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Functional degradation of the water–sediment regulation scheme in the lower Yellow River: Spatial and temporal analyses

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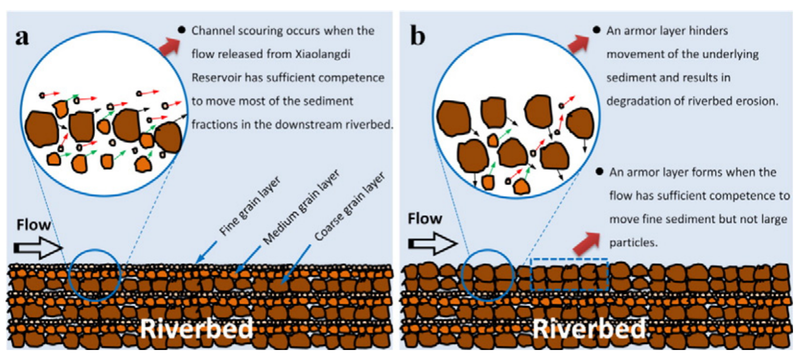
HIGHLIGHTS

- Current WSRS is no longer as effective as its initial functions;
- The degree of erosion declined gradually since the WSRS implementation;
- Reduction in riverbed elevation—a key function of the WSRS—has slowed since 2005

GRAPHICAL ABSTRACT



Schematic diagram illustrating two different programs of sediment transport and deposition.

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ABSTRACT

Heavy sedimentation has led to the phenomenon of a secondary perched river in the lower reaches of the Yellow River. The water–sediment regulation scheme (WSRS) using the Xiaolangdi Reservoir was first implemented in 2002 to try to solve this problem. In this study, we analyzed the spatial and temporal effects of the current WSRS (2005–2013) on the lower Yellow River. Our results suggest that the current WSRS is exhibiting a tendency towards functional degradation, meaning that the scheme is no longer as effective as it was initially for the lower Yellow River. Although the main river channel has been fully scoured in the lower reaches since the implementation of the WSRS, we found that the degree of erosion declined gradually in a top-down fashion from the braided reach, through the transitional reach, to the meandering reach. Of the total eroded sediment, 69.64% came from the braided reach and only 6.61% came from the meandering reach. In addition, the reduction in riverbed elevation—a key function of the WSRS—has clearly slowed since 2005. We discuss the mechanisms underlying this functional degradation of the current WSRS and future challenges for the management of the lower Yellow River. Insights gained from this study will likely be of use to those weighing up options for future implementations of the WSRS.

1. Introduction

River systems are an important component in the circulation of energy and earth materials. Proper management of large trans-boundary rivers is critical because of their ecological importance and because they host 40% of the world's population (Ching and Mukherjee, 2015). On the one hand, such rivers provide water, transportation, and aquatic products to human societies, and shape the landscape. On the other hand, heavy sedimentation can cause a decline in the transport capacity of large rivers, greatly exacerbating the possibility of severe flooding. Large dams and reservoirs have been built to regulate such river systems and to achieve comprehensive utilization of the rivers' resources

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via various operation schemes. A comparison of 72 regulated and unregulated reaches across 36 different rivers showed that large reservoirs reduced the annual peak flood discharge by 67% (Graf, 2006).

At 5464 km, the Yellow River ranks second in length in China (after the Yangtze River) and is the sixth-longest in the world (Fig. 1) (Shiau et al., 2007). Originating in the Bayankala Mountains in Qinghai province in western China, the Yellow River flows eastward through seven provinces and two autonomous regions on its way to the Bohai Sea (Fig. 1a). The Yellow River was the birthplace of northern Chinese civilization and was the most prosperous region in early Chinese history. The Yellow River contributes approximately 6% of global river sediment load, and the annual runoff directly supports 12% of the Chinese population (Miao et al., 2010). In recent decades, frequent devastating flooding, largely due to the elevated riverbed in the lower Yellow River, has earned the river the alternative, unenviable, name "China's Sorrow" (Chen et al., 2012b). The middle section of the Yellow River flows through the easily eroded Loess Plateau region, where it picks up a large quantity of sediment. When the flow reaches the lower Yellow River, which has a significantly less steep longitudinal slope (Fig. 1b), much of the suspended sediment is deposited on the riverbed (Chu, 2014). This accumulation of sediment has resulted in the level of the riverbed rising above cities and farmland along most of the lower Yellow River, a phenomenon known as a "perched river" or "above-ground river" (Fig. 1c) (Chu, 2014).

