2004; Winterwerp, 1998).

Sediment bed erodibility can vary in time and space, impacted by physical sediment properties such as particle size, density, water content, and temperature; geochemical properties such as mineralogy, salinity, pH, and the presence of cations, metals, and organic material; and biological properties such as sediment disturbance, feeding and egestion, and biogenic structures (Fettweis & Baeye, 2015; Grabowski et al., 2011; Jumaras & Nowell, 1984). Active management, through dredging, can also impact bed erosion rates by altering the physical, geochemical, and biological properties. Empirical and semi-empirical formulas for predicting sediment erodibility have been developed from laboratory flume experiments and field measurements (e.g., Mehta, 2013, Section 9.3.4). However, there is currently no physically based model for predicting cohesive sediment erodibility from sediment bed properties (Sherwood et al., 2018).

Field studies have observed spatial variability in erodibility on small horizontal scales (cm-m) as well as larger scales within a single estuarine system (Grabowski et al., 2011). Variation in processes on annual, seasonal, and spring-neap timescales can also impact sediment erodibility. For example, Thompson et al. (2019) observed a seasonal shift in the shear stress needed to resuspend sediment (critical shear stress, τ_{crit}) on the muddy shelf sea of the United Kingdom: τ_{crit} increased through the summer period; Wiberg et al. (2013) saw a winter increase in erodibility in a mesotidal channel flat; Brand et al. (2015) detected higher bed erodibility in spring compared to fall in South San Francisco Bay; and Allen et al. (2019) found an increase in erodibility in winter following a wind event. Even as the biophysical causes of this variation are not well understood, its implications are also insufficiently explored.

With this work, we explore the role of sediment parameter variation on model performance as well as the consequences of environmental variation in these parameters for cohesive sediment transport. Observations for both sediment model calibration and for sediment parameter selection are limited; this work offers methods for selection of model parameters, presents bounds for parameter values, and provides a sensitivity analysis showing the impact of parameter variation. Second, this work addresses the difference that w_s and erosion parameter variation can make to predicted sediment flux and erosion/deposition, and compares these impacts to the effects of other physical forcings such as the spring-neap cycle, wind direction, and wind timing. We then explore the implications of this analysis for sediment behavior in the shallow regions of an embayment within the San Francisco Estuary (San Pablo Bay) under realistic wind conditions, for sediment available to fringing marshes, and for light penetration through the water column. Our results show that model performance in San Francisco Bay depends on the choice of parameters such as settling velocity and bed erosion rate, and reveal sediment behavior in the environment.

2. San Francisco Bay and San Pablo Bay

This study occurs in the northern part of San Francisco Bay, the largest estuary on the west coast of the United States (Figure 1). San Francisco Bay's watershed drains about 153,000 km², and makes up 40% of California's land area (Conomos et al., 1985). The northern part of San Francisco Bay receives most of this freshwater input through the Sacramento and San Joaquin Rivers, which drain the northern and southern parts of California's Central Valley, respectively. The region's Mediterranean climate yields dry summers and wet winters; during the dry season salinity in San Pablo Bay typically oscillates between 15 and 30 PSU on a daily basis, and in wet winters it can completely freshen.

Figure 1. San Francisco Bay model domain and bathymetry used in (a) the overall model and (b) the nested model. Model boundaries and observation points for data-model comparisons are marked in (b). Vertical datum is NAVD88. Bathymetry reflects the model grid, and is sourced from Elias et al. (2013) and Fregoso et al. (2020); land imagery is sourced from USGSTopo (MapServer) (2020).

Throughout San Pablo and Suisun Bays, water depth is less than 30 m, with the deepest parts in a central channel, about 1–1.5 km wide. This channel is bordered by two sets of mudflats in San Pablo Bay extending about 12 km to the northwest and 4 km to the southeast where depths range from 5 m to intertidal. Hydraulic mining in the estuary's watershed between 1852 and 1884 increased sediment supply to the system (Krone, 1979), causing expansion of San Pablo Bay's fringing mudflats and marshes. In the subsequent century the central channel became narrower and deeper (Jaffe et al., 2007). Recent models suggest that the rate of sea-level rise will surpass the rate of sediment deposition, and many fringing marshes will drown by the year 2100 (Elmilady et al., 2018).

Tides in San Pablo Bay are mixed semi-diurnal, with lower-low water following higher-high water, resulting in an ebb-dominated system (Cheng & Gartner, 1984). Tides propagate as a progressive wave through the North Bay. Spring tides have a tidal range of 2.5 m and the neap-tide range is 1 m; the tidal range decreases upstream of San Pablo Bay due to frictional effects. Observations from the 1980s showed that tidal residual currents through San Pablo Bay depend on the bathymetry, the horizontal salinity gradient, tidal current shear, spring and neap variations in tidal currents, and wind forcing (Cheng & Gartner, 1984). North San Francisco Bay frequently experiences strain-induced periodic stratification due to salinity gradients, with gradient Richardson numbers exceeding 0.25 on ebb tides (Stacey & Ralston, 2005).

Waves in San Pablo Bay are locally generated wind waves (Ganju & Schoellhamer, 2009). Wind events can last multiple days in the winter, coming from the east, south, and west. Summer waves occur for shorter periods, generated by afternoon winds, predominately from the west and southwest (Elmilady et al., 2018). In the shallowest parts of San Pablo Bay, resuspension of sediment by waves can lead to sediment-induced stratification; during stormy periods the gradient Richardson number exceeded 0.25 (MacVean & Lacy, 2014).

The primary sediment grain size on the bed through the shallow parts of San Pablo Bay is 8 μm (Allen et al., 2019). Conceptual models suggest that sediment is transported in to San Pablo and Suisun bays during the wet winters, and it is re-worked and eroded by wind waves during the dryer summer seasons (Krone, 1979; Schoellhamer et al., 2008).

3. Methods

3.1. Delft3D Model Description and Setup

Many coupled hydrodynamic and sediment transport models, including COAWST, FVCOM, SUNTANS, and UnTRIM (Fringer et al., 2019), have been used in estuarine settings; here we applied Delft3D, version 4.04.01. This structured grid model allowed us to couple flow and waves with sediment transport in

Table 1
Sediment Parameters^a

	D_{50} (μm)	w_s (mm/s)	τ_{crit} (N/m^2)	Erosion parameter ($\text{kg/m}^2\text{s}$)
Mud		0.2	0.1	10^{-5}
Flocs		1	0.1	$5 \cdot 10^{-5}$
Sand	200			

^aNumerical sediment parameters in use.

three-dimensions (3D), and has been well established in estuarine settings in general (Fringer et al., 2019), and San Francisco Bay in particular (Achete et al., 2017; Elmilady, 2016; White, n.d.). Some numerical models (e.g., Sherwood et al., 2018) use “cohesive” to refer to particles that can aggregate and break up within the water column, shifting concentrations between size classes. Delft3D does not include a flocculation model; in this work cohesive sediments are distinguished from non-cohesive sediments by the empirical definitions of the sediment properties. Elias et al. (2013) developed a simple two-dimensional horizontal (2DH) tidal model of San Francisco Bay that was used to initialize and set up the boundary conditions for a nested 3D model of San Pablo and Suisun Bays, originally developed by Elmilady (2016). Both models are modified in this work.

3.1.1. Overall Model

The basic tide model extends from the Sacramento and San Joaquin Rivers to the east, to the southern tip of South Bay, to ocean boundaries running 250 km north-south (Figure 1a). In San Pablo Bay, the horizontal resolution ranges from 500 to 1,100 m and the time step is 0.5 min. We extend the Elias 2DH model to 3D; now the model implements 10 vertical sigma layers, each representing 2, 7, 20, 20, 20, 13, 8, 5, 3, and 2 % of the water column, from surface to bed.

