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Tidal oscillation of sediment between a river and a bay: a conceptual model

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Abstract

A conceptual model of fine sediment transport between a river and a bay is proposed, based on observations at two rivers feeding the same bay. The conceptual model consists of river, transitional, and bay regimes. Within the transitional regime, resuspension, advection, and deposition create a mass of sediment that oscillates landward and seaward. While suspended, this sediment mass forms an estuarine turbidity maximum. At slack tides this sediment mass temporarily deposits on the bed, creating landward and seaward deposits. Tidal excursion and slack tide deposition limit the range of the sediment mass. To verify this conceptual model, data from two small tributary rivers of San Pablo Bay are presented. Tidal variability of suspended-sediment concentration markedly differs between the landward and seaward deposits, allowing interpretation of the intratidal movement of the oscillating sediment mass. Application of this model in suitable estuaries will assist in numerical model calibration as well as in data interpretation. A similar model has been applied to some larger-scale European estuaries, which bear a geometric resemblance to the systems analyzed in this study.
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1. Introduction

The resuspension, advection, and deposition of fine sediment in the estuarine environment are significant for multiple reasons. Contaminants (e.g. organophosphates, polynuclear aromatic hydrocarbons, mercury) are known to preferentially adsorb to fine sediment particles (e.g. Thompson et al., 2000; Bergamaschi et al., 2001); therefore, the fate of sediment determines the fate of associated contaminants. The accumulation of these contaminants in the estuarine food web is of increasing concern to biologists and ecologists, in some cases leading to restrictions on human consumption of local species (San Francisco Estuary Institute, 2001). Additionally, the attenuation of light by suspended sediment affects food web dynamics by limiting photosynthesis (Cloern, 1987) and altering feeding patterns of fish (Benfield and Minello, 1996). Sediment (and therefore contaminants) and biota can accumulate in estuarine turbidity maxima (ETMs) (Kimmerer et al., 1998).

Sediment is valued as a resource for habitat creation. Restoration efforts in estuaries frequently involve the establishment and maintenance of tidal marshes, which support desirable flora and fauna. Sediment is a major factor in the success of created marshes, because it provides the substrate for marsh development (Goodwin et al., 2001). Therefore, knowledge of sediment transport patterns enables managers to ideally locate restoration projects for maximum sediment trapping.

The accumulation of sediment, however, can be detrimental. High deposition rates of fine sediment in estuaries frequently lead to reduced vessel access,

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requiring dredging of channels to maintain safe navigation. Dredging can be planned efficiently if sediment deposition patterns are known beforehand.

These issues are especially significant where tidal rivers discharge to open bay waters. Contaminants introduced to the environment in watersheds can be transported downstream by rivers and subsequently to bays. Tidal wetlands and mudflats often are located in and near tidal rivers because the rivers are a source of sediment and accretion tends to increase when riverine sediment first encounters slack tide. Tidal rivers frequently are used for harborage, commercial shipping, and navigation due to their proximity to urban areas and access to bays and oceans.

In the light of the aforementioned issues, the purpose of this study is to present a conceptual model of fine sediment oscillating between a river and a bay and to validate the conceptual model with data from two small tributary rivers of San Pablo Bay. The conceptual model describes the variability of suspended-sediment transport on a tidal time scale and identifies areas of high suspended-sediment concentrations.

2. Field observations

2.1. Area description

The interaction between San Pablo Bay and two of its tributaries, the Petaluma River and Sonoma Creek/Second Napa Slough (SNS) (Fig. 1), will be described to illustrate the conceptual model. San Pablo Bay is the northwestern subembayment of the San Francisco Estuary. A deep-water (> 12 m) shipping channel runs through the southern half of San Pablo Bay, between San Pablo Strait and Carquinez Strait. The remainder of the bay is relatively broad and shallow, with depths less than 4 m. Numerous mudflats on the periphery of the bay are exposed at low tide.

Saline water is supplied by the Pacific Ocean by way of the Golden Gate, while the Sacramento/San Joaquin River Delta (Delta) provides the majority of freshwater. Several minor tributaries also feed San Pablo Bay, including the Petaluma River and Sonoma Creek/Second Napa Slough (SNS). Freshwater flow to San Pablo Bay primarily occurs during winter rains, spring snowmelt runoff, and reservoir releases. Low freshwater flow conditions prevail from late spring to early fall. The mixed diurnal and semi-diurnal tidal forcing from the Pacific Ocean results in a maximum spring tide range of 2.5 m, and a minimum neap tide range of 0.4 m. Onshore winds during the summer months generate wind waves and sediment resuspension (Krone, 1979; Ruhl et al., 2001). Bed and suspended sediments mostly consist of silts and clays, while sand is in the deeper channels (Conomos and Peterson, 1977).

The Petaluma River drains a 370 km^2 watershed with diverse land usage (industrial, agricultural, and residential) and delivers freshwater to San Pablo Bay. Sonoma Creek drains 397 km^2 of residential and agricultural land, and is interconnected with a large slough network (Fig. 1). Sonoma Creek meets the Second Napa Slough (SNS) upstream of San Pablo Bay. Sonoma Creek and SNS are primarily affected by tidal exchange with San Pablo Bay, not the eastern portion of the slough network (Warner, 2000).

2.2. Field methods

The Petaluma River and Sonoma Creek/SNS tributary systems were each occupied by two equipment sites. Site Pet was located within the Petaluma River and site CM9 occupied the dredged Petaluma River entrance channel in San Pablo Bay. Site SNS was situated within the slough network of northeast San Pablo Bay, upstream from the mouth of Sonoma Creek. Though site SNS is not in Sonoma Creek proper, water is transported regularly with the tides from Sonoma Creek to SNS. Site Pablo was located at the mouth of Sonoma Creek.

