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Quantifying the impact of climate variability and human activities on streamflow in the middle reaches of the Yellow River basin, China

Guangju Zhao [a,b,c], Peng Tian [d], Xingmin Mu [a,b,*], Juying Jiao [a,b], Fei Wang [a,b], Peng Gao [a,b]

[a] Institute of Soil and Water Conservation, Northwest A&F University, 26 Xinong Road, Yangling 712100, Shaanxi Province, China
[b] Institute of Soil and Water Conservation, Chinese Academy of Sciences & Ministry of Water Resources, 26 Xinong Road, Yangling 712100, Shaanxi Province, China
[c] Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China
[d] College of Resources and Environment, Northwest A&F University, Yangling 712100, Shaanxi Province, China

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SUMMARY

The middle reaches of the Yellow River basin (MRYRB) contribute significantly to the total streamflow and sediment discharge of the Yellow River. Significant changes in streamflow have been detected; these changes result in part from large number of soil and water conservation measures implemented over the past six decades in this area. This study investigates streamflow variations and evaluates the impacts of climate variability and human activity on the mean annual flow in the MRYRB. The non-parametric Mann–Kendall test and Pettitt's test are applied to characterize the trends and abrupt changes of hydro-climatic variables in the MRYRB. The analysis was performed on streamflow data taken over the period from the 1950s to 2010 at 18 hydrological stations and on precipitation, temperature and potential evapotranspiration (PET) data from 43 climate stations. We find that 16 of these stations recorded significant decreases in annual streamflow, with reduction rates ranging from 0.10 mm/yr to 1.61 mm/yr over the study period. Precipitation at all of the stations also had negative trends, with changes ranging from −4.7 mm/yr to −0.19 mm/yr. Temperature increased significantly at most stations, while PET showed a mixed of upward and downward trend. Abrupt changes in streamflow at mainstream stations occurred when large reservoirs were built, while breakpoints of streamflow at tributary stations were mainly driven by the implementation of soil and water conservation measures. We used both Budyko's curve (a simple water balance model) and linear regression to evaluate the potential impacts of climate variability and human activities on mean annual streamflow. Climate variability has a greater effect on the streamflow reduction in the Beiluo River and Yan River, while human activities accounted for more of the streamflow changes in other tributaries, especially in the northern catchments. In general, human activities, including soil and water conservation projects, the operation of dams and reservoirs, and water consumption, are found to be the dominant factors responsible for the significant decline in the annual streamflow in the MRYRB over the last six decades.

1. Introduction

Observational evidence in most regions throughout the world indicates that hydrological cycles are being affected by climate change and human activities (Huntington, 2006). Brutsaert and Parlange (1998) showed that climate change is likely to give rise to warmer atmospheric temperatures and accelerated hydrological cycles globally. Climate variability has also led to changes in precipitation patterns throughout the world, while human activities have altered the spatial–temporal distribution of water resources (Jiang et al., 2010; Milly et al., 2005; Wang et al., 2013a). Because of the importance of avoiding and minimizing the economic loss of frequently occurring floods and severe drought disasters, investigation into the effects of climate change and human activities on streamflow has become an important scientific issue. Understanding these issues is also crucial if water resources management systems are to achieve sustainability.

As a results of the recent strong warming and significant regional precipitation variation as well as the intensification of human activities, such as agricultural irrigation, drinking water extraction, hydraulic projects and soil and water conservation measures, considerable attention has been paid to assessing the impacts of

* Corresponding author at: Institute of Soil and Water Conservation, Northwest A&F University, 26 Xinong Road, Yangling 712100, Shaanxi Province, China.
E-mail address: xmmu@ms.iswc.ac.cn (X. Mu).

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climate variability and human-induced land use changes on water resources (Hang et al., 2011; Ma et al., 2008; Milly et al., 2008; Mu et al., 2007; Tao et al., 2011; Zhai et al., 2010). Assessments of the impacts of climate change on river streamflow are usually performed using hydrological models or by analyzing the variation of hydro-climatic variables. Hydrological models, such as the Soil and Water Assessment Tool (SWAT), the Variable Infiltration Capacity (VIC) model, the Xinanjiang model, the HBV model and the SLURP (Semi-distributed Land Use-based Runoff Processes) model, have been commonly applied to assess the impacts of climate change and human activities such as land use changes on streamflow under various scenarios (Choi et al., 2009; Fohrer et al., 2005). Although hydrological models can provide accurate results, a large number of parameters cannot be obtained from field measurements. Additionally, hydrological modeling requires a large number of input data sets and is often seen as time consuming for model calibration and validation Due to these limitations, new attempts assess the effect of climate variability and human activities have recently been made. In recent years, both the hydrological sensitivity method and a simple water balance model known as Budyko's curve have been widely applied to separate the effects of climate change and human activities on streamflow (Dooge et al., 1999; Milly and Dunne, 2002; Wang et al., 2013b; Zhang et al., 2008).

