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Remarked morphological change in a large tidal inlet with low sediment-supply

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ABSTRACT

Sediment transport within small tidal inlets is sensitive to natural processes, whilst large tidal inlets are relatively robust systems because of their large tidal prism. However, remarked morphological changes may be initiated even under the condition of low sediment supply, as illustrated by Jiaozhou Bay, a large coastal embayment on the Shandong Peninsula, eastern China. Jiaozhou Bay is characterized by its relatively slow rate of natural change, and while the embayment has a flood-dominated entrance channel and muddy seabed, the suspended sediment concentration is generally low due to the lack of abundant source material. Observations of sediment dynamics show that net suspended sediment transport is directed towards outside of the bay, with an order of magnitude of 10^3 t during a tidal cycle. The export of sediment associated with this flood-dominated environment implies that the net transport pattern is controlled by tidal exchange processes rather than the strength of the seabed shear stress. Sediment budget calculations show that supply of artificial sediment into the bay can account for up to 72% of the total input, which is in agreement with the ^{210}Pb and ^{137}Cs radioisotope geochronologies, and this leads to accumulation rates of 10^0–10^1 mm yr^{-1}; without this, the deposition rate would be low under natural conditions. The flood tidal delta area is also influenced by the input of anthropogenic material, and acts as a depocenter with relatively high accumulation rates. Furthermore, although the inlet system has not yet reached its equilibrium state (i.e., the entrance cross-sectional area is still larger than the equilibrium cross-sectional area), land reclamation activities have resulted in a rapid reduction of the embayment area (by 37%) over the last 80 years. Our findings indicate that the rapid changes observed in the tidal basin area and seabed morphology are mainly the result of human activity rather than natural processes.

1. Introduction

Sediment transport and coastal morphology are primarily controlled by hydrodynamic energy and sedimentary supply (Bernabeu et al., 2012). However, geomorphological changes may not be necessarily driven solely by natural hydrodynamics. For instance, high-energy beaches tend to maintain an equilibrium profile and stable morphology; likewise, low-energy coastal environments may experience significant erosion associated with long-term submergence/emergence cycles (Chen et al., 2011). These two opposite extremes of the coastal spectrum illustrate the role of natural forcing in morphological change. Further, in certain circumstances, human activities may overwhelm the natural forcing, resulting in rapid morphological changes (Carrasco et al., 2012; Williams et al., 2013). It is essential to evaluate the role played by human activities so that the mechanisms of human influences on the coastal morphodynamics can be understood.

Large coastal embayments are important habitats for marine life; they also supply many natural resources to support coastal economic development. Human activities, such as land reclamation, marine farming, harbor construction, and tourism, can have major impacts on the ecosystem by initiating geomorphological change and causing pollution. It is well known that small tidal inlets (in terms of tidal basin area; e.g., $<10^1$ km^2) are more sensitive to changes in external forcing; e.g., the entrance becoming unstable due to intense longshore drift and decreasing tidal prism (Bruun, 1978). Vogel and Kana (1984) found a tidal inlet system-wide response to a change in hydrodynamics caused by man-made alterations, which resulted in a change from flood dominance to ebb dominance. However, the artificial closure of

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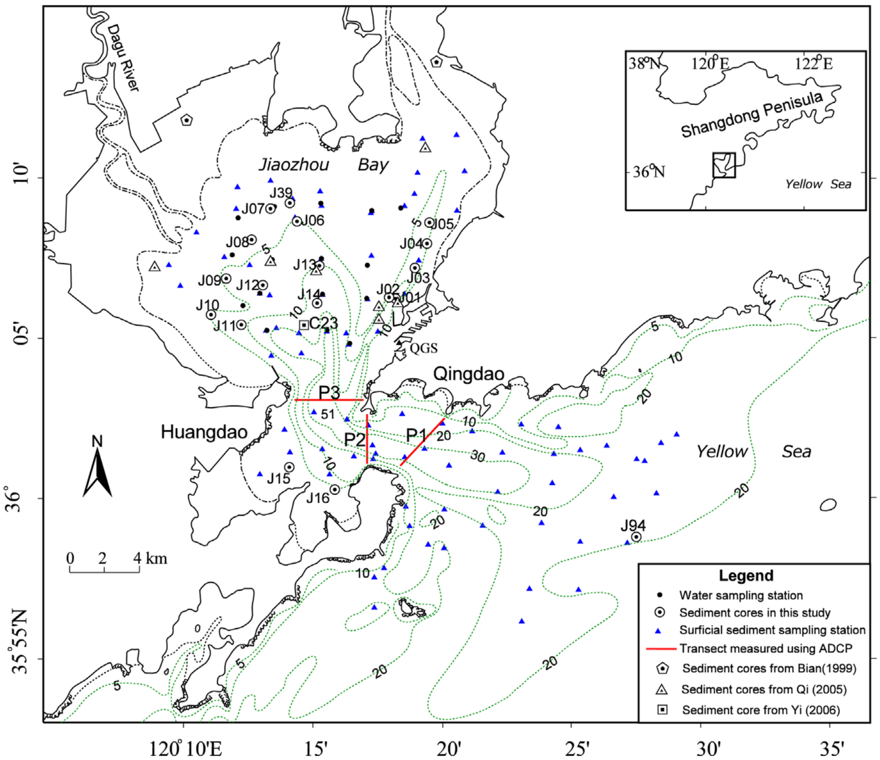

