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Exploratory morphodynamic modeling of the evolution of the Jiangsu coast, China, since 1855: Contributions of old Yellow River-derived sediment

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ABSTRACT

In this study, we aim to investigate the overall morphological evolution of the Jiangsu coast after 1855, when the Yellow River shifted northward. We focus on fine sediment transport between two large-scale geomorphological units, i.e., the Abandoned Yellow River Delta (AYD) and the Radial Sand Ridges (RSRs). An existing morphodynamic model, which was established for reproducing the development of the AYD before 1855, is modified and extended. In addition to the tidal forcing, waves and human interventions (i.e., revetments) are considered in the model. The model results are compared with the existing data. Both the evolution trend of the Jiangsu coast and the spatial distribution of the offshore shoals show good agreement. The simulated fine sediment depositions in different periods are consistent with the geological measurements. The results reveal that the old Yellow River-derived sediment not only contributes to the sedimentation in the RSRs but can also be transported to the adjacent zones, especially farther south/southeast. Moreover, the spatial distribution of fine sediment deposits varies in the RSRs. The different sedimentary environments in the Dongsha and Tiaozini ridges result in significant grain size differences in these two neighboring ridges. A sensitivity analysis indicates that tides play a key role in dominating the long-term morphological evolution of the Jiangsu coast and the total erosion from the AYD. On smaller scales, the effect of revetments (built since the 1930s) on the evolution of the nearshore zone and the effect of wind waves on the erosion of offshore shoals are relatively important. The effect of a gradual coarsening process of bottom sediment along the Jiangsu coast, which may be due to continuous fine sediment removal, is identified. Fine sediment depositions in the Tiaozini ridge and in the northern offshore zone of the RSRs are relatively more sensitive to the coarsening trend of bottom sediment than other areas.

1. Introduction

The geomorphology of a river-dominated delta is strongly determined by river-induced sediment input (Gelfenbaum et al., 2009). If a river goes through changes upstream, e.g., switching courses, a previously formed delta lobe may be abandoned. An abandoned delta experiences significant reworking by marine processes compared with an active delta. Shoreline retreat and destruction of the submerged delta can provide fresh sediment for the surrounding zones and may result in the development of spits and beaches (Nienhuis et al., 2013; Anthony, 2015). Many studies have addressed the modification of abandoned deltas. However, most of the well-studied abandoned deltas (lobes) worldwide are either coarse grained (e.g., the Ebro delta lobe, Batalla et al., 2014; the Po delta, Stefani and Vincenzi, 2005) or wave dominated/influenced (Woodroffe and Saito, 2011), forming well-known beach barrier systems (or cheniers) on sandy (or muddy) substrate, e.g., the Chandeleur Islands in the Mississippi delta (Woodroffe and Saito, 2011; Anthony, 2015). Compared with these deltas, the Abandoned Yellow River Delta (AYD) in the Yellow Sea is unique because it is fine grained and tidally dominated (Woodroffe and Saito, 2011).

The Abandoned Yellow River Delta in the Southern Yellow Sea (SYS), China, was formed and developed during the years 1128–1855 CE (Fig. 1), when the old Yellow River (OYR) reached the Jiangsu coast and discharged into the SYS. In addition to several geological studies on the development of the AYD before 1855 CE (e.g., Liu et al., 2013), a morphodynamic modeling approach has been applied to explore the formation and evolution of the AYD as well as the relevant influence of the OYR-derived sediment on the morphological evolution of the

