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Assessing natural and anthropogenic influences on water discharge and sediment load in the Yangtze River, China

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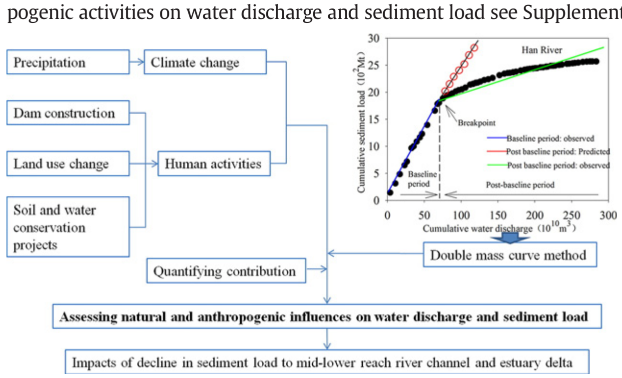
HIGHLIGHTS

- A significant decrease in sediment load in the mainstream and seven tributaries of Yangtze River
- Quantitative assessments of climate and human activity on water discharge and sediment load have been analyzed.
- Dam construction and soil and water conservation played an important role in sediment reduction.
- The change of sediment affected the mid-lower reach river channel and delta of Yangtze River.

GRAPHICAL ABSTRACT

The double mass curve (DMC) were used to detect trends and abrupt changes-points in water discharge and sediment load and to quantify the effects of climate change and human activities on water discharge and sediment load in the Yangtze River. The detail description for quantifying the contributions of climate change and anthropogenic activities on water discharge and sediment load see Supplement data Fig. S1.



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ABSTRACT

The water discharge and sediment load of rivers are changing substantially under the impacts of climate change and human activities, becoming a hot issue in hydro-environmental research. In this study, the water discharge and sediment load in the mainstream and seven tributaries of the Yangtze River were investigated by using long-term hydro-meteorological data from 1953 to 2013. The non-parametric Mann-Kendall test and double mass curve (DMC) were used to detect trends and abrupt change-points in water discharge and sediment load and to quantify the effects of climate change and human activities on water discharge and sediment load. The results are as follows: (1) the water discharge showed a non-significant decreasing trend at most stations except Hukou station. Among these, water discharge at Dongting Lake and the Min River basin shows a significant decreasing trend with average rates of -13.93×10^8 m^3/year and -1.8×10^8 m^3/year ($P < 0.05$), respectively. However, the sediment load exhibited a significant decreasing trend in all tributaries of the Yangtze River. (2) No significant abrupt change-points were detected in the time series of water discharge for all hydrological stations. In contrast, significant abrupt change-points were detected in sediment load, most of these changes appeared in the late 1980s. (3) The water discharge was mainly influenced by precipitation in the Yangtze River basin, whereas sediment load was mainly affected by climate change and human activities; the relative contribution ratios of human

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activities were above 70% for the Yangtze River. (4) The decrease of sediment load has directly impacted the lower Yangtze River and the delta region. These results will provide a reference for better resource management in the Yangtze River Basin.

1. Introduction

Rivers are a major pathway linking continents and oceans and delivering large quantities of land-derived materials (including fresh water, sediments, elements, nutrients, and particularly carbon) into the global ocean (Milliman and Meade, 1983; Ludwig et al., 1996; Smith et al., 2001). They have considerable influence on the fluvial geomorphology of deltas and estuary ecosystems and thus play an important role in land-ocean interactions and ocean biogeochemical cycles (Syvitski et al., 2005). Variations in water discharge and sediment load also have important socio-economic implications, which are mainly affected by climate change and human activities (Syvitski, 2003; Gao et al., 2013). During the last century, global warming has accelerated the hydrological cycle and changed the spatial distribution patterns of precipitation, resulting in an increase in extreme flooding events and changing sediment transport capacity in many rivers around the world (Zhao et al., 2015; Zhang et al., 2009; Easterling et al., 2000). Human activities including water and soil conservation, dam construction, freshwater extraction, and land use changes have intensified at an increasing rate, resulting in direct and indirect influences on global river systems (Syvitski, 2003; Wang et al., 2008). Walling and Fang (2003) indicated that approximately 46.8% of world rivers show evidence of significant increases in suspended sediment loads, while 88.4% show a significant increase in water discharge of the global rivers. However, some typical example of rivers showing decreased in the sediment load such as Nile, Mississippi, Colorado, Indus and Huanghe (Fanos, 1995; Blum and Roberts, 2009; Carriquiry and Sánchez, 1999; Walling and Fang, 2003; Wang et al., 2006). Therefore, a better understanding of these changes and their potential effects on in water discharge and sediment load is crucial for the environment management of river basins around the world.

