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Effects of estuarine and fluvial processes on sediment transport over deltaic tidal flats

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ABSTRACT

Tidal flats at a river mouth feature estuarine and fluvial processes that distinguish them from tidal flats without river discharge. We combine field observations and a numerical model to investigate hydrodynamics and sediment transport on deltaic tidal flats at the mouth of the Skagit River, in Puget Sound, WA, during the spring freshet. River discharge over tidal flats supplies a mean volume flux, freshwater buoyancy, and suspended sediment. Despite the shallow water depths, strong horizontal density fronts and stratification develop, resulting in a baroclinic pressure gradient and tidal variability in stratification that favor flood-directed bottom stresses. In addition to these estuarine processes, the river discharge during periods of low tide drains through a network of distributary channels on the exposed tidal flats, with strongly ebb-directed stresses. The net sediment transport depends on the balance between estuarine and fluvial processes, and is modulated on a spring-neap time scale by the tides of Puget Sound. We find that the baroclinic pressure gradient and periodic stratification enhance trapping of sediment delivered by the river on the tidal flats, particularly during neap tides, and that sediment trapping also depends on settling and scour lags, particularly for finer particles. The primary means of moving sediment off of the tidal flats are the high velocities and stresses in the distributary channels during late stages of ebbs and around low tides, with sediment export predominantly occurring during spring low tides that expose a greater portion of the flats. The 3-d finite volume numerical model was evaluated against observations and had good skill overall, particularly for velocity and salinity. The model performed poorly at simulating the shallow flows around low tides as the flats drained and river discharge was confined to distributary channels, due in part to limitations in grid resolution, seabed sediment and bathymetric data, and the wetting-and-drying scheme. Consequently, the model predicted greater sediment retention on the flats than was observed.

1. Introduction

Sediment transport over intertidal flats depends on a range of forcing processes, including a tidally varying water surface elevation, wind stress, and waves. On tidal flats near a river mouth, additional factors include the volume flux of river discharge and buoyancy effects associated with the fresh water. While observations and theory have evaluated the hydrodynamic and sediment-transport processes over intertidal flats dominated by tidal, wind, and wave forcing, less is known about how river input alters these unsteady, shallow flows (Le Hir et al., 2000).

Tidal forcing drives the periodic inundation and exposure that is characteristic of tidal flats. Tidal bottom stresses over flats with a uniform slope and width can be estimated to first order by assuming continuity and a rigid lid, with the result that stresses on the lower tidal flats are spatially uniform and decrease with distance above the mid-tide elevation (Friedrichs and Aubrey, 1996). The spatial gradient in velocity, in combination with settling and scour lags that tend to move sediment toward regions of lower stress (Postma, 1961), results in generally onshore sediment transport due to tidal forcing alone. To reach equilibrium, the upper flats accrete to a convex profile, decreasing the bottom slope and increasing tidal velocities (Friedrichs and Aubrey, 1996; Pritchard and Hogg, 2003). This idealization of tidal forcing does not account for flood-ebb asymmetries in velocity due to the incident tide, barotropic nonlinearities in shallow water, or bathymetric complexity (Speer and Aubrey, 1985; Friedrichs and Aubrey, 1988).

The addition of river discharge to the intertidal zone creates a shallow estuary where both baroclinic and barotropic pressure gradients alter the bottom stress and sediment flux. Strong horizontal density fronts form at the offshore edge of the tidal flats around low tide, and tidal straining leads to strong stratification during ebbs (Ralston and Stacey, 2005). This stratification reduces bed stresses compared with unstratified flow, leading to flood dominance. Similarly, the baroclinic pressure gradient enhances flood-directed near bed velocities and stresses. The baroclinic and stratification effects on trapping sediment are well documented in deeper estuaries (Meade, 1969; Geyer, 1993), and field and numerical studies suggest that the

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flood-directed stress asymmetry due to estuarine processes can enhance trapping on tidal flats (Ralston and Stacey, 2007; Chen et al., 2010).

An important distinction from deeper estuaries is that when deltaic tidal flats are subaerial around low tide, the river continues to flow across the intertidal zone in shallow channels. Observations and modeling have suggested that offshore sediment flux can occur in these distributary channels, particularly during periods of high river discharge (Ralston and Stacey, 2007; Chen et al., 2010). While sediment export has been noted in tidal drainage channels without river input (Dyer et al., 2000; Mariotti and Fagherazzi, 2011), drainage channels are ephemeral while fluvial channels convey river discharge for the duration of the period that the flats are exposed. The river also provides a source of sediment to the intertidal zone, with sediment load in a river increasing nonlinearly with discharge (Nash, 1994).

The goal of this study is to assess how estuarine and fluvial processes affect flow and sediment transport on deltaic tidal flats. The study examines tidal flats at the mouth of the Skagit River in Puget Sound, Washington, USA, during the spring freshet, when fluvial and tidal processes are dominant and wind forcing is light. The study examines how the stratification, baroclinic pressure gradient, and barotropic flux in distributary channels alter sediment fluxes in the intertidal zone. The analysis combines field observations and numerical modeling, beginning with an assessment of the ability of the model to reproduce the observed conditions.