Data from four additional sites will be utilized to provide boundary conditions in the system. Sites Ben and Car highlight the influence of the Delta, while site PSP establishes the seaward boundary condition of San Pablo Bay. Site PetGS is a discharge gaging station on the Petaluma River, maintained by the U.S. Geological Survey. Flow records are not available for the Sonoma Creek system. Wind speeds at site Novato were obtained from the California Irrigation Management Information System (http://www.cimis.water.ca.gov).

Conductivity, temperature, depth, and optical sensors (CTDO) were deployed at all sites except PetGS and Novato (Table 1). The optical sensors were calibrated for suspended-sediment concentration (SSC) using collected water samples that were analyzed gravimetrically. The actual SSC was related to the sensor output, providing a calibration curve (Warner et al., 1999; Buchanan and Ruhl, 2000). Due to the finite response of the optical sensors, the response reaches a maximum at higher concentrations, and, therefore, concentrations above that value cannot be measured. Spurious spikes in the optical data, caused by debris and bio-fouling, were removed. Three sites were equipped with electromagnetic current meters (EMCM). All data were collected at 15-min intervals.

2.3. Qualitative analysis of field observations

2.3.1. Petaluma River–San Pablo Bay

Bi-directional flow is observed at site PetGS during most of the year when freshwater flow is negligible. Flow records at site PetGS illustrate both the episodic nature of freshwater flow in the Petaluma River, and the

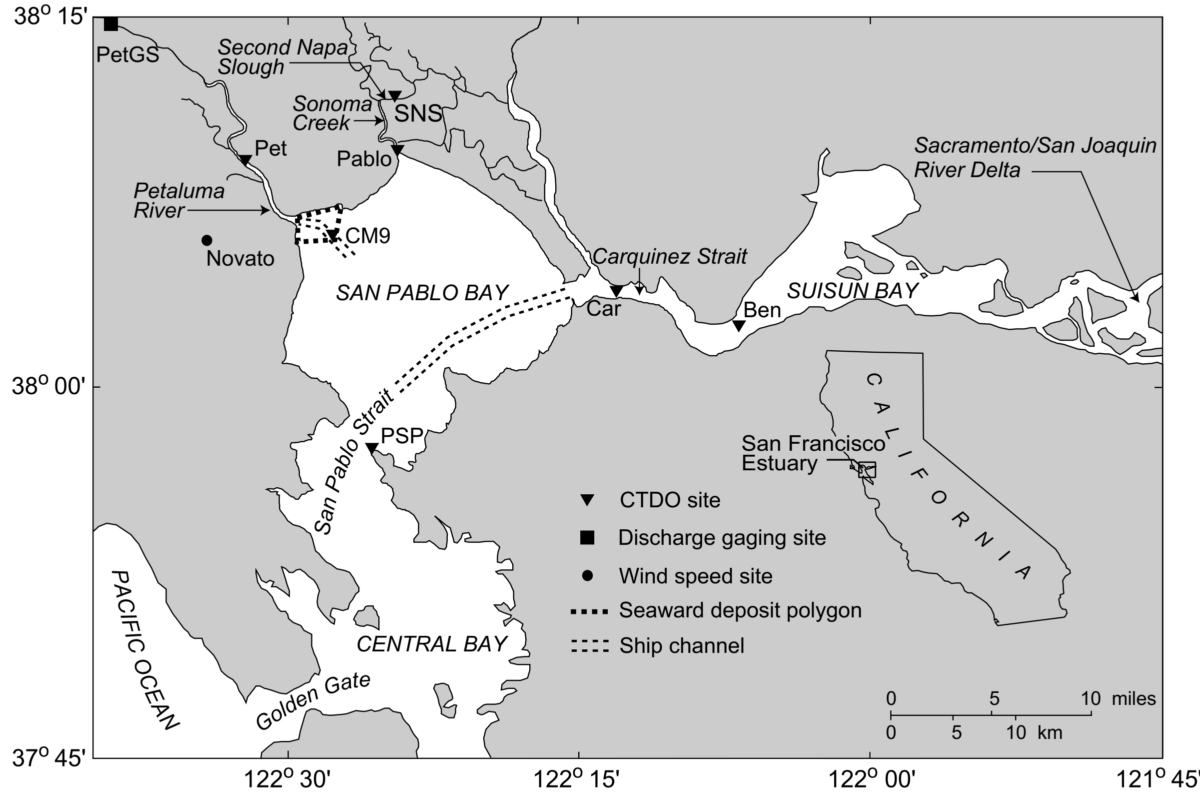

Fig. 1. Location map of the northern and eastern San Francisco Estuary. CTDO = conductivity, temperature, depth, and optical sensors, polygon drawn at http://sfbay.wr.usgs.gov/access/Bathy.

minor effect of freshwater flow on suspended-sediment concentrations at site Pet during the dry season (Fig. 2). The maximum instantaneous flow in 1999 was 122 m^3/s, while minimum flow was near zero. SSC at site Pet is about 500 mg/L during the first large flow peak of 1999 (February 6–8), rather than the typical tidally variable range (<100 to >2500 mg/L) when net flow is negligible (April–December).

The existence of temporary sediment deposits is suggested by the time-series of SSC at sites Pet and CM9. Increasing SSC during the second half of flood at the upstream site (Pet) indicates a downstream sediment source (seaward deposit) being advected upstream, while increasing SSC during the second half of ebb at the downstream site (CM9) indicates an upstream source (landward deposit) being advected downstream. Time-series of concurrent velocity and SSC support this hypothesis (Fig. 3). In addition, note that advection peaks occur during periods of declining velocity, while resuspension peaks occur during maximum velocity. In the quantitative analysis section, the speed of this advection will be calculated and compared with the tidal wave celerity. This will verify that SSC advection peaks are not the result of tidal resuspension.

