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River-sea transitions of sediment dynamics: A case study of the tide-impacted Yangtze River estuary

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ABSTRACT

Hydrodynamics and sediment dynamics vary greatly in tide-dominated estuaries worldwide, but there is a paucity of data of large tide-dominated estuary systems due to difficulties of observation in a large spatial scale. In this study, we investigate sediment dynamic transitions in a 660-km long section between the tidal limit and mouth of the Yangtze River. We found that tidal effects are almost undetectable in the uppermost 100-km section, but the mean tidal range gradually increases downstream to nearly 3 m at the river mouth. Flow is generally unidirectional in the uppermost 400-km section, although its velocity changes in response to flood/ebb tidal dynamics; in the lowest 250-km section, flow is bidirectional, and ebb flow durations decrease towards the sea. In the lowermost 100 km, the ebb flow durations decreases to below 60%, and the flow is dominated by tidal currents. Salinity is only detectable in the lowest 100-km section due to the dominance of Yangtze River water discharge. Bed sediments mainly include sand in the uppermost 500-km section, whereas mud dominates in the remaining areas. In contrast, the median grain size of the suspended sediments was found to be greater in the lowest 100-km section (8–13 μm) than in the upper sections (5–6 μm) due to strong exchanges between suspended and near bed sediments. The suspended sediment concentration (SSC) was found to be low (<0.1 g/L) and homogenous in the uppermost 100-km section, downstream of which the SSC increased rapidly to >1 g/L and both surface-bottom and intratidal variabilities occurred. The rates of sediment parameter changes were rapid in the river-sea transitional zone, and this zone may shift upstream and downstream in response to the relative contributions of the river, tides and waves. A conceptual model of the river-sea transition of sediment dynamics for the Yangtze estuary was established, and this model shed light on quantitative studies of sediment dynamics in other large tide-impacted estuaries worldwide.

1. Introduction

Estuaries are popular sedimentary environments where rivers meet oceans. Physical, geological, chemical and biological processes in estuaries are generally more complex and dynamic than other areas on the Earth's surface (Holligan and Boois, 1993). Fluvial discharges, tides and waves are three main forces that affect estuaries. It is well known that the head of a estuary is controlled by the river, the main estuary in the middle experiences mixed energy from both the river and ocean, and the mouth in the lower section is mainly controlled by the ocean that is involved (Williams et al., 2013). The suspended sediment concentration (SSC) in the estuary is highly affected by catchment activities, such as soil leaching, floods, deforestation and forestation and dam constructions (Pont et al., 2002; Rothe et al., 2002; Yang et al., 2002, 2011). Oceanic forcings like tides, waves and wind can cause changes in the SSC through the process of mixing and resuspension in the estuarine area (De Jorge and Van Beusekom, 1995; Gensac et al., 2016). These processes play a key role in sedimentary processes, morphodynamics, and ecological systems and should also be taken into consideration in engineering construction (Newcombe and MacDonald, 1991; El-Asmar and White, 2002; Yang et al., 2011).

Over the decades, many studies have been conducted on geomorphic processes in estuarine and coastal regions (e.g., Widdows et al., 2000; Andersen et al., 2005; Yang et al., 2008; Grabowski et al., 2011; Liu et al., 2014). Wright and Nittrouer

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(1995) proposed four stages of sediment dispersal in estuaries and adjacent coastal areas: supply via river plumes, initial deposition, resuspension and transport, and long-term net accumulation. Gibbs (1976) reported that Amazon River sediments are transported from its estuary to the continental shelf, but mud components can be separated and carried landward by onshore bottom currents. Fluvial water and sediment discharges, suspended particulate matter concentration and oceanic forcings were closely related to the formation and evolution of mud banks on the Amazon-dominated coast (Anthony et al., 2013; Gensac et al., 2016). For example, increases in riverine sediment resulted in a 150 km-long area of accretion, and water discharge from major rivers greatly affected the migration rates of these mud belts (Gensac et al., 2016).

Estuary sizes vary considerably around the world, generally ranging from <1 km to >100 km (Dyer, 1997). Surveys of longitudinal transects along estuary head, main and mouth areas can provide valuable information on hydrodynamics and sediment dynamics. In tide-dominated estuaries, longitudinal transects can be surveyed hourly to capture temporal and spatial variations. These types of surveys can be applied for small estuaries such as the York River in the Chesapeake Bay and the Tagus, the Seine and the Mondego rivers in Europe (Avoine et al., 1981; Vale, 1990; Brotas and Plante-Cuny, 1998; Lillebø et al., 1999; Le Hir et al., 2001; Friedrichs, 2009). These types of surveys, however, are not practical for large tide-dominated estuaries (such as, the Amazon and Yangtze Rivers), as they are >500 km in length. Logistically it is difficult to use one research vessel to finish even one longitudinal survey during a single tidal cycle (~12 or 24 h). Although many studies have been performed on large river systems, there is still a paucity of data on hydrodynamics and sediment dynamics of large tide-dominated estuarine systems (e.g., Amazon, Yangtze, Ganges, and Mekong).