This model spins up from 1 January to November 1, 2014, and its outputs are used to initialize the nested model on 1 November. Tidal forcings at the ocean boundary are derived from standard tidal constituents; a non-tidal residual is added for the time periods of interest based on water level observations at San Francisco (NOAA site 9414290, National Oceanic and Atmospheric Administration, 2020). On January 1, 2014, salinity is initialized at 0 PSU in the Sacramento and San Joaquin Rivers, at 33 PSU in the ocean, with intermediate values in the Golden Gate, South Bay, and San Pablo and Suisun Bays. Daily freshwater inputs are derived from USGS gages; Sacramento River at Freeport (site 11447650), San Joaquin River at Stockton (11304810), San Joaquin River at Vernalis (11303500), the Petaluma River (11459150), the Sonoma River (11458500), and the Napa River (11458000) (U.S. Geological Survey, 2018). Salinity through the whole system reaches appropriate values within the spin-up period. Wind forcings are derived from the COAMPS model for northern California (*COAMPS Real-Time Forecasts for Central and Northern California in Support of the Central & Northern California Ocean Observing System (CeNCOOS)*, 2020, <https://www.nrlmry.navy.mil/coamps-web/web/cencoos>). Waves are not included in these runs for efficiency. Sediment availability on the bed is based on the bathymetry: At depths shallower than 5 m, 1.05 m of mud is available on the bed, 2.55 m of flocs, and 0.05 m of sand; in deeper parts of the system, we allow 0.05 m each of mud and flocs and 1.1 m of sand. When a single cohesive class is implemented, its availability on the bed follows the flocs description. Other parameters used for these three classes of sediment are shown in Table 1. In particular, the settling velocities chosen here for mud and flocs are similar to the values of 0.1 and 2 mm/s chosen in Chou et al. (2018). At the Sacramento and San Joaquin Rivers, sediment inputs are set as constant values: 0.03 kg/m^3 for flocs, 0.02 kg/m^3 for mud, and 0 kg/m^3 of sand. This simple parameterization does not play a strong role: with the settling velocities applied, sediment from the rivers settles out of the water column and accumulates on the bed upstream of San Pablo Bay, thus an increase in SSC from the Delta would not be observed in San Pablo Bay.

3.1.2. Nested Model

The nested model extends from the Sacramento and San Joaquin Rivers to the sea-ward boundary of San Pablo Bay, near the Richmond Bridge (nest boundaries marked in Figure 1b). Grid spacing ranges from 50 to 450 m in San Pablo Bay; it is coarsest at the outer edges of the shallows. As with the overall model, it has 10 vertical sigma layers partitioned in the same percentages. Bathymetry of San Pablo Bay is refined based on an updated 1-m DEM (Fregoso et al., 2020).

At the Richmond boundary, flow is nested in 3D using a Riemann boundary. To generate the appropriate boundary conditions across this strongly tidal channel, we allow computation of the boundary conditions at depths greater than 2 m. At the Sacramento and San Joaquin River boundaries, total discharge

Figure 2. Comparison of modeled and measured tidal propagation through northern San Francisco Bay. (a) Map of observation locations (NOAA tide gauges) and modeled transect. (b) Amplitudes and (c) phases of modeled (lines) and measured (markers) M2, K1, and O1 tidal constituents from San Francisco Bay mouth into Suisun Bay. Along-transect distances at 20 km intervals are denoted in (a). Bathymetry reflects the model grid, and is sourced from Elias et al. (2013); land imagery is sourced from USGS Topo (MapServer) (2020).

is set to that of the overall model. Salinity and sediment concentrations at Richmond are initialized based on a spatial interpolation of values in the overall model to the nested grid. Since waves are not included in the overall model, this interpolation is less important for sediment. For salinity, it enables us to avoid separately spinning up the salinity field in the nested grid. At the Sacramento and San Joaquin River boundaries, salinity remains at 0 PSU, and sediment is input as a linear profile, with concentrations derived from the overall model. The model also supplies freshwater and sediment from the Petaluma, Sonoma, and Napa Rivers, using USGS observations for river outflow, Q (U.S. Geological Survey, 2018), and assuming that sediment concentration is proportional to Q as $SSC = (7.63 \times Q + 14.6) / 1000$, following Elmilady (2016).

The nested model applies winds as discussed in Section 3.6. Waves are included through SWAN, outputting wave statistics at frequencies from 0.05 to 1 Hz. The Madsen et al. (1988) bottom friction model is implemented, assuming a bottom roughness coefficient of $5 \cdot 10^{-4}$ m; we assume that no ocean-generated swell propagated in to San Pablo Bay, and only local winds are used for wave generation. Enhancement of bed stress due to wave-current interaction is parameterized through Fredsøe (1984).

Sediment availability on the bed is refined following van der Wegen et al. (2011); we initialize the bed with 0.25 m of cohesive sediments and 0.1 m of sand everywhere, with a single bed layer. With no morphological acceleration, we simply allow the sediment composition on the bed to evolve over about 3 months. While the bed does not reach steady state, the constant slope of bed changes and the similar character of the modeled bed to observations indicate that it approaches a consistent starting point, and that model-generated sediment fluxes are not a response to an ‘unbalanced’ bed composition. This 3-month evolved bed is used as the initial condition. The absolute sediment availability is modified slightly across runs, but an approximate 2 : 1 ratio between cohesive sediments and sand is maintained within each run. While this approach differs from strategies including interpolation based on observations (e.g., Bever & MacWilliams, 2013) or the spatial distribution of the time-averaged bed shear stress (e.g., Chou et al., 2018), it matches the goals of this work.

Sediment classes have fixed characteristics; the settling velocity, erosion parameters, grain size, and density do not vary in time or space, although the relative proportions of the classes can vary. This strategy of non-varying sediment parameters has been applied frequently in San Francisco Bay (Bever & MacWilliams, 2013; Chou et al., 2018; van der Wegen & Jaffe, 2013) and around the world (Ralston et al., 2013; van Maren & Winterwerp, 2013; Xue et al., 2012).

3.2. Model Calibration

Model calibration was performed for water level through the hydrodynamic roughness, using observational data from NOAA stations at San Francisco (station number 9414290), Richmond (9414863), Martinez (9415102), and Port Chicago (9415144) (National Oceanic and Atmospheric Administration, 2020). Manning’s n values between 0.02 and 0.025 were tested; using Manning’s n of 0.0225 in the overall model, tidal propagation of the M2, K1, and O1 constituents through the north bay adequately matched the observed values through a 3-month period (Figure 2). Other tidal constituents, including S2 and N2 also followed the observations (not shown).

3.3. Observations

Observations of flow, waves, turbulence, and suspended sediment collected at three stations in the shallows of San Pablo Bay at 0.3 m above bed were used for sensitivity analysis of this model; they are described in detail in Allen et al. (2019).

3.4. Sediment Fluxes, Erosion, and Deposition

We computed the depth-averaged tidal residual sediment flux from model outputs (following Lacy et al., 2014) as $SSF = \langle \overline{uhc} \rangle$, where $\langle \dots \rangle$ represents a tidal average and $\overline{\dots}$ gives a depth average.

Spatial gradients in sediment fluxes lead to bed erosion and deposition, which was computed through mass conservation, following Harris (2002):

$$\frac{\partial \eta}{\partial t} = -\frac{1}{C_b} \left(\frac{\partial q_{sx}}{\partial x} + \frac{\partial q_{sy}}{\partial y} + \frac{\partial V_s}{\partial t} \right) \quad (1)$$

where η is the elevation of the bed surface, C_b is the bed sediment concentration (1-porosity, set as 500 kg/m³ for these runs), q_{sx} and q_{sy} are the depth-integrated suspended sediment volume fluxes in the x and y directions ($q_{sx} = \int_0^h C_s u dz$), V_s is the depth-integrated volume of suspended sediment ($V_s = \int_0^h C_s dz$), and h is the water depth. (Bed load transport is not computed for “cohesive” sediment fractions [Deltare, 2018]). For simplicity V_s is excluded from these computations.