As flood currents develop after slack at CM9 (Fig. 3, tile 3, 1900, 9/26/2000), the seaward deposit is resuspended. SSC at site CM9 peaks and decreases in about an hour as the resuspended sediment moves landward with the flood tide. The sediment is advected to site Pet (Fig. 3, tile 2), where a landward deposit forms at slack after flood (Fig. 3, tile 2, 2400, 9/26/2000). Ebb currents resuspend the landward deposit and advect the sediment downstream to site CM9, where the seaward deposit is re-created at slack after ebb (Fig. 3, tile 3, 0700, 9/27/2000). This process repeats regularly with the tides.

Site Pet occupies an area where the landward and seaward deposits overlap. The time-series from site Pet (Fig. 3, tile 2) shows a plateau and following peak in

Table 1
Site, operation dates, and instrument depths relative to mean lower low water (all measurements shown in meters, N/A = not applicable; CTD = conductivity, temperature, depth; EMCM = electromagnetic current meter)

Site	Dates of operation	Water depth	CTD sensor depth	Optical sensor depth	EMCM depth
Ben	3/15/1996–present	24.4	16.8	16.8	N/A
Car	4/21/1998–present	26.8	25.3	25.3	N/A
CM9	11/12/1998–present	1.8	1.2	1.2	N/A
Pablo	9/2/1997–3/12/1998	1.6	1.3	1.0	1.1
Pet	1/15/1999–8/4/1999 and 9/19/2000–3/8/2001	2.5	1.5	1.9	2.1
PSP	12/1/1992–present	7.9	6.0	7.0	N/A
SNS	9/2/1997–12/4/1997	2.2	1.9	1.9	1.7

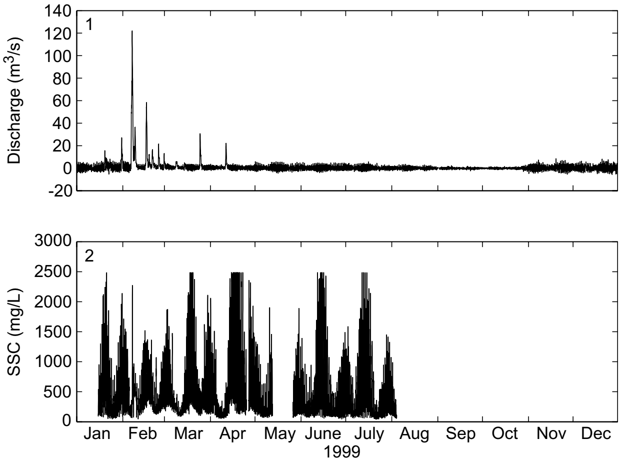

Fig. 2. Petaluma River discharge at site PetGS (1) and suspended-sediment concentrations at site Pet (2) for 1999. Negative discharge values indicate upstream flow. Truncated values in tile 2 reflect maximum instrument response. SSC, suspended-sediment concentration; mg/L, milligrams per liter; m^3/s, cubic meters per second.

concentration during the second half of ebb, though concentrations are lower than the initial resuspension peak at the beginning of ebb. This implies that the landward deposit extends upstream of site Pet, and sediment still is being advected past site Pet during the second half of the ebb tide.

The tidal oscillation of sediment between the Petaluma River and northwestern San Pablo Bay is independent of the SSC variability observed at the open boundary of San Pablo Bay at site PSP (Fig. 3, tile 4). Sites Car and PSP are equipped with two sets of sensors at different depths. For this comparison, the near-bottom sensors were considered to give the greatest SSC at these sites. Though site Car was not functioning at this time (due to bio-fouling), SSC during the previous two-week period never surpassed 200 mg/L.

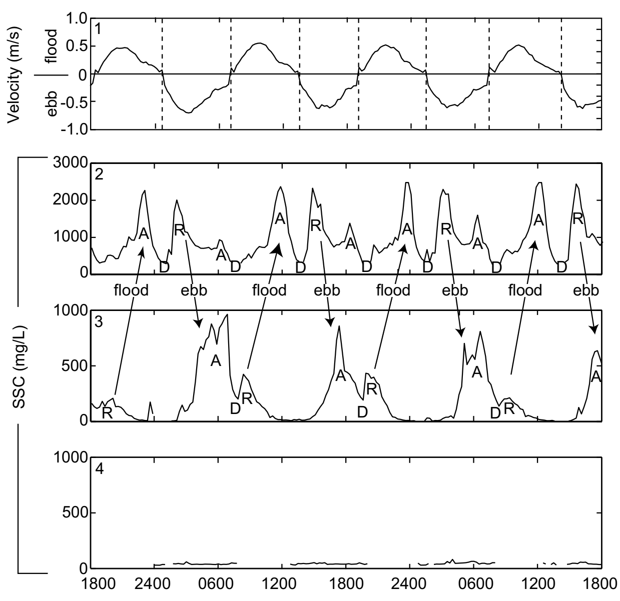

Fig. 3. Time-series of velocity from site Pet (1), suspended-sediment concentrations from site Pet (2), site CM9 (3), and site PSP (4). Vertical dashed lines indicate slack tide at site Pet. A = advection, D = deposition, R = resuspension. Arrows do not indicate the same parcel of sediment advecting from site to site, but rather the general motion of suspended sediment between the deposits.

