Journal of Asian Earth Sciences 87 (2014) 102–115

Contents lists available at ScienceDirect

Journal of Asian Earth Sciences

journal homepage: www.elsevier.com/locate/jseaes

Temporal and spatial variability of sediment flux into the sea from the three largest rivers in China

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ARTICLE INFO

Article history:
Received 7 August 2013
Received in revised form 27 January 2014
Accepted 14 February 2014
Available online 28 February 2014

Keywords:
Yellow, Yangtze and Pearl Rivers
Sediment flux
Change trend
Human activities
Climate change

ABSTRACT

The Yellow, Yangtze and Pearl Rivers supply over 90% of the sediment flux from China to the western Pacific Ocean. Trends and abrupt changes in the water discharge and sediment load of the three rivers were examined and compared based on data updated to the year 2011 at the seasonal and annual scales. The total water discharge from the three rivers shows a statistically insignificant decreasing trend with a rate of 0.62×10^9 m^3/a, and the total sediment load shows a statistically significant decreasing trend at a rate of 31.12×10^6 t/a from the 1950s to 2011. The water discharge of the entire Yellow River and the upstream portion of the Yangtze River shows significant decreasing trends, and that of the mid-lower stream of Yangtze River and the entire Pearl River shows insignificant trends. The sediment loads in the three river basins all show significant decreasing trends at the annual and seasonal scales, and a dramatic decrease in the 2000s resulted in a more obvious decreasing trend over the studied period. From the 1950s to the 2000s, the contribution of sediment flux from the Yellow River to the ocean decreased from 71.8% to 37.0%, and the contributions of the Yangtze and Pearl Rivers increased from 24.2% and 4.0% to 53.0% and 10.0%, respectively. Inter-annual variations in water discharge and sediment load were affected by climate oscillations, such as the El Niño/Southern Oscillation, and the long-term decreasing trend in sediment load was primarily caused by human activities. Dam constructions and soil conservation projects were the major causes of sediment reduction. From the 1970s to the 2000s, the decrease in total sediment load from the three rivers caused by climate change and human activities was 2.24×10^8 t/a (23.0%) and 7.5×10^8 t/a (77.0%), respectively. In the coming decades, the sediment flux from the three rivers into the sea will decrease further with intensifying human activities, resulting in many challenges for the management of river basins and river deltas.

1. Introduction

The sediment flux delivered by rivers is a crucial process that affects the geomorphologic evolution of river channels, deltas and estuaries. As a link between the land and the sea, rivers discharge approximately 200×10^8 t of sediment load globally into the sea every year (Milliman and Syvitski, 1992), which is of great importance in terms of geomorphology and geology. In recent decades, the effects of human activities and climate change have significantly affected natural river processes and have led to a decrease in the sediment discharge into the sea (Vörösmarty et al., 2003; Walling and Fang, 2003; Siakeu et al., 2004; Walling, 2006). Decreased sediment loads have caused the erosion of many river deltas, such as the Nile in Egypt (Fanos, 1995), the Ebro in Spain (Mikhailova, 2003) and the Colorado (Carriquiry and Sanchez, 1999) and Mississippi Rivers (Blum and Roberts, 2009) in America. The erosion of river deltas has become a topic of global interest, attracting significant worldwide attention (Syvitski, 2008; Syvitski et al., 2009). A study on the variations in the river sediment discharge into the sea is essential for understanding the evolution of river deltas, which is a goal of the International Geosphere Biosphere Programme (IGBP) and its core project, the Land–Ocean Interaction in the Coastal Zone (LOICZ) (Syvitski et al., 2005).

The Yellow, Yangtze and Pearl Rivers are the three largest rivers in China in terms of water discharge and sediment load and play a leading role in delivering freshwater and terrestrial materials to the western Pacific Ocean. Due to explosive population growth

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http://dx.doi.org/10.1016/j.jseaes.2014.02.017
1367-9120/

and rapid economic development, the Yellow, Yangtze and Pearl Rivers are among the top global rivers severely affected by human activities (e.g., Wang et al., 2007; Yang et al., 2006; Dai et al., 2008b). Sediment discharge from the three rivers into the sea has decreased due to the human activities, particularly for the Yellow and Yangtze Rivers. For example, the Three Gorges Dam (TGD), which began operating in 2003, has retained 1.5×10^8 t/a of sediment between 2003 and 2005, which has reduced the Yangtze River's sediment discharge to the sea by approximately one-third (Yang et al., 2007). Additionally, by the 2000s, the sediment flux of the Yellow River had decreased to approximately 15% of its levels in the 1950s as a result of human activities, including the construction of large reservoirs as well as water and soil conservation practices (Wang et al., 2010). Although many publications have discussed the variations in sediment discharge in the Yellow (e.g., Xu, 2005; Wang et al., 2007; Miao et al., 2010; Liu et al., 2012a), Yangtze (e.g., Yang et al., 2002, 2007, 2011; Zhang et al., 2006, 2009b), and Pearl Rivers (e.g., Zhang et al., 2008; Dai et al., 2008b; Zhang et al., 2012; Liu et al., 2014), the studies are typically limited to a single river basin, and relatively few systemic summaries including all three rivers have been performed. Thus, it is difficult to examine the changes in total sediment flux from Chinese rivers, which influences the evolution of mega-deltas in East Asia and causes environmental changes on the continental shelf in the western Pacific Ocean. In addition, little is known about how different patterns of change in sediment flux compare across the three rivers or about differences between anthropogenic and climatic effects on sediment flux in the three river basins. Furthermore, most previous studies have concentrated on the period before the early 2000s based on annual hydrological data. Human activities in the three river basins have intensified in the 2000s, including the construction of large dams and reservoirs (e.g., the Longtan and Baise dams in the Pearl River in 2006) and the implementation of soil conservation projects in the three river basins in the 2000s. In addition, global climate conditions have changed; for example, the frequency of global El Niño/Southern Oscillation (ENSO) events has increased in the 2000s (Liu et al., 2012b), and the impacts of ENSO events on the total sediment flux from the three rivers have rarely been discussed. Additionally, changes in the annual hydrological time series may mask the influence of human activities and climate change on the seasonal changes. For example, a significant decreasing tend since the 1970s in the monthly mean water discharge to the sea from the Yangtze River basin during the dry-season was found by Chen et al. (2001), but this trend was not detected in the annual mean water discharge. Thus, it is of scientific and practical importance for river management to detect the changes in the hydrological time series influenced by human activities and climate change with continuously updated annual and seasonal data.

