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Evolution of the Yellow River Delta and its relationship with runoff and sediment load from 1983 to 2011

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SUMMARY

Long-term data from a hydrological monitoring station and remotely-sensed satellite images were used to explore the effects of runoff and suspended sediment load on evolution of the Yellow River Delta (YRD) from 1983 to 2011. During this period, an average runoff of 18×10^9 m^3 yr^{-1} and an average sediment load of 341×10^6 t yr^{-1} flowed through the delta lobes into the sea. The runoff and sediment load exhibited downward trends with time, along with large inter-annual fluctuations. Three stages were evident in the data. From 1983 to the late 1990s, the Yellow River experienced progressively severe droughts which reduced both runoff and sediment load to its delta lobe. The delta nevertheless grew to a peak area of about 3950 km^2 in 2000. From 2000 to 2003, the YRD area decreased. Meanwhile, the operation of the dam at Xiaolangdi and changes in water consumption driven by a new regulatory framework helped stabilize the runoff. Although the sediment load continued to decline, partly due to sediment check dams along the middle Yellow River and the reduced sediment carrying capacity of the river, the YRD area nevertheless increased between 2003 and 2011. The variations in runoff and sediment load directly influenced changes to the plan-form area, shoreline migration, and morphology of the YRD. From 1983 to 2011, the net land area of the delta increased by 248 km^2, its coastline extended by 36.45 km, and its shape became increasingly irregular due to the emergence of its delta lobes. In 1996, an artificial diversion altered the position of the main delta lobe from Qingshuigou to Qing 8. A stepwise multiple regression analysis indicated that the YRD would have required average sediment loads of about 441×10^6 t yr^{-1} before 1996 and 159×10^6 t yr^{-1} after 1996 to maintain equilibrium.

1. Introduction

A river delta is formed by the deposition of river sediment as it enters the sea. Deltas simultaneously respond to environmental change by shrinking and expanding over temporal and spatial scales. Both the runoff and sediment load delivered to the sea are dominant factors affecting the evolution of a delta (Yu et al., 2011). Climate change has a direct affect on river delta systems by altering the upstream runoff (Xu, 2005; Wang et al., 2012; Gao et al., 2012). Furthermore, human activities, such as water diversion works, reservoir dam constructions, and soil and water conservation measures (e.g. sediment check dams, contour farming, afforestation, land consolidation, and water pricing) can also radically alter delta ecosystems by influencing the quantities of water and sediment discharging into the sea through the delta lobes (Xu, 2005; Miao et al., 2010; Wang et al., 2012; Gao et al., 2014a,b). In recent decades, almost all river deltas around the world have been impacted upon by human activities, and the increased frequency and severity of extreme runoff events through climate variability and change. Examples include deltas in the Nile river (El Banna and Frihy, 2009), Ebro River (Mikhailova, 2003), Mississippi River (Snedden et al., 2007), Mekong River (Le et al., 2007), Yangtze River (Yang et al., 2011), Pearl River (Zhang et al., 2010) and Yellow River (Wang et al., 2010). Recent research has established that 85% of the river deltas around the world shrank during the first decade of 21st Century due to sediment capture

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in the upstream reaches of their river basins, and it is believed that this situation will become more severe in the future (Syvitski et al., 2009).

The Yellow River Delta (YRD) provides one of the most poignant examples worldwide of the huge impacts on a delta that can arise from increased droughts and human activities affecting water consumption, river regulation, soil conservation, etc. (Miao and Ni, 2009). As the birthplace of ancient Chinese civilization, the lower Yellow River was the most prosperous region in early Chinese history (Yu, 2002) and remains of major socio-economic importance in modern China. The Yellow River is the second largest river in the world in terms of sediment load, with an average of 1.1×10^9 t yr^{-1} reaching the ocean annually (Milliman and Meade, 1983). Approximately 30–40% of the sediment transported to the sea is deposited at the delta lobe at the mouth of the Yellow River, forming the YRD (Li et al., 1998). Over the past 30 years, many research studies have been carried out on the YRD due to its socio-economic importance and unique ecological environment (Cui et al., 2009). For example, the YRD contains the second largest oilfield in China (Shengli Oilfield). It is also rich in biological resources and is home to 1543 wild animal species, 393 seed plant species, and 283 bird species (including 9 species qualifying as first-level nationally protected birds, and 42 at the second level) (Zhang et al., 1998). The YRD wetland is an important habitat and transfer area for many rare and endangered migrating birds, such as the red-crowned crane, hooded crane, Siberian crane, oriental stork, black stork, and golden eagle (Xu et al., 2002). In recent decades, the combination of decreasing runoff and sediment load due to increasing occurrences and severity of low-flow events (Yang et al., 1998) exacerbated by the influence of human activities (Fan et al., 2006a) have led to significant modifications to the YRD, including changes to its wetland landscape, biodiversity and deltaic configuration (Cui et al., 2013; Higgins et al., 2013).

