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

Edwin P.L. Elias [a,*], Jeff E. Hansen [a,b]

[a] U.S. Geological Survey, Pacific Coastal Marine Science Center, 400 Natural Bridges Drive, Santa Cruz, CA 95062, USA
[b] University of California Santa Cruz, Department of Earth and Planetary Sciences, 1156 High St., Santa Cruz, CA 95064, USA

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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 climatologically 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.

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 embayment's (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 m^3 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

* Corresponding author at: Deltares, P.O. Box 177, 2600 MH Delft, Rotterdamseweg 185, 2629DH Delft, Netherlands. Tel.: +31 88 335 8273; fax: +31 883358582.
E-mail addresses: Edwin.elias@deltares.nl (E.P.L. Elias), Jeff_hansen@usgs.gov (J.E. Hansen).

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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 km^2 watershed to the sea. Bordered 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 levies, 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 (~2×10^9 m^3) 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 km^2 SF Bar has an average depth

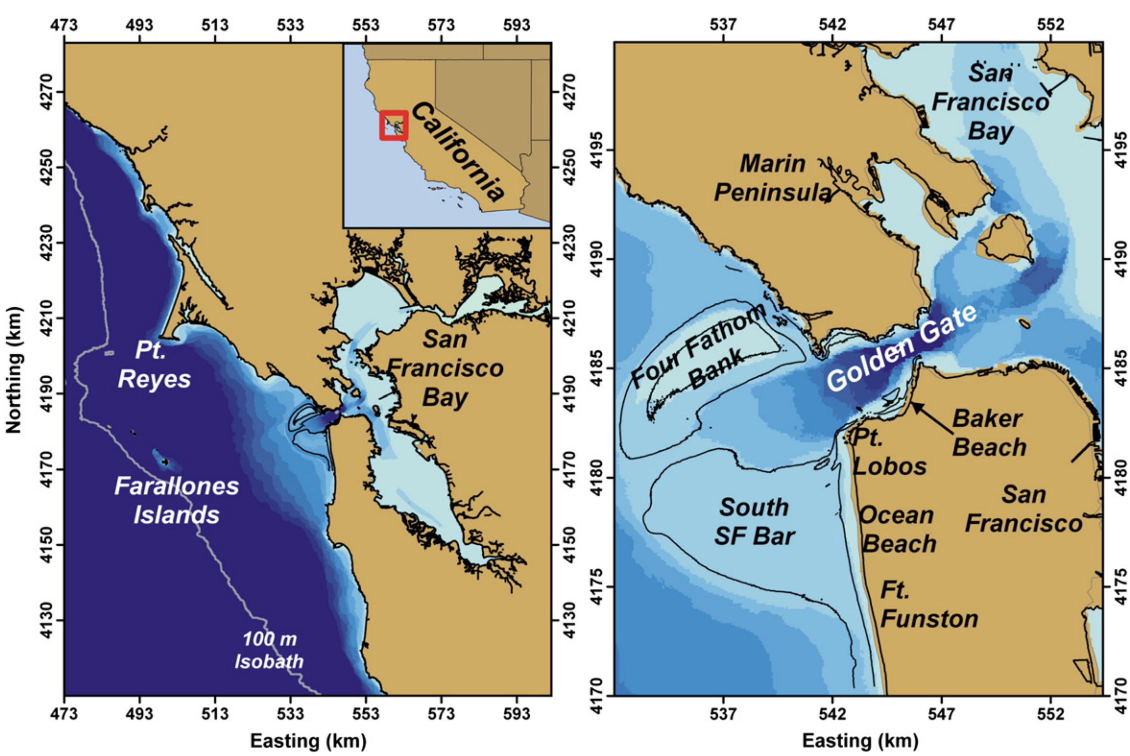

Fig. 1. Left: location plot of San Francisco Bay or bay area. Right: details of the San Francisco Bay coastal system consisting of Golden Gate, San Francisco Bar, and beaches along the Marin Peninsula and San Francisco.