3.5. Model Performance

To evaluate model performance, we compared the observed water level, velocity, salinity, and sediment concentration at sites N1T, S1T, and M2T (Figure 1b) with modeled values at the same location with the normalized unbiased root-mean-square-deviation (ubRMSD_N, Equation 2), the normalized bias (Bias_N, Equation 3), and the Brier skill score (BSS, Brier, 1950). The ubRMSD_N characterizes temporal oscillation in the model. When the magnitude of modeled oscillations is larger than the magnitude of observed oscillations, this quantity is positive; 0 is a perfect match.

$$ubRMSD_N = \frac{\left(\frac{1}{N} \sum_{i=1}^N \left[(X_{Mi} - \overline{X_M}) - (X_{Oi} - \overline{X_O}) \right]^2 \right)^{0.5}}{\sigma_O} \times \frac{(\sigma_M - \sigma_O)}{|\sigma_M - \sigma_O|} \quad (2)$$

Here the model values and averages are X_{Mi} and $\overline{X_M}$, the observed values and averages are X_{Oi} and $\overline{X_O}$, and σ represents the standard deviation, assuming N points in the timeseries. Bias_N characterizes the mean; when the model average is larger than the observed average, it is positive.

$$Bias_N = \frac{\overline{X_M} - \overline{X_O}}{\sigma_O} \quad (3)$$

The Brier skill score offers a single number to characterize model performance. It produces 1 when the model perfectly predicts the observations, 0 when the model performs as well as the mean of the observations at predicting each individual value, and decays to $-\infty$ for worse performance.

3.6. Model Runs

We performed two sets of model runs: idealized runs, using spatially uniform idealized winds, and realistic runs, using the spatially and temporally varying winds predicted for the region by the COAMPS wind model, as described in Section 3.1. With the idealized runs, we explore the impact of forcings without conflating conditions, allowing us to compare their effects. The realistic runs include much more complex forcings, allowing us to draw conclusions about processes in the environment.

The idealized runs lasted for a 1.5-day period, focusing on two consecutive M2 tidal cycles under both spring- and neap-tide conditions, using the salinity conditions spun-up as described. We applied spatially

uniform winds blowing at 15 m/s for 24.8 h, for 6.2 h during the first ebb-tide period, and for 6.2 h during the first flood-tide period, with winds originating from 0, 90, 180, and 270°N. This wind speed represents the upper limit of winds observed in San Pablo Bay, occurring about 1% of each year. Each idealized run was conducted with a uniform settling velocity for cohesive sediments of 0.2 or 1 mm/s. For cases with winds originating from 180°, we allowed spatial variation in sediment bed erodibility: The base case applied the erosion parameter (M) and τ_{crit} as shown in Table 1. We then altered these parameters within the Petaluma River outflow region (outlined in Figure 7), with cases where M_{Pet} was 10^{-5} and $2.5 \cdot 10^{-4}$, and $\tau_{crit,Pet}$ was 0.05 and 0.15 through the no-winds, temporally uniform winds, ebb-winds, and flood-winds cases during both spring- and neap-tides. We investigated this specific spatial variability based on the observations of higher erodibility at site N1T during winter 2014 – 2015, hypothesizing that it was connected to sediment outflow from the Petaluma River (Allen et al., 2019). Tables A1 and A2 show the parameters used in each run with idealized winds.

Sixteen realistic model runs spanned December 14, 2014 to January 1, 2015, with settling velocities of 0.04, 0.2, 1, and 5 mm/s and erosion rate parameters of $2 \cdot 10^{-6}$, 10^{-5} , $5 \cdot 10^{-5}$, and $2.5 \cdot 10^{-4}$ kg/m²s. Two final runs included two cohesive sediment classes, with settling velocities of 0.2 and 1 mm/s and erosion rates of 10^{-5} and $5 \cdot 10^{-5}$ kg/m²s, respectively: the runs were performed with 40% slow-settling and 60% fast-settling, and 60% slow-settling and 40% fast-settling. Table A3 shows the parameters used in each run with realistic winds.

4. Results

4.1. Model Performance

The realistic runs were validated for water depth, velocity, salinity, wave conditions, and suspended sediment concentration at sites in the San Pablo Bay shallows and channel (Table 2). Modeled water levels in the shallows are within 10 – 20 cm of the measured values. The amplitude ratio for water levels is close to 1 at each site in the shallows, and the time lag between observations and models is under 5 min. $Bias_N$ and $ubRMSD_N$ are both less than 0.5 for each location, indicating excellent performance for water level. Velocities in the east and north directions compare reasonably well between the observations and the model, with $Bias_N$ between – 0.09 and 0.22, $ubRMSD_N$ between – 0.52 and 0.33 (with an exception in the east direction at M2T: 0.97), and amplitude ratio between 0.68 and 1.34. An example snapshot of SSC during a model run, with $w_s = 1$ mm/s and $M = 5 \cdot 10^{-5}$ kg/m²s, is shown in Figure 3, and further details regarding SSC performance are discussed in Section 4.4.

4.2. Flow Through San Pablo Bay

On a tidal residual scale, circulation is counter-clockwise in the deeper parts of the shallows during spring and neap calm periods. During spring-tide, this residual velocity extends about halfway in to the shallows and is strongest near the channel, while during neap-tide, it is more uniform through the extent of the shallows. Tidal residual circulation changed minimally between the realistic “low-wind” spring-tide period and the idealized no-wind spring-tide scenario (not shown).

Residual circulation patterns change with the wind direction; not shown, but closely following the residual sediment fluxes under continuous winds (Figures 4a and 4d). Winds from north (and east, not shown) produce counter-clockwise circulation through the broad NW shallows of San Pablo Bay, with flow through the deepest part of the shallows countering the wind direction. Winds from south (and west) yield clockwise circulation. As the wind duration increases, the strength of the residual circulation increases as well, even as the direction of circulation remains unchanged.

4.3. Sediment Transport, Erosion, and Deposition With Idealized Winds

4.3.1. Wind Direction and Wind Timing

In the absence of winds, flocs are exported from San Pablo Bay in largest magnitudes from the edges of the central channel. While sediments are low in concentration throughout the system, at the channel margins

Table 2
Model Validation^a

Site	Parameter	Obs avg	Model avg	Lag (min)	Bias _N	ubRMSD _N	Amp ratio (model/observed)
N1T	Depth	2.17	2.27	5.4	0.18	− 0.12	0.96
	East velocity	− 0.01	< 0.01	10.8	0.09	− 0.52	0.68
	North velocity	− 0.02	− 0.02	8.2	− 0.01	− 0.27	0.84
	Orbital velocity	0.05	0.03	> 60	− 0.39	− 0.73	0.90
	Salinity	12.3	11.7	0	− 0.20	− 0.66	0.79
	SSC	0.23	0.11	4.9	− 0.47	− 0.67	0.64
M2T	Depth	2.94	3.10	1.6	0.27	− 0.10	0.98
	East velocity	− 0.02	< 0.01	− 26.3	0.33	0.97	1.34
	North velocity	0.01	− 0.02	− 4.8	− 0.14	0.33	1.09
	Orbital velocity	0.04	0.02	> 60	− 0.56	− 0.69	0.71
	Salinity	15.2	12.4	38.1	− 0.98	1.02	0.45
	SSC	0.14	0.09	34.7	− 0.27	0.65	1.01
S1T	Depth	2.35	2.21	− 1.0	− 0.26	− 0.10	0.99
	East velocity	0.01	0.03	− 7.7	0.09	− 0.25	0.94
	North velocity	− 0.03	− 0.03	− 10.0	− 0.01	− 0.30	0.89
	Orbital velocity	0.04	0.03	51.9	− 0.33	0.84	1.24
	Salinity	13.6	13.0	0.0	− 0.17	− 0.90	0.34
	SSC	0.12	0.15	31.4	0.18	1.80	1.55
CHT	Depth	10.7	10.8	− 3.7	0.07	− 0.16	0.92
	East velocity	− 0.07	− 0.06	19.4	0.04	− 0.32	0.93
	North velocity	− 0.05	− 0.03	11.1	0.05	− 0.29	0.90
	Salinity	21.4	18.5	7.2	− 0.72	0.39	1.27

Note. Validation metrics are reported for December 13, 2014 through January 1, 2015.

