Continental Shelf Research 60S (2013) S125–S135

Contents lists available at SciVerse ScienceDirect

Continental Shelf Research

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

Research papers

Thermal observations of drainage from a mud flat

J. Paul Rinehimer [a,b,*], Jim Thomson [a,b], C. Chris Chickadel [a]

[a] Applied Physics Lab, University of Washington, United States
[b] Civil and Environmental Engineering, University of Washington, United States

ARTICLE INFO

Article history:
Received 25 February 2012
Received in revised form
15 October 2012
Accepted 1 November 2012
Available online 9 November 2012

Keywords:
Tidal flats
Remote sensing
Infrared

ABSTRACT

Incised channels on tidal flats create a complex flow network conveying water on and off the flat during the tidal cycle. In situ and remotely sensed field observations of water drainage and temperature in a secondary channel on a muddy tidal flat in Willapa Bay, Washington (USA) are presented and a novel technique, employing infrared imagery, is used to estimate surface velocities when the water depth in the channel becomes too shallow for ADCP measurements, i.e., less than 10 cm. Two distinct dynamic regimes are apparent in the resulting observations: ebb-tidal flow and the post-ebb discharge period. Ebb tide velocities result from the surface slope associated with the receding tidal elevation whereas the post-ebb discharge continues throughout the low tide period and obeys uniform open-channel flow dynamics. Volume transport calculations and a model of post-ebb runoff temperatures support the hypothesis that remnant water on the flats is the source of the post-ebb discharge.

1. Introduction

Fine-grained intertidal flats provide habitat for many aquatic species and economic value for fisheries, but their complex environment makes field observations of water and sediment dynamics difficult. Variations in water depth during the tide transform the hydrodynamic environment between a shallow embayment at high tide and a drainage basin at low tide (Le Hir et al., 2000). Within this complex spatial arrangement and varying scales of motion, incised channels convey water and sediment throughout the system (Ralston and Stacey, 2007). It is well known that channels play an important role in the later stages of receding ebb tidal flow (Wood et al., 1998; Nowacki and Ogston, 2013) conveying water on the flats downstream. Water continues to flow out through these channels long after the ebb tide has passed (i.e., after the tide water is below a given location on the flats) (Whitehouse et al., 2000). Although this 'post-ebb discharge' is common, there has been limited quantitative description or dynamic understanding of these flows.

Recent work suggests that post-ebb discharge in channels results from the runoff of remnant water on the surface of the tidal flat (Mariotti and Fagherazzi, 2011; Whitehouse et al., 2000; Allen, 1985) and that runoff patterns control the distribution of many aquatic species (Gutiérrez and Iribarne, 2004). Other studies suggest the post-ebb drainage results from porewater discharge from with the flats, although it is a much slower process (Anderson and Howell, 1984). From either source, these studies agree that post-ebb drainage can be an important mechanism for the transport of water, sediment, and heat.

The drainage of remnant surface water via nearly parallel, ridge-separated channels located on the flat surface called runnels may be particularly important for off-flat transport (Fagherazzi and Mariotti, 2012; Gouleau et al., 2000). Thus, a mass budget for a tidal flat system is incomplete without quantification of post-ebb drainage. For example, in a study of a nearby channel in Willapa Bay, Nowacki and Ogston (2013) find that an equilibrium sediment budget requires additional export that is missing from their analysis of purely tidal flows. Although post-ebb channel discharge appears small by qualitative (visual) observation, recent work by Fagherazzi and Mariotti (2012) has shown that shear stresses due to this process are higher than the critical stress for erosion and that suspended sediment concentrations are greater than during tidal flows. Kleinhans et al. (2009) found post-ebb surface velocities of 0.1–0.2 ms^{-1} and showed that the post-ebb flow controlled channel meandering, as well as bank and backward step erosion in the incised channels.

Estimation of channel discharge requires knowledge of depth and cross-sectionally averaged velocities at all stages of the drainage. One reason that post-ebb drainage has not been well described is the difficulty in measuring very shallow (depth less than 10 cm) flows. Here, we utilize a novel technique to measure shallow flows remotely with infrared (IR) images. The IR method is combined with conventional acoustic Doppler measurements during periods of greater depth, and there is good agreement between the two approaches during these periods. The integration of these data sets provides a continuous time series of the channel discharge velocities.

* Corresponding author at: Applied Physics Lab, University of Washington, United States. Tel.: +1 206 616 5736.
E-mail address: jprine@apl.washington.edu (J. Paul Rinehimer).

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http://dx.doi.org/10.1016/j.csr.2012.11.001

Furthermore, the IR imagery measures the horizontal (cross-channel) variations in surface velocity allowing greater detail in the flow structure to be observed in addition to the vertical velocity profiles from the in situ measurements. Parametric fits for these profiles are then used to make continuous estimates of the volume flux discharged from the channel.

In addition to describing the structure and magnitude of the channel drainage, we compare the temperature of the drainage water to a model prediction for the temperature of remnant surface water (i.e., the hypothetical source of the post-ebb drainage). The model formulation follows Kim et al. (2010), in which the terms of surface heat fluxes are prescribed and the heat exchange between water and sediment is modeled explicitly. The model predicts remnant surface water temperatures that match the observed drainage temperatures and thus support the hypothesis of surface runoff. The corresponding total transport of heat is placed in context with previous observations of low tide heat budgets in muddy tidal flats.

