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ScienceDirect
Journal of Hydro-environment Research 11 (2016) 75–90
Journal of Hydro-environment Research
www.elsevier.com/locate/jher

Research papers

Field and theoretical investigation of sediment mass fluxes on an accretional coastal mudflat

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Received 7 June 2015; revised 29 December 2015; accepted 11 January 2016

Abstract

Variations in suspended sediment concentrations (SSCs) in tidal mudflats are an important influence on the ecological environment, morphological evolution, and pollutant transport. To better understand how the behavior of suspended sediment influences small-scale variations in SSC in the water column, we took simultaneous measurements of water depth, wave height, current velocity, SSC profiles, and intratidal bed-level changes during a series of continuous tidal cycles on a highly turbid macrotidal mudflat, part of a larger accretional coastal mudflat on the Jiangsu Coast, China. We estimated the relative contributions of erosion, deposition, and advection processes to variations in SSC from the field data. We used an empirical orthogonal function (EOF) analysis to examine the influence of hydrodynamic factors (water depth, wind, wave height, and current velocity) and environmental factors (salinity and temperature) on SSC variability, to determine why the contributions of the three processes (erosion, deposition, and advection) to the variability in SSC differed. Our results showed that on average, advection flux was about an order of magnitude higher than erosion–deposition flux of corresponding tide, and that advection, driven by the tidal current velocity, wind, and associated alongshore transport, accounted for most of the variability in SSC at the study site over a complete tidal cycle. An abundant sediment supply and limited resuspension of the bed sediments meant that advection was the main transport process. Our results also demonstrate that detailed analyses of transport processes provide useful information on the sources and fates of suspended sediments, and support the interpretation of morphological changes in accretional intertidal mudflats.

Keywords: Suspended sediment concentration; Resuspension; Deposition; Advection; Bed-level changes; Intertidal mudflat

1. Introduction

Suspended sediment concentrations (SSCs) have a major influence on water quality and play an important role in shaping the geomorphology and ecology of estuarine and intertidal wetlands (e.g., Dyer, 1997; Zheng et al., 2004; Schoellhamer et al., 2007; Li et al., 2012). Suspended sediments can transport trace metals, nutrients, organic carbon, and anthropogenic contaminants through estuarine and coastal waters. Furthermore, suspended sediments limit the amount of light entering the water, thereby influencing primary productivity (Tian et al., 2009) and geochemical cycling (e.g., Li et al., 2012). Therefore, to understand the sources and fates of sediments and their associated contaminants, as well as the morphological evolution of intertidal wetlands in detail, the factors that contribute to the variability in SSCs in estuarine and coastal waters should be identified.

Suspended sediment concentrations vary locally in response to three main processes: resuspension and deposition in the vertical direction, and advection in the horizontal direction (e.g., Weeks et al., 1993; Velegrakis et al., 1997; Jago and Jones, 1998; van de Kreeke and Hibma, 2005; Jago et al., 2006; Andersen et al., 2007; Krivtsov et al., 2008; Salehi and Strom, 2012; Yu et al., 2012). The effect of horizontal diffusion is generally neglected because horizontal concentration gradients in macrotidal coastal waters are much weaker than vertical gradients (e.g., Bass et al., 2002; Stanev et al., 2007). Studies of

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http://dx.doi.org/10.1016/j.jher.2016.01.002
1570-6443/

sediment sources have indicated that resuspension processes can cause increases in SSC (e.g., Velegrakis et al., 1997; Christie et al., 1999; Andersen et al., 2007; Salehi and Strom, 2012; Wang et al., 2012; Zhu et al., 2014), whereas deposition processes can cause reductions in SSC (e.g., Dyer, 1989; Salehi and Strom, 2012). Although these studies have indeed provided a qualitative understanding of the causes of variability in SSCs, they generally quantified erosion, deposition and advection processes using at least two observation sites along the main current direction based on suspended sediment transport equation in tidally-dominated coastal environments (e.g., Fugate and Friedrichs, 2002; Yu et al., 2012). However, few studies have quantitatively estimated the relative contributions of erosion, deposition, and advection to SSC variability using a single observation site. In particular, there are few estimates of the transport processes in shallow intertidal environment where waves dominate the hydrodynamic energy. Furthermore, it is indeed easily understood for us that coastal transport processes are advection dominated, but in shallow intertidal environment, vertical turbulent mixing may be large compared with advective transport due to wave action, in other word, bottom sediment resuspension may be responsible for SSC variability (e.g., Anderson, 1972; Janssen-Stelder, 2000; Le Hir et al., 2000; Green, 2011; Wang et al., 2012). Actually, this lack of information in shallow-water environments may reflect the difficulties in working on intertidal wetlands, which are usually composed of very soft, fine-grained sediment and have complex geomorphologies, especially compared with sandy beaches (Shi et al., 2012, 2014; Wang et al., 2006, 2012). In addition, suitable equipment for the collection of high-resolution measurements of intratidal bed-level changes during the transport and deposition phases has only recently become available. Therefore, much attention has been directed toward separating the relative contributions of resuspension, deposition, and advection processes from SSC time series, which has generally been performed using numerical models (e.g., Weeks et al., 1993; Jago and Jones, 1998; Ellis et al., 2004; Krivtsov et al., 2008; Yu et al., 2012). However, there is a lack of high-quality data describing transport processes, meaning that the models are oversimplified versions of reality and some of the simplifications and assumptions do not have a sound physical basis. For example, modeling studies have usually either neglected or oversimplified the complex physical processes that play important roles in SSC variability, such as residual and M4 tidal currents, or variations in water depth (Cheng and Wilson, 2008; Stanev et al., 2007).

