Science of the Total Environment 634 (2018) 534–541

Contents lists available at ScienceDirect

Science of the Total Environment

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

Driving forces and their contribution to the recent decrease in sediment flux to ocean of major rivers in China

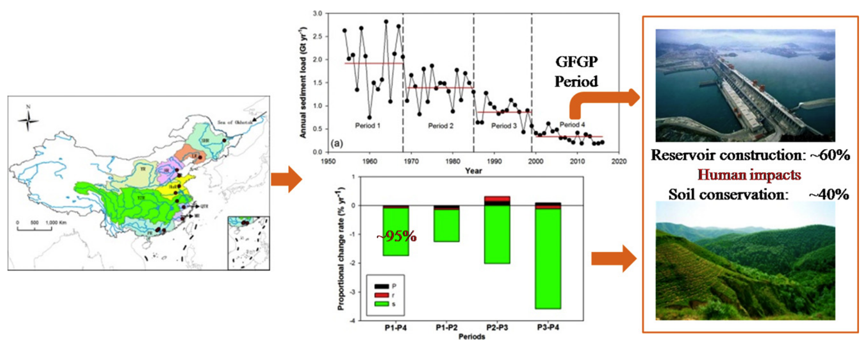
Tong Li, Shuai Wang *, Yanxu Liu, Bojie Fu, Wenwu Zhao

State Key Laboratory of Earth Surface Processes and Resource Ecology, Faculty of Geographical Science, Beijing Normal University, Beijing 100875, PR China
Institute of Land Surface System and Sustainability, Faculty of Geographical Science, Beijing Normal University, Beijing 100875, PR China

HIGHLIGHTS

- Reduction of sediment concentration dominates the sediment load decrease in China.
- Reservoirs especially large reservoirs mainly reduce sediments in Chinese rivers.
- Soil conservation measures enhanced the decrease in sediment flux after 1999.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 8 February 2018
Received in revised form 31 March 2018
Accepted 2 April 2018
Available online xxxx

Editor: F.M. Tack

Keywords:
China
Sediment flux
Sediment concentration
Reservoir construction
Soil conservation

ABSTRACT

Understanding the mechanisms behind land–ocean sediment transport processes is crucial, due to the resulting impacts on the sustainable management of water and soil resources. This study investigated temporal trends and historical phases of sediment flux delivered to the sea by nine major rivers in China, while also quantifying the contribution of key anthropogenic and natural driving forces. During the past six decades, sediment flux from these nine major rivers exhibited a statistically significant negative trend, decreasing from 1.92 Gt yr^{-1} during 1954–1968 to 1.39 Gt yr^{-1}, 0.861 Gt yr^{-1} and 0.335 Gt yr^{-1} during 1969–1985, 1986–1999 and 2000–2016, respectively. We used a recently developed Sediment Identity approach and found that the sharp decrease in sediment load observed across China was mainly (~95%) caused by a reduction in sediment concentration. Reservoir construction exerted the strongest influence on land–ocean sediment fluxes, while soil conservation measures represented a secondary driver. Before 1999, soil erosion was not controlled effectively in China and reservoirs, especially large ones, played a dominant role in reducing riverine sediments. After 1999, soil erosion has gradually been brought under control across China, so that conservation measures directly accounted for ~40% of the observed decrease in riverine sediments. With intensifying human activities, it is predicted that the total sediment flux delivered to the sea by the nine major rivers will continue to decrease in the coming decades, although at a slower rate, resulting in severe challenges for the sustainable management of drainage basins and river deltas.

* Corresponding author at: State Key Laboratory of Earth Surface Processes and Resource Ecology, Faculty of Geographical Science, Beijing Normal University, No. 19, XinJieKouWai St., HaiDian District, Beijing 100875, PR China.
E-mail address: shuaiwang@bnu.edu.cn. (S. Wang).

https://doi.org/10.1016/j.scitotenv.2018.04.007

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 (Walling and Fang, 2003). Land–ocean transfer of sediment by rivers plays an important role in regulating the carbon budget (Ludwig et al., 1996). Changes in sediment fluxes also have important socio-economic implications (Syvitski, 2003). In recent decades, there has been a significant decrease in river sediment loads in approximately 50% of the world's rivers, and reservoir construction is probably the most important factor influencing land–ocean sediment fluxes (Syvitski et al., 2005; Walling and Fang, 2003). Therefore, understanding the mechanisms behind land–ocean sediment transport processes is crucial, due to the resulting impacts on the sustainable management of water and soil resources.

Land–ocean transfer of sediment has attracted increasing attention in recent years, and several studies on land–ocean sediment transport processes have been conducted. Liu et al. (2014a) found that sediment loads from the three largest rivers in China showed significant decreasing trends at the annual and seasonal scales. C. Liu et al. (2008) proposed a classification of large Chinese rivers into the following three groups: 1) rivers with decreasing annual sediment transport and stable runoff, 2) rivers with both decreasing annual sediment transport and runoff, and 3) rivers with greatly reduced annual sediment transport and decreasing annual runoff. Lu et al. (2013) presented a quantitative estimate of changes in sediment loads (from 1.5 Gt yr^{-1} pre-1990 to 0.6 Gt yr^{-1} in 1991–2007) in eight large Chinese rivers in response to climate change. Moreover, the International Geosphere Biosphere Programme (IGBP) set the key goal of surveying terrestrial sediment supply to the sea and analyzing perturbations of this flux (Syvitski, 2003; Syvitski et al., 2005).