Wind and wind-wave resuspension in San Pablo Bay are not major factors in the transport processes described here because the mobilization and deposition of the mobile mass occurs independently from wind events. While sediment in the mobile mass is more likely to stay in suspension when wind waves are present, the magnitude of the advected and resuspended-sediment concentrations is more a function of tidal currents and spring/neap variability. Despite higher wind speeds between November 4, 2000, and November 10, 2000, maximum concentrations are seen during the strongest ebb tides, between November 11, 2000 and November 17, 2000 (Fig. 4). The combination of stronger currents and larger tidal excursion creates a larger mobile mass that is able to reach site CM9 from the Petaluma River during ebb tides.

2.3.2. *Sonoma Creek/SNS–San Pablo Bay*

The cyclical process of resuspension, advection, and deposition, as observed in the Petaluma River and San Pablo Bay, can be seen in the measured time-series of SSC for sites Pablo and SNS (Fig. 5). Starting at the first flood tide of the record, the concentrations at both sites are relatively low. The onset of flood tide (Fig. 5, tiles 1 and 3, 0700, 10/14/1997) is well correlated to the SSC peak at site Pablo. The lower SSC at site SNS (Fig. 5, tile 2, 0700, 10/14/1997) reveals the location of the sediment mass to be at site Pablo, within the seaward

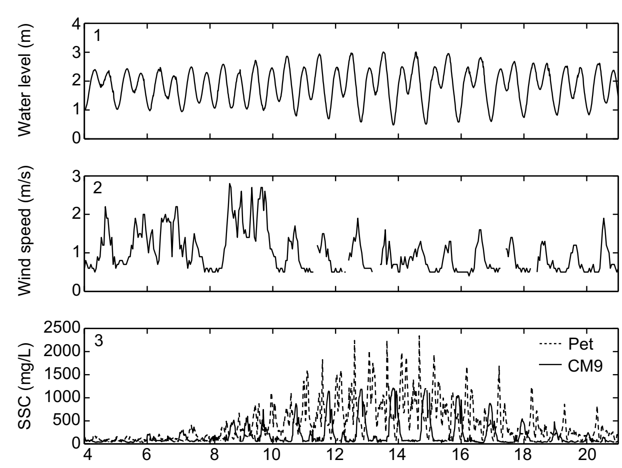

Fig. 4. Time-series of water level at site CM9 (1), wind speed at site Novato (2), and suspended-sediment concentrations from sites CM9 and Pet (3), November 4 to November 21, 2000.

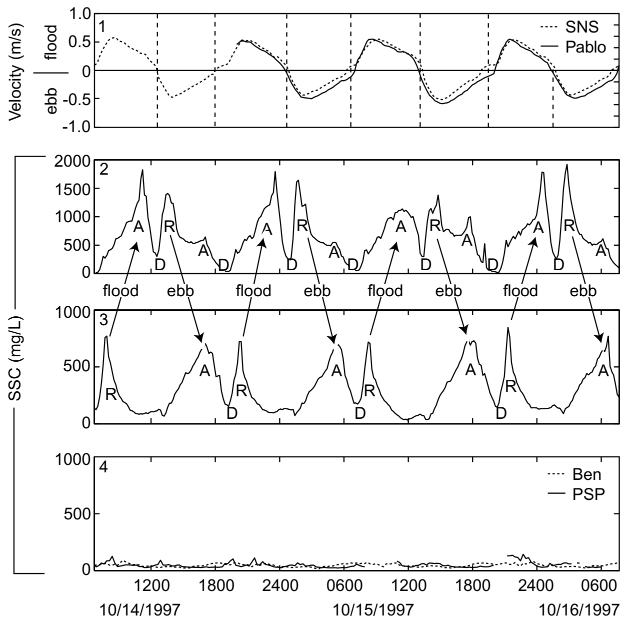

Fig. 5. Time-series of velocity from sites SNS and Pablo (1), suspended-sediment concentrations from site SNS (2), site Pablo (3), sites PSP and Ben (4). Vertical dashed lines indicate mean slack tide of sites SNS and Pablo. A = advection, D = deposition, R = resuspension.

deposit. The flooding current advects the sediment mass into the slough network, with a tidal excursion past site Pablo on the order of 7 km (Warner, 2000). The speed of advection for this system will be calculated and compared with tidal wave celerity as mentioned above.

The following slack tide allows the sediment to quickly settle out of the water column and the SSC to reduce to less than 400 mg/L at site SNS. At the commencement of ebb, currents at site SNS resuspend the same sediment, which is then advected back towards site Pablo. The landward deposit is located closer to site SNS and, therefore, the sediment concentrations at site Pablo remain relatively low at the beginning of the ebb. The mass of sediment is advected back to site Pablo, which shows increased SSC before the end of the ebb tide (Fig. 5, tile 3, 1730, 10/14/1997). This cycle repeats as the forcing tide follows a mixed semi-diurnal pattern. Note that advection peaks occur during periods of declining velocity, while resuspension peaks occur during maximum velocity.

Tidal hydrodynamics and SSC in the Sonoma Creek/SNS system are characterized by nonlinear interaction of the astronomical tides with the local bathymetry. Because tide range η is on the order of the depth h ($\eta/h \sim 0.3$), and the tidal wave speed is a function of the depth, the tidal wave will travel faster at high tides and slower at low tides. This effect will produce a quarter-diurnal (M4) oscillation from the main semi-diurnal tidal constituent (M2), creating a maximum flow earlier in each tidal phase (Warner et al., 2003). At site Pablo, the maximum flood tide shear occurs near the beginning of the flood—producing maximum SSC early in the flood tide. The maximum flood shear at site SNS also occurs at the beginning of its flood phase, however, the seaward deposit is located at site Pablo at this time, so the sediment concentrations at site SNS remain low at the beginning of the flood tide.