Fig. 1. Map of the study area (based on data from 2006) showing locations of the water sampling stations, ADCP cross-sections, and the short cores recovered in this study and previous studies. QGS = Qingdao Gauge Station. Dashed lines = bathymetry (m).

a lagoon caused the small Yuehu tidal inlet to switch from an ebb-dominated system to a flood-dominated system (Gao et al., 1998; Jia et al., 2003b); as a result, the inlet ecosystem deteriorated rapidly (Gao et al., 1998). However, the responses of physical systems and geomorphology to intense human activity in large tidal inlets (e.g., tidal basin area $>10^2$ km^2) remain unclear, although they may be relatively stable in response to external forcing. To investigate this relationship, we examined the large tidal inlet of Jiaozhou Bay (with an area of about 355 km^2; Fig. 1). This embayment has experienced significant anthropogenic activity including: (1) construction of docks and jetties; (2) reclamation of intertidal areas since the 1950s for sea salt production, marine farming, harbor storage, road construction and urban buildings, and industrial uses; (3) the artificial connection of the Island of Huangdao to the mainland in the 1980s; and (4) significant drainage of waste into the bay. As a result, the embayment water area has decreased by 37% over the past 80 years, and serious pollution events occurred along the eastern coast in the 1990s. Studies have indicated that the reduction of the embayment area has caused a weakening of hydrodynamic forcing; e.g., current velocities (Zheng et al., 1991, 1992). Hence, a quantitative assessment of the physical behavior and geomorphological evolution of Jiaozhou Bay is necessary if sustainable utilization of the embayment resources is to continue. In such an assessment, the sediment budget is an important issue. Dyer (1986) has shown that several potential sources contribute to sedimentation, including rivers, streams and outfalls, the seafloor, erosion of the shoreline and tidal flats, and inputs from the open sea, biological production, and the atmosphere. For Jiaozhou Bay, the sediment derived from rivers discharging into the bay was most important before 1980; however, the input of refuse from urban areas has become increasingly important since 1980 (ECCHE (Editorial Committee for "Chinese Harbours and Embayments"), 1993).

In the present study, we attempt to illustrate that remarked morphological changes can occur in a system with low sediment supply, on the basis of analyses of the various data sets with different temporal scales. They are associated with: (1) short term processes, i.e., suspended sediment flux by determining the open boundary conditions of the hydrodynamic system and measuring SSC at the mouth of Jiaozhou Bay; (2) the product of transport processes, i.e., sediment distribution patterns as revealed by seabed sediment sampling; and (3) the depositional chronology using ^{210}Pb and ^{137}Cs dating and the sediment budget were obtained by analyzing the sediment cores. By assessing sediment transport and accumulation rates, over timescales ranging from tidal cycles to decades, we aim to develop an improved understanding of the processes (including human activities, e.g., land reclamation and artificial sediment inputs) responsible for the system behavior of large tidal inlets.

2. The study area

The study site is the large tidal inlet of Jiaozhou Bay, which has a total area of about 355 km^2 (in terms of mean high water level; 2006 data) and is a semi-enclosed shallow embayment located on the southern Shandong Peninsula, eastern China (Fig. 1). The entrance to the bay has a minimum width of 3.1 km and a maximum water depth of 64.0 m (FIO (First Institute of Oceanography, State Oceanic Administration), 1984; ECCHE (Editorial Committee for "Chinese Harbours and Embayments"), 1993). Jiaozhou Bay is characterized by rocky coastlines, with a limited supply of fine-grained sediment from several small rivers.

This area has an average tidal range of 2.8 m and a spring tidal range of 4.8 m; the tides are regularly semidiurnal in character. In the coastal waters of the bay, the tidal currents are mainly rectilinear, with the tidal current velocity during the flood being stronger than during the ebb. Maximum current velocities exceeding 3.0 m s^{-1} have been recorded on flood tides (ECCHE (Editorial Committee for "Chinese Harbours and Embayments"), 1993).