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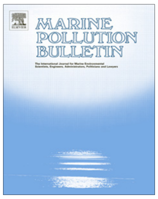

Seasonal variability and flux of particulate trace elements from the Yellow River: Impacts of the anthropogenic flood event

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ABSTRACT

In this study, the suspended particulate matter (SPM) of the Yellow River (Huanghe) was collected biweekly at the outlet and analyzed for particulate trace element contents. The seasonal variations of the trace elements were primarily controlled by hydrological processes, which determined different sources of the SPM. Moreover, As, Co, Cr, and Ni primarily originated from lithogenic sources, whereas Cd, Cu, Pb and Zn were influenced by anthropogenic activities. The Yellow River has suffered moderate to considerable ecological risk during the late stage of Water and Sediment Regulation (WSR). Using the discharge-weighted contents method, the annual trace element fluxes were estimated, with ca. 30% of the annual fluxes occurring within the short WSR period (6% of one year). More specifically, 75% of the Cd flux was from an anthropogenic source, which likely posed a significant threat to the estuary and the adjacent coastal ecosystems.

1. Introduction

Rivers are the major and unidirectional pathway of terrestrial materials (dissolved and particulate forms) to the ocean (Milliman and Farnsworth, 2011), and they play a vital role in the global geochemical cycle (Gaillardet et al., 2003; Ludwig et al., 1996; Martin and Meybeck, 1979; Oelkers et al., 2011; Oelkers et al., 2012; Viers et al., 2009). Recent studies have shown that rivers are the dominant system by which global materials are transported to the ocean as bedload and suspended materials, exceeding the combined mass flux of riverine dissolved forms and atmospheric dusts by a factor of 20 (Gaillardet et al., 2003; Jickells et al., 2005; Walling, 2006). The role of particulate matter fluxes to the ocean has attracted increasing attention because of their sensitivity to climate change and anthropogenic influences (Gislason et al., 2009; Syvitski et al., 2005; Walling, 2006; Hu et al., 2009; Wang et al., 2011). Because of rapid economic growth, human activities have significantly disturbed the biogeochemical cycle of many elements, particularly trace elements (Davide et al., 2003; Thevenot et al., 2007; Viers et al., 2009). Trace elements in rivers from either bedrock weathering or an anthropogenic source are generally transported as suspended particulate matter (SPM) (Martin and Meybeck, 1979; Oelkers et al., 2011). Estuarine and coastal areas are one of the ultimate sinks for trace elements, which may pose a significant risk to the aquatic ecosystem due to their environmental persistence, bioaccumulation, and toxicity (Rainbow, 2007). To evaluate the environmental health risk in estuarine and coastal areas, it is fundamental that the chemical and physical processes occurring during the transport pathways are well documented and that the fluxes of riverine trace elements are accurately estimated.

The Yellow River (Huanghe) is the second largest river in China and is regarded as the cradle of Chinese civilization (Chen et al., 2012b). Currently, the Yellow River plays a critical role in the economic development in China, supporting a population of 107 million, irrigating 15% of the agricultural land, and contributing to 9% of China's gross domestic product (Miao et al., 2010). As reported in the 2006 Bulletin of Yellow River Water Resources, ~4.3 Gt/yr wastewater was discharged into the river, of which 74% was from secondary industry followed by domestic sewage (20%) and tertiary industry (6%). In addition, fertilizer application on agricultural lands in the region has elevated the nitrogen and phosphorus levels in the river water (He et al., 2010; Pan et al., 2013; Yu et al.,

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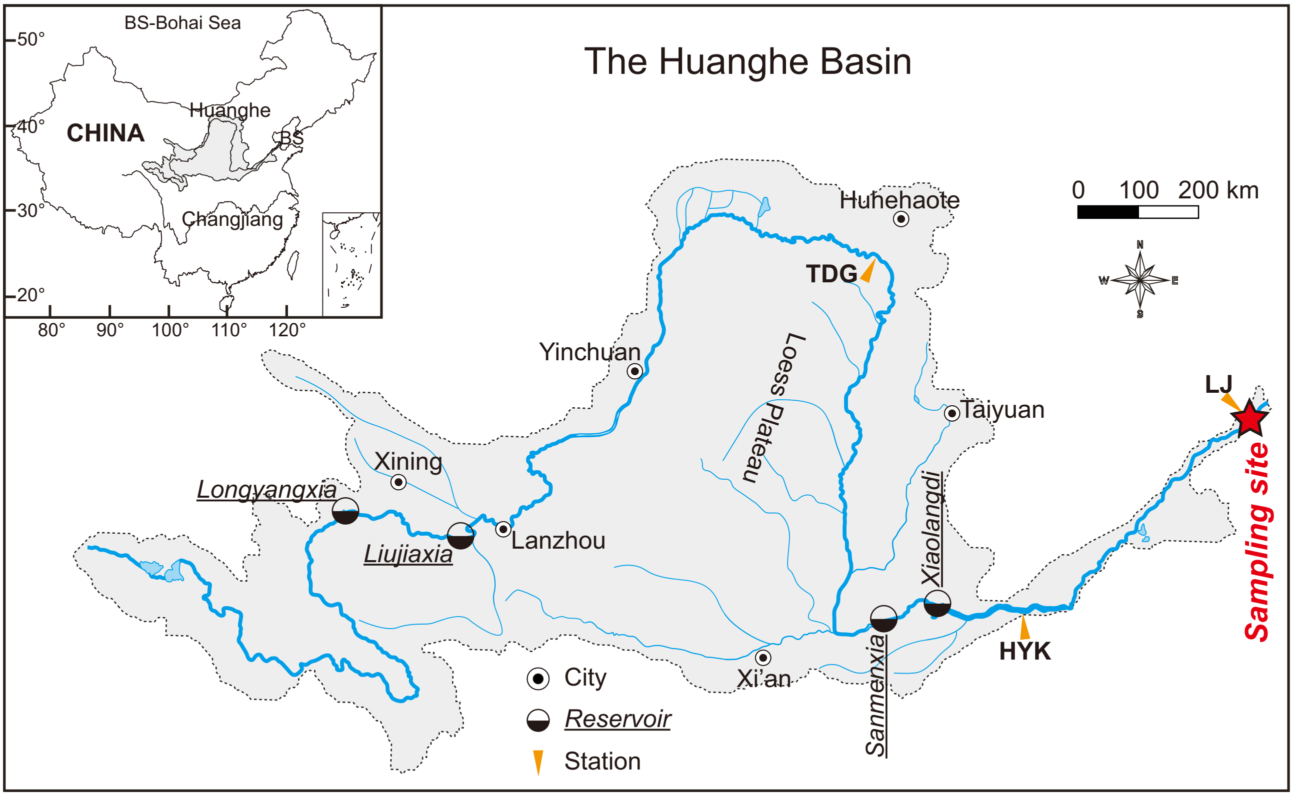