The Yangtze River, the longest river in Asia, historically ranks fifth globally in annual water discharge (920 km^3/year) and fourth in annual sediment load (480 Mt/year) (Milliman and Syvitski, 1992). The river supplies fresh water for approximately 400 million people, accounting for about 6.6% of the world's population (United Nations Department of Economic and Social Affairs, 2001). Over thousands of years, the Yangtze River, together with the Yellow and Taiwan's rivers delivered annual sediment loads of 2000 Mt/year to the China Sea, representing 10% of the estimated global river sediment load to the ocean (Milliman and Farnsworth, 2013). However, since the 1950s, more recent data show that the water discharge and sediment load of the Yangtze River have been significantly altered by the influences of human activities and climate variations (Yang et al., 2002; Chen et al., 2005; Yang et al., 2006; Dai et al., 2008; Xu et al., 2009; Zhao et al., 2015).

The Yangtze River's average annual sediment load transported into the sea was 320 Mt/year between 1986 and 2004, only equivalent to 65% of the 480 Mt/year from 1951 to 1968, whereas the sediment load exported to the ocean at the Datong Hydrological Station decreased to 134 Mt/year between 2003 and 2010, only 30% of the 1951–1968 level (Yang et al., 2006). Sediment loads in this river have shown a progressive decline since the 1970s, which is partly due to natural factors and more importantly to human activities. For example, a series of water and soil conservation projects were implemented in the upper reaches during the 1990s, and over 50,000 dam reservoirs have been constructed in the Yangtze River catchment since the 1950s. In particular, the Three Gorges Dam (TGD), one of the world's largest dams began to impound water in 2003.

These dramatic changes in water discharge and sediment load, as well as the reductions in the water yield capacity and nutrient material over the same period, have had a fundamental environmental and geomorphological impact on the estuarine coastal regions of the western Pacific, especially through the scouring of river channels and erosion of deltas (Yang et al., 2006, 2011; Gao et al., 2015). Several studies have attempted to analyze the water and sediment trends of the Yangtze River and their driving forces, but to date these dynamics and their effects on all tributaries of the Yangtze River have been only minimally discussed. In addition, a more detailed study of the effects of this reduction in sediment load on the river channel in the downstream reaches and delta of the river is needed.

Therefore, in this study, seven catchments within the Yangtze River basin were selected to analyze the water discharge and sediment load along with the effects on the river channel and delta. The specific aims of this study are (1) to detect both trends and abrupt changes and the driving forces on water discharge and sediment load, (2) to estimate the relative contribution of climate factors and human activities to water and sediment load, and (3) to determine the effect of sediment load reduction on river channels and deltas.

2. Study area and data

The Yangtze River, one of the largest and most important rivers in Southeast Asia, which originates on the Tibetan Plateau and extends approximately 6300 km eastward to the East China Sea (Fig. 1). Its catchment covers an area of ~180 × 10^4 km^2 and produces an annual sediment discharge of 480 × 10^6 t (Milliman and Farnsworth, 2013). It ranks 9th in globally in terms of drainage area, 4th in sediment load and 5th in water discharge (Milliman and Farnsworth, 2013; Zhao et al., 2000). The river can be divided into three sections: the upstream portion extends from the headwaters to Yichang, which is the main sediment source of the entire catchment (Shi, 2008); the middle portion extends from Yichang to Hukou; and the lower portion extends from Hukou to Datong (Chen et al., 2014). The seven major tributaries used in this study are distributed between the upper portion and the Datong gauging station (the Jinsha, Min, Jialing, Wu, and Han rivers, along with Donting and Poyang Lakes) (Gao et al., 2015). The Yangtze River's catchment is dominated by a typical subtropical monsoon climate, with the exception of some areas of the Tibetan Plateau. The Indian summer monsoon and the East Asian summer monsoon affect the upper and mid-lower, catchments respectively (Ding and Chan, 2005), and precipitation is mostly concentrated in the summer season.

The annual water discharge and sediment load from the main hydrological stations along the mainstream and seven tributaries of the Yangtze River basin were obtained from the Changjiang Water Resources Commission. The dataset covers a 60 year period from 1953 to 2013 for the stations on the main river, and a 57 year period for the seven tributaries between1956 and 2013. Daily precipitation data from 1953 to 2013, at 138 national standard rain stations in the Yangtze River basin, were provided by the National Meteorological Information Center of China Meteorological Administration and are available at http://data.cma.gov.cn/ (Fig. 1). Detailed information on the precipitation, water, and sediment discharge in the mainstream and seven catchments are shown in Table 1. The reservoir information was obtained from the annual reports published by the Ministry of Water Resources of China were available at http://www.mwr.gov.cn/zwzc/hygb/ (Supplementary data Table S1). The 1:100,000 scale land use/cover datasets,