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The hydro-environmental response on the lower Yellow River to the water–sediment regulation scheme

Dongxian Kong [a,b], Chiyuan Miao [a,b,*], Jingwen Wu [a,b], Qingyun Duan [a,b], Qiaohong Sun [a,b], Aizhong Ye [a,b], Zhenhua Di [a,b], Wei Gong [a,b]

[a] State Key Laboratory of Earth Surface Processes and Resource Ecology, College of Global Change and Earth System Science, Beijing Normal University, Beijing 100875, PR China
[b] Joint Center for Global Change Studies, Beijing 100875, PR China

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ABSTRACT

Heavy sedimentation has led to the phenomenon of a secondary perched river in the lower Yellow River. The water–sediment regulation scheme (WSRS) using the Xiaolangdi Reservoir was implemented in 2002 to solve this problem. In this study, we analyzed the impact of the WSRS on the lower Yellow River and investigated the mechanism by which the WSRS affects channel erosion. We found that the runoff and sediment load, the sediment grain size, and the river channel of the lower Yellow River have all altered dramatically since the implementation of the WSRS. The variations in runoff and sediment load are no longer synchronized: runoff shows a rising trend, whereas sediment load remains relatively stable. The proportions of runoff and sediment load during the rainy season have decreased, whereas the proportions of runoff and sediment load during the dry season have increased. The median sediment grain size displays a gradually increasing trend top–down along the lower Yellow River. The main river channels in the lower Yellow River have been fully scoured, leading to an increase in channel depth and bankfull discharge. In addition, the sediment load flowing into the estuary reach is relatively stable, with an average value of 158.6×10^6 t, which is sufficient to maintain the dynamic balance of the Yellow River Delta. We found that the degree of channel erosion in the lower Yellow River depends mainly on the incoming sediment concentration.

1. Introduction

Dams, especially large dams, have played a pivotal role in the comprehensive utilization of rivers. The earliest dams were built for the purposes of irrigation, flood control, and water supply. Later, most of the world's large rivers were dammed to generate power to help meet the increasing global demand for renewable energy. Dams were built on almost all of the world's large rivers, e.g., the Three Gorges Dam on the Yangtze River (Guo et al., 2012; Su et al., 2013), the Aswan High Dam on the Nile River (Stanley and Wingerath, 1996; Strzepek et al., 2008), and the Hoover Dam on the Colorado River (Kwak et al., 2014). In addition to the intended effects, the construction and utilization of dams simultaneously results in indirect impacts on the river system. Large dams and reservoirs commonly affect the runoff and sediment load into the sea (Dai et al., 2008; Wang et al., 2006a; Yu et al., 2013) and thereby change the evolution of the river delta (Yang et al., 2011). As the river is the prime source of nutrients for estuaries, the composition of material flowing to the sea (e.g., nitrogen content, phosphorus content, and salinity) can be modified by the variations in material flux (Carriquiry et al., 2010; Jin et al., 2013; Gao et al., 2014a). Downstream fluvial sedimentation also changes the morphology of riverbeds due to the loss of energy in the reduced flow (Dai and Liu, 2013). In addition, dams are widely recognized as having significant negative consequences for the surrounding natural ecosystems and environment (Fu et al., 2010; Gao et al., 2014b). The construction and use of dams may affect the distribution of local vegetation (Kellogg and Zhou, 2014; New and Xie, 2008; Su et al., 2012) and destroy animal habitats (Asaeda and Rashid, 2012; Yi et al., 2014, 2010).

The Yellow River is called "the cradle of Chinese civilization", and it was the most prosperous region in early Chinese history (Yu, 2002). To prevent floods and generate electricity, a cascade of large dams has been built along the mainstream Yellow River in

* Corresponding author at: Beijing Normal University, College of Global Change and Earth System Science, Beijing 100875, PR China.
Tel.: +86 10 58804191; fax: +86 10 58804191.
E-mail address: miaocy@vip.sina.com (C. Miao).

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recent decades. Currently, the Yellow River Basin is one of the most manipulated fluvial systems in the world, with dozens of large dams. By 2012, there were 29 large reservoirs scattered widely across the river basin with storage capacities exceeding $0.1 \times 10^9\,m^3$. The Xiaolangdi Dam is located in the mouth of the last gorge in the middle reach of the Yellow River, approximately 40 km north of Luoyang, Henan Province (Fig. 1), and is a key location for the control of flooding and sediment in the lower reaches of the Yellow River. The Xiaolangdi Dam is a multi-purpose project mainly designed for flood control, ice control, and sediment reduction, as well as irrigation, water supply, and power generation. Since the completion of the Xiaolangdi Dam at the end of 2002, a water–sediment regulation scheme (WSRS) has been conducted annually by the Yellow River Conservancy Commission (YRCC) to address downstream flooding, deposition problems, and other issues (Wan et al., 2013).