Fig. 1. Map of the Yellow River basin showing the sampling sites (red pentacle), major tributaries, key gauging stations, and large reservoirs. TDG, Toudaoguai; HYK, Huayuankou; LJ, Lijin. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2010). The combined effects of climate change and human activity have gradually altered the hydrological regimes in the Yellow River basin, especially after the operation of the Xiaolangdi Reservoir in 1999 (Miao et al., 2011; Wang et al., 2007; Yu et al., 2013a; Yu et al., 2013b). Subsequently, approximately 84% of the sediment input has been deposited in the Xiaolangdi Reservoir (Chen et al., 2012a), resulting in a significantly decreased suspended sediment concentration (SSC) at the reservoir outlet.

In 2002, the Yellow River Conservancy Committee began to implement the Water–Sediment Regulation (WSR) Scheme, which is a controlled man-made flood (~20 days during the summer) that regulates the river water flow and controls the sediment level in several reservoirs in the middle reaches (Bi et al., 2014a,b; Wang et al., 2010; Wang et al., 2005). Generally, the WSR Scheme occurs in two stages: (1) floodwater is released from the Xiaolangdi Reservoir to control the sediment level and to improve the reservoir storage capacity, and (2) sediment-containing floods are delivered to the sea to decrease the riverbed sediment deposited in the lower reaches (Huayuankou–Lijin) (Ma et al., 2011). The WSR Scheme has altered the natural patterns of the river water and sediment, caused significant erosion of the channel in the lower reaches, and modified morphological features at the river outlet (Bi et al., 2014a; Wang et al., 2010). During the 2002–2010 WSR periods, the riverbed scoured sediments provided ~60% of the fluvial sediments to the sea, and more was directly released from the Xiaolangdi Reservoir (Yu et al., 2013a; Yu et al., 2013b), which significantly affected the concentrations and fluxes of the nutrients (Chen et al., 2013) and dissolved uranium (Sui et al., 2014) in the river.

A series of studies in the 1990s showed that the trace element contents in the Yellow River sediments are relatively lower than those of other large rivers in the world (Huang et al., 1992; Zhang et al., 1988; Zhang et al., 1994). A subsequent study by Qiao et al. (2007) has suggested that the trace element contents in the Yellow River SPM have not significantly changed over the past 20 years. Most recently, Bi et al. (2014b) have examined the variations in the contents and fluxes of selected particulate heavy metals (Mn, Pb, Zn, V, Cr, and Ni) during the WSR period of 2009. However, few studies have reported the seasonal variations of the particulate trace element contents in the Yellow River SPM; thus, the trace element fluxes in the river are poorly understood. In this study, the objectives were to (1) examine the temporal variations of the particulate trace element contents in the Yellow River SPM; (2) determine the transport dynamics of the particulate trace elements under various hydrological conditions; (3) identify the sources of the trace elements and evaluate their potential ecological risks to the Yellow River estuary-delta ecosystems; and (4) estimate the particulate trace element fluxes from the Yellow River to the sea, focusing on the role of the WSR in the trace element exports.

2. Materials and methods

2.1. Regional settings

The Yellow River originates in the Bayan Har Mountains of the eastern Tibetan Plateau at an elevation of 4600 m and drains into a basin area of 752,000 km^2 (Fig. 1). Before it flows into the Bohai Sea, the Yellow River flows eastward through the semi-arid region of North China, the Loess Plateau, and the North China Plain, with a length of 5464 km. The average rainfall in the Yellow River Basin ranges from 600–800 mm/yr, of which 70–80% occurs during the flood season (July–September). The river can be divided into the upper (prior to Toudaoguai), middle (Toudaoguai and Huayuankou) and lower (post Huayuankou) reaches based on distinctive geomorphology and climatic conditions (Fig. 1). The upper