Understanding processes controlling sediment transports at the mouth of a highly energetic inlet system (San Francisco Bay, CA)

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Abstract

San Francisco Bay is one of the largest estuaries along the U.S. West Coast and is linked to the Pacific Ocean through the Golden Gate, a 100 m deep bedrock inlet. A coupled wave, flow and sediment transport model is used to quantify the sediment linkages between San Francisco Bay, the Golden Gate, and the adjacent open coast. Flow and sediment transport processes are investigated using an ensemble average of 24 climatically derived wave cases and a 24.8 h representative tidal cycle. The model simulations show that within the inlet, flow and sediment transport is tidally dominated and driven by asymmetry of the ebb and flood tides. Peak ebb velocities exceed the peak flood velocities in the narrow Golden Gate channel as a result of flow convergence and acceleration. Persistent flow and sediment gyres at the headland tips are formed that limit sediment transfer from the ebb-tidal delta to the inlet and into the bay. The residual transport pattern in the inlet is dominated by a lateral segregation with a large ebb-dominant sediment transport (and flow) prevailing along the deeper north side of the Golden Gate channel, and smaller flood dominant transports along the shallow southern margin. The seaward edge of the ebb-tidal delta largely corresponds to the seaward extent of strong tidal flows. On the ebb-tidal delta, both waves and tidal forcing govern flow and sediment transport. Wave focusing by the ebb-tidal delta leads to strong patterns of sediment convergence and divergence along the adjacent Ocean Beach.

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1. Introduction

Tidal inlets are a common geomorphic feature along the world’s coastlines and are found in a variety of coastal settings (Glaeser, 1978). These settings range from highly mobile cuts through barrier islands as observed along the U.S. East Coast, bedrock defined drowned river valleys such as the Hudson River Estuary and Chesapeake Bay, and glacially carved embayments (e.g. the Puget Sound in the Pacific Northwest). San Francisco (SF) Bay is a unique example of an over 100 m deep bedrock defined inlet formed due to recent tectonic activity. Numerous conceptual models have been formulated to explain sediment dynamics and interactions at barrier island type inlets (Hubbard et al., 1979; Fitzgerald, 1988, 1996; Oertel, 1988). However these models may not be applicable to considerably larger and deeper inlets such as SF Bay that greatly differ in dimensions, geographic and morphologic setting, and hydrodynamic forcing regime.

It is estimated that anthropogenic activities in SF Bay and its coastal system, such as channel dredging, sand mining and development, have removed or displaced over 200 million m³ of sand-sized-sediment in the last century alone (United States Army Corps of Engineers, 1996; Chin et al., 2004). The impact of these disturbances on the coastal system has not been quantified, but severe hot-spot erosion at Ocean Beach, the shoreline south of the inlet, and shrinkage of the ebb-tidal delta are certainly related (Hansen and Barnard, 2010; Dallas and Barnard, 2011; Hansen et al. (2013–this issue)). Understanding the physical processes that govern water and sediment exchange between San Francisco Bay and the open coast through the Golden Gate inlet is essential for understanding the observed changes and future sustainable management of the coasts.

Understanding sediment dynamics in large and energetic coastal systems like SF Bay is notoriously difficult as flows and sediment transports are often spatially and temporally complex. Collecting in situ field data with the required spatial and temporal resolution is extremely challenging and expensive. Numerical process-based models have reached a stage that they can be used to investigate the circulation dynamics and greatly improve our fundamental understanding of the processes driving sediment transport (Elias, 2006; Lesser, 2009; van der Weegen, 2009). Van der Weegen (2009) illustrated that long term (centuries) morphodynamic simulations are capable of reproducing concepts and equilibrium relations based on measurements and laboratory experiments. Further, Lesser (2009) demonstrated, through agreement between modeled and measured morphodynamic behavior of Willapa Bay (WA), that a process based numerical model could reproduce the most important physical processes in the coastal zone over medium
term (5 year) timescales. Quasi real-time simulations, forcing high-resolution models as realistically as possible by measured time series of wind, waves and discharges, showed the potential of using the models to generate synoptic, more-or-less realistic data of high spatial and temporal resolution over the entire inlet domain (Elias, 2006). Analysis of this data provides valuable information on governing flow and sediment transport patterns in the instrumented and the un-instrumented areas, and allows for identification of the dominant flow and sediment transport processes.

In this paper we use a coupled Delft3D-SWAN hydrodynamic, wave and sediment transport model to quantify the sediment linkages between San Francisco Bay, the Golden Gate, and the adjacent open coast. We do not resolve the full morphodynamic behavior of the system, but use numerically computed “potential” sediment transport by coupling a calibrated flow model to a transport formula (no morphologic change allowed in the model). We use input reduction techniques (Lesser, 2009) to construct representative estimates of the year-averaged tidal and wave forcing. Input schematizations allow us to efficiently compress long-term time series of tides and waves into a limited set of representative forcing conditions. These forcing conditions can be run on high grid resolution resolving the flow and sediment transports in detail. Analysis of these results provides fundamental understanding of the dominant processes and mechanisms; A first essential step for understanding morphodynamic behavior of the system, and a basis for future morphodynamic modeling. Particularly, we investigate the relative importance of waves versus tide in different parts of the inlet and ebb-tidal delta and we hypothesize that spatial patterns of tidal flow and the interaction between tides and waves can be used to understand the observed geographic distribution of the ebb-tidal delta and beaches in and around the inlet.

The study area and field data are briefly described in Section 2. The numerical model and San Francisco Bay application are discussed in Section 3. Availability of coherent and detailed measurements of bathymetry, flow and waves provide a unique model calibration and validation dataset (Section 4). Model schematizations and modeled sediment transport dynamics are discussed in Sections 5, 6 and 7 respectively.