2. Methods

2.1. Site description

Willapa Bay, Washington (Fig. 1) is located on the Pacific coast of the United States, north of the Columbia River mouth. The Long Beach peninsula separates the estuary from the ocean with an 8-km-wide inlet at the northern end of the bay. The tide is mixed semidiurnal with a mean daily range of 2.7 m, varying between 1.8 m (neap) and 3.7 m (spring). The intertidal zone occupies nearly half of the bay's surface area (Andrews, 1965) and almost half of the bay's volume is flushed out of the bay each tide (Banas et al., 2004). Extensive tidal flats occupy much of the bay's intertidal region. Silt and clay sediment predominates in the southern bay and lower energy environments, while fine sand flats are found in higher energy areas, such as along the major channels and locations exposed to waves (Peterson et al., 1984).

The study site is located at the mouth of "D channel" (46° 23′ 26.12″ N, 123° 57′ 43.26″ W) in the southern portion of the bay near the Bear River Channel. The Bear River Channel is the tidal extension of the Bear River which drains into the bay approximately 2 km south of D channel. D channel is a branching, dead end channel (Ashley and Zeff, 1988) that drains 0.3 km^2 of tidal flats into the Bear River channel. At our study site, the channel is incised into the flat about 0.7–1 m deep and 1–2 m wide.

The focus of study is a single spring tide on 31 March 2010. Lower-low water occurred at 10:00 (all times referenced in this paper are local, Pacific Daylight Time) while the period where the regional water level was below the mouth of D channel and all the surrounding flats exposed, (see Fig. 1), lasted approximately 1.5 h, from 09:15 to 10:45. During this period water was observed to continually drain out from D channel. We define this as the 'post-ebb discharge', because the ebb tide effectively finished (i.e., passed the site) at 09:15

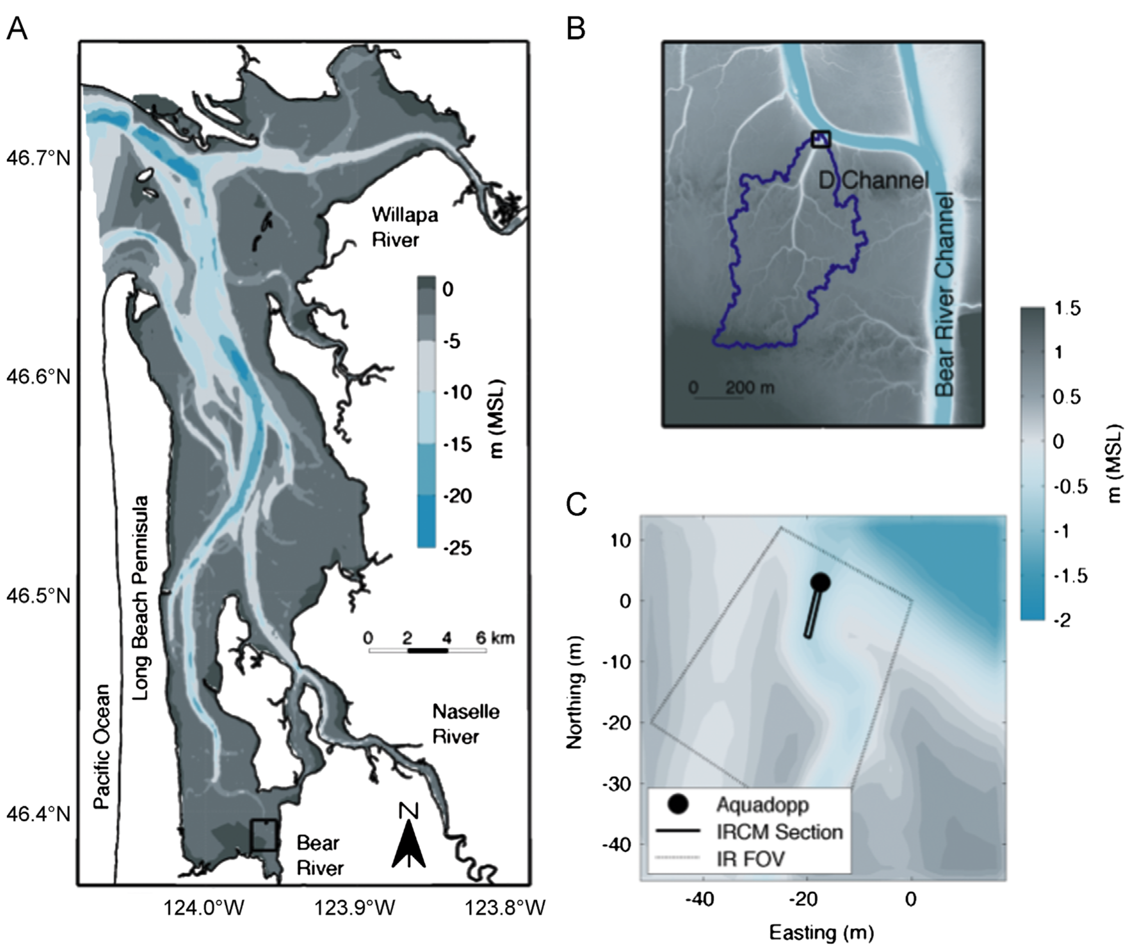

Fig. 1. (a) Willapa Bay bathymetry. The black box indicates the region of sub panel (b) bathymetry of D channel from LiDAR survey and the calculated drainage area. The black box indicates the D channel mouth shown in (c) Close-up of D channel mouth with locations of field instruments. The circle indicates the location of the Aquadopp ADCP, the line is where the IRCM timeslices were taken (see Section 2), and the trapezoid is the infrared camera field of view from the imaging tower at the local origin [0,0]. Bathymetry for (a) is indicated by the inset color bar whereas the right color bar shows the scale for (b) and (c).