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The use of modeling and suspended sediment concentration measurements for quantifying net suspended sediment transport through a large tidally dominated inlet

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ABSTRACT

Sediment exchange at large energetic inlets is often difficult to quantify due complex flows, massive amounts of water and sediment exchange, and environmental conditions limiting long-term data collection. In an effort to better quantify such exchange this study investigated the use of suspended sediment concentrations (SSC) measured at an offsite location as a surrogate for sediment exchange at the tidally dominated Golden Gate inlet in San Francisco, CA. A numerical model was calibrated and validated against water and suspended sediment flux measured during a spring–neap tide cycle across the Golden Gate. The model was then run for five months and net exchange was calculated on a tidal time-scale and compared to SSC measurements at the Alcatraz monitoring site located in Central San Francisco Bay ~5 km from the Golden Gate. Numerically modeled tide averaged flux across the Golden Gate compared well ($r^2 = 0.86$, p-value <0.05) with 25 h low-pass filtered (tide averaged) SSCs measured at Alcatraz over the five month simulation period (January through April 2008). This formed a basis for the development of a simple equation relating the advective flux at Alcatraz with suspended sediment flux across the Golden Gate. Utilization of the equation with all available Alcatraz SSC data resulted in an average export rate of 1.2 Mt/yr during water years 2004 through 2010. While the rate is comparable to estimated suspended sediment inflow rates from sources within the Bay over the same time period (McKee et al., 2013-this issue), there was little variation from year to year. Exports were computed to be greatest during the wettest water year analyzed but only marginally so.

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1. Introduction

Large tidal estuaries located at the interface between rivers and the ocean provide a wealth of natural resources and are often an economic hub in many parts of the world. A quantitative understanding of sediment delivered to, stored within, and exported from an estuary is important for a number of issues including maintenance dredging of navigation channels, sand mining, light availability for primary productivity, creation and sustainability of tidal wetlands, and the transport of particle-bound nutrients and contaminants (Teeter et al., 1996; Zedler and Callaway, 2001). Although an estuary provides a readily definable control volume where point sources and sinks exist in the form of rivers and the open ocean, it is difficult to determine sediment influx to the system and net flux at the estuary–ocean boundary. This is particularly true for large tidal inlets in regions of modest to high tide ranges where it is not physically or economically feasible to continuously monitor sediment flux, and exchange is complicated by variations in bathymetry, topography, and density driven flows.

San Francisco Bay is the largest estuary on the U.S. West Coast (Conomos et al., 1985), with an aerial extent of 1200 km^2 and is one example where these issues arise. Sediment exchange between the Bay and Pacific Ocean, which occurs across the >1.5 km wide tidally dominated Golden Gate inlet, is the least well characterized component of the of the sediment budget. On the basis of conservation of mass, net suspended sediment flux through the Golden Gate has been inferred by accounting of sediment inflows to the Bay and change in sediment storage within the Bay (Ogden Beeman and Associates, 1992; Schoellhamer et al., 2005). Net suspended sediment flux was consistently shown to be seaward with net annual rates decreasing from 5 Mt/yr (million metric tons per year) during the 1990–1995 period to 4.2 Mt/yr for years 1995–2002 (Schoellhamer et al., 2005). Inferences of flux through the Gate can also be made from measurements of water discharge and salinity as a surrogate for scalar components obtained by Fram et al. (2007) and Martin et al. (2007). In that

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study, a series of transects across the Golden Gate were made with a boat-mounted ADCP and a suite of towed instruments. The results showed that both density gradients and bathymetry influence ocean–estuary exchange and that overall, exchange of salinity was far less than prior studies had shown (Parker et al., 1972; Largier, 1996). From the measurements they determined that chlorophyll flux was dominated by tidal pumping, accounting for 64–93% of the net dispersive flux. Similar to the sediment budget studies, net advective flux was shown to be seaward.

Efforts directly aimed at quantifying suspended flux through the Golden Gate were done with the use of numerical model simulations to define sediment transport pathways and in situ measurements for estimation of total net suspended flux over two weeks (Hauck et al., 1990; Teeter et al., 1996). Annual net flux was extrapolated from the two-week measurement campaign encompassing a neap–spring cycle coincident with low freshwater input to the Bay. A shortcoming of that approach is that extrapolating the results to encompass much longer time-periods neglects variations in seasonal patterns of sediment delivery and changing hydrology in response to freshwater inputs and annual tide cycle deviations. In this study, the approach of Teeter et al. is expanded upon and the use of measured suspended-sediment concentrations, along with a simple tidal current model is investigated as means of estimating the suspended sediment flux through the Golden Gate. The use of surrogates to quantify sediment flux through estuarine channels has been done previously for smaller and less energetic embayments (Ganju and Schoellhamer, 2006), but not for large estuaries such as San Francisco Bay. To account for the large geographic scope of San Francisco Bay and high-energy exchange through the Golden Gate, a numerical model simulating sediment transport in the Bay–ocean system was calibrated against measured suspended sediment flux across the inlet. The calibrated and validated model was run for a five month time-period coincident with available suspended sediment concentration (SSC) measurements recorded at Alcatraz Island. Simulation results were then used to derive an equation relating measurements at the Alcatraz monitoring station along with the influence of upstream freshwater loading and sediment flux through the Golden Gate.