2. Regional setting and field data

2.1. Study area

San Francisco Bay is the second largest estuary along the contiguous United States West Coast and connects a 163,000 km² watershed to the sea. BORDER by the major cities of San Francisco, Oakland and San Jose, the ‘bay area’ hosts a population of more than 7 million (Fig. 1). Walters and Gartner (1985) characterize the bay as a shallow, drowned river plain that is cut by deep relic channels. The South Bay is largely well-mixed due to limited fresh-water inflow. The Sacramento and San Joaquin Rivers supply the major freshwater influx (90%) to the partially mixed San Pablo and Suisun Bay sub-embayment’s (see Fig. 2 for locations).

Anthropogenic influence has shaped the bay into its present shape. Before major human settlement a deep channel ran through the center of the bay, following an ancient drowned river valley. The bay shores contained extensive freshwater wetlands, salt marshes and tidal mudflats. Major changes occurred following the hydraulic gold mining operations in the upper Sacramento and San Joaquin rivers during the Gold Rush in the 19th century as large amounts of sediment settled in the bays (Gilbert, 1917). Further sediment deposition and extensive land reclamation by filling in and construction of levees, reduced the bays’ wetlands to less than 4–8% of its original area (Jaffe and Foxgrover, 2006; Jaffe et al., 2007).

The ocean tides are classified as mixed semi-diurnal with a mean tidal range of 1.28 m, and a 28-day lunar variation of spring and neap tides (NOAA — National Oceanic and Atmospheric Administration, 2009). The large tidal prism (~2×10⁹ m³) and associated high velocities (exceeding 2.5 m/s in the inlet throat) have scoured the inlet channel 113 m deep into the bed rock through the Golden Gate inlet at its narrowest point. The strong currents effectively sweep sediments from the channel to its ebb and flood deltas. As the currents decelerate large sand waves are formed and moved on either side of the Golden Gate (Rubin and McCulloch, 1979; Barnard et al., 2006a,b). On the seaward side an ebb tidal delta, the SF Bar, dominates the local offshore bathymetry (Fig. 1 left). The approximately 150 km² SF Bar has an average depth

![Fig. 1](image-url) Left: location plot of San Francisco Bay or bay area. Right: details of the San Francisco Bay coastal system consisting of Golden Gate, San Francisco Bar, and beaches along the Marin Peninsula and San Francisco.
of 17 m with depths in some locations on the northern lobe of less than 10 m (Fig. 1). Over the last half century approximately 920 million m$^3$ of sediment has been lost from this ebb-tidal delta (Dallas and Barnard, 2011). Dallas and Barnard (2011) and Hanes and Barnard (2007) hypothesize that these losses result from dredging activities, sand mining, and reduced tidal prisms and sediment supply. However conclusive evidence physically linking these activities with contraction of the ebb-tidal delta has not yet been presented.

The SF Bight is exposed to an energetic wave climate with a mean annual offshore wave height of 2.5 m and winter storm wave heights commonly exceeding 6 m (Coastal Data Information Program (CDIP), 2010). Ocean waves are considerably modified by the shelf and SF Bar as they propagate to the coastline (Fig. 3). Several studies have documented the focusing effect of the ebb-tidal delta on the typically west to northwest incoming waves (Eshleman et al., 2007; Shi et al., 2011). South of the Golden Gate inlet, Ocean Beach forms a 7-km long sandy beach that stretches south from a rocky headland near the SF Bay entrance (Point Lobos) to the bluffs at Fort Funston (Fig. 1 left panel). Ocean Beach has shown a strong pattern of counterclockwise rotation, manifested in accretion of the north end of the beach and erosion of the south (Hansen and Barnard, 2010). These authors hypothesized that much of the observed counterclockwise rotation of the shoreline is linked to the multi-decadal contraction of the ebb-tidal delta (as presented in Dallas and Barnard, 2011).

3. Model

3.1. Flow model

To investigate physical processes and sediment exchange between SF Bay and the open coast a coupled Delft3D flow and SWAN wave numerical model was created. Delft3D-Flow forms the core of the model system simulating water motion due to tidal and meteorological forcing by solving the unsteady shallow water equations (Stelling, 1984; Lesser et al., 2004). The equations are solved on a staggered Arakawa-C grid using an Alternating Direction Implicit method (Leendertse, 1987; Stelling and Leendertse, 1991).

The flow model consists of six 2-way coupled domains (Fig. 4). These domains vary in resolution to optimize computational efficiency while maintaining high enough resolution to resolve the relevant processes in the areas of interest, in and adjacent to the Golden Gate. Where possible, grids are aligned along the land boundaries and main channels to support the numerical accuracy of the flow solver. Along Ocean Beach, the grid resolution is highest ranging between 12 and 20 m. This high-resolution is needed to accurately capture the surf zone processes. In the Golden Gate, a grid resolution of approximately 50 by 50 m is sufficient to represent the dominant bathymetric features and hydrodynamic variability. Three lower resolution grids cover the Central, South, and North SF Bays (Fig. 4). The Sacramento and San Joaquin river delta are highly schematized and only intended to provide storage to accurately capture the tidal prism, and provide river boundary conditions. Freshwater inflow values for the landward river boundaries were obtained from daily averaged measured flows estimated from the DAYFLOW program (CDWR, 1986). The SF Bar domain is coupled to a large-scale ocean grid that extends of the continental shelf break to minimize boundary effects and to propagate the tide across the shelf. On the open boundaries of the ocean domain, initial estimates of the amplitudes and phases of the 12 largest tidal constituents ($M_2$, $S_2$, $N_2$, $K_2$, $O_1$, $P_1$, $Q_1$, $MF$, $MM$, $M_4$, $MS_4$, and $MN_4$) were obtained from the TOPEX 7.2 global tidal model. The global tidal model is based on satellite altimetry derived data (Egbert et al., 1994; Egbert and Erofeeva, 2002).