^aFor the observed and model averages, depth is reported in m, velocities in m/s, salinity in PSU, and suspended sediment concentration in kg/m³.

material is resuspended from the outer extent of the mudflats and carried by the strong ebb velocities within the channel. When winds are continuous, tidal residual sediment flux follows tidal residual circulation, with smaller fluxes toward the edge of the bay that is most protected by the winds (Figures 4a and 4d). Fluxes are smaller with non-continuous winds. Winds during ebb tide yield residual flux that is offshore directed, and is much larger in magnitude with winds from south than winds from the north (Figures 4b and 4e).

Spatial patterns of erosion and deposition are tied most directly to wind timing (Figure 5). With winds during ebb tide, the margins of San Pablo Bay are erosive, while the shoals bounding the channel are depositional, regardless of the wind direction; the inverse occurs with winds during flood tide. Wind direction yields only minor modifications to these general trends: During flood winds from 0° (Figure 5c) the southeastern margin of the San Pablo Bay shoals is depositional along its length, while during flood winds from 180° (Figure 5f) the channel-ward extent of that region is erosional. Wind direction does play a larger role in the spatial extent of erosion and deposition when winds are continuous; the northern extent of San Pablo Bay is protected from the northerly winds (Figure 5a) and is therefore depositional.

4.3.2. Spring-Neap Cycle and Settling Velocity

While neither particle settling velocity nor the phase of the spring-neap cycle directly impacts sediment erosion, both can affect the spatial patterns of net sediment deposition and erosion through their impact on sediment transport. We evaluate this through Figure 6, which shows the mean (left column) and standard deviation (right column) of bed deposition or erosion during two tidal-cycles across the western shallows of San Pablo Bay. Here, standard deviation expresses the spatial variability in net erosion/deposition,

Figure 3. Suspended sediment concentration in San Pablo Bay, produced using realistic winds and sediment parameters as shown in Table 1. The top three figures show timeseries of observations (black) compared with model results (colors) at sites N1T (blue), S1T (red), and M2T (green); locations shown on the bottom. The bottom map image depicts the model outputs from 08:00:00 on December 25, 2014, with model sediment concentrations from the height above bed comparable to the measurement heights. The map also shows the location of site CHT (gray), discussed in Table 2. Satellite imagery is sourced from OCM Partners (2020).

rather than gross erosion/deposition. Across the northwestern shallows of San Pablo Bay, on average bulk sediment deposition is small when no winds are present, while under high winds there is bulk erosion (Figures 6a–6d).

With no winds, switching from a spring period to a neap period results in a larger decrease in the spatial variation of net erosion than switching from slow-settling floccs to fast-settling (Figure 6e). Under these conditions, bed shear stress is generated by currents alone. Less sediment is resuspended during the weaker currents of neap tides than during spring tides; this is more important for deposition and erosion during no-wind periods than the difference in travel distance of slow-settling floccs and fast-settling floccs.

When winds are present, sediment settling velocity is more important than the phase of the spring-neap cycle: spatial variation in net deposition/erosion is smaller for fast-settling particles than for slow-settling particles (Figures 6f–6h). During spring tides there is more erosion than during neap tides, particularly for continuous- and ebb-wind cases (Figures 6b and 6c), but there is little impact on the spatial variability. Settling velocity does not impact the amount of eroded material; rather faster-settling sediment re-settles closer to where it was eroded, and there is less net erosion or deposition.

4.3.3. Spatial Variation in Bed Erodibility

Sediment fluxes and bed erosion through San Pablo Bay respond to more- or less-easily eroded sediments. Figure 7 compares the roles of spatially varying bed erodibility parameter and critical shear stress on bed evolution, and Figure 8 shows sediment flux along a transect that passes through site N1T (shown in Figure 7a). In the shallow regions 6 – 8 km along the transect, near the boundary between the denoted regions,

Figure 4. Net sediment fluxes across two tidal cycles during spring tide, for $w_s = 0.2$ mm/s. (a) continuous winds from 0° , (b) winds during ebb from 0° , (c) winds during flood from 0° , (d) continuous winds from 180° , (e) winds during ebb from 180° , and (f) winds during flood from 180° .

under no winds, fluxes are directed offshore when M and τ_{crit} allow more erosion in the Petaluma River outflow region, but are directed onshore when M and τ_{crit} allow less erosion there. Closer to the bay margins (10 – 12 km), the flux is offshore even for the low-erosion cases, because the differential between Petaluma River outflow region sediments and bay sediments does not matter there, and residual velocities drive the flux offshore.

The spatial variation in deposition and erosion can be highlighted at the boundary of the Petaluma River outflow region (Figure 7). With no winds, the model shows deposition just shoreward of the boundary when M is low and τ_{crit} is high, and erosion channel-ward of this boundary; the opposite is true for high M and low τ_{crit} cases. This gradient would be expected for any tidal system that has spatially varying sediment availability and reflects diffusive exchange between the regions. Continuous winds produce erosion on both sides of this boundary for high M and both low and high τ_{crit} , demonstrating that the system-wide wind forcing dominates local erosion patterns. The exception of Figure 7g demonstrates that these global patterns can be impacted by a large-enough erodibility variation; likewise sediment flux within the Petaluma River outflow region is onshore directed only when M is small (Figure 8b). Finally, the flood-winds cases display an intermediate result: the near-shore regions of the Petaluma River outflow shown in Figures 7r and 7s show deposition, consistent with the global pattern induced by winds during flood tide, while the channel-ward regions of the Petaluma River outflow show erosion, consistent with the local sediment availability differential induced by the spatially varying M and τ_{crit} . Combined, this demonstrates that winds induce a system-wide sediment transport pattern that can impact sediment transport more strongly than local variation in sediment erodibility. Despite the strong role of winds, the erodibility variation that has been observed in San Pablo Bay (Allen et al., 2019) is enough to change near-shore bed evolution from erosive to depositional.

These results demonstrate the dominant role of wind direction and wind timing on sediment flux magnitude and direction, and bed deposition and erosion. When winds are strong, settling velocity and the spring-neap cycle modify the magnitude of fluxes and erosion/deposition patterns, but do not impact the

Figure 5. Net sediment erosion (blue) and deposition (red) during two tidal cycles during spring tide, for flocs that settle at 0.2 mm/s. (a) continuous winds from 0°, (b) winds during ebb from 0°, (c) winds during flood from 0°, (d) continuous winds from 180°, (e) winds during ebb from 180°, and (f) winds during flood from 180°. The margins regions discussed in Figure 13 are drawn in (c). Note that the China Camp (CHC) boundary is the southwest most.

broad-scale trends. Likewise, spatial variation in bed sediment erodibility impacts flux and bed evolution within the shallows system, yet this spatial variation does not dramatically change total import or export from the shallows region.

4.4. Sediment Transport, Erosion, and Deposition With Realistic Winds

4.4.1. Sensitivity Analysis

With realistic winds, we conducted a sensitivity analysis investigating the impact of settling velocity and sediment erodibility on suspended sediment concentration and transport. A strong wind event occurred on 30–31 December with winds from the north at 10–15 m/s, and SSC reaching 2 kg/m³ at site N1T. Late December 2014 also saw an outflow event from the Sacramento-San Joaquin Delta that reached $6 \cdot 10^4$ m³/s on December 15, 2014; a small event for this system but the largest for the 2014 – 2015 rainy season.