The physical processes that influence SSC variability have been the subject of discussion for many decades. Some researchers have inferred that an increase in the SSC is only caused by resuspension by high flow velocities or strong waves (e.g., Christie et al., 1999; Janssen-Stelder, 2000; Wang et al., 2012). This inference was made without synchronous *in situ* measurements of intratidal bed-level changes. Other researchers assumed that sudden increases in SSCs were caused by nonlocal erosion and were attributable, in some cases, to advection alone (e.g., Dyer, 1989; Andersen et al., 2007; Salehi and Strom, 2012). For example, Andersen et al. (2007) found that a sudden increase in SSC when the tide was in the ebb phase occurred without bed erosion, suggesting that the increase was entirely attributable to advection (note that this conclusion was made using *in situ* synchronous measurements of intratidal bed-level changes). Hence, it is reasonable to believe that variability in SSC should be attributed not only to resuspension and deposition processes, but also to advection (e.g., Dyer, 1989; Andersen et al., 2007; Salehi and Strom, 2012; Shi et al., 2015). The above evidence suggests that field measurements of intratidal bed-level changes are important in identifying the causes of the variability in SSC (e.g., Dyer, 1989; Andersen et al., 2007; Salehi and Strom, 2012). With the development of high-precision instruments, such as acoustic Doppler velocimeters (ADV; e.g., Andersen et al., 2007; Pratolongo et al., 2010; Salehi and Strom, 2012; Wang et al., 2014; Shi et al., 2015) and acoustic scour monitors (ARXII; e.g., Christie et al., 1999, 2000), which can measure intratidal bed-level changes during submergence and through the transport and deposition phases, it is possible to determine whether an increase in the SSC is caused by resuspension or advection processes over an intertidal wetland. These new technologies also allow the quantitative estimation of the relative contributions of resuspension, deposition, and advection processes to SSCs.

The aim of the present study was to investigate the percentage contributions of resuspension, deposition, and advection processes to SSCs in the water column on a highly turbid macrotidal coastal mudflat by monitoring the real-time changes in velocity, water depth, wave height, SSC, and intratidal bed-level. This aim included three specific objectives. First, to quantify the amount of sediment that was resuspended and deposited from *in situ* measurements of the intratidal bed-level changes, and to quantify advection from integrated measurements of the current velocity, depth-averaged SSC, and water depth. Second, to determine the relative contributions of resuspension, deposition, and advection to the SSC in the water column. Finally, to examine the influence of hydrodynamic and environmental factors on the variability in SSC, to extend our understanding of the key controlling variables, and to explain the variability in the contributions from the three transport processes to SSCs. Our results provide new insight into the sources, transport, and fates of sediments. The sediment transport patterns observed in this study have important implications for morphological changes on intertidal mudflats, particularly for accretional intertidal mudflats.

2. Study area

The study area was an exposed mudflat that is part of the larger Wanggang mudflat on the Jiangsu Coast, China, between the abandoned Yellow River Delta and the Yangtze River Estuary (Fig. 1A). The investigated mudflat faces the largest radial tidal sand ridges on the Chinese continental shelf and is northwest of an offshore sand ridge system in the southwestern part of the Yellow Sea (Fig. 1B). The study site is described as a continuous accretional intertidal mudflat because the SSCs over the sand ridge are high (0.2 kg/m^3 on average) throughout the year as a result of the abundant sediment supply provided by the radial tidal ridge system off the Jiangsu coast, the