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The evolutionary process of the geomorphology of tidal embayments in southern Jiaodong Peninsula, China

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ABSTRACT

Based on the theory of flood/ebb asymmetry, the evolution of the geomorphology of representative bays along the southern coast of the Jiaodong Peninsula over the last 40 years was investigated using remote sensing and geographic information system technologies. The results showed that coastal features such as tidal flats and tidal inlets in the bays changed significantly over time. The studied bays are in a ring-shaped geomorphic spatial pattern characterized by shallow water, and they were concentrically ringed by tidal flats and coastal plains before the early 1980s. Later, however, a number of ponds appeared between the coastal plains and tidal flats. The extent of sediment infill for each bay in the 1980s was greater than that in the 1970s. The conversion of flat-inlets and the erosion/deposition change of tidal inlets in these four bays during study period were not synchronized. Each bay was in a state of flood asymmetry, and both the net fine and net coarse sediment deposition took place in the 1970s. From the late 1960s to the early 1980s, Dingzi Bay was characterized by flood asymmetry, and its tidal asymmetry ratio increased. The Jinghai and the Wuleidao bays were in a state of flood asymmetry, and their tidal asymmetry ratios decreased, while Rushan Bay was in a transition state from flood to ebb asymmetry. However, intensive human activities over the last 30 years, especially the construction of coastal ponds, has greatly changed the hydrology and sedimentation of these bays, causing profound changes in geomorphic features; furthermore, these changes have guided the evolutionary process of the bays. Our results suggest that the intensive human activities were key factors that caused changes in the geomorphic evolution of the studied tidal embayments, especially the sudden change from a state of rising flood asymmetry to ebb asymmetry in Dingzi Bay.

1. Introduction

Human activities are having increasing influence on the marine environment, of which the coastal zone may be the most significantly impacted in the short term (Doney, 2010; Halpern et al., 2008). Bays are generally exploited more frequently than other parts of the coastal zone because of their position adjacent to and surrounded by accessible land. Therefore, bays have been impacted by human activities, both by indirect activity in adjacent terrestrial river basins and direct activity on the sea, such as land reclamation, enclosing tidal flats for cultivation (Bournazel et al., 2015), construction of coastal dams (Gao, 1998), and building coastal ponds on tidal flats (Santos et al., 2015). In recent years, many studies have focused on the ecological and environmental impacts of human activities, such as building coastal ponds (Rekha et al., 2015; Santos et al., 2015; Suarez-Abelenda et al., 2014; Thomas et al., 2010). This is one of several common patterns of human activities in bays, and it has been found that extensive construction coastal ponds significantly alters the morphodynamic conditions of bays and their geomorphic evolution (Stokstad, 2010).

The Jiaodong Peninsula, located in the eastern Shandong province of China, is a representative temperate rocky coast (Fig. 1).

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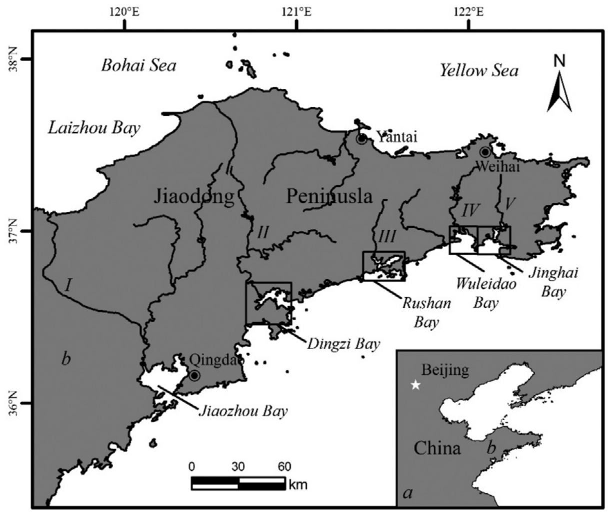

Fig. 1. Study region and location of the four representative tidal embayments. I: Jiaolai River, II: Wulong River, III: Rushan River, IV: Laomuzhu River, V: Qinglong River (Arcmap).

During the Holocene maximum transgression, the sea invaded the southern part of the peninsula along river valleys, and the lower parts of many rivers became drowned river valleys, which have evolved into large tidal embayments (Wang, 1993; Xia and Liu, 1990; Zhang and Li, 1994). Dingzi Bay, Rushan Bay, Wuleidao Bay, and Jinghai Bay are typical of these tidal embayments. They comprise tidal inlets and tidal flats, wide and shallow, with large width/depth aspect ratios. Ribbon-shaped tidal flats are broadly and evenly distributed along both sides of the tidal inlets. The broad intertidal zone has played an important role in the morphodynamic conditions of these bays, for which the morphodynamic evolution differs significantly from other bays (Brown and Davies, 2010; Prandle, 2003; Townend, 2005). During the last one hundred years, many tidal embayments in Jiaodong Peninsula have been in a state of continuous deposition because of serious upstream soil erosion in adjacent river basins (Wang, 1993). These bays were great important fishing grounds, significant ports or channels in history. Since the 1980s, the function of aquaculture in those bays has been strengthened because extensive areas of tidal flats, shallow water, and marsh were reclaimed into coastal ponds (Wang, 1993).