We compare model SSC and observed values first through the $uBRMSD_N$ and $Bias_N$, focusing on site S1T during the calm period from 17–30 December (Figure 9). In observations and model results, SSC responds to M4 frequencies: strong flood and ebb velocities resuspend material which settles out at slack water. This location shows the worst performance of the three sites, and therefore provides a valuable view into model performance metrics. There, settling velocities of 0.04, 0.2, 1, and 5 mm/s all yield comparable error magnitudes when paired with erosion rate parameters running from low to high, and all yield SSC roughly on par with the observed values (Figure 9a). For the slowest settling particles, the model yields insufficient temporal oscillation; for $w_s = 0.2$ mm/s and above, temporal oscillation in the model was too large (Figures 9a and 9b). While we have high confidence in the reproduction of wave statistics and bed shear stresses in these model runs (Table 2), the remaining uncertainty in the forcing conditions combined with significant uncertainty in sediment parameterizations illustrates the challenge in sediment modeling. Figure 9b illustrates another challenge with these error metrics: when w_s is high and M is low, not enough sediment is eroded off the bed to produce appropriate concentrations, and both error metrics appear near –1. How-

Figure 6. (a–d) mean and (e–h) standard deviation of sediment eroded or deposited (in mm) in the northwestern shallows of San Pablo Bay (≤ 5 m), under different wind conditions. Black shows runs with $w_s = 0.2$ mm/s, and gray has $w_s = 1$ mm/s. Bars show uniform sediment parameters, triangles show results from $M(\text{Pet}) = 10^{-5}$ and 2.5×10^{-4} , and circles show results from $\tau_{\text{crit}}(\text{Pet}) = 0.05$ and 0.15 .

Figure 7. Sediment deposition and erosion under spring tidal conditions, with slow settling particles during (a–e) no winds; (f–j) continuous winds from 180°; (k–o) winds from 180° during ebb; and (p–t) winds from 180° during flood. (a, f, k, p) uniform sediment parameters; (b, g, l, q) $M = 10^{-5}$ in the Petaluma River outflow region; (c, h, m, r) $M = 2.5 \cdot 10^{-4}$ in that region; (d, i, n, s) $\tau_{crit,Pet} = 0.05$; and (e, j, o, t) $\tau_{crit,Pet} = 0.15$. The Petaluma River outflow region is outlined in black in each subfigure, and the location of the transect shown in Figure 8 is shown in (a).

ever, when w_s is low and M is high, modeled concentrations are much higher than observed, and the error metrics appear at values of 200, far beyond the displayed ranges. It is challenging, therefore, to compare the relative difference between model runs producing concentrations that are too low and concentrations that are too high.

The BSS offers a single metric for model performance (Figure 10). During a non-windy period (17–30 December), when current-induced resuspension dominates, a settling velocity of 0.2 mm/s performs best at N1T, with M of 10^{-5} (Figure 10). During the windy period (30 December–1 January), when wave-induced resuspension is most important, a settling velocity of 1 mm/s performs best at N1T and S1T, with M values of $5 \cdot 10^{-5}$ and 10^{-5} , respectively. These findings suggest that increased local resuspension created by wind events may yield a wider range of resuspended particle size classes and/or more sediment flocculation. They also demonstrate that the model performs well even during more energetic periods when sediment transport is greatest.

While the BSS offers context about model performance relative to a mean value, it can yield negative values even when the time-varying model results offer valuable information, as is the case at S1T during 17–30 December. There, the four model runs along the diagonal each reproduced aspects of the observed SSC (Figure 9a), though none yielded a positive BSS. Despite the limitations of model skill and model skill metrics, the conservative assessment of model performance offered by the BSS suggests that particularly at site N1T, these model runs are performing well.

Figure 8. Total sediment fluxes (kg/m s) from runs with no winds, continuous winds, winds during ebb, and winds during flood, for the spring-tide, slow settling particles case. Varying sediment parameters in the Petaluma River outflow region are identified by the legend. The top row shows the transect depth profile from the channel through site N1T to the north margin. Fluxes are in the cross-shore (along-transect) direction; positive onshore. Vertical lines show the channel-shoal shoulder, and the Petaluma River outflow region boundary.

tling velocity is 5 mm/s. At lower settling velocity, the spatial extent of net erosion is larger around the channel, but it is smaller in magnitude. The combined effect yields the largest net export from San Pablo Bay under $w_s = 0.2$ mm/s (Figures 12a and 12b). Conversely, Delta outflow was not important in driving the local sediment budget under the range of conditions investigated (Figure 12b). It positively impacted

Allowing the fractions of mud ($w_s = 0.2$ mm/s, $M = 10^{-5}$ kg/m²s) and floes ($w_s = 1$ mm/s, $M = 5 \cdot 10^{-5}$ kg/m²s) to vary, we see that during the non-windy period, the run with 60% mud, 40% floes performs slightly better (Figure 11, top, BSS = 0.315 at N1T), while during the windy time the floes-only run has the best metrics (middle, BSS = 0.612). Across the full time period (bottom), the 40% mud, 60% floes run (BSS = 0.315) performs similarly to the floes-only run (BSS = 0.318). That is, during a tidally dominated period, a slower settling velocity is more appropriate, while during windy periods a faster settling velocity performs better. Runs with multiple fractions allow both sediment classes to operate, and therefore function best across the range of scenarios.

4.4.2. Implications of Parameterizations

These results demonstrate how erosion off the bed and sediment availability on the bed are inter-related. To produce appropriate concentrations with a faster w_s , the model requires a higher M , varying at a rate of approximately 1 – 1. There is little physical rationale to justify a two order-of-magnitude range in erodibility: in San Pablo Bay M varies between $5 \cdot 10^{-6}$ and $5 \cdot 10^{-5}$, and the representative w_s varies between 0.1 and 1 mm/s (Allen et al., 2019). The same model performance could be derived by enforcing a constant M and allowing the fraction of cohesive sediment to non-cohesive sand to increase when w_s is large. van Maren and Cronin (2016) also found that similar suspended sediment concentrations were observed with different parameter settings, although sediment concentrations for areas beyond the region of calibration were dramatically different. Complex numerical models therefore must both be well calibrated to local conditions and tuned not only with a mind toward model accuracy but also toward physical representativeness of model parameters.

In practical terms, numerical models of sediment transport in San Pablo Bay (with only one cohesive sediment class) perform best with settling velocities of 0.2–1 mm/s and sediment erosion parameters of $1 - 5 \cdot 10^{-5}$ kg/m²s. Beyond these ranges, the model performs less well, and the parameter values are less supported by observations. These values are consistent with the settings of $w_s = 0.1$ and 2 mm/s, erosion parameter of 10^{-5} kg/m²s, and τ_{crit} of 0.1 N/m² in a well-calibrated model of South San Francisco Bay (Chou et al., 2018). While model parameters control sediment concentrations within the bay, import and export to the shallows is dominated by wind speed.

4.4.3. Basin-Scale Flux

To investigate basin-scale sediment flux patterns in San Pablo Bay, we focus on the runs shown along the lower-left to upper-right diagonal in Figure 10, and identify them via settling velocity only. Under low winds (tidal cycle average wind speeds of less than 7 m/s), a small amount of sediment is imported or exported from San Pablo Bay, for a large range of settling velocities (Figure 12c). At high wind speed, sediment is transported counter-clockwise through the system, similar to the “continuous winds from 0 deg” idealized case (Figures 4a and 5a), and exported from the system in quantities an order of magnitude larger, except when settling

Figure 9. (a) Near-bed suspended sediment concentration at S1T from four model runs and observations. Note that the $w_s = 0.04, M = 2 \cdot 10^{-6}$ run is highlighted with a dotted black line, for clarity. (b) ubRMSD_N and Bias_N at the same site from 16 runs, for 17 December, 12 : 00 to 30 December, 12 : 00. Blue, green, and black circles show combined error of 0.5, 1, and 1.25, representing excellent, good, and fair model performance, respectively. Runs shown in (a) are circled in (b).

sediment input through the Carquinez Strait (locally sourced sediment was transported with the larger water flux), but that effect was an order of magnitude smaller than the increase in export from San Pablo Bay under strong winds. In summary, local wind forcing is more important in driving the overall sediment budget than non-local river outflow during the 2-week investigation period.

