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Spatial–temporal variation and periodic change in streamflow and suspended sediment discharge along the mainstream of the Yellow River during 1950-2013

Yanhong Wei [a], Juying Jiao [a,b,*], Guangju Zhao [a,b], Hengkang Zhao [b], Zhong He [a,b], Xingmin Mu [a,b]

[a] State Key Laboratory of Soil Erosion and Dryland Farming on Loess Plateau, Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, 26 Xinong Road, Yangling 712100, Shaanxi Province, China
[b] Institute of Soil and Water Conservation, Northwest A&F University, 26 Xinong Road, Yangling 712100, Shaanxi Province, China

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ABSTRACT

Objectives: Under the background of global climate change, variations in streamflow and sediment discharge in the Yellow River would continue with intensified human activities and changes in the ecological environment. To harness the Yellow River, analyzing the degrees of change and the reasons for the streamflow and sediment discharge, as well as predicting the future trends, are urgently needed.
Methods: In this paper, the non-parametric Mann–Kendall test, Sen's estimator of slope, Pettitt's test and wavelet transform were applied to detect the trends, the magnitude of the trends and the abrupt changes and periodic variation in streamflow and suspended sediment discharge at eight hydrological stations from 1950 to 2013 along the mainstream of the Yellow River.
Results: Over the past 64 years (1950–2013), the spatial distribution of the annual average streamflow was of the “M” type, and the annual average suspended sediment discharge had a parabolic curve shape along the mainstream of the Yellow River. The temporal variation showed a distinct decreasing trend in streamflow since the 1990s and in suspended sediment discharge since the 1980s. Many cycles of oscillations occurred in the streamflow and suspended sediment discharge variation, leading to an alternate change in the wet/dry periods and the high/low sediment discharge periods.
Conclusions: In various regions of the Yellow River Basin since the 1970s, climate changes contributed reductions of 17.0–45.0% and 12.2–50.3% for streamflow and suspended sediment discharge, respectively, whereas human activities contributed reductions of 55.0–83.0% and 49.7–87.8%. Therefore, human activities were the major causes of the significant decline in the streamflow and the suspended sediment discharge of the Yellow River over the past six decades. Reasonable and possible measures should be taken to achieve water resources optimization and configuration and to promote watershed management and sustainability in the regions of the Yellow River Basin.

1. Introduction

Water is the base of the life on earth and a major limiting factor for socio-economic development in the world (Miao and Ni, 2009). At the same time, sediment transport from continents to oceans via rivers is one of the most important processes regulating river-bank stabilization, soil formation, biogeochemical cycling of elements, crustal evolution and many other earth-related processes. However, the available water resources throughout the world are becoming depleted, and the sediment loads delivered to the sea are decreasing, which will accelerate coastal erosion and habitat reduction and will result in many challenges for the management of river basins and river deltas (Liu et al., 2014; Miao and Ni, 2009). Therefore, more attention should be paid to river management, and more studies should be focused on the periodic variation, oscillation and prediction of streamflow and sediment discharge in river systems.

Many rivers across the world have experienced a significant reduction in streamflow and sediment load over the last decades. By assembling long-term records of annual sediment load for 145 major world rivers, Walling and Fang (2003) found that ca. 50% of the sediment load records showed declining loads. According to 10 gauging stations on 10 large rivers across China, there was little change in average annual runoff but a dramatic decrease in annual sediment transport in the southern rivers (Huaihe River, Yangtze River, Qiantang River, Minjiang River, Dongjiang River and Xijiang River), and both annual sediment yield and runoff showed significant evidence of reduction in the

* Corresponding author at: No. 26, Xinong Road, Institute of Soil and Water Conservation, Yangling, Shaanxi 712100, China.
E-mail address: jyjiao@ms.iswc.ac.cn (J. Jiao).

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northern rivers (Songhua River, Liaohe River, Yongding River and Yellow River) (Liu et al., 2008). Panda et al. (2011) illustrated dramatic reductions in sediment load in tropical river basins: approximately 88% (62%) of 133 gauging stations showed declines in sediment loads in the monsoon (non-monsoon) season. Salmoral et al. (2015) demonstrated that the upper Turia basin of Spain exhibited significant decreasing trends in streamflow. The mean annual flow decreased by 16.5% in the Columbia River at the Dalles (Naik and Jay, 2011). Since 1950, the annual peak discharges of the Colorado River and its major tributary, the Gunnison River, have decreased by 29–38% and annual suspended sediment loads have likewise decreased (Van Steeter and Pitlick, 1998).

The Yellow River has suffered from severe problems of water scarcity, sedimentation, and flood risk (Barnett et al., 2006). Since the late 1950s, streamflow and sediment discharge of the Yellow River exhibited a significant decreasing trend (Gao et al., 2010; Wang et al., 2007). The source region of the Yellow River above the Longyang Gorge is the most important water holding area for the Yellow River, producing approximately 49.2% of the annual total runoff (Feng et al., 2006). However, the source region above the Tangnaihai station is characterized by an overall tendency towards decreasing water availability during 1959–2008 (Hu et al., 2011). The streamflow was dominated by a significant decreasing trend at the 95% confidence level in the mainstream of the Yellow River from 1950 to 2009 (Liu et al., 2012a). Annual runoff at the Lijin station, forty kilometers from the river mouth at the Bohai Sea, showed a significant downward trend and declined by approximately 10.8 mm every 10 years (10 a) (Wang et al., 2012). It was found that sediment loads in the middle and lower reaches also exhibited a gradual decreasing trend from 1950 to 2007, and that at the Lijin station was only 0.15 Gt/year (2000–2007), suggesting that the estuarine delta has been starved of sediment (Peng et al., 2010). The reduction in sediment load can directly impact the lower Yellow River and the delta region, causing alternate changes between siltation and scouring in the lower river channel together with an increasing erosion rate in the Yellow River Delta as a whole. Furthermore, reduced streamflow is the major concern in the Yellow River Basin, which supplies a large amount of fresh water for agriculture and industry and is home to 12% of the population in China (Barnett et al., 2006; Gao et al., 2013). Thus, further dramatic decreases in water discharge and sediment load in the Yellow River will trigger profound geological, morphological, ecological and biogeochemical responses in the estuary, delta and coastal sea (Wang et al., 2007).

