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Effect of water-sediment regulation of the Xiaolangdi reservoir on the concentrations, characteristics, and fluxes of suspended sediment and organic carbon in the Yellow River

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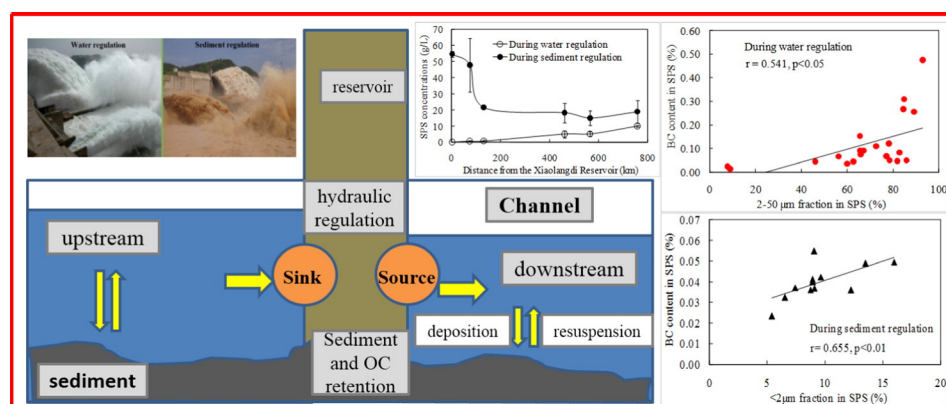
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HIGHLIGHTS

- Suspended sediment concentration increased with the river flow velocity as a power function.
- Impact of both water and sediment regulation on DOC concentration is insignificant.
- Impact of both water and sediment regulation on POC and suspended sediment is significant.
- Black carbon content in suspended sediment elevated along the river during both regulations.
- Black carbon, affected by sediment source and characteristics, mainly exists in fine particles.

GRAPHICAL ABSTRACT



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ABSTRACT

Water-sediment regulation (WSR) of the Xiaolangdi Reservoir in the Yellow River is different from other water conservancy projects, with sediment resuspending along the river downstream of the reservoir during water regulation while some suspended sediment depositing during sediment regulation. In this study, samples were collected before, during, and after WSR to investigate the effect of WSR on the suspended sediment and organic carbon downstream of the reservoir. The suspended sediment concentration ([SPS]) increased with the river flow velocity (V) as a power function ($[SPS] = 1.348 V^{2.519}$) during the three periods. The suspended sediment grain size decreased along the river during water and sediment regulations and after WSR; they were generally below $200 \mu\text{m}$ with the fine particles ($<50 \mu\text{m}$) of 68.0%–93.7% and positively correlated with the flow velocity. The black carbon content in suspended sediment elevated along the river during both water and sediment regulations, and it increased with 2–50 μm fraction during water regulation and with $<2 \mu\text{m}$ fraction during sediment regulation, suggesting that black carbon mainly exists in fine particles and is influenced by both suspended sediment source and characteristics. There was no significant difference in dissolved organic carbon (DOC)

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concentration during water regulation, sediment regulation, and after WSR, inferring that the effect of sediment resuspension/deposition on DOC concentration was insignificant. The contribution of DOC flux (27.3%) during WSR period to the annual flux was comparable to that (22.6%) of water, but lower than the sediment (32.5%) and particulate organic carbon (POC) (49.5%). This study suggests that WSR will exert significant influence on the concentrations, characteristics and fluxes of POC ($p < 0.05$) and sediment ($p < 0.05$) but have no significant influence on DOC ($p > 0.1$) of the Yellow River.

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1. Introduction

Rivers play a vital role in the transport of water, sediment, and nutrients from terrestrial to marine ecosystems. The concentrations, characteristics, and fluxes of suspended sediment and organic carbon (OC) in rivers not only have remarkable effects on their transport from land to ocean but also exert a controlling influence on the fates of nutrients, organic pollutants, and heavy metals in rivers (Balakrishna and Probst, 2005; Dong et al., 2013; Wölz et al., 2010; Xia et al., 2013). Therefore, research on suspended sediment and OC is important for the study of water quality throughout the river system.

Anthropogenic activities, such as the operation of water conservancy projects, could change hydrodynamic condition of rivers, inducing sediment resuspension or suspended sediment deposition. This will further affect the discharge of water as well as the concentrations, characteristics, and fluxes of suspended sediment and OC (Dai and Liu, 2013; Meybeck et al., 2004; Yang et al., 2006; Yang et al., 2007). Many researchers have reported that hydropower dams and reservoirs have exerted influence on water discharge, sediment retention, and nutrient fluxes in large rivers around the world, such as the Mekong River (Kummu and Varis, 2007; Lu and Siew, 2006), the Danube River (Teodoru and Wehrli, 2005), the Indus River (Giosan et al., 2006), and the Yangtze River (Xu and Milliman, 2009). For example, >80% of water discharge from the Gwydir River (New South Wales, Australia) has been altered significantly by the Copeton Dam (Rolls et al., 2013). After the impoundment of the Three Gorges Dam in June 2003, the sediment discharge of the Yangtze River decreased by 60% (Xu and Milliman, 2009). Teodoru and Wehrli (2005) indicated that 5% of total nitrogen, 12% of total phosphorus, and 55% of suspended sediment for the Danube River was trapped in the Iron Gate I Reservoir.