5. Discussion

5.1. Sediment Flux and Bed Evolution in San Pablo Bay

Our simulations show that wind timing relative to tidal stage can impact the location and magnitude of deposition and erosion. This result suggests that predictions of long-term bed evolution incorporating different timescales of wind variation might differ from those of Elmilady et al. (2018), who applied daily winds from the west (for the idealized wet and half of dry seasons) and from the southeast (for the second half of dry season). In addition, the dominant sediment settling velocity will drive whether the system is predominately depositional or erosional under low wind conditions (Figure 12c); if a supply of fine material ($w_s = 0.2$ mm/s) is deposited, it can be exported when it aggregates to slightly larger flocs ($w_s = 1$ mm/s). In a similar system, wind direction and magnitude, along with intratidal asymmetries in sediment concentration induced by circulation patterns, were observed to play a dominant role in sediment transport over tidal flats (Colosimo et al., 2020). As simulated in a numerical model, wind (yielding wind wave height of 5–10 cm) produced a stabilizing feedback loop on the morphodynamic evolution of a mudflat (Maan et al., 2018). In the absence of wind waves, accretion dominated and eventually tidal creeks incised into the elevated plain. Understanding the intratidal dynamics of sediment transport, in a region that is so responsive to wind waves, can drive management decisions for sediment placement.

Spatially averaged bed erosion is larger in magnitude under continuous winds, ebb winds, and flood winds cases when particles settle at 0.2 rather than 1 mm/s (Figures 6b–6d). Observations show that floc size in San Pablo Bay varies on a tidal scale: larger, faster-settling flocs dominate at slack water, while smaller, slower-settling flocs appear during flood and ebb (Allen et al., 2019). Bed erosion predicted by the numerical model may therefore be smaller than what is seen in the environment; settling velocity variation on a tidal timescale allows transport on the scale shown by the $w_s = 0.2$ mm/s case, but accumulation (in the new

Figure 10. Model skill at reproducing the measured suspended sediment concentrations at sites N1T, S1T, and M2T shown through the Brier skill score for a non-windy period (17 December through 30 December), a windy period (30 December through 1 January), and the full modeled time (13 December through 1 January), for runs with a range of M and w_s .

location) in line with the $w_s = 1$ mm/s case. Tidal scale settling velocity variation was similarly one of the most important drivers of landward sediment flux in lower South San Francisco Bay (Livsey et al., 2020b).

Spatial variation in bed evolution is caused by the combination of winds, tides, and sediment parameters. During calm periods, there is more spatial variation between spring and neap tides (Figure 6e), while under windy conditions, the bed evolves more when settling velocity is smaller (Figures 6f–6h). When M increases in the Petaluma River outflow region, the standard deviation of erosion and deposition for all runs approximately doubles, showing that the bed erodibility parameter strongly impacts sediment redistribution across the whole shallows system. Yet, the low impact of M on spatially averaged bulk deposition shows that this redistribution is largely limited to the northwestern shallows; the system as a whole is not losing more sediment to other parts of San Francisco Bay.

Coastal systems with strong connectivity between near-shore and shelf showed that higher erodibility leads to more offshore sediment transport and faster erosion of the onshore sediment supply (Bever & Harris, 2014; Grifoll et al., 2014; Moriarty et al., 2014). With spatially varying sediment erodibility (higher

Figure 11. Skill metrics comparing suspended sediment concentration at sites N1T (blue), S1T (red), and M2T (green) for four model runs for (top) a non-windy period (17 December through 30 December); (middle) a windy period (30 December through 1 January), note S1T data were located near $ubRMSD_N \approx 3$ and $Bias_N \approx 4$; and (bottom) the full modeled time (13 December through 1 January). As in Figure 9b, blue, green, and black circles represent excellent, good, and fair model performance, respectively.

in the shallow regions), Moriarty et al. (2014) found that deposition on the shelf was higher than with both high and low uniform erodibility cases; spatially varying erodibility more closely matched the observations and allowed for more efficient transport of onshore sediment to offshore. While our work focuses on variation within an embayment, this matches our observation that increased erodibility at a river outflow leads to increased transport within the system.

5.2. Sediment Transport to Fringing Marshes

In San Francisco Bay, daily winds in the summer are strongest from 14 : 00 to 19 : 30 (local time; PDT), and very regular. In addition, an analysis of tidal cycle timing, using NOAA data from Richmond (station 9414863) from 1996 through 2020, shows that flood tides are 1.06–1.77 times more likely to occur than ebb tides during April–July afternoons. Because deposition or erosion at the margins is driven more by wind timing than by wind direction or spatial variation in sediment parameters (Figures 5c, 5f and 7p–7t), this bias implies that the consistent daily winds of summer are more likely to lead to sediment import to the margins of San Pablo Bay, even as the Bay as a whole is erosive. This observation adds spatial precision to the theory by Krone (1979) which suggests that San Pablo Bay is depositional in the winter, and erosional in the summer; under summer wind conditions the whole system is erosive, but the margins accumulate sediment.

When winds occur during flood tide, near-shore deposition varies little with the wind direction at the northern edge of San Pablo Bay (Figure 13a). Meanwhile, the suspended sediment concentration at high water (when marshes are inundated) immediately following the windy period is much greater along the northern margin with winds from 5° or 180° (Figure 13b), since onshore waves are not fetch-limited. Along the northeastern margin, the most sediment accumulation occurs under the wind conditions that supply the most suspended sediment to the near-shore. Along the China Camp and western San Pablo Bay margins, the change in bed elevation is largely disconnected from the SSC at high water: winds from 90° yield high near-shore SSC, yet the bed accumulates less material than when winds are from 0° . To generalize: near-shore deposition is not strongly dependent on wind direction, whereas the amount of sediment present in the water column is. Observations show that the amount of sediment present in the water column at the boundary of the marsh is directly tied to deposition within the marsh (Lacy et al., 2020); onshore winds can increase the amount of sediment available to be transported on to a marsh. Despite the significance of near-shore SSC for accumulation on marshes, increases in suspended concentration do not imply trends in erosion or deposition at the estuary margins. Because SSC available to be transported on to a marsh and vertical erosion at a marsh edge are both important to the fate of marshes in the face of sea level rise, we must continue to model each explicitly.

5.3. Light Penetration Depth

Light attenuation through the water column directly impacts phytoplankton growth, and it is strongly impacted by sediment parameterization. Light attenuation in surface waters occurs due to absorbance and scattering; commonly the irradiance at depth z , I_z (W/m^2), is estimated based on the irradiance just below the surface, I_0 , and a light attenuation coefficient, k_d , as

Figure 12. Sediment import to San Pablo Bay defined as sediment supplied through the Carquinez Strait minus sediment removed past the Richmond Bridge per daily tidal cycle (24.83 h) from 19–31 December, plotted against (a) daily mean wind speed and (b) average daily Delta outflow. The boxplots in (c) aggregate these values from 19 through 30 December (31 December with high winds is removed), and the y-axis is scaled accordingly. Marker size shows (a) Delta outflow, and (b) daily wind speed, linearly proportional to the observed values. For the strongest winds, export is larger when settling velocity is smaller. Delta outflow negligibly impacted sediment import.

$$I_z = I_0 e^{-k_d z}. \quad (4)$$

This k_d can be computed from the depth below surface at which a secchi disk is no longer seen (z_{SD}),

$$k_d = \frac{1.7}{z_{SD}} \quad (5)$$

following Poole and Atkins (1929). In addition, k_d can be estimated from material in the water column such as SSC and Chlorophyll *a* (Lopez et al., 2006) or SSC alone (Lucas et al., 2002). We generate

$$k_d = 72.7 \times \bar{c}, \quad (6)$$

based on measured k_d and c (kg/m^3 , point measurements in the surface 1–3 m, assumed to represent the average surface concentration $\bar{c}$) in San Pablo Bay, using data from 1969 to 2019 (Cloern & Schraga, 2016; Schraga et al., 2020). Equations 5 and 6 imply that at $\bar{c}$ of $0.0234 kg/m^3$, the secchi depth is expected to be 1 m. Equations 4 and 5 show that 82% of light would be attenuated when the secchi depth is reached.

