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Quantifying the anthropogenic and climatic contributions to changes in water discharge and sediment load into the sea: A case study of the Yangtze River, China

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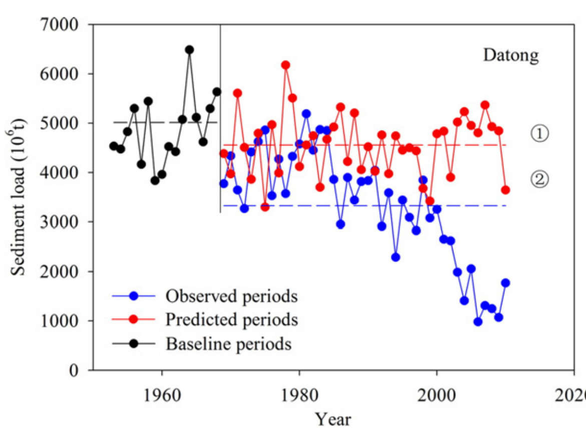
HIGHLIGHTS

- Quantitative assessments of climate and human activity are very important for the further understanding of estuarine and delta evolution.
- In recent decades, the decrease in sediment load has mainly been caused by human activities, especially dam construction.
- The effects of human activities on sediment load have increased over time.

GRAPHICAL ABSTRACT



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ABSTRACT

Based on data from the Datong hydrological station and 147 meteorological stations, the influences of climate change and human activities on temporal changes in water discharge and sediment load were examined in the Yangtze River basin from 1953 to 2010. The Mann–Kendall test, abrupt change test (Mann–Kendall and cumulative anomaly test), and Morlet wavelet method were employed to analyze the water discharge and sediment load data measured at the Datong hydrological station. The results indicated that the annual mean precipitation and water discharge exhibited decreasing trends of −0.0064 mm/10 yr and -1.41×10^8 m^3/yr, respectively, and that the water sediment load showed a significant decreasing trend of -46.5×10^6 t/yr. Meanwhile, an abrupt change in the water discharge occurred in 2003. The sediment load also exhibited an abrupt change in 1985. From 1970 to 2010, the climate change and human activities contributed 72% and 28%, respectively, to the water discharge reduction. The human-induced decrease in the sediment load was 914.03×10^6 t/yr during the 1970s and 3301.79×10^6 t/yr during the 2000s. The contribution from human activities also increased from 71% to 92%, especially in the 1990s, when the value increased to 92%. Climate change and human activities contributed 14% and 86%, respectively, to the sediment load reduction. Inter-annual variations in water

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discharge and sediment load were affected by climate oscillations and human activities. The effect of human activities on the sediment load was considerably greater than those on water discharge in the Yangtze River basin.

1. Introduction

As links between the land and ocean, rivers are the major pathways of water, sediment load, and other terrestrial materials into the sea, and the cycling of these materials plays an important role in delta and estuarine evolution (Walling and Fang, 2003; Wang et al., 2011). In recent decades, global climate change may have accelerated the global hydrological cycle (Allen and Ingram, 2002). The accelerating global hydrological cycle has changed the spatiotemporal patterns of precipitation, resulting in increased occurrences of extreme precipitation events (Easterling et al., 2000). The increase in the frequency of extreme precipitation events has triggered more extreme floods in many regions of the world. Moreover, human activities have already disturbed river systems (e.g., land-use change, reservoir construction, water abstraction and irrigation). Climate change and human activities significantly affect natural river processes, and dramatic variations in water discharge and sediment load have occurred in many large rivers around the world (Walling, 2006; Milliman et al., 2008). Decreased sediment loads have caused erosion in many river deltas, including the Nile in Egypt (Fanos, 1995), the Ebro in Spain (Mikhailova, 2003), the Mississippi River (Blum and Roberts, 2009) and the Colorado River (Carriquiry and Sanchez, 1999) in the United States. The response of river water discharge and sediment load to climate change and human activity have become hot topics, garnering significant attention worldwide (Wang et al., 2006; Liquete et al., 2009; Syvitski et al., 2005). However, most studies have primarily concentrated on human activities (especially dam construction in particular), which has been identified as the main cause of the decreasing trend in river sediment loads (Vorosmarty et al., 2003; Xu et al., 2006; Zhang et al., 2008; Li et al., 2011). The effect of climate change on sediment load in rivers has received less attention. Therefore, quantitative assessments of the contributions of climate change and human activity are extremely important for increasing our understanding of estuarine and delta evolution.

