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# Progradation of the Yellow (Huanghe) River delta in response to the implementation of a basin-scale water regulation program

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ABSTRACT

The water and sediment supply to the lower reach and estuary of the Yellow (Huanghe) River have been altered to a very significant degree by the construction of numerous small to large reservoirs and the progressive implementation of water and soil conservation measures across the entire drainage basin since the late 1950s, followed by a basin-scale water regulation program since 2002. There is an urgent need to know how progradation of the Yellow River delta (YRD), an area on which people live and farm, has continued and will continue to respond to these controls. This study examines the changing patterns of water and sediment supply to the YRD over the period of 1950–2013 and, using remote sensing, it evaluates the morphological changes of the delta during 1976–2013. Although both water and sediment input to the delta have been described as declining significantly since the mid 1960s, we show that since 2005 the supply of water has remained at around 20 billion $m^3\ yr^{-1}$ and that for sediment at about 0.13 billion t $yr^{-1}$; water input has been even slightly increasing. The dynamics of extension/shrinking and avulsion in river-mouth channels and accretion/erosion of shorelines is an integrated response to the complex variations in both sediment and water supply. This study develops a quantitative relationship between water and sediment supply and the area of land accretion and it predicts the critical condition for land accretion in the YRD. To ensure that delta land will not be lost, care is needed in the future implementation of the basin-scale water regulation program.



## 1. Introduction

The Yellow (Huanghe) River delta (YRD) is one of the most rapid sedimentation areas on Earth because the river is the most sediment-laden in the world and supplies a very large amount of sediment to its estuary each year. As it has been estimated that the Yellow River historically delivered annually some 1.08 billion t of sediment to the sea, accounting for 6% of the total fluvial terrestrial-sediment into global oceans (e.g. Milliman and Meade, 1983; Saito et al., 2007). In contrast to such dynamic river processes, the delta has been subject to relatively weak ocean dynamics due to a low tidal range and a slow rate of sea-level rise (e.g. Ren and Shi, 1986; Wang et al., 1992, 2012; Zeng, 1997; Saito et al., 2001; Hu and Cao, 2003). As a result, a large amount of sediment carried by the Yellow River has been deposited near the river mouth, forming a vast delta that has extended over 800 km during the Holocene from the Bohai Sea in the north to the Huanghai Sea in the south (Chinese Academy of Sciences, 1980; Hillel, 1991; Li and Finlayson, 1993; Van Gelder et al., 1994).

In line with the creation of such an extensive delta, the course of the river to the sea has often changed according to historical documents over the past 4200 years (e.g. Chinese Academy of Sciences, 1980; Pang and Si, 1980; Li and Finlayson, 1993; Zeng, 1997; Saito et al., 2000). In some cases this affected a large number of people and the collapse of regional economies (e.g. Wang and Liang, 2000; Zhu et al., 2003). To reduce the oversupply of sediment and to make optimal use of the water, many approaches have been adopted, including systematically building numerous small to large reservoirs and adopting effective water and soil conserving measures across the entire basin of the Yellow River since the late 1950s. These intensive human activities, together with the regional climate change consisting of higher temperatures and the increasing frequency and intensity of droughts in recent decades, have lowered water and sediment yields significantly from the upper and middle Yellow River Basin (e.g. Fan et al., 2006a,b; Wang et al., 2007; Peng et al., 2010; Ringler et al., 2010; Yu et al., 2013a,b). Consequently, the amount of water and sediment delivered to the YRD has reduced and the rate of sedimentation in the estuary slowed greatly, causing significant coastal erosion in many parts of the delta (e.g. Chu et al., 2006; Saito et al., 2007; Wang et al., 2010; Ma et al., 2012; Yu et al., 2013a,b; Chu, 2014; Liu et al., 2014; Zhou et al., 2014). The delta today supports a human population of more than

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two million who obtain their livelihood from farming, fishing and oil-exploiting, so changes to its water and sediment supply and land area can have profound impacts.

Associated with water and sediment reduction, there have been numerous times during the 1980s and 1990s when water flow to the estuary has ceased completely, causing wide ranging concern as to the health of the second largest river in China (e.g. Giodano et al., 2004; Yang et al., 2004). To address this, a water regulation program has been enforced by the government of China since 1999 and enhanced since 2002 after the Xiaolangdi Reservoir became fully operative. This regime of regulation controls the supply of water and sediment to the YRD to a significant degree and yet little is known as to how progradation and erosion of the YRD have responded.

The morphological development of a delta is determined by many factors, such as sediment input, tidal regime, wave energy, river discharge, and littoral currents (e.g. Wright and Coleman, 1973; Allison et al., 1995; Roberts, 1997; Zhao et al., 1997; McManus, 2002; Bridge, 2003; Blum and Roberts, 2009; Lamb et al., 2012; Nanson et al., 2013). Among so many potential factors, detailed studies of the changes in the accretion of the YRD during 1953–1997 have shown that sediment input is the major factor driving progradation (e.g. Wang and Liang, 2000; Chu et al., 2006; Wang et al., 2006; Bi et al., 2014), but water supply is also important (e.g. Xu, 2002; Zhang and Hu, 2007a,b; Cui and Li, 2011). Sediment input provides material for delta construction while water supply provides the dynamic conditions for sediment transport and deposition. Xu (2002) suggested that the effects of both water and sediment supply on the progradation of the YRD need to be determined in an integrated way; however, most studies so far have focused on these parameters separately (e.g. Wang et al., 2006, 2010; Cui and Li, 2011; Bi et al., 2014). The lack of an integrated approach makes it difficult to evaluate the combined effects of water and sediment supply on delta progradation.