To achieve acceptable model run times, all flow grids were run in depth averaged mode (2DH). This approach is acceptable as we are primarily interested in the flow and transport of coarser sediments (sand) adjacent to the well mixed inlet where stratification is less likely to be important. However, Wilkerson et al. (2002) did document that during high freshwater discharge events resulting from large winter storms the salinity can be significantly depressed in the Golden Gate. Realistic treatment of water temperature variations related to wind driven upwelling and downwelling and the effects of
Fig. 3. Wave roses constructed for (a) Point Reyes (01-01-1997/12-01-2010), (b) NOAA SF buoy (01-01-1997/12-01-2010), (c and d) SF Bar buoy and station TV1 (07-25-2007/05-27-2011); see Fig. 5 for locations.

Fig. 4. Overview of the curvilinear San Francisco flow domain (left) and details of the high resolution Ocean Beach domain (right). Red lines indicate boundary locations for the six coupled sub grids (Ocean, SF Bar, Ocean Beach, Golden Gate, South Bay, North Bays and schematized delta).
these variations on the circulation is also not possible with the 2DH approximation, but temperature effects are not likely to impact the results described here.

3.2. Wave model

The spectral wave model SWAN (version 40.72ABCDE) was applied in stationary, third-generation mode to propagate waves from the continental shelf to the coastline. SWAN simulates the evolution of wave action density using the action balance equation (Holthuijsen et al., 1993; Booij et al., 1999; Ris et al., 1999). The model takes into account propagation in geographical space, depth- and current-induced refraction, shifting of the intrinsic radian frequency due to variation in mean current and depth, as well as the generation and dissipation of waves by wind and breaking respectively.

Three grids of progressively increasing resolution were created to accurately resolve the wave propagation, growth and decay into the nearshore (Fig. 5). The highest resolution wave grid adjacent to Ocean Beach is 18 m in the alongshore and between 12 and 20 m in the cross-shore (similar to the model). The largest wave domain that extends off the shelf is rotated such that the northeast corner is near the Point Reyes buoy and the offshore boundary is approximately parallel to the continental shelf break. Sensitivity testing revealed that this domain is large enough to capture the complex wave refraction and wave sheltering patterns around the Pt. Reyes headland and the Farallon Islands (~30 km offshore of SF, Fig. 1). For model calibration, the two-dimensional directional spectra from the Pt. Reyes Buoy were uniformly applied along all three open boundaries. This uniform boundary specification introduces some errors in the nearshore area due to water depth restrictions. By using a sufficiently large wave grid, these disturbances are damped before the area of interest is reached and therefore do not affect the model results adjacent to the Golden Gate.

Given the magnitude and spatial extent of strong tidally-driven currents in the SF Bight, inclusion of wave–current interactions is critical for accurate wave modeling. The hydrodynamic and wave models were therefore run in so-called quasi-nonstationary mode. This involves a two-way coupling of a nonstationary hydrodynamic calculation in combination with regular stationary wave simulations. Every 15 min during the hydrodynamic simulation, SWAN is activated. SWAN then performs a stationary simulation, using the measured wave spectra, and computed water levels, currents and bed levels passed from the flow model. The results of the wave simulation are stored on the computational flow grid and included in the flow calculations through additional forcing terms near surface and bed, enhanced bed shear stresses, streaming and increased turbulence (Fredsoe, 1984; Dingemans et al., 1987; Walstra et al., 2000).

3.3. Sediment transport and bathymetry

The online morphology addition to Delft3D is used to compute sediment transport in the flow domains (Lesser et al., 2004). The TRANSPOR2004 transport equations are used to model the movement of non-cohesive sand fractions and are implemented in the Delft3D flow solver. The Delft3D implementation of this formulation follows the principle description of Van Rijn (2007a,b,c), separating the sediment transport into suspended and bed-load components. Suspended sediment transport is computed by the advection–diffusion equation, and includes the effect of sediment in suspension on the fluid density. Bed load transports represent the transport of sand particles in the wave boundary layer in close contact with the bed surface, and include an estimate of the effect of wave orbital velocity asymmetry. The bed was schematized as a single sediment fraction with a $d_{50}$ of 250 μm (representative for the ebb-tidal delta deposits). Similar tidal sediment transport patterns were obtained for sediment fractions in the 200 to 350 μm range.

The bed level in the model was held constant to prevent feedback between the flow and changing bed level. This was done to isolate the role of the changing flow on the sediment transport patterns that result from the interaction with the observed morphologic features. Accurate predictions of the bed level change would require long-term simulations, calibrations and detailed descriptions of the bed composition that are beyond the scope of this study.

A variety of data sources were used to create a Digital Elevation Model (DEM) for use in the flow and wave models. Bathymetry west of the Golden Gate, covering the SF Bar was derived from a 2004 and 2005 multi-beam bathymetric survey (Barnard et al., 2006a). The remaining

Fig. 5. Overview of the nested SWAN wave grids (left) and details of the higher resolution SF Bar and Ocean Beach domains (right). Red stars indicate locations of available wave measurements used for model validation.
portions of the ocean domain were filled in with data from the NOAA NGDC Coastal Relief Model (http://www.ngdc.noaa.gov/mgg/coastal/crm.html). The nearshore Ocean Beach bathymetry is an average of several personal water craft surveys (Barnard et al., 2007). The adjacent sub-aerial beach topography is a compilation of several monthly topographic surveys (Hansen and Barnard, 2010). In South and Central SF Bay depth points were derived from 1996 to 2005 multi beam surveys (Foxgrover et al., 2007). Data collected in 1979 and 1985 (30 m resolution) were used to fill in the remaining portions of SF Bay and to schematize the Sacramento Delta (Jaffe and Foxgrover, 2006). Each of the datasets was projected to NAD83 UTM Zone 10N and elevations were adjusted to NAVD88. All bathymetry and topography data were merged together smoothly to avoid discontinuities. In areas where multiple bathymetry data points occupied a single grid cell those data were averaged, in areas of sparse bathymetric data the depth samples were triangulated iteropolated. Sensitivity testing by using slightly different variations of the bay DEM (up to +1 m height variation) and various level of smoothing did not have a significant impact on circulation and sediment transport in the Golden Gate and adjacent areas.

