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Tidal and meteorological forcing of sediment transport in tributary mudflat channels

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Abstract

Field observations of flow and sediment transport in a tributary channel through intertidal mudflats indicate that suspended sediment was closely linked to advection and dispersion of a tidal salinity front. During calm weather when tidal forcing was dominant, high concentrations of suspended sediment advected up the mudflat channel in the narrow region between salty water from San Francisco Bay and much fresher runoff from the small local watershed. Salinity and suspended sediment dispersed at similar rates through each tidal inundation, such that during receding ebbs the sediment pulse had spread spatially and maximum concentrations had decreased. Net sediment transport was moderately onshore during the calm weather, as asymmetries in stratification due to tidal straining of the salinity front enhanced deposition, particularly during weaker neap tidal forcing. Sediment transport by tidal forcing was periodically altered by winter storms. During storms, strong winds from the south generated wind waves and temporarily increased suspended sediment concentrations. Increased discharge down the tributary channels due to precipitation had more lasting impact on sediment transport, supplying both buoyancy and fine sediment to the system. Net sediment transport depended on the balance between calm weather tidal forcing and perturbations by episodic storms. Net transport in the tributary channel was generally offshore during storms and during calm weather spring tides, and onshore during calm weather neap tides.

Keywords: Sediment transport; Intertidal sedimentation; Salinity gradients; Tidal inlets; Topographic effects; San Francisco Bay, California, USA

1. Intertidal sediment transport

Sediment transport is closely linked to both the morphology and ecology of mudflats and marshes. The balance between erosion and deposition controls local bed elevation, and bed elevation with respect to mean sea level feeds back into sedimentation through inundation frequency and duration (Friedrichs and Perry, 2001). Sediment transport mechanisms are spatially heterogeneous across the intertidal zone, from vegetated marsh surface to unvegetated mudflats to deeper subtidal channels. However, sediment fluxes among mudflat, marsh, and channel regions are coupled and depend on the hydrodynamic forcing (Yang et al., 2003). Although field studies have documented sediment transport processes on mudflats (Christie et al., 1999; Dyer et al., 2000; Le Hir et al., 2000), and in marshes (Leonard et al., 1995a, b; Christiansen et al., 2000),

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observations remain limited because of logistical challenges with soft substrate, small and variable water depth, intermittent erosion events, and spatial variability between channels and shoals (Dyer et al., 2000).

Sedimentation in the intertidal zone depends in large part on settling and scour lag asymmetries (Postma, 1961). Sediment advected into the intertidal zone during flood tides can settle and deposit around high water slack. Bed sediments partially consolidate during slack water such that equivalent ebb velocities may not be sufficient to resuspend deposited sediment. On marsh surfaces, vegetation reduces flow velocity and suppresses turbulence, enhancing settling and suppressing scour (Leonard and Luther, 1995). Deposition is enhanced by flood dominant tidal velocities, when faster flood velocities of shorter duration are balanced by longer, slower ebbs. Flood dominant velocities and settling around high water contribute to suspended sediment concentration maxima during flood tides for a range of shallow tidal systems: shallow estuaries (Chant and Stoner, 2001; Fettweis et al., 1998), mudflats (Le Hir et al., 2000; Christie et al., 1999), and marshes (Lawrence et al., 2004). On ebb dominant mudflats, the settling and scour lag effect can generate greater sediment concentrations during floods than ebbs (Dyer et al., 2000).

Astronomical tides are not the only source of energy for intertidal sediment transport. Wind waves can generate bed stresses much greater than tidal currents alone, but the effects depend greatly on wind direction and water depth (Le Hir et al., 2000). Because near-bed wave orbital velocities are greater in shallower depths, mudflat shoals are more exposed to wave stresses than deeper channels. Wave bed stresses suspend sediment, and tidal flows advect the increased sediment concentrations. Consequently, the timing of winds with respect to ebb/flood and spring/neap cycles impacts net transport (Leonard et al., 1995b; Le Hir et al., 2000; Yang et al., 2003). Generally, storms (especially around high water) reverse calm weather onshore transport of sediment and drive net export of sediment from mudflats (Wells and Park, 1992; Shi and Chen, 1996; Christie et al., 1999; Dyer et al., 2000; Le Hir et al., 2000; Janssen-Stelder, 2000; Yang et al., 2003). While erosive response to storms occurs over time scales of days, recovery to pre-storm elevations can take weeks to months (Yang et al., 2003).

Sediment transport on intertidal mudflats can be broadly summarized as varying between calm, depositional periods when tidal forcing dominates and stormy, erosional periods when wind waves are significant. During stormy periods, export depends both on wave stresses that suspend bed material and on water column mixing that inhibits settling around high water. However, sediment transport in mudflat channels may be significantly different than on adjacent shoals, as channels have stronger tidal velocities and are less impacted by waves. As a result, sediment exchanges between shoals and channel—mud can be stored in channels after storms (Yang et al., 2003) and during neap tides (Christie et al., 1999), and resuspended during calm and spring periods. Contrary to the intertidal zone as a whole, channels may offer conduits for export of sediment during calm conditions (Wells et al., 1990; Dyer et al., 2000).

In estuaries, the salinity distribution impacts sediment transport through baroclinic circulation convergence (e.g., Schubel, 1968) or through tidal asymmetries in velocity (Jay and Musiak, 1994) and turbulent mixing (Geyer, 1993). Sediment deposits and suspended sediment maxima are typically found near the limit of the salinity intrusion, either at low salinity (Geyer, 1993; Burchard and Baumert, 1998; Chant and Stoner, 2001; Sanford et al., 2001) or in the fresh region immediately upstream of the salt field (Uncles and Stephens, 1993). In some estuaries, maximum sediment concentrations have been found toward the middle of the salinity distribution due to lateral exchange with supplies of erodible bed sediment (Geyer et al., 1998; Blake et al., 2001). As we present in these observations, the salinity field is closely linked to the suspended sediment distribution in a shallow mudflat channel, with peak sediment concentrations consistently in the middle of the salinity gradient, albeit over a much narrower spatial region than in most estuaries. Observations of a shallow channel in the Tavy Estuary (UK) also found maximum turbidity corresponded with the middle of a relatively compact salinity field (Uncles and Stephens, 2000). Although the Tavy channel was deeper, sediment and salinity patterns there were in many ways similar to these observations—the water column was well mixed and highly turbid early during flood tides, and strongly stratified with decreased near-bed suspended sediment during ebbs.

There has been relatively little research on sediment transport in channels through intertidal regions (Wells and Park, 1992; Shi and Chen, 1996;