Site SNS occupies an area where the landward and seaward deposits overlap. The time-series from site SNS (Fig. 5, tile 2) shows a plateau in concentration during the second half of ebb, though concentrations are lower than the initial resuspension peak at the beginning of ebb. This implies that the landward deposit extends upstream of site SNS, and sediment still is being advected past site SNS during the second half of the ebb tide. Due to an extended period of slack water after ebb at site SNS (Warner et al., 2003), deposition after ebb is markedly longer than deposition after flood at SNS. This phenomenon, caused by a truncating sill at the mouth of Sonoma Creek, also results in a delayed flood current at site SNS after slack. This explains the almost nonexistent resuspension signal seen at the start of flood at site SNS. The formation of deposits at site SNS during both periods of slack water indicates that site SNS is within the overlapping area.

The time-series of SSC at the bay boundary sites, PSP and Ben, demonstrates the minimal interaction between the Sonoma Creek/SNS system and San Pablo Bay (Fig. 5, tile 3). Site Car was not in operation at this time, therefore, site Ben was used to highlight the lack of Delta influence. Site Ben is also equipped with two sets of sensors, the near-bottom sensor was considered here for the same aforementioned reasons.

2.4. Quantitative analysis of field observations

2.4.1. Methods

In order to determine if water flowing from the tidal portion of the Petaluma River during an ebb tide could occupy San Pablo Bay up to site CM9, water volume estimates were compared. The average volume of water leaving the Petaluma River on ebb was estimated as the product of average tidal excursion and cross-sectional area, while the maximum was estimated using the maximum tidal excursion. Channel geometry at site Pet was obtained from the U.S. Army Corps of Engineers (Dillabough, U.S. Army Corps of Engineers, pers. comm., 2001). A mean water depth of 3.88 m (mean level from the September 22, 2000 to March 7, 2001 period), top channel width of 223 m (at site Pet), and trapezoidal cross-section with 3:1 side slopes (total area = 817 m^2) were used to calculate the cross-sectional area. Excursions were determined by integrating velocity records at site Pet. This will be compared with the volume estimate of San Pablo Bay, spanning from the mouth of the Petaluma River to site CM9. Volume estimates of this area were performed using the

U.S. Geological Survey's San Francisco Bay bathymetry web page (http://sfbay.wr.usgs.gov/access/Bathy). At low water, the volume was calculated as the volume of a polygon spanning from the mouth of the Petaluma River eastward along the shore of San Pablo Bay, south to site CM9, west to the shore of San Pablo Bay, and north to the mouth of the Petaluma River (Fig. 1).

The sediment load contributed by the Petaluma River was estimated to determine if annual sediment delivery could deliver the mass of sediment oscillating between the deposits. The total water volume transported past site PetGS was obtained by integrating discharge through time during the 1999 flow peak (Fig. 2). The load was calculated as the product of this volume and the quasi-steady-state suspended-sediment concentration at site Pet during the flow peak (500 mg/L). Minimal erosion and deposition are assumed between sites PetGS and Pet, as are well-mixed conditions at site Pet. Water volume estimates of the area overlying the estimated seaward deposit were performed as mentioned above. This assumes that site CM9 is the seaward boundary of the seaward deposit. This polygon volume can be multiplied by an estimate of the SSC throughout the area during flood tide resuspension (∼500 mg/L) to calculate a total mass resuspended from the deposit.

SSC peaks may be caused by the hypothesized advection of a sediment mass or by local tidal resuspension. To determine which is occurring, the time-delay between peak resuspension and peak advection can be divided by the distance between the two sites to yield a peak-to-peak velocity (U_{SSC}). This procedure was performed for both systems, and compared to the tidal wave velocity [U_{wave} = (acceleration due to gravity × water depth)$^{0.5}$] and water velocity (U_{water}). Data shown in Figs. 3 and 5 were used to calculate U_{SSC} and U_{water}. Water velocity at site CM9 was estimated using a tidal current prediction table.

The boundaries of the sediment mass oscillation were estimated and compared between the two systems. Velocity measurements (at all sites except for site CM9) on flood and ebb tides were integrated from the point at which advection of sediment was first observed to slack after the corresponding tide. This provides an estimate of the distance the mobile sediment mass traveled past the given site (assuming a constant channel cross-section) and, therefore, boundaries of the sediment oscillation. Because velocity was not measured at site CM9, we assume that it is the seaward boundary of the oscillation.

2.4.2. Results

2.4.2.1. Ebb water from Petaluma River occupies San Pablo Bay out to site CM9. Water volume estimates confirm that ebbing water from the Petaluma River can occupy San Pablo Bay out to site CM9. The volume of the water parcel overlying the seaward deposit (10 × 10^6 m^3) is bracketed by the maximum (14 × 10^6 m^3) and average (4.9 × 10^6 m^3) volumes of the river parcel. This implies that the river parcel can occupy the seaward deposit water parcel (up to site CM9) during strong ebb tides, and half that volume during average ebb tides. The suspended-sediment record from site CM9 confirms this, as sediment leaving site Pet reaches site CM9 only during stronger ebbs (Fig. 4). A mean ebb tidal excursion of 6.0 km was calculated and used to estimate the average volume and the maximum volume was similarly calculated using a maximum ebb tidal excursion of 17 km.

2.4.2.2. River sediment load comparable to mass in seaward deposit. The contribution of the Petaluma River during the first large flow peak of 1999 (4.1 × 10^6 kg) is on the same order of magnitude as the mass resuspended from the seaward deposit (5.0 × 10^6 kg). Due to the episodic nature of flow in this river, it is clear that the Petaluma River supplies enough sediment during one flood to maintain the sediment mass on a yearly basis.