Through painful lessons learned and subsequent great efforts, the lower Yellow River has for decades now been made somewhat safer; however, the current practices are barely sustainable and siltation in the lower Yellow River is still an unsolved problem. Since 2002, to alleviate the pressing situation caused by the raised riverbed and heavy sedimentation in the Xiaolangdi and Sanmenxia Reservoirs, the Yellow River Conservancy Commission (YRCC) has enacted an annual water–sediment regulation scheme (WSRS) for the Yellow River (Kong et al., 2015b). The WSRS regulates and controls flow and sediment transport in the lower reaches of the Yellow River via reservoirs on the mainstream and tributaries (Li and Sheng, 2011), and is considered to be the largest human-designed hydrological experiment in the world. Many previous studies have reported the effects of the WSRS on the lower Yellow River, including changes in the river channels (Chen et al., 2012a; Ma et al., 2012; Qi et al., 2013; Xia et al., 2014b; Xu and Si, 2009), hydrological characteristics (Yu et al., 2013), and sedimentation features (Kong et al., 2015b), as well as changes in the evolution of the Yellow River Delta (Kong et al., 2015a; Wang, 2005). Remarkable achievements have been obtained since the implementation of the WSRS, in particular a significant enhancement in discharge capacity (Xia et al., 2014a; Zhang et al., 2009). The bankfull discharge at Huayuankou station increased from 3700 m^3 s^{-1} in 2000 to 6900 m^3 s^{-1} in 2012 (Qi et al., 2013) and, overall, the lower Yellow River channel has switched from a sediment-deposition state to an erosive state (Xu et al., 2005). However, previous research on the implementation of the WSRS has seldom focused on the segmental differences within the lower Yellow River, and analysis of changes in the functioning of the WSRS over the years has not been conducted. In the present work, we have therefore re-evaluated the influence of the WSRS on the lower Yellow River from these new perspectives, and highlight the potential threat that the current WSRS poses to channel evolution in the lower Yellow River. Insights gained from this study about the impact of the current WSRS will likely be of use to those weighing up options for future implementations of the WSRS in the

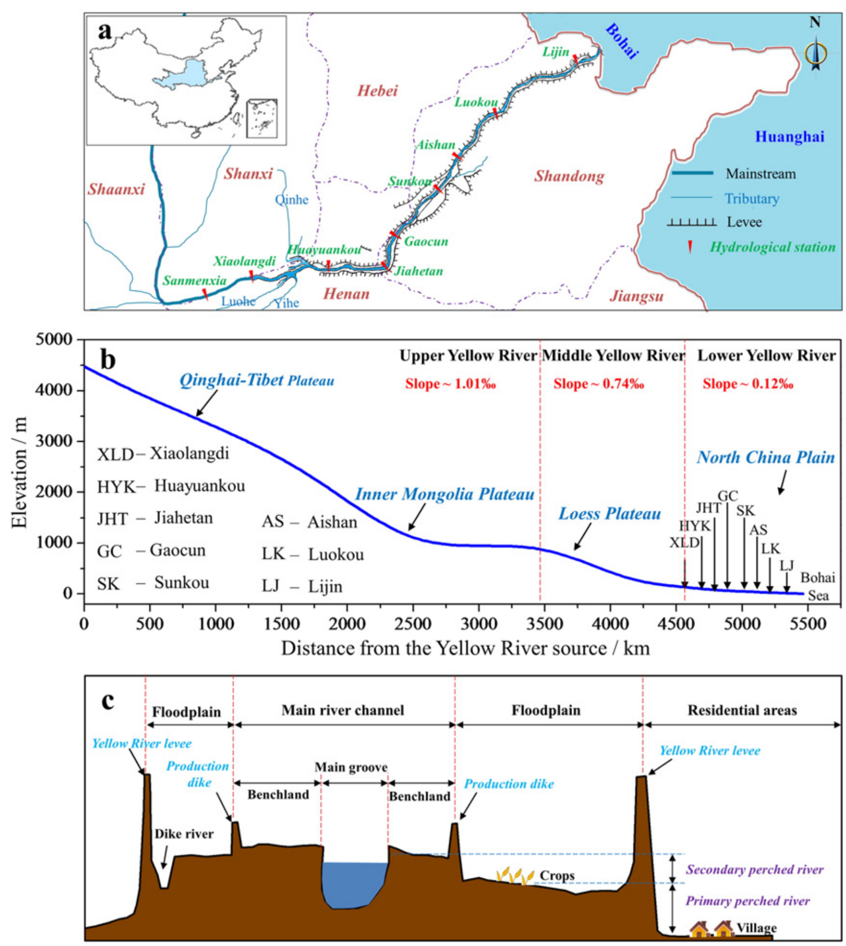

Fig. 1. Location of the study area (a), the longitudinal profile of the Yellow River (b), and a schematic representation of a typical cross-section of the lower Yellow River (c).