Previous studies primarily focused on the qualitative relationship between the evolution of YRD and the stream-flow and sediment load in the delta lobe (Chu et al., 2006; Peng et al., 2010; Wang et al., 2010; Yu et al., 2011), land-use of the YRD (Chen et al., 2011; Zhang et al., 2011; Miao et al., 2012b; Ottinger et al., 2013), and shoreline changes (Cui and Li, 2011; Yang, 2012; Liu et al., 2013). Less attention was paid to quantitative contribution of runoff and sediment load on the YRD, the influence of artificial shifts of the course of the main delta lobe channel on the overall balance of the YRD, and the impacts of drought and human activities in the Yellow River basin on the evolution of YRD.

The aim of the present study is to examine the evolution of the Yellow River delta from 1983 to 2011 during which major droughts occurred (due to a combination of reduced runoff caused by climate change, increased water consumption driven by population change, rapid socio-economic development and poor irrigation practice), an artificial diversion of the delta lobe was implemented, a major reservoir began operation for flushing sediment and flood control, and changes that took place in regulation practice by the Yellow River Conservancy Commission from water and soil conservancy to an integrated framework. The YRD therefore provides a very useful exemplar to scientists, engineers, environmentalists and decision makers as a case study of the effects of drought-driven and anthropogenic changes to a key river delta. This paper analyzes the variations in runoff and sediment load in the Yellow River, and their effect on the morphological evolution of the delta. An assessment is made of the threshold values of sediment load required to main the equilibrium of the delta before and after artificial diversion led to a new delta lobe at Qing 8 in 1996. An error analysis is included. The insights gained about the temporal behavior of the YRD should be useful to decision makers weighing up future options for large-scale constructions and environmental protection measures affecting the YRD.

2. Yellow River Delta: study area, event chronology, and data sources

2.1. Study area

The YRD is located in the northeast of Shandong Province, China (Fig. 1). The northern and eastern portions of the YRD are adjacent to the Bohai Sea and Laizhou Bay. Three large artificial diversions of the main channel in the YRD were implemented in the past five decades (Fan et al., 2006b; Syvitski and Saito, 2007). In July 1964, the course of the Yellow River delta lobe was altered artificially from the Shenxiangou route to the Diaokou course to help alleviate potential flood problems. In May 1976, development of the Shengli Oilfield caused the delta lobe to shift course into the Bohai Sea through the Qingshuigou River. In August 1996, the main channel of the delta lobe was diverted northeast to the 8th section of the Qingshuigou River forming the Qing 8 course (Xu et al., 2002) in order to facilitate the offshore to onshore operation of the Xintan and Kendong Oilfields. Since then, the course of the delta lobe of the Yellow River has remained essentially unchanged, apart from some minor movements.

The YRD region is characterized by a warm-temperate continental monsoon climate with distinct seasons (Sun et al., 2014). The annual mean temperature ranges from 11.5 to 12.4 °C, with highest monthly temperature of 26.6 °C in July and lowest of −4.1 °C in January. The YRD is located in a semi-arid zone where the annual rainfall is 590.9 mm and pan evaporation exceeds 1500 mm. The monthly maximum rainfall is 227 mm in July and

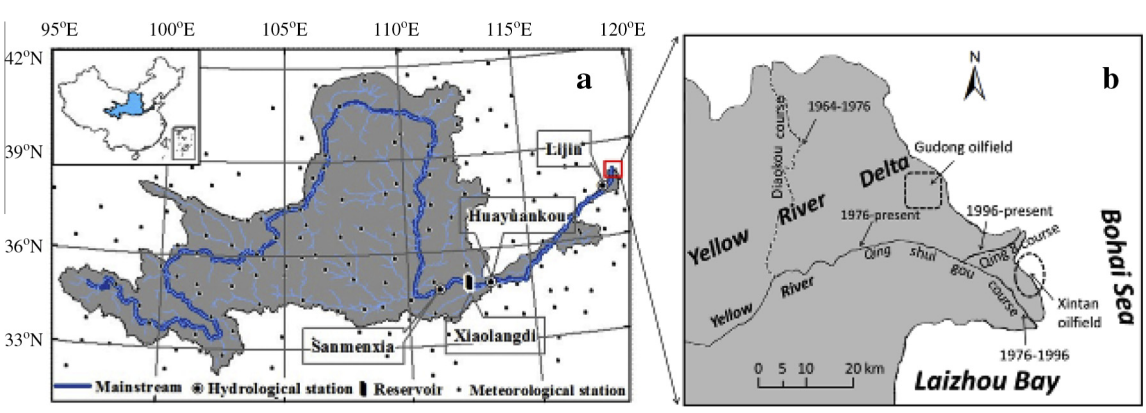

Fig. 1. Location of the Yellow River Delta (a) and the study area (b).