4. Model calibration and validation

4.1. Flow model

A three step approach was followed to ensure accurate flow model results. Firstly, tidal propagation was calibrated using 12 primary tidal constituents at NOAA tidal stations within and outside of SF Bay (see Fig. 2 for locations). Secondly, model performance was evaluated by comparison of the tidal fluxes through the Golden Gate using the measured data at two transects across the inlet transects (TR1 and TR2 in Fig. 2). As a final step the calibrated flow model was validated against independent observations of nearshore flow along Ocean Beach obtained in 2005, 2006 and 2008 field campaigns (for details see Barnard et al., 2007). Agreement between the model and observations was assessed using the ‘index of agreement’ or skill as proposed by Wilkott (1981). This index reads

\[
Skill = 1 - \frac{\sum |X_{\text{mod}} - X_{\text{obs}}|^2}{\sum (|X_{\text{mod}} - \bar{X}_{\text{obs}}| + |X_{\text{obs}} - \bar{X}_{\text{obs}}|)^2}
\]

where X and \( \bar{X} \) are time-series and time-average of the selected model and observed variable. Skill varies between 0 (complete disagreement) and 1 (perfect agreement).

4.1.1. Calibration of tides

Accurate modeling of the tidal prism and flows through the Golden Gate requires a correct representation of the bathymetry as well as an accurate modeling of the tidal elevations, tidal propagation and wetting and drying within the bay. Continuous and historic measurements of water levels and harmonic tidal constituents are available at Point Reyes, the Golden Gate, and various locations throughout the bay (Fig. 2 right). An initial estimate of the tides was obtained by forcing the model with the 12 main tidal constituents on the open boundaries. In the Sacramento delta, at the confluence of the Sacramento and San Joaquin rivers, a combined river inflow of 840 m³/s was added. This value represents the average of the 1955–2009 DAYFLOW data (CDWR, 1986). Sensitivity testing showed that the modeled tidal components at the area of interest were insensitive to river inflow variations (ranging between 0 and 2000 m³/s). The goodness of fit of the computed free surface was determined by performing harmonic tidal analysis on the computed and observed water levels over synoptic 1-month time frames using the t-tide toolbox (Pawloczewicz et al., 2002). The observed amplitude variations between the tidal stations reveal the changing tidal wave shape as it propagates through the bays. In South Bay, the mean tidal range increases due to the funnel shape of the lower estuary. In the North Bays, the tidal amplitude initially remains constant though San Pablo Bay, then rapidly reduces towards the Delta due to topographic constriction, the dominance of bed friction, and opposite-directed river flow. Similar propagation characteristics are obtained in the calibrated model (Table 1).

The flow model proved to be most sensitive to variations in the bathymetry and topography as well as the bed roughness and these were the primary calibration parameters. The sensitivity of the tidal propagation for a range of constant Manning (0.020, 0.0225, 0.0275 and 0.0300) and Chézy roughness coefficients was examined (55, 60, 65 and 70 m¹/²/s). Initial simulations using constant bottom drag coefficients showed poor skill in reproducing the tidal propagation in the North Bays. An improved schematization of the major tidal flats and careful reconstruction of the channels and nearshore features significantly improved the results in these areas. In addition, best results were obtained by applying a similar depth dependent bed roughness in the bay domains as used by Cheng et al. (1993) and Gross et al. (2010). The ocean and Golden Gate proved fairly insensitive to roughness settings and a constant Chézy value of 65 m¹/²/s was used (default in the model). After fine-tuning the roughness, minor corrections to the boundary tidal constituents based on the model error at the SF tide gauge (less than 4% modifications) were applied. The calibrated model shows good skill at the Point Reyes and SF tide stations, for the five major constituents (M2, K1, S2, O1, N2 and P1). In the bays amplitude errors of the major constituents are generally below 0.05 m, and phase differences generally within 15° (Table 1).

4.1.2. Evaluation of tidal fluxes

The performance of the calibrated tidal model is evaluated using recent measurements of flow at the Golden Gate (Wright et al., 2008). During this experiment velocity data were obtained by boat-mounted ADCPs along two transects inside of the Golden Gate (TR1 and TR2 in Fig. 2). Both transects were run continuously during neap tide and spring tide conditions in January 2007. For each of the 25 completed ship tracks the total flux of water across both transects was calculated by vertically integrating the fluxes perpendicular to the boats path. A model simulation was performed over the same time frame using the calibrated tidal constituents on the ocean boundaries and representative time series of daily averaged river flow at the Sacramento and San Joaquin rivers. Evaluation of the cross-sectional averaged fluxes showed acceptable results with fluxes at peak ebb and flood being accurately reproduced by the model (Fig. 6). Largest deviations between the model and observations occur at the outer transect during the neap tides closest to slack tide. As the flow reverses during the tide, interaction of the ebb outflow and incoming flood develops spatially complex and variable flow patterns with local eddies and opposing directions.

