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Water and sediment transport of channel-flat systems in a mesotidal mudflat: Willapa Bay, Washington

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ABSTRACT

The muddy tidal flats of southern Willapa Bay, Washington are tidally dominated and receive little direct freshwater input. We use data from instruments deployed in channels of different size and on their adjacent flats to investigate the hydrodynamics and sediment dynamics of each morphological setting under a range of seasonal and meteorological conditions, including rain and wind events. Interaction between the morphology of the channel/flat complex and tidal water-level variations produces well-defined velocity pulses during both flooding and ebbing tides. These pulses represent about 27% of the total along-channel water transport and 35% of the suspended-sediment transport of the system. Maintenance of continuity produces the velocity pulse, and pulse magnitude is determined by tidal range. Wind alters the flow regime in channels and on the flat, enhancing over-flat ebb flow in this study location while decreasing ebb-pulse intensity. Wind speed was positively correlated with minimum suspended-sediment concentration. Precipitation falling directly on flats was found to erode flat sediment, which subsequently formed a temporary deposit in the adjacent channel. Residual along-channel water transport in channels and on nearby flats was flood dominant under all seasonal conditions sampled, and sediment flux was flood dominant during winter and spring deployments.

1. Introduction and background

Intertidal flats are an important gateway for particles transported from terrestrial source to marine sink and are characterized by a network of channels that incise them. Tidal forcing is one of the strongest drivers of variability in tidal-flat systems. It modulates residual flows and circulation (e.g., Kjerfve, 1986), can control the relative magnitudes of peak velocity on flood and ebb (Fortunato and Oliveira, 2005), and modifies net sediment accumulation (Allen et al., 1980) in tidal flats and estuaries. Velocity in tidal channels often is flood dominated (i.e., greater peak flood velocity than ebb velocity; Postma, 1967) but the observed balance varies widely among study locations. For example, in the macrotidal Namyang Bay flats of western South Korea, which lack major river input, ebb speeds are 5–10% faster than flood speeds (Wells et al., 1990). Analytical modeling suggests that tidal flats generally enhance ebb velocity dominance when the flats are at mean sea level or above, whereas flood dominance is promoted by large tidal amplitudes and increased friction (Fortunato and Oliveira, 2005). Velocity dominance has also been related to the ratios of channel depths and widths at high and low tide (Friedrichs et al., 1992).

Landward, or upstream, transport of sediment is often observed in tidal environments (Postma, 1967; Pejrup, 1988; Christie et al., 1999; Le Hir et al., 2000) and is attributed variously to asymmetric tidal currents, settling lag, scour lag, and flocculation effects. Yet channels may also be net exporters of sediment. Studies in macrotidal flats (Wells et al., 1990) have observed channels to be conduits for offshore sediment dispersal during ebb tides. Events, including storms and increased riverine water and sediment input, are also recognized as important to the sedimentological and morphological dynamics of these systems (e.g., Anderson et al., 1981; O'Brien et al., 2000; Yang et al., 2005). Wind-generated waves associated with storms are effective in resuspending sediment in tidal-flat environments (Anderson et al., 1981; Sanford, 1994; Brand et al., 2010), and storms have been shown to be important remobilizers of tidal-flat sediments into channels (Wells et al., 1990; Yang et al., 2003). Waves also have been observed to temporarily change the sediment flux balance on tidal flats from flood dominance to ebb dominance (Christie et al., 1999; Dyer et al., 2000; Lee et al., 2004). Relevant event time scales range from days to seasons, and the onset of event influence can be rapid or gradual and have short- or long-term effects. For example, sediment resuspended by waves and precipitation may be stored within channels immediately but subsequently eroded over days to months after the event has passed (Yang et al., 2003).

Short-lived occurrences of elevated velocity, which we term pulses, have been observed in tidal creeks for decades (e.g.,

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Pestrong, 1965), and a specific study of the pulse as a phenomenon dates to as early as 1979 (Bayliss-Smith et al., 1979). The pulse is often framed using continuity arguments as water level crosses a marsh platform or tidal flat (Boon, 1975; French and Stoddart, 1992; Allen, 1994). Most published observations of the pulse have been made in salt marshes where it occurs at higher relative water depths than in lower-elevation tidal flats. Although the pulse may only occur in salt marshes on the greatest spring tides or during storm surges, it occurs with regularity in lower-elevation intertidal flats and is a more consistent feature in the flow regime.

Rain events in shallow-water environments have been shown to reduce the critical sediment erosion threshold (Green and Houk, 1980) and increase erosion rates, particularly in muddy sediments (Mwamba and Torres, 2002; Tolhurst et al., 2006; Pilditch et al., 2008). Bed shear stresses induced by direct (exposed surface) rainfall generally exceed the critical stress values for intertidal sediments and can be much larger than stress associated with waves and tidal forcing (Mwamba and Torres, 2002). Rainfall on exposed cohesive sediment has resulted in suspended-sediment concentration (SSC) values 2–100 times those observed without raindrop-induced sediment erosion (Mwamba and Torres, 2002).

In this paper we present water-column data collected over a period of 10 months on the tidal flats of southern Willapa Bay, Washington. We examine processes that transfer fine-grained sediment within and between the flats and the channels that incise them. We calculate the water and sediment fluxes of the system and examine the dynamics of short-lived velocity pulses that contribute significantly to the budget.