The theory of flood/ebb asymmetry is important for studying the evolutionary process of the geomorphology of tidal embayments (Dastgheib et al., 2008; Plecha et al., 2010). Tidal embayments are widely distributed all over the world. Previous studies suggested that the frictional drag of current decreased as the instantaneous water depth increased, and the net sediment transport in such bays depends on differences in the magnitude and duration of ebb and flood tidal currents (Dronkers, 1986; Prandle, 2003; Soulsby, 1997). The difference of maximum ebb and flood tidal currents determines the net transport of coarse sediment (fall velocity ≥ 0.1 m s^{-1}), while the difference of slack water periods before ebb and flood tides determines the net transport of fine sediment (fall velocity ≤ 0.01 m s^{-1}; de Swart and Zimmerman, 2009; Dronkers, 1986). In the early stages of bay formation, the flood current velocities are usually high, with a short flood current phase, because the mean depth at high water is greater than that at low water. Correspondingly, the ebb velocity is usually low with a long ebb phase, causing coarse sediment import to be favored. At the same time, the long slack water periods before the ebb tide favors the net import of fine sediment. After a flood and ebb period, net sediment deposition takes place in the bay, which is the so-called flood asymmetry (Friedrichs and Aubrey, 1988). Because of net sediment deposition over several thousand years since the beginning of bay formation, broad inter-tidal flats, narrow tidal channels, and connecting tidal creek systems form in the bay. The mean low water depth then exceeds the mean high water depth, owing to low water currents bound in tidal channels. As a result, the ebb velocity increases and the ebb phase decreases, favoring the loss of coarse sediment. At the same time, the long slack water periods before the flood tide favors the net export of fine sediment. After a flood and ebb period, the bay undergoes a net sediment erosion, the process is called ebb asymmetry (Friedrichs and Aubrey, 1988). In the next stage, when the downward erosion in the tidal inlet resulting from net sediment loss occurs, the mean high water depth increases, and a state of flood asymmetry resumes. Previous studies confirm that changes in tidal conditions at the open boundary can result in notable changes in flood/ebb asymmetry and sediment erosion/deposition (Roberts et al., 1998). A bay is thought to naturally alternate between states of flood and ebb asymmetry on a time scale of approximately one hundred years (Dastgheib et al., 2008; Plecha et al., 2010).

Based on the above theory, a wide set of parameters and formulae have been developed to relate tidal embayment morphology to predicted tidal asymmetry and the resulting net sediment transport. The control of tidal asymmetry by basin geometry can be explained to a great extent by the analytical solution for the propagation speed of the tidal phase along the axes of tidal embayments (Friedrichs, 2010; van Maanen et al., 2013 et al.). Numerical experiments have been carried out to show the numerically derived transition between ebb and flood dominance (Friedrichs and Aubrey, 1988; Friedrichs, 2010). Numerical model simulations of basin evolution (Dastgheib et al., 2008; van Maanen et al., 2013) have also shown that the geometries of such embayments approach the numerical equivalent presented by Friedrichs and Aubrey (1988). The flood-ebb asymmetry ratios γ_1 and γ_2, which are widely used to reveal the net transport of fine sediment and coarse sediment, hold reasonably well for many existing tidal embayments found along the coast of northwest Europe (Dronkers, 1986, 1998; van Maanen et al., 2013). The γ_2 highlighted in this paper from Dronkers (1998) produces nearly the same separation between ebb and flood-dominated systems as the numerical experiments of Friedrichs and Aubrey (1988) and is also effectively the same as the analytical parameterization of flood/ebb-dominant geometries (Friedrichs, 2010).

Based on theory of flood/ebb asymmetry, the sediment erosion-deposition process over 40 years in Dingzi Bay, Rushan Bay, Wuleidao Bay, and Jinghai Bay was studied be applying surveying technologies of RS, GIS, and GPS. The purposes of the present study are to 1) clarify the evolution of coastal geomorphic spatial patterns, 2) evaluate changes in coastal geomorphic features and deposition/erosion processes, and 3) reveal the functions of intensive human activities on the geomorphic evolution process of tidal embayments in southern Jiaodong Peninsula, China.

2. Study area

Jiaodong Peninsula (36°12′-38°12′N, 119°30′-122°43′E), with an area of 34,000 km^2, is the largest peninsula in China. It extends from east to west; the Bohai Sea is to the northwest, and the Yellow Sea is to the northeast and south (Fig. 1). Controlled by terrain and climate, there are a number of large seasonal mountainous streams including the Dagu River, Wulong River, Rushan River, Huanglei River, Laomuzhu River, and Qinglong River in the southern part of the peninsula. Dingzi Bay is located at the mouth of the Wulong River, Rushan Bay at the mouth of the Rushan River, Wuleidao Bay