To evaluate how the YRD tends to respond to the implementation of the basin-scale water regulation program, this study examines the changing patterns of annual runoff and sediment supply from 1950 to 2013 and assesses the degree of human control that has influenced the morphological changes of the delta. Furthermore, using remote sensing images, the extension/shrinking and avulsion of river mouth channels and the corresponding accretion/erosion patterns of the shorelines during the period 1976–2013 are analyzed. Finally, an integrated quantitative relationship between land-accretion and water and sediment supply to the YRD is developed and the potential effects of the implementation of the basin-scale water regulation program on the progradation of the YRD are evaluated.

## 2. Geographic characteristics of the study area

The vast YRD consists of two parts, the ancient delta and the modern one. They were separated in 1855 when a major switch occurred in the Yellow River's course, from the Huanghai Sea in Southeast China (south of the Shandong Peninsula) to the Bohai Sea in Northeast China (south of Tianjin) (e.g. Pang and Si, 1980; Wang and Liang, 2000; Ganti et al., 2014). Since the switch, a delta of about 6113 km$^2$ has formed in the northeast part of Shandong Province, with the delta's vertex moving downstream gradually from Lijin (Wright et al., 1990; Li et al., 1998; Shi and Zhang, 2003) (Fig. 1).

Across the current delta, abundant wetlands have developed largely from the abandoned river mouth channels. These wetlands host a diverse biological habitat that include over 1900 ground animal and plant species, as well as over 260 bird species. Importantly, the YRD provides a resting place for migrating birds, including about 152 protected species from the inland of the northeastern Asia and the western Pacific Ocean. Because the delta has undergone rapid economic development including exploitation of its associated oil field, the question of how to keep the structure and function of these wetlands secure has been the subject of numerous studies. Negative impacts of development include seawater intrusion due to reduced water and sediment discharges and associated weakening river dynamics in recent decades (e.g. Lian et al., 2008; Ottinger et al., 2013; Kuenzer et al., 2014).

Since the modern YRD development initiated in 1855, the river's major courses to the sea have shifted frequently. The last three major courses of the river have been Shenxiangou from 1953, Diaokougou from 1964, and Qingshuigou from 1976 (Fig. 1b). The last of these is the main focus of this study because it bears a clear imprint of the influences of human intervention on the delta's development, especially the effect of the water regulation program which was implemented over the entire drainage basin of the Yellow River since 2002.

## 3. Changing patterns of water and sediment supply to the YRD during 1950–2013

### 3.1. Water regulation program

The water regulation program of the Yellow River was initiated for ensuring that the Yellow River mouth would receive water throughout the entire year. This program initially developed from a cross-provincial, quota-based water allocation agreement enforced by the Government of China in 1999 (Chen et al., 2002; Zhu et al., 2003). The main reason for implementing the program is that the YRD frequently encountered very low flows and even no-flow periods during the 1980s and the 1990s, with devastating effects on wetland ecosystems and serious water-use problems in the lower Yellow River and the YRD (Cai and Rosegrant, 2004). Three large reservoirs have been operated jointly by the Yellow River Water Conservancy Commission to control the use of water from the Yellow River in each of the eight provinces that constitute the basin (Fig. 1a), during 1999–2002. The reservoirs include the Liujiaxia and Longyangxia Reservoirs constructed on the upper Yellow River in 1974 and 1985, respectively, with respective volumes of 5.7 and 24.7 billion m$^3$, and the Sanmenxia Reservoir built near the end of the middle Yellow River (where it leaves the uplands) in 1960 (Fig. 1a). Although the Sanmenxia Reservoir initially had a volume of 36 billion m$^3$, heavy sedimentation after its construction has reduced its available volume to less than 1 billion m$^3$ (Chen et al., 2002; Ma et al., 2012). Despite such a substantial loss, it still has some capacity for adjusting runoff and sediment, and the joint operation of these three large dams has successfully ended more than two decades of no-flows in the lower Yellow River and the YRD (e.g. Chen et al., 2002; Wang, 2005, 2010).

In 2002, the newest large reservoir (Xiaolangdi) became fully operational. Because of its large available volume (12.65 billion m$^3$) and location at the exit of the last gorge in the middle reach of the Yellow River, about 130 km downstream of the Sanmenxia Reservoir (Fig. 1a), it provides a very effective control over the release of water and sediment to the lower Yellow River and the YRD. This has significantly enhanced implementation of the water regulation program in the lower drainage basin. In particular, the joint operation of the four large reservoirs (Longyangxia, Liujiaxia, Sanmenxia and Xiaolangdi) not only ensures that water flow to the estuary of the Yellow River will not be cut off in dry seasons, but also makes it possible to release specially modulated water and sediment regimes through Xiaolangdi Dam to the lower reach and estuary of the Yellow River. Since 2002, this water-sediment modulated scheme has been conducted in June every year and as a result, a considerable amount of sediment deposited in the Xiaoliangdi Reservoir has been expelled out and the uplifted bed of the lower reach of the Yellow River scoured to a considerable degree (e.g. Wang et al., 2010; Chen et al., 2012; Chu, 2014). Due to the heavy deposition of sediment, the channel bed of the lower reach has become elevated above the adjacent valley floor by some 8 to 12 m over the past 40 years, so this water-sediment modulated scheme helps to reduce the discrepancy in channel and ground elevation (Ma et al., 2012; Chu, 2014).