The Yellow River basin has served as the "cradle of Chinese civilization" over the past millennia and continues to play a critical role in the development of China (Zhao et al., 2013). The Yellow River is a major source of freshwater for the approximately 107 million people who live within the river basin. However, streamflow in the Yellow River basin displays evident decline, particularly in the recent ten years after the "Grain for Green" project launched in 1999. The middle reaches of the Yellow River basin (MRYRB) between Toudaoguai and Huayuankou stations are an important section that contributes significantly to the total streamflow and sediment discharge of the Yellow River. In the last six decades, numerous soil and water conservation measures have been implemented in the MRYRB, including the construction of check-dams, reservoirs and terraces, returning croplands to grasslands and reforestation. Significant reductions in both streamflow and sediment flux in this region have been detected at rates of decrease up to 60% and 80%, respectively (Zhao et al., 2012).

Thus, many studies have investigated the variability of MRYRB streamflow in response to climate changes and human activities to support future water resource management and to strategize approaches to maintaining the aquatic ecosystems of the rivers (Liu and Zheng, 2004; Wang et al., 2013a; Zhao et al., 2012). Piao et al. (2010) showed that climate was the dominant factor controlling runoff; increased withdrawals can explain approximately 35% of the declining runoff observed at the Huayuankou station in the lower reaches of Yellow River over the last half-century. Wang et al. (2006) found that human activities referring to the construction of dams and reservoirs and increasing water consumption were responsible for the decreased streamflow in the Yellow River. Gao et al. (2011) assessed the changes in streamflow between the Toudaoguai and Huayuankou stations, and found that a decrease in precipitation was responsible for 28% of the decrease in streamflow from 1986 to 2008 in the MRYRB, while the remaining 72% was due to human activities. However, most of these studies primarily analyzed streamflow variations by using the mainstream gauging stations (Liu and Cui, 2011; Lu, 2004). The changing streamflow properties and their connection to natural and anthropogenic impacts in the MRYRB have not been extensively analyzed, especially after the "Grain for Green" project launched by Chinese government in 1999. Furthermore, the scientific community still disagrees on how climate change and human activities affect the regional water resources in the Yellow River basin. The objectives of this study, therefore, are (1) to assess the spatial and temporal variation of streamflow in the MRYRB and (2) to quantify the effects of climate variability and human activities on streamflow there.

2. Study area and data

2.1. Geographic setting

The middle reaches of the Yellow River are located between Toudaoguai and Huayuankou hydrological stations, a section of the mainstream river 1234 km in length (Fig. 1). The drainage area covers six provinces (Gansu, Ningxia, Inner Mongolia, Shaanxi, Shanxi and Henan) and an area of 362,000 km^2. There are more than 30 large tributaries (catchment areas larger than 1000 km^2) along the middle reaches; these tributaries contribute nearly 44% of the total discharge of the Yellow River. The middle reaches of the Yellow River flow through the Loess Plateau, where severe erosion occurs. The large amounts of mud and sand discharged into the river here accounting for 88% of the total sediment in the Yellow River and make it the most sediment-laden river in the world (Zhao et al., 2012). The basin lies in a semi-arid climate zone that is dominated by the Southeast Asian summer monsoon. The spatial and temporal distribution of the precipitation within the middle reaches of the Yellow River basin is uneven. Average annual precipitation ranges from 320 mm in the north to 836 mm in the south, and the potential evapotranspiration (PET) ranges from 810 to 1260 mm. The rainfall in the rainy season, from May to October, accounts for more than 70% of the total annual rainfall.

The sustainable development of the region's society and economy over the past six decades has been restricted by changes that occurred in the Yellow River (Song et al., 2007; Zhao et al., 2013). As shown in Fig. 2, the annual runoff of the Yellow River has decreased significantly since the 1980s due to climate change and intensive human activities. For example, at Huayuankou station, the annual runoff was 23.56 km^3/yr in 2000–2010, which was only 51.43% of that observed in 1950–1960 (Fig. 2). To meet the demands of the large regional population, agriculture and industry, the average annual water withdrawal from the river was approximately 47.80 km^3 over the period from 2000 to 2009 (YRCC, 2013). The amount of water used to fill reservoirs increased rapidly over the past 60 years and has reached up to more than 30 km^3/yr in recent years. Three large reservoirs with total storage capacity of 43.05 km^3, Longyangxia, Liujiaxia and Xiaolangdi (shown in Fig. 2), have greatly reduced the annual streamflow due to their extraordinary trapping effects (Yao et al., 2011). In addition, large-scale soil and water conservation measures have been applied to control severe soil erosion in the upper-middle reaches of the Yellow River basin since the 1950s and particularly after the 1980s. By 2006, various soil and water conservation measures had been applied to approximately 1.03×10^5 km^2 of the catchment; these measures have significantly altered the hydrological regime of the river. Thus, there is a great need to quantitatively assess the changes in water resources and the potential effects of climate changes and anthropogenic measures in the Yellow River basin over the past decades.

2.2. Data

The hydrological data include monthly observed streamflow at gauging stations located in the mainstream and tributaries (Table 1) throughout the study area (Fig. 1). Stations with data records less than 54 years in length were excluded from this analysis. Hydrological data at 4 mainstream stations and 14 stations in the tributaries from the 1950s to 2010 were provided by Yellow