The Yangtze River is one of the largest rivers in the world in terms of water discharge (920×10^9 m^3/yr) and sediment load (480 Mt/yr) (Milliman and Meade, 1983; Milliman and Syvitski, 1992). Along with explosive population growth, more than 400 million inhabitants live in the Yangtze River basin, more than 50,000 water reservoirs have been constructed, and the Water and Soil Conservation Project (WSCP) is within this watershed. The sediment load of the Yangtze began to decline in the 1970s. Therefore, the Yangtze River is one of the rivers most severely affected by human activities. Chen et al. (2001) analyzed the mean annual discharge of the Yangtze River based on data from three hydrological stations to determine the human influences on the discharge during the dry season. Yang et al. (2002) analyzed variations in the river sediment supply to the delta. Yang et al. (2006) found a significant decreasing trend in the riverine sediment supply since the late 1960s and attributed this decreasing sediment to dam construction. Yang et al. (2007) indicated that the Three Gorges Dam (TGD), which was completed in 2003, retained 1.5×10^8 t/yr of sediment load between 2003 and 2005, reducing sediment discharge from the Yangtze River into the sea by approximately a third. Many studies have discussed the temporal changes in water discharge and sediment load and their causes in the Yangtze River Basin (Yang et al., 2002, 2011; Zhang et al., 2006a,b, 2009). However, these studies have primarily focused on the influence of human activities and on the analysis of the climate change impact. In addition, as global climate conditions change, the frequency of global El Niño/Southern Oscillation (ENSO) events has increased during the 2000s (Liu et al., 2012). However, the effects of ENSO events on the total sediment load from the Yangtze River basin have rarely been discussed. More importantly, the quantifications of anthropogenic and climatic effects on water discharge and sediment load in the Yangtze River basin have also received little attention in previous studies. Hence, in this study, we aimed to (1) provide updated estimations of the water discharge and sediment load from the Yangtze River into the sea; (2) analyze the effects of climatic events on water discharge and sediment load; and (3) conduct a systematic and quantitative analyses of the changes in water discharge and sediment load at the basin scale to respond to the contributions of human activities and climate change. This study expects to provide a better understanding of human and natural contributions to the major river water and sediment transport processes, which will provide further scientific guidelines for global river management.

2. Data and methods

2.1. Study area and data sources

The Yangtze River is one of the most important rivers in the world. The river lies between 91–122 °E and 25–35 °N. The Yangtze River is the third longest river in length and ninth largest in catchment basin (Wang and Zhu, 1994). The Yangtze River originates on the Qinghai–Tibetan Plateau and extends approximately 6300 km eastward to the northern East China Sea (Fig. 1). The Yangtze River basin is located in the Asian monsoon region. The Indian summer monsoon (ISM) and the East Asian summer monsoon (EASM) are two weather features that affect the upper and mid-lower Yangtze catchments, respectively. The average rainfall is 1000–1400 mm/yr for the whole basin (Ding and Chan, 2005). The annual mean temperature of the middle and lower Yangtze River basin is 19 °C in the southern part and 15 °C in the northern part, respectively. The monsoon-driven precipitation causes seasonal variability in the river flow, with high water and sediment discharge in the flood season (i.e., from May to October).

The observed daily precipitation data from 1953 to 2013 were collected from 135 national standard rain stations in the Yangtze River basin (Fig. 1). Daily precipitation data were provided by the National Meteorological Information Center of China Meteorological Administration (http://www.nmic.gov.cn). Monthly sea surface temperature (SST) data from 1953 to 2010 over the central Pacific Ocean region (4°N to 4°S; 90°W to 150°W), and the ISM index were used to represent large-scale climate anomalies. Both datasets were obtained from http://climexp.knmi.nl/. The hydrological data (monthly and annual water discharge and sediment load) used in this study, which cover the period from 1953 to 2010, were measured at the Datong gauging stations in the Yangtze River. These data were obtained from the Changjiang Water Resources Commission (http://www.cjw.com.cn/), and some of the data were derived from the River Sediment Bulletin of China published by the Ministry of Water Resources, China (IRTCES, 2000–2007). To calculate the sediment load, the suspended load was measured by submerging a bucket into the water current. The sediment was collected after retrieving the bucket and was then dried and weighed. The river sediment load was measured according to the Chinese national standard criteria. At each gauging station, successive samples and flow readings were conducted along the same section of the river. Water samples were collected at different depths through the water column to measure the sediment concentrations. The flows are recorded at the same time. The daily, monthly, and annual sediment