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Spatial and temporal shoreline changes of the southern Yellow River (Huanghe) Delta in 1976–2016

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ABSTRACT

In this study, 364 Landsat satellite images were utilized to study the spatial and temporal shoreline changes of the southern Yellow River Delta in 1976–2016, and a new method revised and improved after Zhang et al. (2016) was proposed. By employing that method, the calculated sea levels calculated from simulated tidal heights and instantaneous shoreline positions rather than simulated tidal heights were used to correct fluctuations in instantaneous shoreline positions caused by tidal height and seasonal sea level changes and other random sea level fluctuations. When calculating the shoreline erosion rates and beach slopes, a statistical analysis of a large number of corrected shoreline positions was used to reduce the influence of random errors that were mainly caused by waves and other casual factors. The shoreline erosion rates and beach slopes presented in this paper are therefore more precise and reliable than those derived in previous studies, which only used two satellite images.

The results of this study show that the shoreline of the southern Yellow River Delta primarily experienced gradual erosion during 1976–2016, with an average erosion rate of 26.9 m/year. The average shoreline erosion rate increased from 24.9 m/year in 1976–1996 to 34.9 m/year in 1996–2016—an increase of 40%—probably due to the reduction in sediment discharge and shifting northward course of the Yellow River after 1996. The shoreline erosion rate of the central coast decreased from 50.2 m/year in 1976–1996 to 27.1 m/year in 1996–2016—a decrease of 46%—probably due to the protection offered by coastal hard structures. The average shoreline erosion rate caused by relative sea level rise was 8.5 m/year or 32% of the total average shoreline erosion rate. Relative sea level rise plays an important role in the erosion of the southern Yellow River Delta due to its flat beach. The beach slope of the southern Yellow River Delta was flat and stable in 1976–2016, and the average slope over most of the beach was 0.043%.

1. Introduction

Shorelines are very dynamic geomorphic systems where continuous changes occur at different spatial and temporal scales (Eman et al., 2015). In particular, due to the construction of reservoirs and diversions of freshwater for consumptive uses over the last century, reductions in river sediment loads have become a global concern and have led to the erosion of many deltas, including those of the Nile, Colorado, Ebro, Mississippi, Yangtze, and Yellow Rivers (Eman et al., 2015; Carriquiry et al., 2001; Batalla et al., 2004; Blum and Roberts, 2009; Li et al., 2014; Zhang et al., 2016). Decreases in river sediment loads joined with rising eustatic sea levels associated with global warming, isostatic loading factors, sediment compaction and the accelerated subsidence of deltaic sediments have moved many deltas from a condition of active growth to a destructive phase (Milliman et al., 1989; McManus, 2002).

Shoreline change is a considerable long process. Many shoreline samples over a sufficient number of years are required to analyze variations and trends in shorelines. In previous researches (e.g., Chu et al., 2006; Chen and Chang, 2009; Liu et al., 2013; Kuenzer et al., 2014), two satellite images were typically used to calculate shoreline erosion rates (SERs), which are also called end-point rates (Thieler et al., 2009). End-point rates are susceptible to shoreline position errors from the images, which finally result in large SER errors (Jaime et al., 2016).

Because of the dynamic nature of shorelines, researchers typically adopt shoreline indicators, of which high-tide line is the most popular. Although high-tide lines are not susceptible to sea level fluctuation compared with instantaneous shorelines, they may not appear as distinct lines but rather as transitional zones or not be visible at all (Crowell et al., 1991). Interpretations of high-tide lines from aerial photographs or satellite images can potentially be a significant source of errors (Boak and Turner, 2005). The interpretation of low-tide lines is more difficult because oftentimes they cannot be seen.

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Compared to high-tide and low-tide lines, instantaneous shorelines are obvious on satellite images. However, in addition to long-term shoreline changes, instantaneous shorelines are also influenced by short-term sea level fluctuations mainly caused by waves and tides. Due to the paucity of historical sea level data, researchers usually use simulated tidal heights to correct instantaneous shorelines (e.g., Chen and Chang, 2009; Liu et al., 2013). In addition to associations with astronomical tidal heights, historical sea levels are associated with seasonal sea level changes and waves. Therefore, the use of simulated tidal heights instead of historical sea levels to correct instantaneous shorelines will inevitably introduce errors; in particular, sea level errors will be greatly increased for flat beaches (Zhang et al., 2016).

Based on the above reasons, the SERs of the southern Yellow River Delta derived by previous researchers differ greatly, for example: 0–83 m/year in 1976–2000 by Chu et al. (2006) using high-tide lines; − 31–51 m/year in 1973–2009 by Liu et al. (2013) using instantaneous shorelines corrected by simulated tidal heights; and about 0–120 m/year in 1976–2013 by Kuenzer et al. (2014) using high-tide lines. The existence of such large differences means that the errors are very large, which is unfavorable to the study of shoreline change.

Some researchers have recently begun to use statistical analyses of large numbers of instantaneous shoreline positions to study SERs (e.g., Sabyasachi and Amit, 2009; Jaime et al., 2016; Zhang et al., 2016). They are more reliable than analyses based on two or a few images. In this study, instantaneous shoreline positions distinguished from 364 Landsat satellite images (http://glovis.usgs.gov) were used to study changes in the shoreline of the southern Yellow River Delta for 1976–2016. Sea level corrections performed to eliminate the influence of historical sea level fluctuations on instantaneous shoreline positions and the SERs and beach slopes obtained using the statistical analysis of the corrected shoreline positions are discussed. The influences of relative sea level rise, reductions in river sediment and engineering hard structures on shoreline changes are also discussed.