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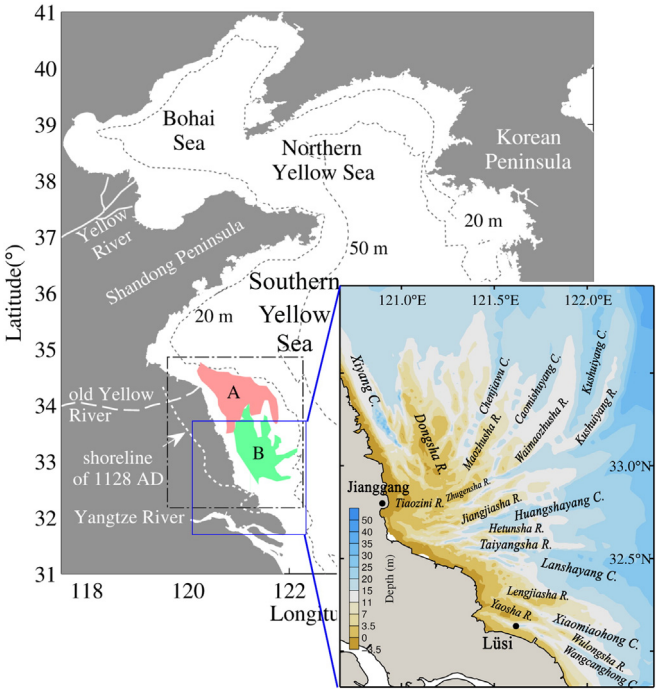

Fig. 1. Maps of the study area, with 20-m and 50-m isobaths. The reference shoreline of the Jiangsu Coast in 1128 CE is modified after Gao (2009) and Yang et al. (2003). The location of the OYR is modified after Lim et al. (2007) and Liu et al. (2013). Colored regions A and B represent the approximate location of the AYD and the Radial Sand Ridges field, respectively (modified after Park et al., 2000). The detailed diagram for the RSRs is enlarged and marked with the name of local ridges (abbr. R.) and channels (abbr. C.).

Jiangsu coast during the years 1128–1855 CE (Su et al., 2016). Since 1855 CE, the Yellow River has shifted its course to the Bohai Sea due to a natural breaching (Ren and Shi, 1986; Xue, 1993; Saito et al., 2000; Liu et al., 2013). Both the subaerial and subaqueous parts of the AYD have experienced severe morphological changes (mainly erosion) due to the cutoff of the sediment supply and local energetic hydrodynamic conditions (Saito and Yang, 1995; Zhou et al., 2014).

In this study, we focus on updating our understanding of the morphodynamic changes along the Jiangsu coast after 1855 when no more sediment was provided by the OYR. Many existing studies have investigated the morphological and hydrodynamic changes during this period, especially concentrating on the erosion of the AYD, e.g., the cross-shore profile changes (Zhang et al., 1998), the estimated volume of overall erosion (Saito and Yang, 1995), the transport direction of eroded sediment (Ren and Shi, 1986; Saito and Yang, 1995; Shi et al., 2012; Zhou et al., 2014) and the feedback of erosion to tidal dynamics (Chen et al., 2009). Most of the studies are based on shoreline comparisons in different periods (e.g., Chen et al., 2009; Zhou et al., 2014). However, the reliability of the shorelines obtained from historical maps is questionable (Su et al., 2016). Furthermore, such methods do not provide details of the process dynamics.

