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Geomorphic evolution of the Yellow River Delta: Quantification of basin-scale natural and anthropogenic impacts

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ABSTRACT

The intensified impacts of both natural and anthropogenic processes in river basins on the sustainabilities of river deltas worldwide have necessitated serious international socioeconomic and environmental concerns. The Yellow River Delta (YRD), which formed within a relatively weak coastal dynamic environment, provides an excellent opportunity for a quantitative study of basin-scale natural and human influences on deltaic transformation. An examination of long-term bathymetric data demonstrates that the annual volumetric change of the YRD has experienced a statistically distinct declining trend during 1977–2005 with substantial inter-annual variations. Consequently, the decadal geomorphic evolution of the YRD has successively undergone three stages, namely, quick, stable and slow accumulation stages. Taking the fluvial supply as a link in combination with long-term hydro-meteorological data, the geomorphologic processes of the YRD are closely associated with the rainfall, air temperature and water diversion within the Yellow River catchment. A significant quantitative relationship exists between the deltaic land accretion and basin controls, indicating that annual morphological change will decrease by 4×10^8 m^3/yr with every decrease of 100 mm/yr in annual precipitation, decline by 2.49×10^8 m^3/yr with every increase of 1 °C/yr in annual air temperature, and diminish by 1×10^8 m^3/yr with every increase of 100×10^8 m^3/yr in annual water abstraction. Further non-dimensional analysis reveals that 50.55%, 36.26% and 13.19% of the inter-annual variation of the morphological change can be attributed to inter-annual variations of the precipitation, air temperature and water diversion, respectively. Natural environmental changes can account for 86.81% of the overall variations, while human-induced changes can explain the rest. Moreover, the contributions from rainfall, air temperature and water diversion to the decadal landform evolution transition from quick accumulation to stable accumulation were estimated as 46.59%, 35.23% and 18.18%, respectively, and their respective contributions to the transition to the subsequent slow accumulation stage were 2.09%, 92.67% and 5.24%. The natural contributions to the inter-decadal shifts were calculated as 81.82% and 94.76%, which are much greater than the respective human-related contributions of 18.18% and 5.24%. Our quantification results highlight that since the late 1970s, the changes of natural environment throughout the watershed have played a strikingly important role in both the inter-annual and inter-decadal changes of the sedimentary processes of the YRD. This study provides valuable quantitative references for the validation of basin-delta process-based research and for the sustainable development of the YRD. Furthermore, the YRD can be regarded as a typical case for deltaic systems that are currently being subjected to catchment-scale natural and anthropogenic influences, thereby suggesting the direction of future research.

1. Introduction

River deltas formed as a result of the accumulation of substantial quantities of terrestrial sediments near estuaries are of great importance from a human perspective because they are host to numerous major cities, encompass vibrant wetland ecosystems and provide abundant sediment-associated resources for the global biogeochemical cycle (Overeem and Brakenridge, 2009; Syvitski, 2008; Wright, 1977). Understanding the transformations of river deltas affected by global environmental changes has been set as a goal of the International Geosphere Biosphere Programme, and consequently raised strong co-ordinated international efforts (Holligan and Boois, 1993; Syvitski et al., 2009). Generally, the accretion of land within river deltas crucially depends on the fluvial material supply, namely, water and sediment discharges into the sea (Saito et al., 2001), and the coastal environment of the receiving sea, including the tidal regime and wave

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climate (Galal and Takewaka, 2011). Other than coastal dynamics, river hydrological conditions vary radically and rapidly at inter-annual and longer timescales due to natural (e.g., rainfall and air temperature) and human-induced (e.g., dam and reservoir operations and implementations of water-soil conservation measures) environmental changes in river basins (Liu et al., 2014b; Syvitski and Milliman, 2007; Tian et al., 2016; Walling and Fang, 2003). Here, a river basin is defined as a river catchment area where water collects and drains off. In recent decades, the quantity of terrestrial materials transported into the oceans through many large rivers, including the Mississippi River, the Mekong River, the Pearl River, the Yangtze River and the Yellow River (Meade and Moody, 2010; Wang et al., 2011), has drastically declined, thereby exacerbating the vulnerabilities of estuarine sedimentary systems (Giosan et al., 2014; Tessler et al., 2015). Under the combined influences of natural processes and human activities throughout watersheds, most deltas face threats represented by the erosional retreat of shorelines, the recession of wetland ecosystems and the destruction of coastal infrastructures (Syvitski, 2008; Syvitski et al., 2009).

The temporal variations of basin natural and human-related factors and their spatial variations play extremely important and complex roles in runoff generation and sediment yield within a catchment and indirectly affect the deltaic geomorphological processes (Syvitski and Milliman, 2007; Wang et al., 2007; Walling and Fang, 2003). Therefore, the identification of basin controls on the deltaic evolution and the clarification of their relative quantitative impacts are both of great challenge, which have been inadequately addressed to date. In addition, a comprehensive quantification of the relationship between deltaic and basin processes is urgently needed to maintain or restore the sustainabilities of river deltas. Process-based numerical models, which are being increasingly utilized to simulate the short-term morphodynamic evolution of river deltas, appear to be both inefficient and inaccurate at the long-term scale for several reasons, including fugitive meteorological conditions, irregular basin-scale human interventions, strong couplings between river hydrological processes and channel bed evolutionary processes, complex river-ocean interactions and massive data processing requirements (Fagherazzi et al., 2015; Lespinas et al., 2014; Santos et al., 2014; Wang et al., 2006a). In contrast, multivariate statistical analysis could represent a practical approach for determining the dominant basin-related drivers of deltaic transformations, and differentiating their respective impacts on the deltaic evolution at multiple timescales by relating morphological changes to macro-scale influences from a statistical perspective. Among the worldwide-renowned deltas, the Yellow River Delta (YRD) in China provides an ideal site for such a statistically quantitative study, which could be a reference for similar deltaic systems.

