Marine Geology 345 (2013) 235–253

Contents lists available at ScienceDirect

Marine Geology

journal homepage: www.elsevier.com/locate/margeo

Simulating sediment transport processes in San Pablo Bay using coupled hydrodynamic, wave, and sediment transport models

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ARTICLE INFO

Article history:
Received 30 March 2012
Received in revised form 6 June 2013
Accepted 15 June 2013
Available online 26 June 2013

Keywords:
San Francisco Bay
San Pablo Bay
sediment transport
numerical modeling
channel and shoals
shallow water

ABSTRACT

San Pablo Bay is a tidal sub-embayment of the San Francisco Estuary which is dominated by broad shallow shoals bisected by a deep channel. Under the conceptual model of sediment transport in San Pablo Bay proposed by Krone (1979), sediment typically enters San Pablo Bay during large winter and spring flows and is redistributed during summer conditions through wind wave resuspension and transport by tidal currents. Numerical simulations of sediment resuspension due to wind waves and the subsequent transport of this sediment by tidal currents show that sediment concentrations and fluxes throughout the channel–shoal system result from a complex temporal and spatial interaction of the waves and tides. The three-dimensional UnTRIM San Francisco Bay-Delta Model was coupled with the Simulating WAves Nearshore (SWAN) wave model and the SediMorph morphological model, to develop a three-dimensional (3D) hydrodynamic, wind wave, and sediment transport model of San Francisco Bay and the Sacramento–San Joaquin Delta. The coupled model was validated using water level, velocity, wind waves and suspended sediment data collected in San Pablo Bay, and then used to quantify the spatial and temporal variability of sediment fluxes on the extensive shoals in San Pablo Bay under a range of tidal and wind conditions. The model validation shows this modeling system can accurately predict hydrodynamics, waves, and suspended sediment concentration in San Pablo Bay. The predicted bottom orbital velocities are elevated across the shoals during large wave events regardless of tidal stage, but near low tide orbital velocities are increased even under low to moderate waves. Sediment fluxes between the shoals and the deeper channel are highest during spring tides, and are elevated for up to a week following wave events, even though the greatest influence of the wave event occurs abruptly.

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1. Introduction

Within San Francisco Bay, tidal flats and shallow water areas (less than ~4 m) provide extensive habitat for birds, fish, and crustaceans (Nichols and Pamatmat, 1988; Galbraith et al., 2002) and attenuate waves protecting the shoreline from erosion (Lacy and Hoover, 2011). Traditionally, high winter freshwater flows supplied sediment to San Francisco Bay, where it deposited on these mudflats and shallows (Krone, 1979). Tidal and wave reworking eventually exported the sediment to the Pacific Ocean or moved the sediment to a location of long-term accumulation. Over the last 50 years, however, the sediment supply to San Francisco Bay has decreased due to relict hydraulic mining debris having completely moved through the system (Schoellhamer, 2011). A reduction in sediment supply coupled with 0.2 to 0.5 m of predicted sea level rise over the next 100 years (Bindoff et al., 2007; Cayan et al., 2008) make shallow water areas within the Bay particularly vulnerable to inundation and erosion. As such, a detailed understanding of the processes driving sediment fluxes onto or off of shallow water areas is critical to helping determine how well these areas may keep up with future sea level rise.

Recent observations within San Pablo Bay, a sub-embayment of San Francisco Bay composed of a narrow deep channel and extensive shoals and mudflats, show wind wave induced sediment resuspension and sediment fluxes are intricately tied to the tidal water level and current direction during wave events (Schoellhamer et al., 2008b). Schoellhamer et al. (2008b) also determined that the directions of residual sediment fluxes were different during spring and neap tides at a location on the northern flank of the channel. These data suggest the sediment that fluxes onto and off of the shoals is potentially a complex interaction of not only the tidal currents, wind waves, and sediment bed, but also the timing of the waves in relation to the tidal water level and current direction, all of which may vary spatially within San Pablo Bay.

Although Schoellhamer et al. (2008b) give valuable insight into the processes driving the suspension and transport of sediment, the data only provide information at a few points. A detailed hydrodynamic, sediment transport, and wind wave modeling framework is ideal for investigating the physical processes driving suspended sediment concentrations and fluxes throughout San Pablo Bay. This study uses coupled hydrodynamic, sediment transport, and wave models to

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0025-3227/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.margeo.2013.06.012

investigate sediment transport within San Pablo Bay. The main objectives are to: 1) evaluate how the timing of strong wind waves with varying tidal stage drives suspended sediment concentration throughout the San Pablo Bay shoals and 2) determine how different tidal and wave conditions transport sediment between the deep channel region and the shallow shoals.

2. Background

Barnard et al. (2013a) present detailed background information on San Francisco Bay. This section presents a brief overview of the estuarine transport processes evaluated in this study and how they relate to the longer-term sediment dynamics observed in San Pablo Bay.

2.1. Estuarine sediment transport

Current and wave induced resuspension, aggregation/disaggregation processes, and sediment trapping at estuarine turbidity maximum dominate sediment transport dynamics in estuaries. Waves and currents interact nonlinearly to create stresses on the seabed (e.g., Grant and Madsen, 1979). Once the bed shear stress exceeds the sediment's critical shear stress for erosion, sediment is suspended from the seabed and transported by ambient currents (Miller and Komar, 1973; Hill and McCave, 2001). In many estuaries tidal currents are the single most important process that causes sediment resuspension and transport (e.g., Ruhl and Schoellhamer, 2004; Friedrichs, 2009). The flocculation of sediment particles within estuaries is a major factor in the settling and deposition of sediment on the seabed (see reviews by van Leussen, 1988 and Hill, 1998).