Sediment flux from rivers greatly impacts coastal seas and the health of marine ecosystems (Syvitski et al., 2009). The overall sediment flux from Chinese rivers to the sea was previously estimated to represent 10% of the world total (Wang et al., 1986). A decrease in sediment supply from rivers can cause negative impacts, such as retreat of river deltas and reduction of nutrient inputs to the sea, posing a serious threat to ecosystem sustainability in coastal regions (Liu et al., 2014b; Wang et al., 2016a; Yang et al., 2011). Dai et al. (2009) estimated that annual sediment transport by nine large Chinese rivers declined by 70% during the last half century, from 1809 Mt (1954–1963) to 540 Mt (1996–2005). It is widely accepted that anthropogenic influences are the main cause of changes in terrestrial sediments entering the ocean. Chu et al. (2009) estimated that during 1959–2007, human activities led to a decrease in total sediment transport from nine large Chinese rivers of 50 Gt, of which 28 Gt (56%) were attributed to dams and reservoirs, 11.5 Gt (23%) to soil and water conservation, 7.5 Gt (15%) to water consumption and 3 Gt (6%) to in-channel sand mining. Liu et al. (2013) concluded that the decrease in sediment load observed in 10 major Chinese rivers was due to the combined effects of soil and water conservation projects, water and sediment regulation by reservoirs, sediment abstraction by irrigation, sediment mining and climate change. Although these studies have confirmed that the total amount of sediment flux has decreased, novel quantitative estimation about the underlying driving forces and their contribution in China is still needed as time elapsed. Previous studies used a simple linear regression method to estimate the contributions of precipitation changes and human activities to changes in sediment load (Liu et al., 2014a; Miao et al., 2011). These studies lumped all factors other than precipitation into one explanatory variable (human activities), without further discriminating among different driving forces. Wang et al. (2016b) developed the “Sediment Identity” attribution approach to estimate the relative contributions of precipitation, water yield capacity and sediment concentration to sediment yield reduction during the last 60 years in the Loess Plateau. The advantages of this new method are that it helps better link indicators such as sediment concentration and water yield capacity to specific human activities and appears promising when extrapolating to larger scales.

With the booming economy, industrial development and urbanization, several characteristics of Chinese river basins may have dramatically changed. Based on data from river gauging stations covering 63 years (1954–2016), we examined temporal trends and historical phases of sediment flux delivered to the sea by nine Chinese rivers, and we used the Sediment Identity and multiple linear regression approach to quantify contribution of driving forces to the changes of sediment flux.

2. Materials and methods

2.1. Study area

There are nine major rivers in China entering the coastal ocean from north to south: Songhua (a major tributary of the Amur River, which flows into the Sea of Okhotsk), Liao, Hai, Yellow, Huai, Yangtze, Qiantang, Min and Pearl (Fig. 1). These rivers flow from west to east into the Pacific Ocean, playing a leading role in transporting terrestrial materials to the coast. They have a combined drainage basin area of 4.53×10^6 km^2 (Fig. 1), which constitutes 74% of the total external drainage area and 47% of the total area of China. Suspended sediment flux from these rivers to the sea represents 85% of China's total flux (Dai et al., 2009). Additional geographic information for the nine rivers is reported in Table 1.

2.2. Datasets

Annual runoff and suspended sediment data for the study rivers were obtained from the auxiliary material provided by Chu et al. (2009) and Dai et al. (2009) for the period 1954–2007 (Hai River: 1960–2007; Qiantang River: 1977–2007). We then retrieved annual runoff and suspended sediment data for the period 2008–2016 from the Chinese river sediment bulletin (http://www.mwr.gov.cn/sj/#tjgb), which is compiled by the Chinese Ministry of Water Resources. These measurements were taken at the lowermost hydrological stations in the drainage basins, near the river mouth (Fig. 1), where water and sediment discharged into the sea are routinely monitored. Due to the short length of record for the Hai and Qiantang rivers (Table 1), the records from the other seven rivers (Songhua, Liao, Yellow, Huai, Yangtze, Min, and Pearl River) were used to calculate summary statistics representative of the nine rivers.

Annual precipitation data (1954–2016) recorded at 756 gauging stations in mainland China were obtained from the Information Center of the Meteorological Administration of China (http://data.cma.cn). We used precipitation and drainage area data to calculate area-weighted average precipitation.

Annual data on the number and volume (large, medium and small) of reservoirs and on soil conservation areas in mainland China for the period 1973–2012 were obtained from the China Water Conservancy Yearbook (http://tongji.cnki.net/). Annual data for the period 2013–2016 were obtained from the Statistic Bulletin on China Water Activities (http://www.mwr.gov.cn/sj/#tjgb).

2.3. Sediment identity factor decomposition

We used the Sediment Identity approach to attribute observed changes in river sediment load to different drivers. River sediment load was expressed as the product of three driving factors (Wang et al., 2016b):

$$S = P\left(\frac{R}{P}\right)\left(\frac{S}{R}\right) = Prs \tag{1}$$

where S is sediment load, P is precipitation, R is runoff, r is water yield