There have been many researches on the discussions of water discharge and sediment load in large rivers, especially in the Yellow River Basin, China. However, the majority of previous studies focused on the variation of runoff or sediment yield of the main sections or tributaries in the Yellow River Basin, fewer analyses have been conducted of the changes in runoff and sediment along the mainstream of the Yellow River. Moreover, under the background of global climate change, the variations in streamflow and sediment discharge in the Yellow River would continue with intensified human activities and a changing ecological environment. To harness the Yellow River, analyzing the degrees of change and the reasons for the streamflow and sediment discharge, as well as predicting the future trends, are urgently needed. Therefore, both streamflow and suspended sediment discharge at eight gauging stations along the mainstream of the Yellow River were applied to analyze their spatiotemporal variations from 1950 to 2013. The objectives of the study were to 1) identify the spatial distribution and temporal variation in streamflow and suspended sediment discharge, 2) predict the changing trends in streamflow and suspended sediment discharge in the short term and 3) discuss the main reasons for the variations in streamflow and suspended sediment discharge. The results of this study will be helpful for understanding the detailed hydrological regime of streamflow and sediment discharge and to provide a reference for watershed water resource planning and effective management in the Yellow River Basin.

2. Study area

The Yellow River is the second longest river in China and is regarded as the cradle of Chinese civilization (Xu and Ma, 2009). The river originates from the eastern Qinghai–Tibet Plateau at an elevation higher than 5000 m above the sea level, then it flows eastward through the Loess Plateau and the North China Plain and finally enters the Bohai Sea (Wang et al., 2013). The Yellow River Basin is located between 96 and 119°E longitude and 32–42°N latitude, with a drainage area of 752,443 km^2 and a length of 5464 km, and it passes through nine provinces and autonomous regions (Fig. 1) (Li et al., 2009; Miao et al., 2011). According to its geomorphological features, the river is usually divided into three reaches by the Toudaoguai and Huayuankou stations. The upper reaches extend over a length of 3471 km from the river source to the Toudaoguai station, and they drain an area of 385,996 km^2. The middle reaches stretch 1206 km from the Toudaoguai station to the Huayuankou station and have an area of 343,751 km^2. A considerable number of tributaries join the mainstream in the middle reaches. The lower reaches stream down from the Huayuankou station, stretching over 786 km through the North China Plain to the river mouth, and they drain an area of 22,726 km^2 (Liu et al., 2012a).

The mean annual precipitation and temperature of the Yellow River Basin vary substantially in space and time. The mean annual precipitation increases from 368 mm in the upper reaches to 530 mm in the middle reaches and then to 670 mm in the lower reaches (Wang et al., 2007). More than 60% of the annual precipitation occurs during the period from June to September (Yang et al., 2010). The mean annual temperature varies from 1 to 8 °C in the upper reaches, 8 to 14 °C in the middle reaches, and 12 to 14 °C in the lower reaches, with the highest temperatures occurring in July and the lowest in January (Chen et al., 2005).

Due to rapidly increasing population and economic development, water shortages have become more serious in the Yellow River Basin (He et al., 2013; Miao et al., 2012; Xu and Ma, 2009). Furthermore, the spatial distribution of water resources is highly heterogeneous. The upper reaches are known as a "relatively clear water area", contributing 56% of the total runoff. The middle reaches produce 42% of the total basin runoff, and the lower reaches provide only 2% of the total basin runoff (Liu et al., 2012a; Yang et al., 2010). Due to the flowing of the river through arid and semi-arid regions, with the torrential rainfall and the lack of natural vegetation protecting against soil erosion by runoff, there is a high potential for producing and exporting large quantities of sediment (Bracken and Kirkby, 2005; Zuazo et al., 2012). The average annual erosion rate reached 2480 t/km^2 for the entire Yellow River Basin in 1989, which is the highest of any major river system and is famous for the largest amount of sediment discharge and sediment concentration in the world (Shi and Shao, 2000). At present, the average sediment delivery modulus in the sediment-rich region of the Yellow River decreased from 7767.4 t/(km^2·a) in 1951–1969 to 980.5 t/(km^2·a) in 2000–2010 (Jiao et al., 2014).

3. Methodology

3.1. Data

Annual streamflow and suspended sediment discharge records at eight representative gauging stations (the Tangnaihai, Lanzhou, Toudaoguai, Longmen, Tongguan, Huayuankou, Aishan and Lijin stations, abbreviated as TNH, LZ, TDG, LM, TG, HYK, AS and LJ, respectively) along the mainstream of the Yellow River from 1950 to 2013 were obtained from the Yellow River Conservancy Commission (YRCC). The measurement of streamflow and suspended sediment discharge was conducted by the hydrological stations of YRCC according to the Chinese national standard criteria. At each gauging station, successive water samples and flow were taken at the same section of river and at the same time daily by current meter basically all the year round. Water