2. Study area

Willapa Bay is a bar-built estuary located in southwest Washington (Fig. 1), and is the first embayment north of the Columbia River mouth, covering an area of approximately 350 km^2. Extensive tidal flats are found in Willapa Bay, and 50% of the bay's surface area and volume are in the intertidal zone (Andrews, 1965). Willapa Bay has a mixed semidiurnal tidal regime with a mean daily tidal range of 2.7 m (Banas et al., 2004).

This study was undertaken on the muddy tidal flats of southern Willapa Bay, in an area known as Shoalwater Bay, which is approximately 4 km by 2.5 km in size. Most observations were made in the thalweg of a secondary – alternately inundated and exposed – channel known as "C channel" and on the adjacent flat to the north (Fig. 1). At the measurement location, C channel was approximately 15 m wide at bankfull and had a maximum depth of 1 m below the flat elevation. Maximum water depth above the channel bottom was more than 4 m during spring tides. Observations were also made in the larger, primary (always inundated) Bear channel. Near the study site, median sediment grain size corresponds to fine-to-medium silt, with representative distributions of 10–20% sand, 50–60% silt, and 30–40% clay (Boldt et al., 2013). Shoalwater Bay receives little direct riverine input. The Naselle River is the primary freshwater source for the southern portion of Willapa Bay, and it drains a portion of the coastal mountain range that forms the bay's eastern border. The Naselle represents 20% of the bay's total freshwater input (Banas et al., 2004), with an 80-year mean discharge of 12 m^3 s^{-1}, and its mouth is approximately 6 km northeast of the study site. The North and Willapa Rivers contribute most of the rest of the freshwater input and enter the bay near its northern end. The small Bear River is the closest freshwater source and seaward of its mouth forms Bear channel (Fig. 1). While presently unmonitored, the Bear River was gauged from 1963 to 1975, and regression of concurrent Bear River and Naselle River (which is currently monitored) discharge data indicates a linear relationship ($r^2 = 0.86$), with Bear River discharge about 17% of Naselle River discharge. Using this relationship, the Bear River contributes about 3% of the total freshwater input to Willapa Bay. River input to Willapa Bay is strongly seasonal, with winter discharge approximately two orders of magnitude greater than summer discharge.

Circulation in Shoalwater Bay is tidally driven, with significant spring–neap variations in tidal amplitude. Salinity is variable and depends primarily on freshwater input, generally ranging from 15–21 PSU during winter and 21–28 PSU during summer (Boldt et al., 2013). Stratification in channels during the winter and spring is moderate, with a salinity range of approximately 4 PSU between near-surface and near-bed waters. During the summer, the water column is well-mixed and stratification is minimal. Modeling studies indicate that circulation within the central and northern parts of Willapa Bay is influenced by river discharge, although these effects are less important in Shoalwater Bay (Banas and Hickey, 2005).

The regional climate of southwest Washington is characterized by dry summers and mild, wet winters. Precipitation measures

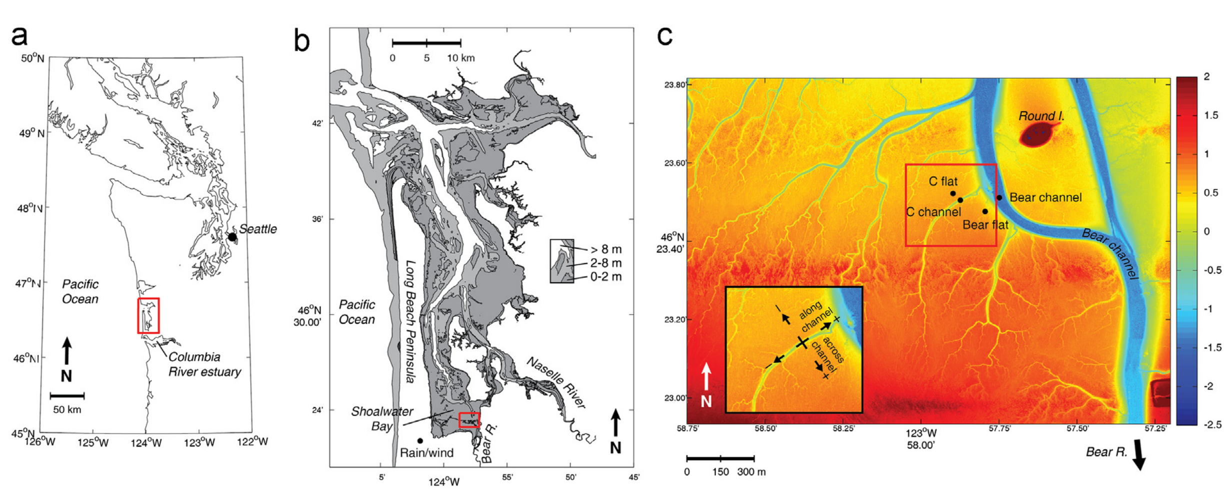

Fig. 1. (a) Map of the Pacific Northwest coastal region, with Willapa Bay indicated by red box. (b) Willapa Bay bathymetry relative to mean sea level, with study area indicated by red box. The black circle southeast of Shoalwater Bay marks the location of the WSU AgWeatherNet station. (c) Study area map showing bathymetry relative to NAVD 88 (Buijsman et al., 2002) and instrument locations indicated by black circles. The inset, denoted by the red box, shows the rotated channel-wise coordinate system. The on-site weather station was located near the Bear flat location.