The model results allows us to incorporate vertical variation in SSC in estimating light attenuation; we compute

$$\int_{z_1}^h c(z) dz \approx \bar{c} z_{SD} = 0.0234 kg/m^2 \quad (7)$$

where z_1 is defined as the depth from the surface above which the cumulative suspended mass reaches $0.0234 kg/m^2$. This z_1 thus approximates the secchi depth, allowing the surface concentration to be depth varying. Returning again to Equation 5 yields a light attenuation coefficient (k_d) that incorporates vertical variation in suspended sediment concentration. We apply this technique to the model results from the realistic winds cases, and generate temporally averaged light attenuation coefficients during daylight hours for each day.

The results illustrate how particle settling velocity influences spatial patterns of light attenuation (Figure 14). Notably, when settling velocity is very low, light attenuation is high through much of the shallows, while with a high settling velocity, light attenuation is low everywhere, during both windy and non-windy periods. With realistic settling velocities of 0.2 and 1 mm/s, light attenuation is highest (and secchi depth is lowest) near the channel during a non-windy period and near the margins during a windy period. We also note the importance of allowing for depth-varying concentration: if SSC follows a simple Rouse profile, the point estimate of k_d can over- or under-predict k_{d1} by up to a factor of 2, and the direction of error changes

Figure 13. (a) Median change in bed elevation from along-shore transects (shown in Figure 5c) near China Camp (CHC), Western San Pablo Bay (WSPB), Northern San Pablo Bay (NSPB), and North-Eastern San Pablo Bay (NESPB), under winds during flood coming from varying wind directions. (b) Median near-bed suspended sediment concentration in each transect during high water immediately following the windy period.

with the magnitude of turbulent mixing. Applying the considerations discussed in this work and multiple particle size classes will enable sediment transport models to more appropriately predict light attenuation and the possibility for phytoplankton blooms.

5.4. Modeling Approach

Limitations of this modeling approach include the disconnect in sediment supply from the rivers: Even with the slower settling velocity, sediment input from the river boundaries settled in the Sacramento and San Joaquin Rivers, and did not make it to San Pablo Bay within the time period investigated. The simple model for river supplied sediment used in this work was most likely not important. A range of suspended particle sizes (including very slow settling particles) or a much higher Delta discharge would be required to capture sediment transport from the Sacramento-San Joaquin Delta. The conclusions of Section 5.1 are therefore tied to sediment dynamics within San Pablo Bay, and do not reflect the increase in sediment supply that would be expected with an increase in Delta outflow.

Because the nested domain extends only 5 km beyond the cross-section at the Richmond Bridge, the tidal excursion lengthscale is 5 – 10 km, and the overall model does not include waves, the modeled sediment input to San Pablo Bay at the Richmond Bridge during windy periods may be too low. Without this potential error, the sediment export from San Pablo Bay would be reduced the most with the slowest settling particles

Figure 14. Time-averaged k_{dl} for the daylight hours of (a–d) a non-windy tidal cycle, 17 December and (e–h) a windy tidal cycle, 31 December. (a, e) $w_s = 0.04$ mm/s, (b, f) $w_s = 0.2$ mm/s, (c, g) $w_s = 1$ mm/s, and (d, h) $w_s = 5$ mm/s. Note that the color scales differ for the two time periods.

during these times. Twice the quantity of particles settling at $w_s = 0.2$ mm/s are exported compared to $w_s = 1$ mm/s during the largest winds (Figures 12a and 12b); this uncertainty in input would not reverse that trend.

In addition, the model applies a single initial condition for sediment available on the bed (described in Section 3.1); this condition does not vary between any of the runs. While this enables direct comparison of model outputs, it may not be adequately flexible to the varying processes. For example, erodible bed sediment at the margin of the channel may be completely depleted by spring tides and redeposited during neap tides; such processes are not considered in this work. Likewise, changes in time and space of suspended sediment settling velocity, induced by resuspension and flocculation, are not considered; they are addressed only on the systemwide scale as discussed in Section 4.3.2.

Finally, the estimates of bed erosion across the shallows (Figure 6) represent values much larger than estimates of 0 – 0.5 cm/year from 1951 – 1983, or 0 – 0.015 mm per 24.8-h tidal cycle (Jaffe et al., 2007). Part of this difference is easily attributed to the high wind speeds included in this work. Yet even under no winds, with fast-settling particles during a neap tide, we predict 0.02 mm of sediment eroded during a single 24.8-h period. Our work reproduces measured concentrations well, but long-term projections of erosion and deposition (e.g., Elmilady et al., 2018) require careful tuning.

6. Conclusions

This paper investigates the implications of modeling choices for model performance and for learning about sediment dynamics in the environment.

Modeling sediment transport requires selection of specific parameter values; in San Pablo Bay, settling velocity of $w_s = 0.2$ to 1 mm/s and erosion rate parameter of $M = 10^{-5}$ to $5 \cdot 10^{-5}$ kg/m²s yield strong performance for this muddy, easily eroded system. At the northern observation site (N1T), $w_s = 0.2$ mm/s performs best during a non-windy period, and $w_s = 1$ mm/s is best during a wind event, demonstrating that a

model needs to have multiple classes of cohesive sediments. Only runs where w_s and M vary together yield predicted SSC better than a constant value for the full time period (Figure 10). Settling velocity impacts the magnitude of sediment fluxes: sediment flux, erosion, and deposition are more than two times as large in the Petaluma River outflow region when settling velocity is smaller and winds are timed with the tides. Allowing suspended particle size variation (flocculation) in the model may further increase the observed total flux. The choice of settling velocity also strongly impacts light penetration through the water column, and even changes the spatial patterns of the light attenuation coefficient. Selection of appropriate sediment parameters yields more predictive light fields through systems like San Francisco Bay.

In the environment, particles settle and erode off the bed, and the parameters controlling these processes change in time and in space. A fivefold change in particle settling velocity has the strongest impact on spatial variation in erosion and deposition (threefold) under strong continuous winds; with no winds the spring-neap tidal conditions have a larger effect than the settling velocity. Sediment erosion parameter variation within the Petaluma River outflow region does not strongly impact mean erosion and deposition across the shallows, though variation within the shallows can double. Under strong winds, this variation can change near-shore bed evolution patterns from erosive to depositional. Near-shore suspended sediment concentrations at high water (which can drive whether a fringing marsh can accrete sediment) are strongly impacted by wind direction; they peak when the winds are blowing directly onshore, even though near-shore bed evolution is not connected to wind direction. Seasonal patterns drive sediment delivery from the Sacramento-San Joaquin Delta (more supply in the winter rainy season) and temporal frequency of local winds (summer has consistent daily winds). This work explores only the latter; we observe that summer wind patterns can create transport to the margins even when the system as a whole is exporting sediment.

Appendix A: Detail Model Runs

As described in Section 3.6, we performed idealized and realistic model runs. Tables A1 and A2 show the parameter values used in runs with idealized winds, and identify the figures that rely on these runs. The Petaluma River outflow region, identified as “Pet,” is shown in Figure 7. Table A3 details the parameter values used in runs with realistic wind forcings, and which figures show outputs of these runs.