2.4.2.3. Advection peaks are not caused by local tidal resuspension. The average sediment mass advection velocities for both systems are on the order of the water velocity, not the tidal wave celerity (Fig. 6). U_{water} at site Pet is probably lower than the actual mean velocity of the river, because the current meter was located on the edge of the broad river channel. Because the oscillating sediment mass is several kilometers long, peaks at a pair

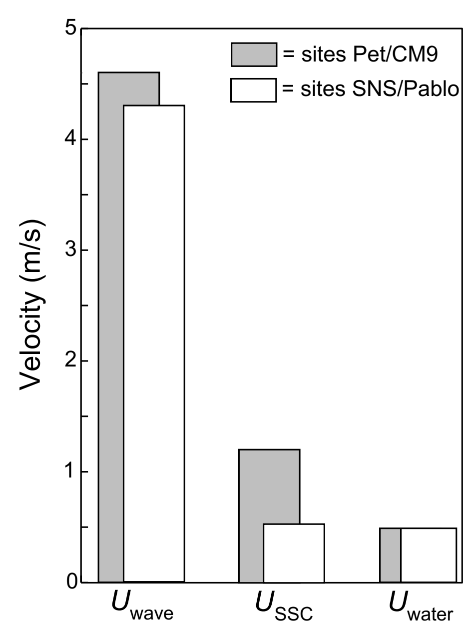

Fig. 6. Wave velocity, SSC peak-to-peak velocity, and water velocity comparison.

of sites may not represent the same parcel of sediment. This would cause U_{SSC} to be overestimated when the sites are further apart, as is the case with sites Pet and CM9 as compared to sites SNS and Pablo.

2.4.2.4. Sediment mass excursions are comparable between the two systems. The sediment mass excursions are similar between the two systems, varying between 11 and 31.5 km. Maximum values occurred during spring tides, due to enhanced currents and tidal excursions. In the Petaluma River system, the excursions of the sediment mass varied between 11 and 24.5 km, while the distance in the Sonoma Creek/SNS system varied between 15 and 31.5 km. Though the seaward extent in the Petaluma River system during this period is not known due to a lack of velocity data at site CM9, the transitional regime reached at least as far as site CM9 during strong ebb tides due to the observation of deposition there (Figs. 3, 4). It should be noted that the channel cross-sections increase rapidly as the regime opens to the shallow, broad plain of San Pablo Bay, and the assumption of longitudinal homogeneity is no longer valid.

2.5. Discussion

2.5.1. Similarity of river/bay processes to narrow estuary/continental shelf processes

The aforementioned cyclical processes have been identified in other estuarine systems, most notably Germany's Weser Estuary (Grabemann and Krause, 1994). In that system, measurements confirmed the existence of a "turbidity zone", which contained an oscillating sediment mass. The resuspension, advection, and deposition events described earlier in this paper are used to explain this phenomenon as well. The cyclical process is also present in the Tamar Estuary (U.K.) (Uncles and Stephens, 1993), which shares many sediment transport phenomena with the Weser Estuary (Grabemann et al., 1997).

Though the scales of these two estuaries are much larger than the typical river/bay system discussed in this paper, the geometries are similar. The Weser and Tamar are narrow estuaries that quickly widen onto the continental shelf, much like the narrow river regime that expands at the bay regime. The turbidity zone in these estuaries, analogous to the transitional regime, similarly occupies the tidally influenced reaches of the river and can be flushed out during periods of high river flow. The system returns to its cyclical behavior after some recovery period.

While the general cyclical process is present in the systems mentioned here, several researchers have identified estuary-specific factors that contribute to ETM formation and maintenance. We do not intend to suggest that the underlying hydrodynamics and sediment bed dynamics are identical between all systems mentioned.

2.5.2. Major factors

During the prevalent low-flow conditions, the major factors that create tidally oscillating sediment are geometry and tidal ranges/velocities. Assuming that the ocean and deep-water channel are permanent sediment sinks, the geometric isolation of suspended sediment in the river/bay system allows the mass to persist. Mean ebb tidal excursion at site Pet (6 km) is less than the distance to the deep channel (19 km), indicating that sediments can only reach the permanent sink during strong ebb tides or during episodic river discharge, as is the case with the Sonoma Creek/SNS system. The sediment mass in both cases is unable to consistently advect to the permanent sink (channel/open ocean), thereby promoting sediment retention within the system. Seaward tidal flats in the systems mentioned may assist in controlling further downstream/ebb transport.

Large tidal ranges (and hence velocities) are necessary to maintain the tidally oscillating sediment mass. While sediment supply is required to create the mobile mass, sufficient shear stress on the bed is necessary to mobilize the sediment. The systems considered here, as well as the aforementioned European estuaries, are non-microtidal systems with maximum currents greater than 0.5 m/s. A microtidal estuary with lower velocities would favor deposition and not mobilization, reducing the likelihood of maintaining a mobile mass in suspension.

3. Conceptual model

The similarities between the two tributaries of San Pablo Bay suggest that a conceptual model may adequately characterize the sediment transport patterns for systems of this configuration and morphology. The conceptual model consists of the three regimes that occupy the space between the land and the open ocean. The focus of the conceptual model is the transitional regime, which contains a tidally oscillating sediment mass. The upstream limit of this oscillation demarcates the river regime, while the downstream limit marks the bay regime.