In addition to the AYD, another large-scale geomorphological unit in the SYS is a series of distinct sand ridges (Liu and Xia, 1985), named the Radial Sand Ridges (RSRs; Fig. 1). The RSRs cover an area of 22,470 km^2 (200 km in the north-south direction and 140 km in the east-west direction) with water depths ranging from 0 to 25 m (Wang et al., 1999; Li et al., 2001). Most of the ridges are submerged, accounting for 86% of the RSRs area (Wang, 2002). The Tiaozini ridge and the Dongsha ridge are the two largest ridges in the RSRs (Fig. 1). Previous research has revealed that tidal currents play a dominant role in the formation and development of the RSRs, while the contributions of storms/waves are secondary (Zhang et al., 1999). It is generally accepted and understood that the formation of the RSRs occurred several thousand years ago (Wang et al., 2012; Zhang, 1991). However, the relevant sediment sources of the RSRs are debatable, according to various existing published results (Chen et al., 2013), although these results are based on geological (e.g., Li et al., 2001; Yang et al., 2002; Wen et al., 2011; Wang et al., 2012) and geochemical (e.g., Yang et al., 2002; Wang et al., 2015) measurements. Most remaining questions are concentrated on the OYR and the Paleo-Yangtze River, both of which have discharged into the SYS but during different periods (Liu et al., 1989; Yin et al., 2008). Specifically, with respect to the role of the OYR, there is a wide range of viewpoints: (1) it provides a majority of the sediment for the whole RSRs (Ren and Shi, 1986; Zhang, 1991); (2) it is a sediment source for the northern RSRs (Cai and Ma, 1992; Wang and Zhang, 1998; Li et al., 2001); (3) it is source for the fine sediment (e.g., clay) for the northern RSRs (Wang et al., 2012); and (4) it is not a sediment source, whereas the sediment derived from the Paleo-Yangtze River during the Late Pleistocene (Li et al., 2001; Wang et al., 2012) is the single material basis for the RSRs (Yang, 1985; Fu and Zhu, 1986). These conflicting viewpoints may be due to the inherent restriction of geological approaches (e.g., localized measurements), which lack a large-scale dynamic point of view associated with sediment transport and morphological changes. The existing knowledge regarding the RSRs is insufficient for understanding its formation and evolution for both hindcast and forecast purposes.

The total amount of sediment eroded from the AYD since 1855 CE has been estimated as approximately 5×10^8 t/year (Hu et al., 1998). It is unknown whether such amounts of sediment contribute to the development of the RSRs. Furthermore, the bed sediment types throughout the RSRs vary greatly (i.e., from fine silt to fine sand, Li et al., 2001; Zhang, 2012). For example, the average grain sizes of the two largest ridges, i.e., the Tiaozini ridge and the Dongsha ridge, significantly differ: the Dongsha ridge is rich in sand, whereas silt is abundant in the Tiaozini ridge, although these two ridges are located near each other (Fig. 1). The processes and mechanisms behind the complicated sediment distribution patterns deserve more attention.

Since 1855, the dominant coastal processes significantly changed due to the abrupt end of the water/sediment discharges of the OYR. For example, compared with the fluvial and tidal processes, the wave effect was relatively weak during the period of 1128–1855. However, since 1855, wind waves have been more significant for erosion of the AYD, as well as for sediment transport in the RSRs and tidal flats (Zhang et al., 1999; Wang et al., 2014a). It is uncertain whether the wave effect is as important as previous studies estimated and how it affects the long-term morphological changes of the Jiangsu coast. Furthermore, to prevent a retreat of the shoreline, sea dikes have been built near the river mouth of the OYR since the 1930s (Liu et al., 2013). At present, most of the Jiangsu coastline is sheltered by artificial sea dikes (Ma et al., 2014; Syvitski, 2015). Due to this human intervention, landward retreat of the shoreline has been significantly reduced. However, the erosion of the shore-face and offshore seabed has become more acute (Cai et al., 2009). The importance of human activity on the large-scale and long-term morphological evolution of the Jiangsu coast (including both the AYD and the RSRs) requires further attention.

In this study, we aim to understand the morphodynamic processes along the Jiangsu coast since 1855, focusing particularly on the role of the OYR-derived sediment for the evolution of the RSRs. First, our process-based morphodynamic model (i.e., Su et al., 2016) is modified for application to the period after 1855. The model takes tides, waves and human interferences (i.e., sea dikes) into account to provide reliable predictions regarding the long-term morphological evolution of the Jiangsu coast. Subsequently, qualitative validations of the model results (i.e., shoreline evolution, distribution of offshore shoals, deposition of the fine sediment in the RSRs) are performed. Based on the analysis of the fine sediment deposition and sediment budget in the RSRs, the contribution of sediment eroded from the AYD to the development of the RSRs is investigated. Furthermore, the relative importance of tides, waves and human activities on the large-scale and long-term morphological evolution of the Jiangsu coast, is evaluated. Finally, since the

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