Several studies have been conducted on the Yangtze River and its dispersal system over the past 20 years, but most of them have focused on either the 200 km-long funnel-shaped Yangtze River mouth only (Milliman et al., 1985; Li et al., 2012b; Liu et al., 2014) or the river drainage basin itself (Chen et al., 2007; Xu and Milliman, 2009; Luo et al., 2012). Although it is well known that river-ocean interactions occur along the low-gradient 660 km-long section of the Yangtze River, systematic and comprehensive measurements of this area are still limited, partially due to the aforementioned logistics challenges. In this study, we focus on the entire 660 km-long Yangtze estuary from Datong Station to the Yangtze subaqueous delta and study the interactions among the river, tides, waves, and SSC levels. We strive to filling in this knowledge gap by studying: (1) river flow speeds and directions, (2) suspended sediment concentrations, and (3) sediment grain sizes for the entire Yangtze estuary. We perform systematic and labor-intensive hourly surveys and samplings over more than one semi-diurnal tidal cycle (about 13–14 h) at nine stations. Our study sheds light on the quantitative studies of tide-dominated large river estuarine systems and our datasets can be compared with those of other tide-dominated rivers worldwide.

With a length of ~6.3 × 10^3 km, the Yangtze River is the longest in Asia and is the third longest in the world. It originates from the Qinghai-Tibet Plateau, flows eastward, and debouches to the East China Sea. The Yangtze ranks fifth globally in terms of water discharge (~900 km^3/yr) and fourth in terms of historical sediment load (~470 Mt/yr, Million tons per year) (Milliman and Farnsworth, 2011). In estuarine systems, the tidal limit is defined as the site at the most landward extent of spring tides during the dry season where the tidal range is null; the flood tidal current limit is defined as the farthest limit that a flood tide current (opposite to the dominant river flow direction) can reach. Datong Station (Fig. 1) is a tidal limit station that is used to carry out water discharge and sediment load measurements for this study.

2. Study area

The estuary of the Yangtze River is defined as a ~660 km-long section from Datong Station to the subaqueous delta at 30–50 m isobaths (Shen et al., 2003). Xuliujing Station is a key site that separates the estuary into two distinct parts (Fig. 1). From Datong to Xuliujing, the river channel is elongated (~510 km) and narrow and the river flows are fast (~0.56 m/s). Downstream from Xuliujing, the Yangtze River transforms to a broad and bifurcated estuary with four major outlets. Seaward of the river mouth (~90 km wide), subaqueous sand ridges form as a result of energetic tidal currents (Shen and Pan, 2001). At the seaward-most station in Jiuduansha (Fig. 1), mean and maximum tidal ranges are 2.7 and 4.6 m, respectively (GSICI, 1996). Wind-driven waves and swells are two major types of waves found in this estuary, and wave energy levels increase rapidly seaward. Long-term mean wave heights increase from 0.2 m at Gaoqiao Station (in the middle of the bifurcated estuary) to about 1.0 m at Yinshuichuan Station (~60 km seaward of Gaoqiao; Fig. 1) (Yang, 1999).

During its geological development, the Yangtze Delta has shifted its depocenter southeastward since the 18th century. By the 1950s, >98% of Yangtze River discharge had entered the sea through the South Branch (Chen et al., 1985). Yangtze sediment loads into the East China Sea are mainly composed of suspended sediment (>99%) (Yang et al., 2002). When suspended sediment is transported downstream to the estuary, an Estuarine Turbidity Maximum (ETM) zone forms in the mouth bar area due to flocculation and canceling energy between the river and the sea (Jiang et al., 2013). Semidiurnal ebb currents are generally faster than flood currents. The depth-averaged velocity is ~1.4 m/s and the peak tidal current velocity can reach 2 m/s at the river mouth (Chen et al., 2014; Hu et al., 1988), which is generally comparable to that of the Amazon River (1–2 m/s) (Gensac et al., 2016).

Over recent years, as a result of anthropogenic changes (particularly with the construction of the Three Gorges Dam -TGD) (Yang et al., 2015), the SSC at Datong Station decreased from 0.62 g/L in 1958 to 0.35 g/L in 2000 (Yang et al., 2003) and then to only 0.17 g/L during the post-TGD period (after 2003). Numerous human activities have also happened in the Yangtze basin and estuary (e.g., water reservoir construction, sand mining, navigational dredging, shoreline protection and coastal reclamation) (Yang et al., 2006; Li et al., 2011; Jiang et al., 2012). It is likely that sediment dynamic processes have changed due to a variety of human activities. In this study, most observations were conducted in April of 2013, April of 2014 and October of 2015, when water discharge levels were close to the mean water discharge level of the past 65 years (averaged at 28,300 m^3/s).

3. Materials and methods

In this study, fieldwork was conducted at sites G and I in April of 2013, at sites A, B, C, D, E and H in April of 2014 and at site F in October of 2015 (Fig. 1; Table 1). It is well known that the river's effects are more prominent in July–August and that wind-driven waves play a more central role in January–February (Chen et al., 2004; Xu and Milliman, 2009). To minimize the impact from seasonal variation, observations of all sites were made in April and October, during which river discharge and wind energy levels are both at moderate levels. To be specific, fluvial discharges in these two months are close to the mean water discharge, usually between 20,000 and 30,000 m^3/s (See Table 1). These values differ from that in dry (~10,000 m^3/s) and flood season (~50,000 m^3/s). Thus our