Most previous studies related to the WSRS focused on changes in the hydraulic characteristics (Yu et al., 2013; Zhang et al., 2009), sediment transportation (Miao et al., 2010; Xu and Si, 2009), and channel adjustment (Xu et al., 2005) of the lower Yellow River, as well as on the evolution of the Yellow River Delta (Wang, 2005; Yao et al., 2012). However, these studies mainly focused on only one or two indices individually. Several studies have attempted to explain the patterns of erosion and sediment deposition in the channel of the lower Yellow River. Some researchers have attributed the channel erosion to the artificially high flow rate during the WSRS (Wan et al., 2013; Xu and Si, 2009), whereas others suggest that the dominant factor is the large volume of water discharged from the Xiaolangdi Reservoir during the WSRS (Qi et al., 2012; Yu et al., 2013). Thus, the mechanism by which the WSRS influences the evolution of the lower Yellow River is still unclear and needs further quantification. In this study, we assess the implementation of the WSRS in detail and comprehensively analyze the effects on runoff, sediment load, sediment grain size, and channel erosion, as well as on the evolution of the estuary delta. In addition, we also investigate the mechanism though which the WSRS affects channel erosion in the lower Yellow River. This exploration of the impact of the WSRS on the lower Yellow River will provide a reference case and a theoretical basis for the management of other rivers.

2. Study area and data collection

2.1. General description of the study area

The Yellow River is the second largest river in China, with a drainage area of 795,000 km^2 and a length of 5464 km. The mean annual natural runoff of the Yellow River is normally $58 \times 10^9\,m^3$, and the mean annual suspended sediment load is $1.6 \times 10^9\,t$, ranking it first in all of the world's rivers in terms of sediment load (Wu et al., 2008a,b). In general, the lower Yellow River is defined as the reach between Mengjin in Henan province and Lijin in

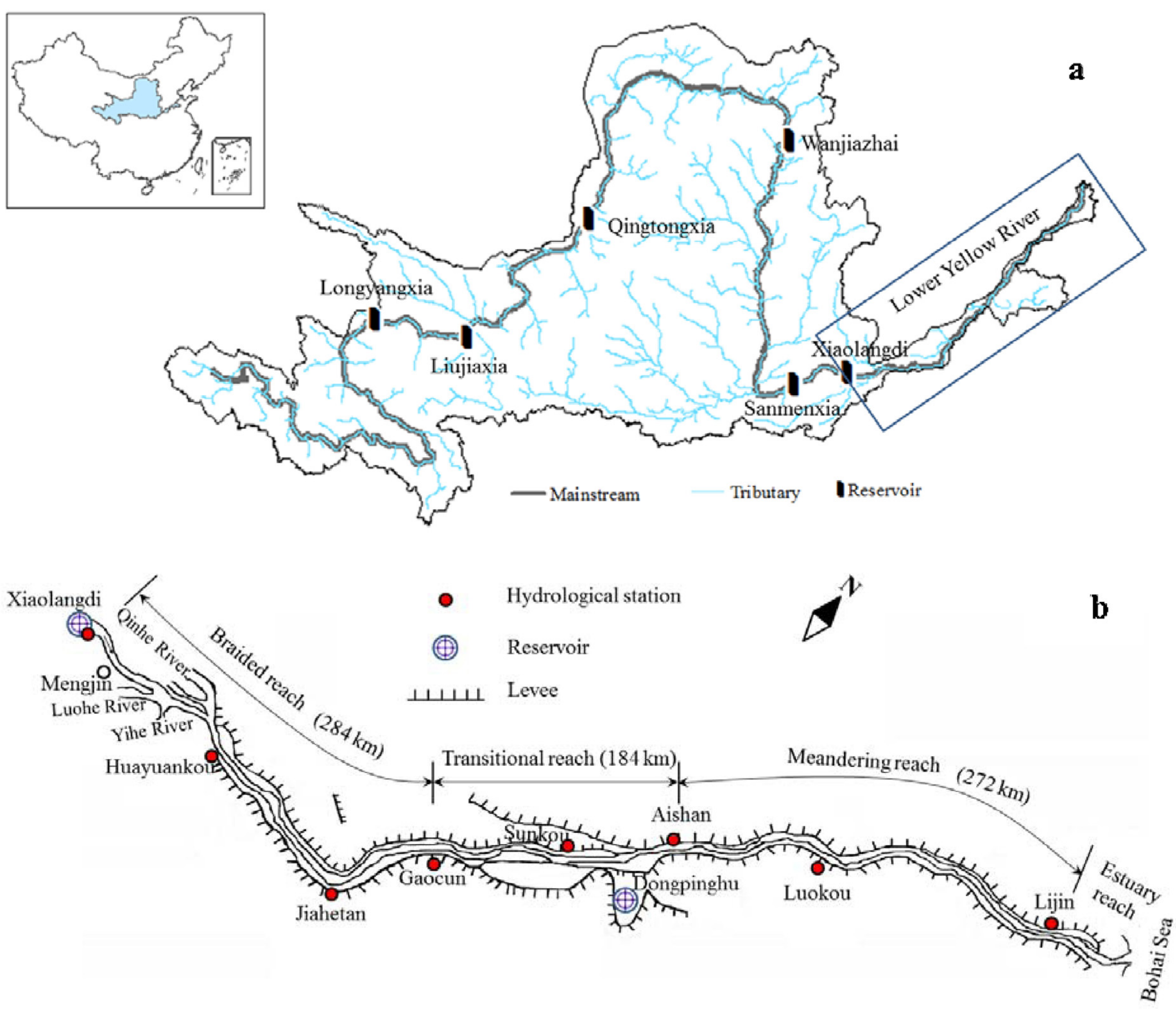

Fig. 1. Map of the Yellow River drainage basin showing the locations of the major reservoirs (a) and the study area showing the locations of the major hydrological stations (b).