<table>
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<th>Station</th>
<th>Constituent</th>
<th>M2 (m)</th>
<th>K1 (°)</th>
<th>O1 (°)</th>
<th>S2 (m)</th>
<th>N2 (°)</th>
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exact timing and magnitude of these eddies in the model might not fully correspond to the observations.

4.1.3. Validation of flow model

Hydrodynamic model validation of coastal flow and water levels focuses on field data obtained in the summer of 2005 and winter of 2006. During these experiments RDI Acoustic Doppler Current Proﬁlers (RDI ADCP) and Nortek Acoustic Wave and Current Meters (AWAC) were deployed at sites 1–3 and 5 (Fig. 2 and Table 2). Details of the 2005 and 2006 deployments can be found in Barnard et al. (2007). For both the summer and winter campaigns, the model was run over coherent time series forced by the calibrated constituents at the open ocean boundaries and with DAVYFLW estimates of freshwater discharge. Waves were not included in these simulations because the flows at sites 1–5 are believed to be mostly tidally dominated given their depth. Skill values between the measured and modeled water levels ranged between 0.97 and 0.99 (Table 2). Similar skill values are obtained for the individual tidal components, derived by performing harmonic tidal analysis on both the computed and observed water levels over synoptic time frames. These comparable results suggest that water level variations (roughly at 10–15 m depths) are indeed tide dominant with only minor contributions due to wind or waves. Lesser but acceptable skill, ranging between 0.68 and 0.90 is obtained for the flow velocity vectors. With exception of the offshore station 4, alongshore flow is modeled more accurately (skill 0.94–0.97) than cross-shore flow (skill 0.25–0.89). This discrepancy might partly be related to the depth-averaged approximation, and the absence of wave driven flow which is likely still evident at the ~11 m depth of the instruments. In addition, the coarser grid, resolution and bathymetric gridding poorly resolving local bathymetric effects (such as rip channels observed during deployment) at stations 3 and 4 potentially play a role. Poor cross-shore performance at Station 1 might be related to the inaccurate schematization of Point Lobos, where depth measurements near the steep cliffs and isolated sub- and supra-tidal rock platforms are absent. Nearshore bathymetric variability was clearly illustrated by the measurements at station 1 as these were truncated due to a buried instrument after six days in the summer campaign, and an ADCP deployed at this same site for the winter deployment was never recovered.

4.2. Wave model

Wave model validation focuses on a coherent dataset with wave observations from three wave buoys and a nearshore Nortek AWAC instrument (TV1) deployed offshore of Ocean Beach in 2008 (Fig. 5). As illustrated in Fig. 3, waves are signiﬁcantly modiﬁed in height and particularly direction as they propagate across the shelf to the nearshore. Wave sheltering by the Point Reyes headland for northerly directions prohibits most of the northerly waves (315°–360°) from reaching the NOAA SF buoy. The distinct west-southwesternly dominance at the CDIP SF Bar Buoy is linked to its location on the northern embankment of the dredged shipping channel in approximately 15 m of water (Fig. 5). As waves reach station TV1 off of Ocean Beach their direction is mostly fixed to a relatively narrow range by refraction around the SF Bar. Extensive SWAN wave model calibration using the 2005 and 2006 campaigns is described in Eshleman et al. (2007) and Barnard et al. (2007). The best agreement between modeled and observed wave conditions was found using the following settings: (1). The default JONSWAP bottom friction value for swell propagation of 0.038 m2/s3 (Hasselmann et al., 1973; Van Vledder et al., 2010). (2). Dissipation by whitecapping using the van der Westhuysen formulation (Van der Westhuysen, 2007). Wave heights within the surf zone were found to be sensitive to the specific method of dissipation implemented in the SWAN model. The best agreement between modeled and observed wave heights in the surf zone was obtained by applying the recently implemented bi-phase breaker model of van der Westhuysen (2010) with the default coefﬁcients. (3). Non-linear triad interaction using the Lumped Triad Approximation (LTA) following Eldeberky and Battjes (1996) was de-activated because of increased run times and poor performance at sites that feature narrow banded swell similar to the SF Bight (e.g. Gorrell et al., 2011). Thirty-seven frequency bins between 0.03 and 1 Hz were used along with 72 directional bins in full circle. (4). Convergence criteria were set to 99% of cells and maximum 50 iterations, to obtain full convergence for all wave cases.

As wave model validation, the coupled and calibrated wave and flow model was run over a two week time frame (19 January–1 February, 2008) using time varying full two-dimensional spectra at the CDIP Point Reyes buoy as forcing. During the selected time frame coherent measurements for all instrument locations over a wide range of representative forcing conditions were present. Fig. 7 summarizes the validation results. Highest model skills were obtained at Point Reyes as this station is used as boundary forcing, and in the nearshore area of interest (TV1, Fig. 5). The largest deviations at Point Reyes correspond to southerly wave conditions. For these wave conditions implementing the Point Reyes spectra as boundary forcing is not accurate due to the orientation of the grid and possible sheltering and refraction by the Farallon islands. Model skill is lowest (0.86) at the SF Bar Buoy, likely because of the buoys location on the flank of the shipping channel which is not fully resolved in the model. This discrepancy is consistent with lower flow skill at this location. High model skill for the nearshore TV1 location indicates that wave sheltering and refraction on the ebb-tidal delta is modeled accurately.