3.1. River regime

The river regime is influenced by events that occur over the corresponding watershed. Rainfall and snowmelt that occur within a given river's watershed escape by evaporation, percolation, or runoff. The primary source of river water is runoff (with the exception of spring-fed rivers), which is a function of precipitation and watershed characteristics. The flow in the river regime is mostly unidirectional due to land slope, though undissipated tidal energy can enter at the downstream fringes, causing bi-directional tidal currents. Sediment is introduced to the river regime through runoff and bed/bank erosion. The sediment then is advected downstream to the transitional regime. In this model, river discharges are assumed to be episodic and seasonal. The downstream boundary of the river regime is determined by the landward extent of the oscillating sediment mass.

3.2. Transitional regime

The transitional regime's boundaries are determined by the extent of the sediment mass oscillations, which is governed by tidal forcing (in the absence of episodic river discharge). Tidal energy is transferred from the ocean to the bay and further upstream, causing oscillations of the water surface throughout the regime. These oscillations cause periodic gradients in the water surface, leading to flood and ebb tidal currents and slack tides. During periods of relatively large river discharge, ebb currents are intensified and flood currents are reduced. This regime can encompass open channel, open water, or both simultaneously.

Fine sediment from the river and bay regimes can be supplied to the transitional regime and deposited there at slack tide, creating an easily mobilized sediment mass. Sediment from the river advects to the transitional regime while sediment from the bay can be transported into the transitional regime by flood tides and other mechanisms (e.g. gravitational circulation). On the tidal time scale, deposition occurs at slack tide and the newly deposited sediment is an easily erodible fluid mud or concentrated benthic suspension that overlies less-erodible, more consolidated sediment.

The flood and ebb tidal currents govern sediment mobility in the transitional regime. On flood tides, the currents resuspend sediment throughout the sediment mass and advect the suspension upstream, where the sediment deposits at slack after flood tide. Ebb tides then resuspend sediment in the mass, and advect the suspension downstream, where the sediment deposits on slack after ebb tide. While suspended, the sediment mass forms an estuarine turbidity maximum. This pattern repeats continuously, halted only by episodic river flows that overcome the flood tidal currents and transport the mass downstream.

Due to the dynamic nature of the sediment mass, the mass deposited at slack tide forms a transient sediment deposit on the bed. Seaward and landward deposits are formed at slack after ebb and flood tides (Figs. 7, 8). The transitional regime is hereby defined as the area between and including the two deposits. The interaction between these deposits will be described for when there is no overlap of the deposits and when overlapping is occurring. The limits of the transitional regime are

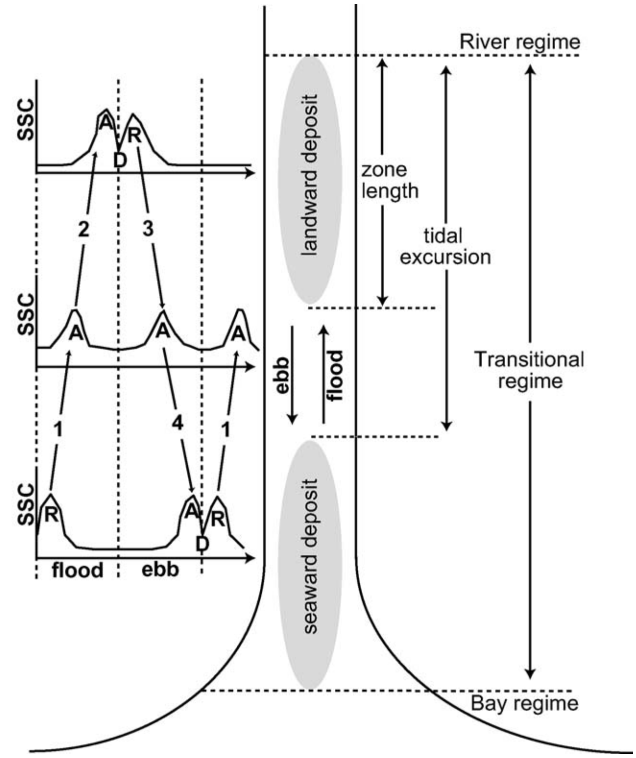

Fig. 7. Schematic of nonoverlapping transient sediment deposits. Gray ellipses represent sediment deposits within transitional regime. Flood and ebb currents mobilize the deposits; time-series on left hand side represents SSC at three locations within transitional regime, with dashed lines representing slack water. Resuspension (R) occurs as currents increase after slack, advection (A) of sediment commences with persistent currents, and deposition (D) increases as currents reduce near slack.

determined by the maximum upstream/downstream locations of the deposits. It should be noted that the idealized shape of the deposits may not represent reality; the masses can be amorphous as well as discontinuous.

3.2.1. Nonoverlapping deposits

The seaward and landward deposits do not overlap when their length is less than the tidal excursion. As the tide turns to flood, sediment in the seaward deposit resuspends and is advected upstream (1, Fig. 7). The sediment is advected past the nonoverlapping area of the transitional regime with no noticeable deposition. The same suspension is advected upstream (2, Fig. 7) until slack tide, when it deposits in a broad zone upstream, forming the landward deposit. The ensuing ebb currents resuspend sediment in the landward deposit and advect the suspended sediment downstream past the nonoverlapping area, again with little deposition (3, Fig. 7). The suspension continues downstream until slack tide (4, Fig. 7). The sediment deposits, recreating the seaward deposit. This process repeats as the tidal currents follow a periodic cycle.