When freshwater and saltwater mix within an embayment, the water column is stratified and baroclinic pressure gradients drive a near bed flow up estuary, while the surface fresher water flows down estuary (Chatwin, 1976; Hetland and Geyer, 2004). Sediment is preferentially transported up estuary near the bed creating turbidity maxima in regions where stratification breaks down, at the landward extent of the salt intrusion where currents converge, or at bathymetric sills (Geyer, 1993; Lin and Kuo, 2001; Schoellhamer, 2001). The seabed under a turbidity maximum is generally composed of unconsolidated fine sediment that is relatively easy to erode (Woodruff et al., 2001; Dickhudt et al., 2009).

Large expanses of shallow water in estuaries lead to reductions in wave height and current speed that can translate to varying sediment fluxes near the shoreline. For example, in Corte Madera Bay to the south of San Pablo Bay, Lacy and Hoover (2011) observed wave attenuation and a decrease in significant wave height toward shallower water, although the bottom orbital velocity remained constant. They also observed a decrease in the amplitude of spring tide currents from 0.8 to 0.1 m s^{-1} as the mean water depth decreased from about 6.0 m to 0.5 m mean lower low water (MLLW).

2.2. San Francisco Bay

San Francisco Bay is the largest estuary on the U.S. west coast, covering an area of about 4100 km^2. San Francisco Bay is composed of four distinct sub-embayments: Suisun Bay, San Pablo Bay, Central Bay, and South Bay (Fig. 1). Freshwater and sediment are supplied to San Francisco Bay from the Sacramento–San Joaquin Delta to the east and from local tributaries. Gravitational circulation and bathymetric sills create estuarine turbidity maxima in the San Pablo Bay and Suisun Bay regions (Schoellhamer, 2001). Readers are referred to Barnard et al. (2013a) for a detailed description of San Francisco Bay hydrodynamics and regional setting.

Historically, San Francisco Bay received tremendous amounts of sediment from hydraulic gold mine tailings that have been moving through the system since the late 1800s (Gilbert, 1917). Sediment is supplied to the bay by high river discharge during winter and deposits on the shallows, where it is later resuspended by waves and transported by tidal currents during the summer months (Krone, 1979). Over time, much of this sediment has accumulated in the sub-embayments of San Francisco Bay, increasing the extensive areas of shallow shoals in San

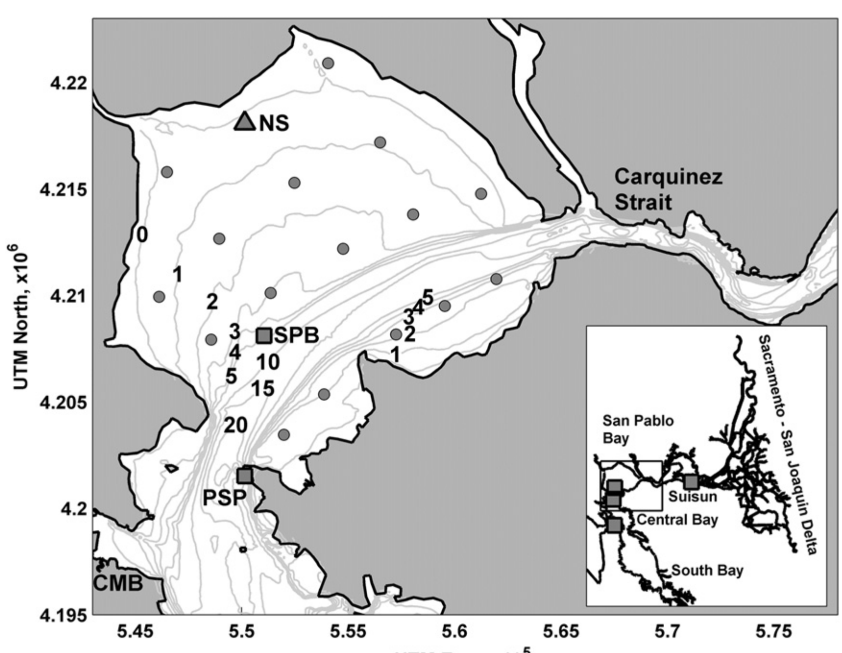

Fig. 1. San Pablo Bay and the UnTRIM San Francisco Bay-Delta model domain (inset), with the sub-embayments of the San Francisco Bay. The locations of the time-series stations (squares) used in the model validation and the locations used in the suspended sediment, wave, current, and water surface elevation correlation calculations (circles) are shown. The time-series stations (squares), from east to west on the inset, are Mallard Island, San Pablo Bay, Point San Pablo, and Alcatraz. The circles are also the locations where sediment flux is calculated. Water depth is contoured in meters below mean lower low water in one meter intervals to 5 m and 5 m intervals thereafter. The San Pablo Bay (SPB), North Shoals (NS), and Point San Pablo (PSP) locations are labeled. Corte Madera Bay (CMB) is also labeled.

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