5. Model schematization

Long term (multi-year) simulations would be needed to create representative sediment transport patterns over the complete range of forcing conditions. Such simulations are computationally unfeasible given the spatial extent of the model and resolution required in the areas of interest.
Input schematization techniques (De Vriend et al., 1993; Lesser, 2009) were used to schematize the wave and tidal boundary forcing. A representative single 24.8 h tidal cycle was derived from the calibrated constituents. Fourteen years (January 1997–December 2010) of hourly offshore buoy observations of significant wave height ($H_s$), peak period ($T_p$), and peak direction ($D_p$) at the Pt. Reyes Buoy were used to derive a set of 24 wave conditions that adequately represent the full climatology. Each of the 24 wave cases was then run over one representative tidal cycle with the coupled flow-wave model.

The complete wave record was binned in 1 m wave height increments and 25° directional bins. Swell and wind sea were separated using a 12 s cut off value for $T_p$ (as suggested by Bromirski et al., 2005). This cut off value approximately divides the complete wave record in half (54% sea, 46% swell). To optimally fit data density, wind waves were binned between 0.75 and 3.75 m, while the limits for swell waves are between 1 and 4 m. An additional 3.75–5.75 and 4–6 m bins for wind waves and swell respectively capture the large wave events. Peak directions for both classes vary between 180° to 330° (nautical convention). From the resultant 48 entries, representing 93.1% of the total probability, the 24 most probable wave cases, representing 89% of the total probability, were selected. The parametric wave statistics for each of the wave cases were converted by SWAN to JONSWAP spectra and used as boundary input (Table 3).

Tides were schematized by reducing a typical full monthly spring/neap tidal cycle into a morphologically representative 24.8 h tidal cycle.

![Fig. 7. Comparison of modeled and observed significant wave heights at (a) Point Reyes, (b) NOAA SF Buoy, (c) SF Bar buoy, and (d) the nearshore TV1.](image)

**Table 3**

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<th>Case number</th>
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<th>$T_p$ (s)</th>
<th>$D_p$ (°)</th>
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following Lesser (2009). The representative tidal cycle is a combination of the $M_2$, $K_1$, and $O_1$ tidal constituents with a 1.07 enhancement factor. The enhancement factor is based on the complete set of observed tidal constituents from the NOAA SF tide gauge and is required to increase the magnitude of the tidal signal because only three constituents are used in the representative tide. Since the representative tide roughly equals 1.1 times the mean tide the absolute peak velocities are underestimated in the model. During spring, the ebb velocities in the Golden Gate can reach 2.5 m/s, while the representative tide produces 2.0 m/s. Sensitivity testing for simulations for spring, neap, and the representative tide showed that both the residual flow and sediment transport patterns are similar in the area of interest. The wave-averaged sediment transports are obtained by running the coupled wave flow model for each of the 24 wave cases over one representative tidal cycle. The tide-averaged velocity and sediment transport for each simulation was weighted by the normalized probability of occurrence for each wave case. The probability weighted results were then summed to generate an ensemble of all 24 wave cases. These results were also compared to a tide only simulation to determine the impact of the waves on the flow and sediment transport.

It is important to realize that the model in its present form provides estimates of the sediment transport potential; we do not allow morphological updating. Without quantitative comparison of measured and modeled sediment fluxes it is difficult to assess the model validity in terms of sediment transport rates. The main uncertainties are the use of a single grain size fraction that is uniformly available through the domain (processes of sediment sorting and bed armoring are not accounted for). Secondly, the assumption of unlimited sediment supply (with the exception of well-known rock headlands, outcrops and cliffs). The implications of these assumptions are especially relevant for the sediment transports at the Golden Gate, where the channel is deeply embedded in bedrock, and thus extremely sediment limited. For quantitative predictions we would need an accurate schematization of the sediment gradation and bed stratigraphy, and rigorous validation.

6. Model results

In the throat of the Golden Gate inlet (between the Golden Gate Bridge and Pt. Bonita–Pt. Lobos) the residual sediment transport is nearly identical between the simulation with tides alone and the ensemble of all 24 wave cases (Fig. 8a–b). During high waves, such as wave cases 9 and 24, sediment can bypass the northern boundary of Ocean Beach, Pt. Lobos, and enter the inlet circulation (Fig. 8c and d). However, these wave cases have relatively low probability (Table 3) and thus do not greatly influence the ensemble of all 24 wave cases. The difference in total summed residual sediment transport when waves are added is less than 10% compared to the tide only case (Fig. 9c).

The most prominent feature in the residual transport patterns is the distinct lateral segregation in large ebb-dominant sediment transport (and flow) along the deeper north side of the Golden Gate channel, and smaller flood dominant transport along the shallow southern margin (Fig. 10). The distinct ebb dominant transport is linked to: (1) velocity asymmetry between the larger ebb than flood flow, and (2) ebb outflow concentrates along the northern margin of the inlet, while flood inflow is most pronounced along the southern margin (Fig. 11). Ebb outflow from the bay increases towards a maximum in the narrow Golden Gate cross-section (approximately 2 m/s) and retains high velocities in the entire Golden Gate channel before dispersing on the ebb-tidal delta (Fig. 11a). Ebb flow concentrates along the central/northern margin of the inlet. During flood a similar but opposite pattern occurs on the landward (western) site of the Golden Gate (Fig. 11b). The flood flow and sediment transport seaward of the Golden Gate, with the exception of local flow acceleration at the tips of Pt. Lobos and Pt. Bonita, are typically smaller than the ebb (Fig. 11d). Flood is most pronounced along the southern margin of the inlet.

Residual flow and sediment transport is most pronounced along the southern coastline, but limited in the central part of the channel (Fig. 11c). The flood dominated transports along Baker Beach result from an ebb eddy trapped behind the Golden Gate headland (Fort Pt.) during most of the ebbing tide. This eddy is advected seaward during the transition to flood and modifies the net circulation introducing a larger flood-dominant (bay directed) residual flow along the southern margin of the inlet compared to the Golden Gate channel. Sediment recirculation from the ebb-jet into the nearshore area (Baker Beach), in combination with sediment bypassing at Pt. Lobos during high wave events, might explain the presence of this shallow shoal area and the stability of the adjacent beaches.

