Changes in runoff and sediment discharge and influencing factors analysis in the Xiliugou Basin, China

Suzhen Dang*, Manfei Yao, Le Bai and Guotao Dong

1 Yellow River Institute of Hydraulic Research, Yellow River Conservancy Commission, Zhengzhou, 450003, China
2 School of Water Conservancy, North China University of Water Resources and Electric Power, Zhengzhou, 450046, China

*Corresponding author’s e-mail: dangsz_hky@163.com

Abstract: Based on the observed runoff, sediment discharge and precipitation data of the Xiliugou Basin from 1960 to 2015, the changes in runoff and sediment discharge were analyzed, and the attribution of precipitation and human activities to runoff and sediment discharge changes in the Xiliugou Basin was quantitatively assessed by using the hydrological modeling method. The results showed that, the runoff and sediment discharge in the Xiliugou Basin showed a significant decreasing trend from 1960 to 2015, and the change point for runoff and sediment discharge was around 2005. Human activities was the main driving factor for the runoff and sediment discharge change for the period of 2006-2015, which accounted for 74.6% and 88.5% of the runoff and sediment discharge reduction, respectively. Precipitation was responsible for 25.4% and 11.5% of the runoff and sediment discharge reduction, respectively.

1. Introduction

In recent decades, climate change and human activities have led to considerable alterations of hydrological regimes worldwide[1][2]. Runoff and sediment discharge are the key and most active parts of the river system, and the study of runoff and sediment changes provides important information for soil erosion and transport of materials within watersheds[3]. In the context of global warming, the impact of climate changes and human activities on soil erosion in the Loess Plateau, and even the impact of runoff and sediment discharge in the Yellow River basin is a research topic.

The Xiliugou Basin is a primary tributary of the Yellow River, located in the hilly and gully loess region with serious soil erosion. Since the late 1970s, numerous soil conservation practices have been implemented in the Loess Plateau, such as afforestation, terraces and check dam. Vegetation changes and check dams are the main underlying surface factors in the Xiliugou Basin. With the implementation of the ecological recovery program (i.e., the “Grain for Green Project” (GGP)) since 1999, the vegetation coverage in the Xiliugou Basin has greatly increased. These extensive activities in combination with climate change have dramatically altered the hydrological regimes in the study area. Previous studies have examined the characteristics of runoff and sediment discharge in this region[4][5], but the impacts of climate change and human activities on the changes of runoff and sediment discharge is limited.

This study chose a typical catchment in the Loess Plateau, the Xiliugou Basin, to investigate the variations of runoff and sediment discharge based on the observed data from 1960 to 2015, and to quantitatively assess the relative influences of climate change and human activities on runoff and sediment discharge. This is important for sustainable ecosystem restoration, as well as water resources.
planning and management within the catchment.

2. Study Area and Data
Xiliugou River originates from Dongsheng district, Erdos city, Inner Mongolia, with a drainage area of 1180 km². The total length of the river is 106.5 km, with an average gradient of 3.6‰. The watershed is located in the semi-arid area. The mainly topography of the upper reaches of the basin is a loess hilly and gully region, the middle reaches are the Kubuqi desert, and the lower reaches are the alluvial fans. The annual average temperature of the basin is 6.8°C. The average annual rainfall is 260.3mm from 1960 to 2015. Intra-annual distribution of precipitation is extremely uneven, 79.8% of the total annual precipitation occurs in the period from June to September.

The observed daily precipitation data collected from rainfall stations and hydrological stations and the annual runoff and sediment discharge data at Longtouguai Station from 1960 to 2015 in the Xiliugou Basin is from the Yellow River Conservancy Commission. The rainfall stations and hydrological station locations are shown in Figure 1.

Rainfall indexes used in this study refer to the total annual rainfall ($P$), rainfall in flood season ($P_{6-9}$, from June to September), and categories are divided based on daily precipitation amounts that were greater than 10 mm, 25 mm, 50 mm and 100 mm, which were expressed as $P_{10}$, $P_{25}$, $P_{50}$ and $P_{100}$, respectively, and were measured in mm.

3. Methods

3.1. Mann-Kendall test
Non-parametric Mann-Kendall trend method (MK) is a simple and robust test method widely used in examining trends and abrupt change of hydrological and meteorological series (Zheng et al., 2009; Dang et al., 2018). The MK test is applied to analyze the changes in runoff and sediment discharge in this study. The detailed description of MK test can be found in many studies[6], it will not be discussed here.

![Figure 1 The location of the study area](image)

3.2. Quantitative assessment of the changes in runoff and sediment discharge
The changes in observed runoff under the influences of precipitation and human activities can be
expressed as:

\[ \Delta W_R = \Delta W_P + \Delta W_H \]  

(1)

Where \( \Delta W_R \) is the observed runoff difference between the impacted period and the natural period, \( \Delta W_P \) and \( \Delta W_H \) represent the changes in runoff due to precipitation and human activities, respectively.