2. Study area

The Yellow River Delta is located on the western coast of the Bohai Sea and is among the most active regions of land-ocean interactions among the largest river deltas in the world (Yang et al., 2016). The study area is located on the southern Yellow River Delta and was mainly formed from 1929 to 1953 (Fig. 1). The surface sediment of Laizhou Bay is mainly composed of silt and clayey silt (Qiao et al., 2010). The alongshore sediment transport of the study area is southward, and the suspended sediment, which primarily derives from the Yellow River, can be transported southward in windy weather as far as the Xiaoqinghe river mouth along the coast (Chen, 1982). At this time, the southern Yellow River Delta is mostly undergoing erosion (Chu et al., 2006; Liu et al., 2013; Kuenzer et al., 2014).

The tidal regime off the Yellow River Delta is dominated by irregular semi-diurnal tides with mean ranges of 0.8–2.6 m. The lowest tidal range of 0.8 m occurs at the amphidromic point of the M2 tide (next to the Shenxiangou course) and gradually increases westward and southward (Hu and Cao, 2003). The climate in the study area has a distinct seasonal variability that is associated closely with monsoon activity. The prevailing northerly winds in winter are much stronger than the dominant southerly winds in summer; waves are generated mainly by local winds in the Bohai Sea, and the prevailing wave direction is northeast (Zang, 1996).

3. Data source

3.1. Satellite images

A total of 364 Landsat satellite images from 1976 to 2016, including MSS, TM, ETM + and OLI_TIRS images, were utilized in this study. The data set was provided by the Earth Resources Observation and Science Center (http://glovis.usgs.gov) and the International Scientific & Technical Data Mirror Site, Computer Network Information Center, Chinese Academy of Sciences (http://www.gscloud.cn). Fig. 2 shows the sensor types and imaging dates and times of the 364 satellite images. All the images were obtained at 1–3 GMT h, and the MSS and TM images were generally obtained prior to the ETM + and OLI_TIRS images both in acquisition date and time.

3.2. Simulated tidal heights and monthly mean sea levels of the Bohai Sea

Owing to the deficiency of measured historical sea level data, a tidal hydrodynamic model was used to determine the historical sea levels. Matsumoto et al. (2000) developed a global ocean tidal model (NAO.99b) that included 16 major short-period constituents. The simulated hourly tidal heights at T1 (T1 is located in the center of the study area) and Weifang Port (Fig. 1) during 1976–2016 were calculated using NAO.99b. Based on the acquisition dates and times of all the satellite images, the simulated tidal heights at the dates and times of the satellite images were calculated via linear interpolations of the simulated hourly tidal heights.

The monthly mean sea levels of the Bohai Sea (SL1) is from China Sea level bulletin 2015 (http://www.soa.gov.cn). The seasonal sea level change of the Bohai Sea is associated with local monsoon winds; in winter, the currents flow southward under strong northerly winds, leading to low sea levels, and in summer, the prevailing southerly winds cause influxes of current and lead to high sea levels (Li et al., 1982).

4. Methods

The methods used in this paper were revised and improved after Zhang et al. (2016). The pre-processing of the satellite images was performed following the steps described by Zhang et al. (2016) and included image synthesis, histogram equalization, geographic correction and computer-aided shoreline identification. Sixteen transects (S1–16) were used to study the shoreline changes (Fig. 1). The 16 transects were perpendicular to the local shorelines and away from the local river mouths. The average interval of adjacent transects was 2.5 km. On each transect, the farthest position from land of all the shoreline positions was used as the base point, and the distance of current shoreline position to the base point was recorded as the instantaneous shoreline position (ISP). The correlation coefficients between the corrected tidal heights at T1 and the 16 ISP sequences were 0.68–0.79 and averaged 0.75. The good correlations were the foundation for calculating beach slope using regression analysis.

In order to get more accurate results, ISPs were corrected not only for simulated tidal heights but also for seasonal sea level change, yearly shoreline change and random sea level fluctuation, which means the sea level data used in this study to correct the ISPs were not simulated tidal heights but rather sea levels calculated using the average ISPs of S1–3 and S10–16 ($\overline{ISP_{raw}}$), simulated tidal heights and seasonal sea level changes following the workflow presented in Fig. 3A. S4–9 were excluded when calculating the average ISPs because the following results showed that the slopes of S4–9 were not consistent over the entire beach. The sea level corrections of the 16 ISP_{raw} sequences were performed using the calculated sea levels following the workflow in Fig. 3B. All the variable abbreviations used in this paper were listed in Table 1.

4.1. Calculation of beach slope

The ISPs increase linearly with corrected tidal heights, and the linear regression coefficients are as high as 0.71–0.73 (Fig. 4A, B, C). According to the linear assumption of beach topography, the beach slope can be obtained using the reciprocal of the regression coefficient. The calculations were performed four times (Fig. 3). We first used $\overline{ISP_{raw}}$ versus the corrected tidal heights to calculate the average beach slopes