On the San Francisco Bar, sediment is transported by a combination of both waves and tides (Fig. 8b and c–f). The ensemble of all 24 wave cases shows a distinct difference between transport on the northern and southern lobes of the San Francisco Bar (Fig. 8b). Sediment recirculation dominates sediment transport on the northern lobe; while on the southern lobe waves mainly augment the seaward and southward transport onto and over the ebb-delta platform. This difference partly results from the larger tidal flow and from the lower wave energy dissipation rates.

The tidal ebb jet transports sediments onto the shallow Four Fathom Bank (see Fig. 1 for location). This transport is enhanced by waves as increased bed stress by shoaling and wave breaking during storm suspends additional sediment that is then advected by the tidal flow. Along the northern lobe of the shoal (depth $< 10$ m), the larger wave events (Hs $> 4$ m) can contribute directly to landward sediment transports through wave-breaking, and the associated wave-driven currents and sediment transports (Fig. 8c, d). Largest sediment transports correspond to the shallowest areas which are the areas of most intense wave dissipation. These landward transported sediments are redirected along the Marin coast towards the inlet through the marginal flood channel. Even during extreme wave events only little sediment bypasses Pt. Bonita on the southern side of the inlet into the Golden Gate channel. The major part of the sediments are recirculated at the tip of Pt. Bonita back onto the ebb-tidal delta.

On the southern lobe of the ebb-tidal delta wave energy dissipation is lower primarily due to the greater depths compared to the northern lobe and wave refraction (Fig. 9a, b). Wave energy dissipation is largest along Ocean Beach with features a wide surf zone, and pronounced non-uniformity in wave heights (Fig. 9a, b). The spatial wave variability is partly driven by larger-scale variations in wave height as the Farallon Islands and Point Reyes provide wave-sheltering (Esplenier et al., 2007), and further augmented by local wave refraction on top of the ebb-tidal delta. As a result a wave focal zone develops at Northing km 4178, and wave heights on either side of the focal area decrease. The alongshore variability is reflected in the complex patterns of sediment divergence and convergence observed along Ocean Beach (Fig. 8c, d). The competing contributions of northward wave generated currents and southward tidal flow results in strong, local horizontal shear of the velocities and transports. At the north end of Ocean Beach the residual flow pattern switches direction between the shoreline and 10 m depth. On the ebb-tidal delta tide-driven flow is to the south. Inshore of 5 m depth, flow is wave-driven and to the north. At the northern end of Ocean Beach, net northward littoral drift captured behind the Pt. Lobos rock outcrop plausibly explains the wide beach observed for the northern 1.5 km of Ocean Beach (Hansen and Barnard, 2010).

7. Discussion

The coupled flow and wave model predicts highly spatially variable flow and sediment transport patterns at the mouth of San Francisco Bay and along the adjacent open coast. In the Golden Gate Channel the distinct variation in lateral and residual flow distributions and magnitude seem to correspond, at least qualitatively, to reported field observations (Stacey and Thomas, 2005; Fram et al., 2007). An important feature of the flow, relevant for sediment transport on the open coast, is the relative
confinement of the ebb to a narrow jet. The distinctively larger (peak) ebb than flood governs the ebb-dominant sediment transport in the Golden Gate channel. Additionally, the dominant ebb leads to recirculation eddies that form at the tips of the headlands at the Golden Gate, Pt. Bonita and Pt. Lobos. Thus, the flow is mostly directed in the same direction during both the flood and ebb. Sediment recirculation limits the transfer from the ebb-tidal delta to the inlet and has significant implications for transport processes at the north end of Ocean Beach. The persistent presence of an ebb eddy at the Golden Gate headland leads to a small flood dominant flow along Baker Beach and might explain the stability of this beach and shoal complex.

Various studies show the direct link between bedform morphology (viz. size and orientation of ripples), and tidal dominance and flow magnitude (Boothroyd and Hubbard, 1975; Rubin and McCulloch, 1980; Ashley, 1990). Assuming that the bedforms are created by and in equilibrium with present-day hydrodynamic conditions, the bedform distribution, arrangement and morphology provides information about bottom currents and associated sediment transports. Qualitatively the distinct lateral variation in sediment transport rates and direction corresponds to the observed bedform asymmetry (Fig. 10) which suggests that the model is well replicating the transport patterns. The largest bedforms just west of the Golden Gate (up to 10 m in height) have a

Fig. 8. Modeled residual sediment transport patterns for a simulation with: (a) tides only, (b) tides and waves (ensemble average of the 24 wave cases). Bottom panels illustrate the residual sediment transports for dominant wave cases 9 and 24 (c and d respectively).
pronounced ebb-asymmetry. These bedforms occur where the model predicts the strongest ebb. Smaller bed-forms (<20 m wavelength) are found in the far field where ebb jet velocities dissipate, and along the southern margins of the inlet (flood-dominant). The residual transport patterns with distinct segregation in ebb-dominant sediment transport and flow along the deeper northern side, and smaller (near-zero) flood dominant flow along the southern part, correspond well with these observations, providing confidence in the model results.

The conceptual sediment transport model posted by Battalio et al. (1996) suggests significant bypassing of sediment around Pt. Lobos into San Francisco Bay. Based on the model results presented in this study it is found that sediment transport from the ebb-tidal delta towards the bay is limited. The main reasons for this difference are: firstly the model predicts large sediment gyres at the tips of Pt. Lobos and Pt. Bonita (Fig. 8). These gyres indicate that on either side of the inlet most of the bayward directed transport is picked up by the dominant ebb currents and transported back onto the ebb-tidal delta. Significant sediment bypassing of Pt. Lobos is only observed during large waves (Hs > 4 m) from directions between south and west. These larger wave cases however have a low probability of occurrence. Secondly, the distinctively larger tide-dominated residual sediment export within the inlet is likely to limit the transfer of wave-driven sediments from the ebb-tidal delta to the basin.

