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Tidally dominated sediment dispersal offshore of a small mountainous river: Elwha River, Washington State

E.F. Eidam [a,*], A.S. Ogston [a], C.A. Nittrouer [a], J.A. Warrick [b]

[a] University of Washington, School of Oceanography, Box 357940, Seattle, WA 98103, United States
[b] U.S. Geological Survey, 400 Natural Bridges Drive, Santa Cruz, CA 95060, United States

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ABSTRACT

Sediment supplied by small mountainous rivers (SMRs) represents a major fraction of the global ocean sediment budget. Studies from the past two decades have shown that much of this sediment is dispersed by episodic wind and wave energy along storm-dominated coasts. In tidally dominated environments, however, different transport styles and deposits may result from persistent tidal dispersal. This study investigates episodic sediment releases generated by dam removal from a SMR in Washington State, in order to evaluate the mechanics of tidally dominated sediment dispersal in an energetic marine environment. The results indicate that asymmetric tidal currents with peak magnitudes of ~50 to >80 cm/s produce daily sediment export in the direction of the dominant tidal phase (i.e., the semi-diurnal phase with faster currents and longer duration), resulting in dispersal of fluvially derived fine sediment to distal sinks. These effects are observed throughout all seasons in the presence or absence of wave events. During the first two years of dam removal, more than 8 million tonnes of sediment were discharged to the coast. The net result was little to no change in grain size at 10–60 m water depth across >70% of the seabed offshore of the river mouth. Over the remaining ~2 to 3 km^2 of the subaqueous delta, several cm of mud and sand accumulated in a sheltered coastal embayment adjacent to the river mouth. These results demonstrate that SMR discharge events may form patchy, isolated deposits—or even no deposits—along coastlines with strong tidal currents, in contrast to the mid-shelf mud belts formed on storm-dominated shelves. Over longer timescales, knowledge of the erosional capacity of local and regional tidal currents may be key to interpreting the terrestrial event record preserved in (or possibly excluded from) marine SMR deposits.

1. Introduction

Small mountainous rivers (SMRs) are a key source of sediment to the coastal ocean, especially along tectonically active continental margins (Milliman and Syvitski, 1992). Because they drain small basins, these rivers often deliver much of their annual sediment load in conjunction with discrete events such as floods, forest fires, landslides, or earthquakes. Recently, SMRs have been the focus of studies investigating the sediment transport effects of "wet" storms that bring brief periods of simultaneous/coherent precipitation and energetic ocean conditions to mountainous coastlines (e.g., Wheatcroft, 2000; Sommerfield et al., 2007; Fain et al., 2007; Bourrin et al., 2008; Drexler and Nittrouer, 2008; Harris et al., 2008; Ulses et al., 2008; Kniskern et al., 2011; Bever et al., 2011; Grifoll et al., 2014). The common result is rapid sediment delivery from rivers and efficient transport of that sediment through the shallow marine environment, leading to broad dispersal and deposition in continental-margin flood deposits.

In contrast to these storm-dominated systems, some SMRs discharge to tidally dominated environments where sediment delivery is episodic, but transport energy is periodic—and in some cases sufficient to mobilize the majority of supplied particle sizes each day. Tidally dominated systems account for ~17% of the world's continental shelves (Walker, 1984; Swift et al., 1986), and include macrotidal and mesotidal embayments/estuaries and also tidal straits (Reading, 2009). In order to better understand the timing, variability, and depositional impacts of tidally dominated transport in these environments, the present study investigates sediment pathways and deposits offshore of a SMR during a dam deconstruction/river restoration project. The dam removal project, which involved two 100-year-old hydroelectric dams on the Elwha River in Washington State, released ~8.2 million tonnes of total sediment including ~6.3 million tonnes of suspended sediment to the coastal ocean between Sep 2011 and Sep 2013 (Magirl et al., 2015; Warrick et al., 2015). Episodic fluvial sediment pulses with a

* Corresponding author.
E-mail addresses: efe@uw.edu (E.F. Eidam), ogston@ocean.washington.edu (A.S. Ogston), nittroue@ocean.washington.edu (C.A. Nittrouer), jwarrick@usgs.gov (J.A. Warrick).