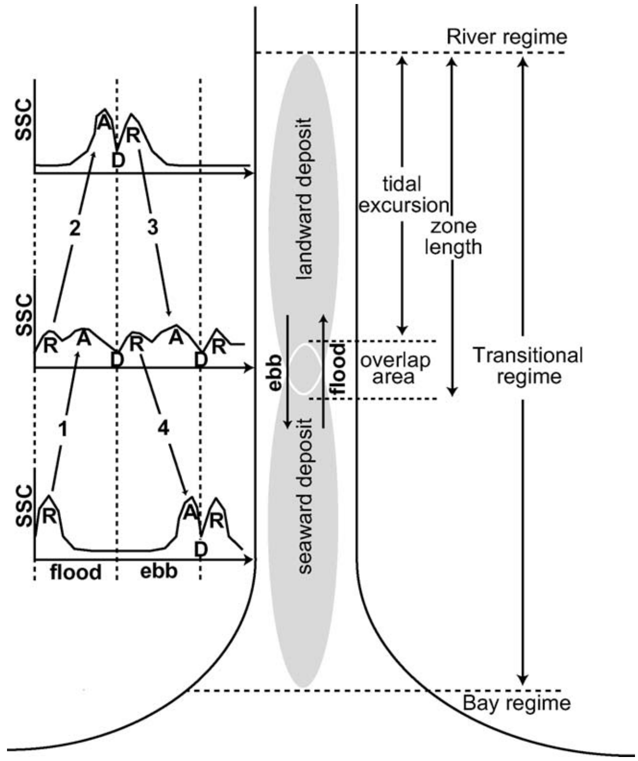

Fig. 8. Schematic of overlapping transient sediment deposits. Gray ellipses represent sediment deposits within transitional regime. Flood and ebb currents mobilize the deposits; time-series on left hand side represents SSC at three locations within transitional regime, with dashed lines representing slack water. Resuspension (R) occurs as currents increase after slack, advection (A) of sediment commences with persistent currents, deposition (D) increases as currents reduce near slack. Large deposit length relative to tidal excursion creates an overlapping area of the seaward and landward deposits.

3.2.2. Overlapping deposits

The seaward and landward deposits overlap when their length is greater than that of the tidal excursion. As with the previous case, slack after ebb tide is the initial condition when only the seaward deposit exists. In this case, however, the overlapping area of the transitional regime is within the seaward deposit at slack after ebb tide. Flood currents resuspend sediment throughout the seaward deposit, and advect it upstream (1 and 2, Fig. 8). At the overlapping area, SSC is relatively large throughout the flood tide because the sediment mass is always present, unlike the nonoverlapping case. During flood tide, sediment from the overlapping area is resuspended from the seaward deposit and advected to the upstream limit of the transitional regime (2), and sediment from the downstream limit of the transitional regime is resuspended and advected to the overlapping area. Resuspended sediment from the entire seaward deposit drops out at slack after flood tide, forming the landward deposit. Note that the landward deposit overlaps a portion of the previous location of the seaward deposit. Ebb currents resuspend sediment throughout the landward deposit. Again, at the overlapping area, SSC is relatively large throughout ebb tide because the sediment mass is always present. On ebb tide, sediment is advected from the upstream limit of the transitional regime (3) and deposits in the overlapping area. Concurrently, sediment from the overlapping area resuspends and is advected to the downstream limit of the transitional regime (4). As the sediment deposits at slack after ebb tide, the seaward deposit is formed. This cycle also repeats with the tidal currents.

3.2.3. Tidal and seasonal variabilities

Tidal variability can alter the patterns observed at a specific location in the transitional regime. The spring/neap cycle is capable of altering the amount of sediment (and, therefore, concentrations) entrained in the mass, as well as the tidal excursion of the mass (which determines the extent of the transitional regime). Spring tides entrain more sediment due to increased energy and, therefore, can increase the mass of the mobile mass. Diurnal inequality can also alter the limits of the transitional regime (and the deposits) on a daily time scale. For instance, a fixed observer at the downstream limit of the transitional regime might witness the deposition of the seaward deposit on a strong ebb tide, but the following weak ebb tide may not be sufficient to advect the sediment mass to the same spatial location. In this case, the transitional regime no longer contains the observer's location but ends at the maximum downstream limit of the new seaward deposit. Whether nonoverlapping or overlapping deposits are present varies with tidal variability.

Seasonal variability of river discharge alters the functioning of the system. Relatively high river flows intensify ebb currents and force the mobile sediment mass downstream, perhaps flushing the mass permanently from the system and halting these processes until normal low-flow conditions prevail.

3.3. Bay regime

The bay regime is located from the downstream edge of the transitional regime to the open ocean. This regime is influenced mostly by the ocean tides, though large freshwater flows can override tidal forcing during extreme flow events. The tidal forcing causes the water surface in the bay to oscillate periodically and bi-directional currents alternately supply the bay with saltier water from the ocean and fresher water from river sources. The bay, therefore, becomes a mixing zone between fresh and saline waters. Wind-generated waves also can develop due to the large fetch commonly present over the open bay waters.

Bed sediment is mobilized within the bay by way of tidal currents and wind waves. The river regime, which can periodically deliver large loads of sediment during floods, is a potential sediment source to the bay. Ocean waters generally are low in fine sediment concentrations, especially when compared to the river and transitional regimes.

4. Conclusions

The conceptual model illustrated in this paper describes the tidally induced oscillation of a mobile sediment mass between a river and a bay. This model is applicable to two rivers entering San Pablo Bay, indicating a common mechanism that is congruent with the physics of fine sediment transport. Both river systems considered here consist of a river that widens into a shallow bay, with extensive mudflats. On ebb tides, sediment fans out and deposits (seaward deposit formation), never quite escaping to the open bay waters. The tidal excursion is not large enough to allow for significant transport into the open bay. On the following flood tide, the deposits are resuspended and sent upriver to deposit during slack water (landward deposit formation). River discharge may modulate this process and relatively large river discharge may halt it altogether.

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