The observed loss of sediments from the San Francisco Bar (Hanes and Barnard, 2007; Dallas and Barnard, 2011) might be attributed to offshore losses. Although in need of additional research, an interesting observation is the offshore loss of sediments during extreme conditions. During these conditions wave breaking on the outer fringes of the delta leads to elevated water levels over the delta that cause flow and sediment divergence from the delta. The ~16 m depth dredged ship channel through the center of the delta provides a natural escape for the elevated water levels on both the northern and southern lobes.
of the delta that occur during large wave conditions. As such, the model predicts relatively large offshore directed sediment transports through the ship channel during large wave conditions (Fig. 8c and d).

Modification of the wave climate by the ebb-tidal delta plays a dominant role on the development of the adjacent coastlines. Typically, at tidal inlets the ebb-delta’s shelter the adjacent coasts from wave-energy. At the San Francisco Bar however, wave refraction on the southern lobe of the ebb delta results in a wave focal point and shadow zones on either side. The alongshore variability in wave height distribution creates a complex alongshore pattern of local flow acceleration and deceleration. The associated convergence and divergence of sediment transport might explain the observed hot-spot erosional patterns.

In this paper we did not resolve the full morphodynamic behavior of the system, but instead we used the numerically computed “potential” sediment transport. The potential sediment transport was derived by coupling a calibrated (high-resolution) flow model to a transport formula (no morphologic change). Input schematization techniques were used to construct representative estimates of the tidal and wave forcing, thus allowing the long-term forcing time series for tides and waves to be compressed into a limited set of representative forcing conditions. Analysis of the transport potential provides us with knowledge of the dominant sediment transport processes and mechanisms. This knowledge is a first essential step for understanding the morphodynamic behavior of a system, and for

Fig. 10. Modeled residual tide-driven sediment transport patterns at the mouth of the Golden Gate overlain on a high-resolution rendering of the bedform morphology.

Fig. 11. Overview of the modeled tidal flow velocities for: (a) maximum ebb flow, (b) maximum flood flow, and (c) residual flow pattern. The lower right panel (d) illustrates the ratio between maximum ebb and flood currents. Ratio < 1: ebb flow is smaller than the flood flow. Ratio = 1: max ebb flow equals max flood flow. Ratio > 1: ebb flow exceeds the flood flow.
future morphodynamic modeling. This step is often not made (stay with the flow) or overlooked (jump into long term modeling). The method presented in this study is widely applicable. The model validation presented in this study showed that the present-day flow models can resolve the hydrodynamics accurately using near-default settings. Standard techniques of wave and tide input reductions are applied to obtain schematized input series. As nowadays many of the inhabited coastal systems have measurements of flow and waves available, these measurements can be used for the input schematization, model calibration and model validation.

The SF Bay model provides a test lab to test the sensitivity of the sediment transport (patterns and magnitudes) to changes in forcing. Effects of changes in wave climate, sea-level rise or human intervention (dredging) can easily be addressed. The ultimate goal of SF Bay model is to expand the simulations to include the full morphodynamic behavior. This requires development of both the model numerics (parallelization and optimization of the code to increase runtime), model formulations (bed slope effects) and schematization techniques to correctly represent sediment composition and bed stratigraphy.

8. Conclusions

A coupled Delft3D–SWAN hydrodynamic, wave and sediment transport model was used to understand the sediment transport patterns and dominant processes between San Francisco Bay, the Golden Gate, and the adjacent open coast. Particularly we investigated the relative importance of waves versus tide in different parts of the inlet and ebb-tidal delta. By using representative estimates of the tidal and wave forcing, annual sediment transport predictions are possible on high spatial grid resolution. The full morphodynamics were not resolved but numerically computed potential sediment transport (no morphologic change allowed in the model) was used to understand the patterns of sediment transport and dominant processes in the SF Bay coastal system. This knowledge is a first essential step for understanding the morphodynamic behavior of a system, and for future morphodynamic modeling.

A dominant feature for the sediment transports in the SF Bay Coastal System is the pronounced tidal ebb jet that results from convergence and flow acceleration through the Golden Gate. High velocities carry sediments well outside the Golden Gate forming the ebb-tidal delta. Ebb-dominant sediment transport prevails in the Golden Gate due to tidal velocity asymmetry of larger peak ebb than peak flood flow. The presence of a recirculation eddy likely explains the presence of relatively stable beaches along the southern portion of the Golden Gate. Waves redistribute the sediments on the ebb-tidal delta. Sediment gyres at the tips of the adjacent headlands redirect inlet directed sediment transports back towards the ebb-delta, mostly preventing sediment from the adjacent coastline from reaching the inlet. During large wave events, breaking on the outer reaches of the ebb-tidal delta can lead to large seaward fluxes of sediment, elevated water levels and divergence of the sediment entrained from wave motions. Along Ocean Beach alongshore variability in the wave height distribution associated with the formation of a wave focal point might explain the observed hot-spot erosional patterns.

Acknowledgments

This work and funding was made possible through a Collaborative Research Agreement between the U.S. Geological Survey Coastal Marine and Geology Program and Deltarop (Netherlands). Additional funding and support was provided by the U.S. Army Corps of Engineers (San Francisco District). Li Erikson, Patrick Barnard and Dan Hanes help in providing data, and their discussions, insights and interpretations of data and model results are greatly appreciated.

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