2. Methods

The study area is at the mouth of the Skagit River, the largest river flowing into Puget Sound, with a mean annual discharge of 470 $m^3 s^{-1}$ (USGS #1220050 at Mount Vernon, WA). Seasonally, the maximum discharge occurs in the late spring and early summer due to snowmelt (May–June) and in the fall and winter due to storms (November–January). The Skagit splits into two major distributaries near its mouth, the North Fork and the South Fork. The river enters Skagit Bay, where a broad shallow delta forms tidal flats with across-shore width ranging from about 3 km off the North Fork to about 6 km off the South Fork. The tidal flats are composed predominantly of sand, with increased concentrations of mud near distributary channels and at the seaward edge (Webster et al., 2013). The tidal range varies between 2.5 and 5 m, with mixed semi-diurnal and diurnal forcing and significant diurnal inequalities.

2.1. Observations

During June 2009, we conducted a field campaign with fixed and shipboard observations to measure flow and sediment transport on the Skagit tidal flats (Fig. 1). Instrument frames for high resolution sampling within about 1 m of the bed were deployed at five locations in the intertidal zone. Near-bed instruments included pulse-coherent acoustic Doppler profilers (pcADPs), acoustic backscatter sensors (ABSs), acoustic Doppler velocimeters (ADVs), conductivity-temperature (CT) sensors, and optical backscatter sensors (OBSs), as well as upward-looking acoustic Doppler current profilers (ADCPs) and pressure sensors. Surface buoys at each station had CTs and OBSs for near-surface water properties, and two of the buoys had meteorological instrument packages for wind, air temperature, and barometric pressure.

The instruments were deployed offshore of the South Fork in an area of sandy tidal flats with a braided network of distributary channels. Typically, the distributary channels were 0.2–1.0 m deeper than the surrounding tidal flats and were 50–200 m in width (Fig. 2). The frames were deployed in an array designed to measure gradients both across-shore (i.e., from the river mouth to Whidbey Channel, the passage east of Whidbey Island) and between the distributary channels and adjacent flats. Instruments were deployed at 3 locations along a distributary channel of the

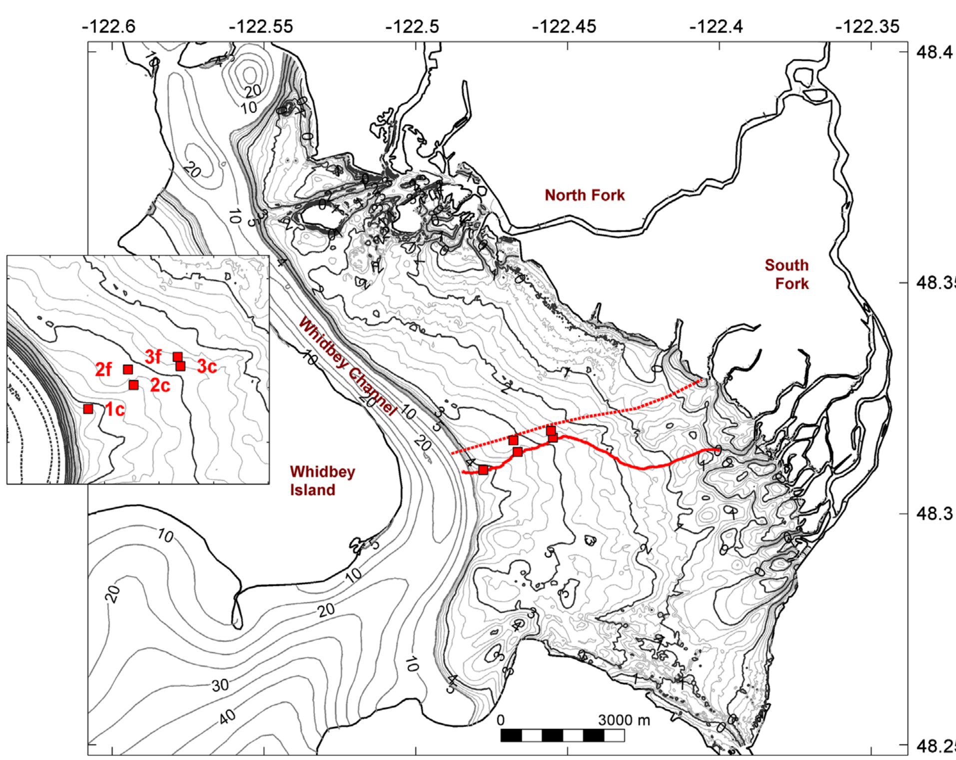

Fig. 1. Map of Skagit Bay and the mouth of the Skagit River showing instrument locations (squares, labeled in inset) during field deployment. Positions of across-shore transects are shown, one following a distributary channel (solid red line) and one on adjacent flats not in a channel (dashed red line). Bathymetric contours are relative to mean sea level. Limitations in bathymetry data resolution resulted in smoothing of distributary channel features on the tidal flat (shown in Fig. 2).