The remainder of this paper describes the study site, outlines the data and methods employed, presents the results, and concludes with a discussion and conclusion. In the results section, measurements obtained at the Golden Gate are first presented in order to highlight the variability of water and sediment flux across the channel. Numerical model results are then compared to the flux measurements at the Gate and used to explain some of the variability noted in the observations. The third and final results sub-section presents SSC values from the continuous Alcatraz monitoring station, a model for estimation of currents at Alcatraz, and the equation relating Alcatraz SSC and currents to suspended flux at the Golden Gate.

2. Study site

The San Francisco Bay Coastal System is a complex coastal–estuarine system, with often highly energetic physical forcing, including spatially and temporally variable wave, tidal current, wind, and fluvial forcing. The open coast at the mouth of San Francisco Bay is exposed to swell from almost the entire Pacific Ocean, with annual maximum offshore significant wave heights (h_s) typically exceeding 8.0 m, and mean annual $h_s = 2.5$ m (Scripps Institution of Oceanography, 2012). Inside the Bay, wave forcing is less important, except on shallow Bay margins where local wind-driven waves, and occasionally open ocean swell can induce significant turbulence and sediment transport (Talke and Stacey, 2003).

Tides at Fort Point (NOAA/Co-ops station 9414290) are mixed, semi-diurnal, with a maximum tidal range of 1.78 m (MLLW–MHHW, 1983–2001 Tidal Epoch). Due to the large volume of the Bay (spring tidal prism of 2×10^9 m^3) currents are strong at the Golden Gate constriction where peak ebb tidal velocities exceed 2.5 m/s and peak flood currents reach 2 m/s (Rubin and McCulloch, 1979; Barnard, 2007). The strongest tidal currents throughout the other sub-embayments are focused in the main tidal channels. Though far less dominant physical forcing mechanisms compared to tidal forcing, which causes most of the estuarine mixing (Cheng and Smith, 1998), gravitational circulation and freshwater input (1% of the daily tidal flow, ~19% during record flow) are occasionally important during strong stratification events, with the effects most pronounced in the sub-embayments most distal from the inlet mouth (Monosmith et al., 2002).

Freshwater discharge into the Bay is predominantly from the Central Valley watershed, fed through San Joaquin–Sacramento Delta, which enters the Bay at Mallard Island (Figs. 1 and 2B) and historically supplied 83–86% of the fluvial sediments that enter the Bay (Conomos, 1979; Porterfield, 1980; Smith, 1987). Inputs from the Delta are controlled by water operations and reservoir releases, which are strictly managed during the low-flow season (~May–November) to keep the 2-psu isohaline seaward of the Delta. During wet winters, turbid water plumes from the Central Valley watershed have extended into South Bay (Carlson and McCulloch, 1974) and out past the Golden Gate (Ruhl et al., 2001).

The majority of sediment delivered to the Bay has historically been from the Delta (Porterfield, 1980), with nearly all (87–99%) of it in suspension (Schoellhamer et al., 2005; Wright and Schoellhamer, 2005). In recent years, suspended sediment loads from the Delta have diminished in response to ceased hydraulic mining of the 19th Century and other factors (Wright and Schoellhamer, 2004; Singer and James, 2008; McKee et al., 2013-this issue) causing the relative importance of loads from the small 250+ local tributaries to increase. These local watersheds may now account for ~61% of the total suspended load entering San Francisco Bay (McKee et al., 2013-this issue), but are typically episodic such that 90% of the total annual sediment load is released during only a few days (Kroll, 1975; McKee et al., 2006).

San Francisco Bay sediment consists primarily of silts and clays in South, San Pablo, and Suisun Bays and the shallow waters of Central Bay (Fig. 1), while sands dominate in the deeper parts of Central, San Pablo and Suisun Bays and in Carquinez Strait (Conomos and Peterson, 1977). Sediment grain sizes range from 2 μm to 430 μm in the northern embayments (Locke, 1971; Jaffe et al., 2007), from 62 μm to 350 μm in Central Bay (Chin et al., 2010; Barnard et al., 2011), and are on the order of 290 μm at the open coast (Barnard et al., 2007). Due to strong tidal currents, the 113 m deep channel floor at the Golden Gate is void of sediment with exposed bedrock.

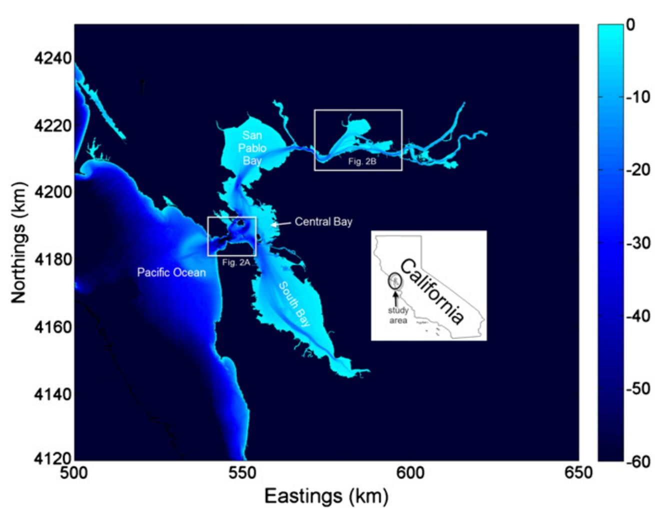

Fig. 1. Site study map showing San Francisco Bay, North and Central Bays, and the Sacramento/San Joaquin Rivers (Delta).