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range of magnitudes were generated, offering the opportunity to investigate the dispersal of sediment from SMR delivery events.

Data collected from boundary-layer instruments near the river mouth and from ship-based surveys across the delta were used to: (1) characterize the transfer of material from the buoyant surface plume into the underlying water column; (2) describe tidally dominated patterns of sediment resuspension, advection, and settling in the water column and bottom boundary layer; and (3) understand the location of new seabed deposits and predict their evolution. The results of this study expand our understanding of tidally driven dispersal systems and their deposits offshore of SMRs.

2. Regional characteristics

2.1. Physical characteristics of the river and receiving basin

The Elwha River flows 72 km from the tectonically active Olympic Mountains to the Strait of Juan de Fuca in northwest Washington State (Fig. 1). Like many SMRs, the Elwha has a steep gradient, large sediment discharge relative to river size (1.2–2.9×10^5 m^3/yr upstream of the former reservoirs; Curran et al., 2009), and small drainage basin (827 km^2; Konrad, 2009), and therefore a large sediment yield. The basin receives 100–500 cm of precipitation in the form of rain and snow each year (Philips and Donaldson, 1972) and the river hydrograph is characterized by a mean annual flow of 42.8 m^3/s at USGS site 12045500 (Curran et al., 2009; USGS, 2015) with peaks reaching ~200 to 300 m^3/s during autumn/winter storms and spring freshets/snowmelt periods (USGS, 2015).

The river discharges into the Strait of Juan de Fuca, a roughly 20-km wide, 100-km long east–west channel connecting the Pacific Ocean to inland seas (Fig. 1). The subaerial river delta extends ~2 km into the Strait of Juan de Fuca, and a relict, subaqueous delta (henceforth referred to as the "delta") extends an additional 2–5 km. This platform dips ~1° toward a slope break at 40–60 m depth; the adjacent channel floor is ~120 m deep. The delta began forming about 12,500 years ago during a high stand in sea level after the Vashon Glaciation (Anderson, 1968; Downing, 1983; Webster, 2014). As the earth's crust rebounded, sea level fell to 60 m below the modern shoreline (Mosher and Hewitt, 2004), and the delta prograded into the Strait. Finally, eustatic sea level rose to its present level ~5000 years ago and flooded the lowstand delta (Downing, 1983; Webster, 2014), which is the study area for this work.

The delta lies in the Elwha littoral cell between Freshwater Bay and Ediz Hook (Fig. 1). Freshwater Bay is a sheltered region that receives sediment from both the river and eroding glacial bluffs (Shaffer et al., 2008). Ediz Hook is an active spit formed from eastward longshore transport of river and bluff sediments (Galster and Schwartz, 1990). Prior to the release of sediment from the reservoirs, the substrate across the relict, subaqueous delta was a mixture of sands, gravels, and irregularly distributed boulders, with the finest sediments (typically sands) found in Freshwater Bay (Warrick et al., 2008; Webster, 2014). The coarser gravelly and sandy substrate on the remainder of the delta has been interpreted as a lag layer (Webster, 2014). Little data are available on