Table A1

Runs With Idealized Winds, During a Spring Tide, $w_s = 0.2 \text{ mm/s}$

M	τ_{crit}	M	τ_{crit}		
SPB		Pet		Winds	Figures
$5 \cdot 10^{-5}$	0.1	$5 \cdot 10^{-5}$	0.1	No winds	6, 7, 8
$5 \cdot 10^{-5}$	0.1	$5 \cdot 10^{-5}$	0.1	From 0, continuous	4, 5
$5 \cdot 10^{-5}$	0.1	$5 \cdot 10^{-5}$	0.1	From 0, ebb	4, 5
$5 \cdot 10^{-5}$	0.1	$5 \cdot 10^{-5}$	0.1	From 0, flood	4, 5, 13
$5 \cdot 10^{-5}$	0.1	$5 \cdot 10^{-5}$	0.1	From 90, continuous	
$5 \cdot 10^{-5}$	0.1	$5 \cdot 10^{-5}$	0.1	From 90, ebb	
$5 \cdot 10^{-5}$	0.1	$5 \cdot 10^{-5}$	0.1	From 90, flood	13
$5 \cdot 10^{-5}$	0.1	$5 \cdot 10^{-5}$	0.1	From 180, continuous	4, 5, 6, 7, 8
$5 \cdot 10^{-5}$	0.1	$5 \cdot 10^{-5}$	0.1	From 180, ebb	4, 5, 6, 7, 8
$5 \cdot 10^{-5}$	0.1	$5 \cdot 10^{-5}$	0.1	From 180, flood	4, 5, 6, 7, 8, 13
$5 \cdot 10^{-5}$	0.1	$5 \cdot 10^{-5}$	0.1	From 270, continuous	
$5 \cdot 10^{-5}$	0.1	$5 \cdot 10^{-5}$	0.1	From 270, ebb	
$5 \cdot 10^{-5}$	0.1	$5 \cdot 10^{-5}$	0.1	From 270, flood	13
$5 \cdot 10^{-5}$	0.1	10^{-5}	0.1	No winds	6, 7, 8
$5 \cdot 10^{-5}$	0.1	10^{-5}	0.1	From 180, continuous	6, 7, 8

Table A1
Continued

M	τ_{crit}	M	τ_{crit}		
SPB			Pet	Winds	Figures
$5 \cdot 10^{-5}$	0.1	10^{-5}	0.1	From 180, ebb	6, 7, 8
$5 \cdot 10^{-5}$	0.1	10^{-5}	0.1	From 180, flood	6, 7, 8
$5 \cdot 10^{-5}$	0.1	$2.5 \cdot 10^{-4}$	0.1	No winds	6, 7, 8
$5 \cdot 10^{-5}$	0.1	$2.5 \cdot 10^{-4}$	0.1	From 180, continuous	6, 7, 8
$5 \cdot 10^{-5}$	0.1	$2.5 \cdot 10^{-4}$	0.1	From 180, ebb	6, 7, 8
$5 \cdot 10^{-5}$	0.1	$2.5 \cdot 10^{-4}$	0.1	From 180, flood	6, 7, 8
$5 \cdot 10^{-5}$	0.1	$5 \cdot 10^{-5}$	0.05	No winds	6, 7, 8
$5 \cdot 10^{-5}$	0.1	$5 \cdot 10^{-5}$	0.05	From 180, continuous	6, 7, 8
$5 \cdot 10^{-5}$	0.1	$5 \cdot 10^{-5}$	0.05	From 180, ebb	6, 7, 8
$5 \cdot 10^{-5}$	0.1	$5 \cdot 10^{-5}$	0.05	From 180, flood	6, 7, 8
$5 \cdot 10^{-5}$	0.1	$5 \cdot 10^{-5}$	0.15	No winds	6, 7, 8
$5 \cdot 10^{-5}$	0.1	$5 \cdot 10^{-5}$	0.15	From 180, continuous	6, 7, 8
$5 \cdot 10^{-5}$	0.1	$5 \cdot 10^{-5}$	0.15	From 180, ebb	6, 7, 8
$5 \cdot 10^{-5}$	0.1	$5 \cdot 10^{-5}$	0.15	From 180, flood	6, 7, 8

Table A2

Runs With Idealized Winds, Each One Was Run for (a) Neap Tide, $w_s = 0.2$ mm/s, (b) Spring Tide, $w_s = 1$ mm/s, and (c) Neap Tide, $w_s = 1$ mm/s

M	τ_{crit}	M	τ_{crit}		
SPB			Pet	Winds	Figures
$5 \cdot 10^{-5}$	0.1	$5 \cdot 10^{-5}$	0.1	No winds	6
$5 \cdot 10^{-5}$	0.1	$5 \cdot 10^{-5}$	0.1	From 180, continuous	6
$5 \cdot 10^{-5}$	0.1	$5 \cdot 10^{-5}$	0.1	From 180, ebb	6
$5 \cdot 10^{-5}$	0.1	$5 \cdot 10^{-5}$	0.1	From 180, flood	6
$5 \cdot 10^{-5}$	0.1	10^{-5}	0.1	No winds	6
$5 \cdot 10^{-5}$	0.1	10^{-5}	0.1	From 180, continuous	6
$5 \cdot 10^{-5}$	0.1	10^{-5}	0.1	From 180, ebb	6
$5 \cdot 10^{-5}$	0.1	10^{-5}	0.1	From 180, flood	6
$5 \cdot 10^{-5}$	0.1	$2.5 \cdot 10^{-4}$	0.1	No winds	6
$5 \cdot 10^{-5}$	0.1	$2.5 \cdot 10^{-4}$	0.1	From 180, continuous	6
$5 \cdot 10^{-5}$	0.1	$2.5 \cdot 10^{-4}$	0.1	From 180, ebb	6
$5 \cdot 10^{-5}$	0.1	$2.5 \cdot 10^{-4}$	0.1	From 180, flood	6
$5 \cdot 10^{-5}$	0.1	$5 \cdot 10^{-5}$	0.05	No winds	6
$5 \cdot 10^{-5}$	0.1	$5 \cdot 10^{-5}$	0.05	From 180, continuous	6
$5 \cdot 10^{-5}$	0.1	$5 \cdot 10^{-5}$	0.05	From 180, ebb	6
$5 \cdot 10^{-5}$	0.1	$5 \cdot 10^{-5}$	0.05	From 180, flood	6
$5 \cdot 10^{-5}$	0.1	$5 \cdot 10^{-5}$	0.15	No winds	6
$5 \cdot 10^{-5}$	0.1	$5 \cdot 10^{-5}$	0.15	From 180, continuous	6
$5 \cdot 10^{-5}$	0.1	$5 \cdot 10^{-5}$	0.15	From 180, ebb	6
$5 \cdot 10^{-5}$	0.1	$5 \cdot 10^{-5}$	0.15	From 180, flood	6

Table A3
Runs With Realistic Winds (COAMPS), for December 13, 2014 to January 1, 2015

M	τ_{crit}	w_s	M	τ_{crit}	w_s	Figures
All regions			All regions			
$2 \cdot 10^{-6}$	0.1	0.04				9, 10, 12, 14
$2 \cdot 10^{-6}$	0.1	0.2				9, 10
$2 \cdot 10^{-6}$	0.1	1				9, 10
$2 \cdot 10^{-6}$	0.1	5				9, 10
10^{-5}	0.1	0.04				9, 10
10^{-5}	0.1	0.2				9, 10, 11, 12, 14
10^{-5}	0.1	1				9, 10
10^{-5}	0.1	5				9, 10
$5 \cdot 10^{-5}$	0.1	0.04				9, 10
$5 \cdot 10^{-5}$	0.1	0.2				9, 10
$5 \cdot 10^{-5}$	0.1	1				9, 10, 11, 12, 14
$5 \cdot 10^{-5}$	0.1	5				9, 10
$2.5 \cdot 10^{-4}$	0.1	0.04				9, 10
$2.5 \cdot 10^{-4}$	0.1	0.2				9, 10
$2.5 \cdot 10^{-4}$	0.1	1				9, 10
$2.5 \cdot 10^{-4}$	0.1	5				9, 10, 12, 14
$5 \cdot 10^{-5}$	0.1	1	10^{-5}	0.1	0.2	11 ^a
$5 \cdot 10^{-5}$	0.1	1	10^{-5}	0.1	0.2	11 ^b

^a40% mud; 60% flocs. ^b60% mud; 40% flocs.

Data Availability Statement

Observational data used in this effort are available on USGS Science Base (<https://doi.org/10.5066/F7HM-56MX>; Lacy et al., 2017). Input files and timeseries model outputs for a realistic model run are also available on Science Base (<https://doi.org/10.5066/P9GLTWS0>; Allen & Stevens, 2021); other runs referred to in this work can be re-created from this one. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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