In order to deal with the problems of the high suspended sediment concentration and severe sediment deposition along the Yellow River, the impoundment of the Xiaolangdi Reservoir began in October 1999, and the water-sediment regulation (WSR) of the reservoir has been in operation since 2002. The WSR of the Xiaolangdi Reservoir aims at controlling flood, mitigating further infilling of sediment in the Sanmenxia (SMX) Reservoir, maintaining the reservoir capacity, and scouring the elevated river-bed in the lower reaches of the Yellow River. The WSR is divided into two periods: water regulation and sediment regulation. During water regulation, the overlying water with low suspended sediment concentration is released from the reservoir at a high flow velocity to scour the riverbed, resulting in sediment resuspension along the river downstream of the reservoir. During sediment regulation, the bottom water containing as much as 300 g/L of sediment is ejected from the reservoir at a high speed to maintain reservoir capacity (Hu et al., 2012), with some suspended sediment deposition along the lower reach. Therefore, the WSR of the Xiaolangdi Reservoir is clearly distinct from the operations of other water conservancy projects around the world. Thus, the effect of WSR on the concentrations, characteristics, and fluxes of suspended sediment and OC might be remarkably different from the other water conservancy projects.

The effect of WSR of the Xiaolangdi Reservoir on the fluxes of sediment and OC has been studied by several researchers (Yao et al., 2009; Zhang et al., 2015; Miao et al., 2016). For example, Zhang et al. (2013) mentioned that the contributions of the fluxes of dissolved organic carbon (DOC) and particulate organic carbon (POC) during WSR to the annual fluxes in 2008 were 35% and 56%, respectively. Yu

et al. (2013) provided a good overview of the role of the Xiaolangdi dam in influencing the sediment flux of the Lower Yellow River and the effect of WSR on the suspended sediment concentration and median grain size. However, the effect of such large-scale sediment resuspension/deposition events like the WSR on suspended sediment and OC is not well understood. Especially, as sediment resuspension occurs during water regulation while suspended sediment deposits along the river during sediment regulation, the variations of concentrations and characteristics of suspended sediment and OC might be different during the two periods. However, there was no research report about the comparison of the effects of water regulation and sediment regulation of the Xiaolangdi Reservoir. Furthermore, there is limited knowledge about the effect of hydrodynamic conditions on suspended sediment during WSR of the Xiaolangdi Reservoir.

Therefore, the present study was conducted to investigate the effect of the WSR on the concentrations and characteristics of suspended sediment and OC downstream of the Xiaolangdi Reservoir along the Yellow River. Water and suspended sediment samples in six sampling sites were collected during water regulation, during sediment regulation, and after WSR. The suspended sediment size and OC composition, including DOC and POC (black carbon and amorphous organic carbon), during the three periods were examined. The impacts of water regulation and sediment regulation on suspended sediment as well as OC transport along the studied stretch were compared, and the effect of hydrodynamic conditions on suspended sediment was also investigated. In addition, the fluxes of suspended sediment and OC were estimated during WSR.

2. Materials and methods

2.1. Study area

The Yellow River, which originates from the Qinghai-Tibetan Plateau, is >5400 km long and has a drainage area of 752,443 km². Most of the Yellow River basin is located in arid and semiarid regions with an annual average temperature of 8–14 °C (Chen et al., 2005). The mean annual precipitation is highly variable across the river basin, increasing from 368 mm in the upper reaches to 530 mm in the middle reaches and to 670 mm in the lower reaches (Wang et al., 2006). However, the water primarily originates from the upper reaches of the river, while the sediment is primarily derived from the upper and middle reaches of the Yellow River, which is located in the Loess Plateau (from 100°54'E to 114°33'E and from 33°43'N to 41°16'N).

The Xiaolangdi Reservoir, which is 130 km long and has a water area of 272 km², is the most downstream reservoir on the Yellow River. Its upstream drainage area occupies 92.3% of the Yellow River basin. The maximum reservoir capacity is 12.65 km³, and the capacity of WSR is 1.05 km³ (Li et al., 2007). The construction of the Xiaolangdi Reservoir was completed in October of 1997. Since 1999 and before the WSR operation in 2002, the suspended sediment-containing water released from the SMX Reservoir was trapped in the Xiaolangdi Reservoir, and there were 933 million tons of sediment trapped in the reservoir during this period (Sediment Bulletin in Chinese Rivers, 2001). According to the data obtained from the Yellow River Conservancy Commission (YRCC), the annual water and sediment discharges downstream of the Xiaolangdi reservoir after its operation (2002–2013) are 16.5 km³ and 160 Mt, respectively; the annual water and sediment discharges

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