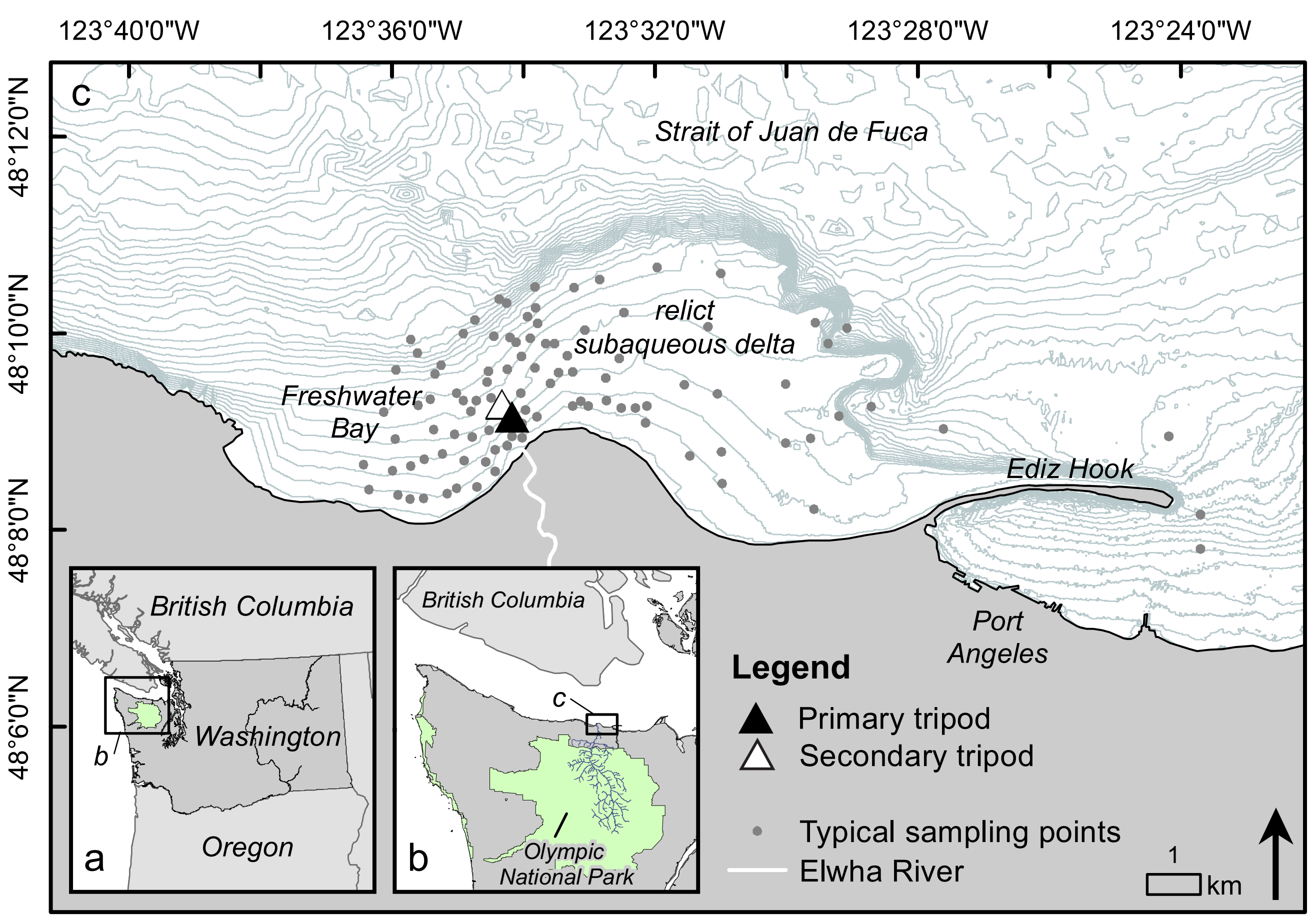

Fig. 1. Study area, composed of (west to east): Freshwater Bay; the relict, subaqueous Elwha Delta; and Ediz Hook. Instrumented tripods were located northwest of the river mouth in 15–25 m water depth. Seabed grab samples, water samples, and CTD transects were collected primarily at sites 10–60 m deep within 3 km of the river mouth. Bathymetric contour intervals are 5 m (courtesy of UW School of Oceanography, www.ocean.washington.edu/data/pugetsound).