Once hailed as the world's most rapidly constructive delta (Xu et al., 2002), the YRD formed from a large and heavily sediment-laden river, namely, the Yellow River, within a micro-tidal estuary characterized by weak wave activity (Hu et al., 1996; Ren and Shi, 1986). Over the past few decades, the hydrological processes of the Yellow River have been subjected to enormous influences from natural and human-induced environmental changes within the Yellow River catchment (Jiang et al., 2017; Wang et al., 2006b, 2007; Xu, 2005), thereby triggering profound morphological and ecological responses of the YRD (Cui et al., 2013; Peng et al., 2010). The water and sediment discharges of the Yellow River system have been intensively monitored since the 1950s. Similarly, the basin-scale precipitation, earth surface air temperature and various types of human activities have been observed since the 1960s. A series of high-resolution satellite images and detailed underwater bathymetric soundings have been acquired throughout the YRD since the 1970s. Collectively, these unique and valuable long-term datasets make it possible to reliably and statistically isolate the basin-scale natural and human-related impacts on the land accretion of the YRD in greater detail than most other river deltas. Previous extensive qualitative descriptions have been provided for the interrelations between the evolution of the YRD and natural and anthropogenic changes within the catchment (Kong et al., 2015; Peng and Chen, 2010; Yu et al., 2011; Zhou et al., 2015), but quantitative analyses have received much less attention. Xu (2006, 2008) quantitatively linked the coastline migration of the YRD to basin influences and performed estimates of both natural and human contributions to the inter-annual variations of deltaic morphological changes. However, these investigations were insufficient, as they considered only the transformation of the Yellow River Subaerial Delta (YRAD) while ignoring that of the Yellow River Submerged Delta (YRSD). However, the subaqueous delta is an indispensable component of a deltaic system, as it not only supports the subaerial delta but also reflects the principal outcome of river-ocean interactions (Elliott, 1989). Jiang et al. (2017) revealed a close association between the progradation of both the YRAD and the YRSD at an inter-annual timescale. Such a quantification is credible only when the topographic changes of the YRAD and the YRSD are investigated in tandem. In addition, the impacts of catchment-scale natural processes and human activities on the transition of medium-term geomorphic evolution of the YRD also require some understanding. Jiang et al. (2017) and Wang et al. (2007) evaluated the contributions of various basin factors to the change in fluvial sediment supply of the Yellow River over different decades and indirectly and qualitatively demonstrated the association between basin influences and the medium-term evolution of the YRD, but their proposed direct quantitative relationships still needs to be further studied.

Hence, the main objectives of our research are to: 1) examine the volumetric change of the YRD (1977–2005), including the YRAD and YRSD, 2) identify the natural and human drivers within the catchment that dominate the deltaic transformation using fluvial input as a link, 3) establish a quantitative association between the deltaic morphological changes and influential basin parameters, and 4) quantify the natural and anthropogenic contributions to the inter-annual and inter-decadal changes of the deltaic geomorphological processes. This research could be conducive to bridge the knowledge gap between short-term seasonal and long-term (i.e., centennial- to millennial-scale) sedimentary evolutionary trends of the YRD under changes to the catchment environment. Moreover, the insights gained from this study could provide policy makers with valuable quantitative references for the sustainability of the YRD and guide public concerns regarding the further development of other deltas.

2. Overview of the study area

As the second largest river in China, the Yellow River originates from the Qinghai-Tibet Plateau, loops around the Loess Plateau (LP), and then flows generally eastwards across alluvial plains into the Bohai Sea (Fig. 1a). The Yellow River is the largest contributor in Asia of fluvial sediments into the sea, and it ranks second globally in terms of the quantity of sediment discharged into the sea over the past millennium (Milliman and Meade, 1983). The Yellow River can be divided into three sections according to its geographic characteristics: the upper reaches, the middle reaches and the lower reaches (Fig. 1a). The average annual precipitation is highly variable across the river basin and ranges from 368 mm in the upper reaches to 530 mm in the middle reaches and to 670 mm in the lower reaches. The average annual air temperature varies from 1 °C to 4 °C in the upper reaches, from 8 °C to 14 °C in the middle reaches, and from 12 °C to 14 °C in the lower reaches (Chen et al., 2005). Over the past few decades, the average annual precipitation within the catchment has declined significantly while the average annual air temperature has increased markedly (Wang et al., 2013; Yao and Wu, 2014). During the latter half of the 20th century, a series of water-soil conservation measures were implemented within the middle reaches to improve the soil anti-erosion ability and prevent soil loss within the LP (Wang et al., 2007). By 2005, these erosion control practices, which included the construction of terraces, the implementation of reforestation and the planting of grass, had controlled an area of approximately 78,000 km^2 throughout the