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Stepwise decreases of the Huanghe (Yellow River) sediment load (1950–2005): Impacts of climate change and human activities

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Abstract

The sediment load delivered from the Huanghe (Yellow River) to the sea has decreased sharply to 0.15×10^9 metric tons per year (0.15 Gt/yr) between 2000 and 2005, and now represents only 14% of the widely cited estimate of 1.08 Gt/yr. The river seems to be reverting to the pristine levels characteristic of the middle Holocene, prior to human intervention. Datasets from 1950 to 2005 from four key gauging stations in the main stream reveal distinct stepwise decreases in sediment load, which are attributed to both natural and anthropogenic impacts over the past 56 yr. Completions of two reservoirs, Liujiaxia (1968) and Longyangxia (1985), in the upper reaches of the river and their joint operations have resulted in stepwise decreases in sediment load coming from the upper reaches. Effective soil conservation practices in the middle reaches since the late 1970s, combined with the operation of the Sanmenxia and Xiaolangdi reservoirs, have also caused stepwise decreases in sediment load at Huayuankou in the middle reaches, but the decrease differs from that observed in the upper reaches. Decrease in precipitation is responsible for 30% of the decrease in sediment load at Huayuankou, while the remaining 70% is ascribed to human activities in the river basin, of which soil conservation practices contribute 40% to the total decrease. Sediment retention within reservoirs accounts for 20% of the total sediment load decrease, although there was notable sediment retention within the Xiaolangdi reservoir from 2000 to 2005. The remaining 10% of the decrease in sediment load is a result of the operation of reservoirs in the upper reaches. In the lower reaches, 20% of the sediment passing Huayuankou has been lost as a result of channel deposition and water abstraction. Soil conservation practices and the operation of reservoirs have lowered the content of coarser sediment ($D > 0.05$ mm) at Huayuankou, and reduced channel deposition in the lower reaches. In contrast, sediment loss owing to water abstraction in the lower reaches has increased considerably as water consumption for agricultural needs has increased. Therefore, the combined effects of climate change and human activities in the upper, middle, and lower reaches have resulted in stepwise decreases in the sediment load delivered from the Huanghe to the sea. The Huanghe provides an excellent example of the altered river systems impacted by climate change and extensive human activities over the past 56 yr. Further dramatic decreases in sediment load and water discharge in the Huanghe will trigger profound geological, morphological, ecological, and biogeochemical responses in the estuary, delta, and coastal sea.

Keywords: Huanghe (Yellow River); stepwise decrease; sediment load; climate change; human activity; dam and reservoir

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1. Introduction

Rivers represent the major link between continents and oceans within the global geochemical cycle and are major pathways for the delivery of terrestrial materials to the oceans (Milliman and Meade, 1983; Walling and Fang, 2003; Meybeck and Vörösmarty, 2005). Understanding the flux of these materials has been set as a goal of the International Geosphere Biosphere Programme and its core project, Land Ocean Interaction in the Coastal Zone (Syvitski, 2003; Syvitski et al., 2005). The river sediment-associated transport accounts for more than 90% of the total river-borne flux of elements such as P, Ni, Mn, Cr, Pb, Fe, and Al (Martin and Meybeck, 1979). Furthermore, 43% of the total transport of organic carbon from the land to the oceans by rivers is in particulate form (Ludwig et al., 1996) and is thus closely associated with river sediment transport. Milliman and Syvitski (1992) estimated global sediment flux to the ocean to be 20×10^{9} metric tons (Gt/yr); this value has been widely cited in the scientific literatures. In recent years, studies of riverine sediment flux to the oceans, and the processes of sediment transport, have increasingly received more attention as variations of riverine sediment flux have become an important index for the effects of climate change and human activities in river basins (e.g., Yang et al., 2002; Walling and Fang, 2003; Meybeck and Vörösmarty, 2005; Nilsson et al., 2005; Syvitski et al., 2005; Walling, 2006; Yang et al., 2006). During the latter half of the 20th century, the global changes resulting from human activities, including population increases, water use, fertilizer consumption, and damming of rivers, have intensified at an increasing rate, and have altered the global river systems (Steffen, 2004). Recent studies have documented, on a global scale, many examples of rivers that have shown marked decreases in both water discharge and sediment load delivered to the sea; for example, the Colorado, Mississippi, Indus, Nile, Changjiang (Yangtze River) and Huanghe (Yellow River) (Meade and Parker, 1985; Yang et al., 1998; Stanley and Warne, 1998; Walling and Fang, 2003; Yang et al., 2006; Wang et al., 2006). Among these, the Huanghe provides an excellent illustration of the interaction between climate change, extensive implementation of soil and water conservation, and sediment control measures (Walling and Fang, 2003).

The Huanghe is regarded as the second largest river of the world in terms of sediment load over the last several thousand years, with a widely cited annual sediment load (Qs) of 1.08 Gt/yr (Milliman and Meade, 1983), which represents 6% of the estimated global river sediment flux to the ocean. However, more recent data (1990–2005) show that the annual sediment load reaching the sea is only 0.3 Gt/yr, less than one-third of that estimated by Milliman and Meade (1983). In particular, in the most recent 6 yr (2000–2005) the Huanghe discharged only 0.15 Gt/yr of sediment load to the Bohai Sea, reverting to its pristine levels of the middle Holocene, prior to human intervention (Milliman et al., 1987; Ren and Zhu, 1994; Saito et al., 2001). The decline of the Huanghe sediment load, as well as synchronous decreases in water discharge (Wang et al., 2006) and total dissolved solid flux (Chen et al., 2005), has had profound physical, ecological, and geomorphological effects on the lower reaches of the river, the coastal area near the river mouth, and the Bohai Sea (e.g., Deng and Jin, 2000; Jin and Deng, 2000; Lin et al., 2001; Huang and Fan, 2004).

Over thousands of years of Chinese history, frequent catastrophic floods in the Huanghe river basin have resulted in tremendous losses of life and property (Hu et al., 1998). The high sediment load, most of which is eroded from the Loess Plateau, has become a concern. This is because the annual water discharge of the Huanghe is only 49 km^3/yr, equivalent to approximately 5% of that of the Yangtze River (900 km^3/yr), whereas the annual sediment load is more than twice that of the Yangtze River (Milliman and Meade, 1983). Since the 1950s, many dams and reservoirs have been constructed in the Huanghe river basin to intercept discharge and trap sediment, and soil conservation practices have been implemented in the middle reaches. Consequently, there have been no floods other than those caused by winter ice jams (Fuggle et al., 2000). Since the 1970s, water consumption in the river basin has accelerated because of increasing water demand by a growing population and extensive agricultural development. Over the same period, climatic changes have led to a reduction in precipitation in the river basin (Xu, 2003; Wang et al., 2006). As a result, the annual sediment load discharged from the Huanghe to the sea has decreased synchronously with the decrease in water discharge, as documented by Yang et al. (1998) and Walling and Fang (2003). Recent studies of the ecosystem and depositional systems of the Huanghe delta have revealed distinct responses to decreases in water and sediment flux (Jin and Deng, 2000; Huang and Fan, 2004; Wu et al., 2004). It is therefore important to make use of the most recently available data from the Huanghe to elucidate the causes of decreases in sediment load, which will provide a reference for consideration of the alteration of global river systems during the Anthropocene.

Although there have been many publications that discuss the decreases in sediment load of the Huanghe over the past 50 yr, especially in the Chinese literature