The objectives of this paper are (1) to provide updated estimation of the sediment flux from three large Chinese rivers into the western Pacific Ocean; (2) to examine and compare the temporal and spatial changes in the sediment flux from the three rivers on seasonal to decadal scales; and (3) to quantitatively evaluate the contributions of climatic and anthropogenic impacts on the changes in sediment flux. Our study will contribute to a better understanding of regional changes caused by human activities and climate change in the context of global change and will supply scientific guidelines for river management globally.

2. Study area

The Yellow, Yangtze and Pearl Rivers, located from the north to the south, are the three largest rivers in China. The three rivers discharge more than 1.2×10^{12} m^3/a of freshwater and 13.6×10^8 t/a of sediment into the western Pacific Ocean, accounting for more than 85% and 95% of the total water and sediment discharge from all Chinese rivers into the ocean, respectively. The Yellow and Yangtze Rivers originate from the Qinghai-Tibet Plateau at an altitude of 4000–5000 m, with mainstream lengths of 5464 km and 6300 km, respectively, and catchment areas of 750,000 km^2 and 1800,000 km^2, respectively. The Pearl River originates from the Yunnan Plateau with a length of 2400 km and a catchment area of 450,000 km^2 (Fig. 1 and Table 1). According to geomorphologic distinctions, the Yellow River is usually divided into three reaches at Toudaiguai and Huayuankou; the upper and middle reaches generate almost all the runoff for the river basin, and the sediment primarily originates from the middle reach, which provides approximately 90% of the total sediment discharge. The lower reaches are heavily deposition area and almost do not generate water and sediment discharges. The Yangtze River can also be divided into three reaches at Yichang and Hukou, and approximately half of the river water and almost all the sediment originate upstream from Yichang. The Pearl River is a compound river system involving three main tributaries, the West River, the North River and the East River (Fig. 1); the West River is the largest tributary and provides approximately 77% and 89% of the total water and sediment of the Pearl River, respectively.

The climate within the three river basins is the dominated by the Asian monsoon. The Asian monsoon is a major component of the global circulation system, which results in a seasonal pattern of precipitation (Li and Zhang, 2009). In this system, the Asian summer monsoon carries considerable moisture from the ocean and often causes high levels of precipitation. Inter-annual variations in the onset and withdrawal dates of the Asian monsoon are significant (Wang et al., 1998). In general, the Asian monsoon begins in April–May and withdraws in September–October, respectively (Wang et al., 1998; Li and Zhang, 2009). Due to the influence of the monsoon, more than 70% of the annual precipitation of the three rivers is concentrated in the wet season. However, the three rivers flow across different climatic zones with different climate conditions. The Yellow River basin is characterised by an arid and semi-arid continental monsoon climate in the northwest and a semi-humid climate in the southeast with an average basin precipitation of 450 mm/a. The Yangtze River flows across a region of subtropical monsoon climate with an average basin precipitation of 1070 mm/a. The Pearl River basin covers a region with a subtropical to tropical monsoon climate with a mean precipitation of 1475 mm/a.

3. Data and methods

3.1. Data

The hydrological data used in this study consists of monthly and annual water discharge and sediment load at gauging stations in the three rivers since the 1950s. The hydrological data were collected from government agencies including the Yellow River Conservancy Commission (YRCC), the Yangtze Water Conservancy Committee (YWCC), the Water Bureau of Guangdong Province (WBGP) and the Bulletins of Chinese River Sediment from 2001 to 2011 (BCRS, 2001–2011), which were compiled by the Ministry of Water Resources (MWR). In this paper, considering the characteristic of sediment yield in the three river basins, the annual precipitation above the Huayuankou station in the Yellow River and the annual basin precipitation in the Yangtze and Pearl Rivers were used to examine the climatic effects since the 1950s. Finally, precipitation time series for the three river basins since the 1950s were collected from the Information Centre of the China Meteorological Administration. The quality of the hydrological and