To quantitatively identify the influences of precipitation and human activities on the runoff changes, the empirical model is used due to their good performance in modeling the runoff in the Loess Plateau [7].

According to the results of correlation analysis between runoff and sediment discharge and different rainfall indexes in the natural period (Table 1), \( P_{25} \) has the highest correlation with runoff and sediment discharge. Therefore, \( P_{25} \) is used to establish the relationship between rainfall runoff and rainfall and sediment transport.

The relationship between precipitation and runoff in the natural period is given as follows:

\[ W_R = 1405 \times e^{0.0082P_{25}} \]  

(2)

Where \( W_R \) is the runoff; \( P_{25} \) is the rainfall factor.

The effects of precipitation and human activities on runoff can be calculated as follows:

\[ \Delta W_{RP} = W_{R0} - W_{R2} \]  

(3)

\[ \Delta W_{RH} = W_{R2} - W_{R1} \]  

(4)

Where \( W_{R0} \) is the runoff in the natural period; \( W_{R1} \) and \( W_{R2} \) are the observed and calculated runoff in impacted period, respectively.

The same method is used to separate the influences of precipitation and human activities on sediment discharge, and the relation between precipitation and sediment discharge in the Xiliugou Basin is as follows:

\[ W_S = 20.519 \times e^{0.0302P_{25}} \]  

(5)

Where \( W_S \) is the sediment discharge.

Table 1 Correlation between runoff, sediment discharge and rainfall indexes from 1960 to 2005

| Hydrological features | \( P \) | \( P_{6.9} \) | \( P_{10} \) | \( P_{25} \) | \( P_{50} \) | \( P_{100} \) |
|-----------------------|--------|-------------|-------------|-------------|-------------|-------------|
| Runoff                | 0.652**| 0.727**     | 0.713**     | 0.801**     | 0.541**     | 0.532**     |
| Sediment discharge    | 0.356* | 0.396*      | 0.380*      | 0.617**     | 0.534**     | 0.524**     |

**Significant at the 0.01 level, *Significant at the 0.05 level.

4. Results

4.1. Changes in annual runoff and sediment discharge

The average annual runoff of the Xiliugou Basin is \( 2694 \times 10^4 \) m\(^3\). Figure 1 shows the changes in the annual runoff in the Xiliugou Basin from 1960 to 2015. The annual runoff exhibits a significant decreasing trend at the significance level of 0.05 over the past 56 years. The maximum and minimum of annual runoff are \( 9659 \times 10^4 \) m\(^3\) in 1961 and \( 105 \times 10^4 \) m\(^3\) in 2006, respectively. Abrupt change detection made by the MK test indicates that the change point for the annual runoff series is around 2005.
The average annual sediment discharge of the Xiliugou Basin is $353.6 \times 10^4$ t. Figure 2 shows the changes in the annual sediment discharge in the Xiliugou Basin from 1960 to 2015. The annual sediment discharge exhibits a significant decreasing trend at the significance level of 0.05 over the past 56 years. The maximum and minimum of annual sediment discharge are $4750 \times 10^4$ t in 1989 and $0.013 \times 10^4$ t in 2011, respectively. Abrupt change detection made by the MK test indicates that the change point for the annual runoff series is around 2005.

4.2. Driving factors of annual runoff and sediment discharge change

Changes in runoff and sediment discharge are influenced by the combination of climate change and human activities. Therefore, quantifying the effects of precipitation and human activities on runoff and sediment discharge can better reveal the dominant factors of runoff and sediment discharge changes, as well as the importance of human activities on runoff and sediment discharge.

As shown in figure 2 and figure 3, the abrupt change point of runoff and sediment discharge was 2005. Before that, the hydrological process of the Xiliugou Basin could be considered to be in a nature state. After that, it was severely affected by human activities. Therefore, the runoff and sediment discharge from 1960 to 2005 are regarded as the natural state.

The hydrological modeling method was used to estimate the attribution of precipitation and human activities to the changes in runoff and sediment discharge in the Xiliugou Basin for the period of 2006-2015. The annual runoff and sediment discharge reached $3057 \times 10^4$ m$^3$ and $428.5 \times 10^4$ t in the baseline period, respectively. The hydrological modeling results showed that precipitation led to $516.2 \times 10^4$ m$^3$ and $42.2 \times 10^4$ t changes in runoff and sediment discharge for 2006-2015, respectively (Table 2). Human activities led to $1514.8 \times 10^4$ m$^3$ and $325.1 \times 10^4$ t changes in runoff and sediment discharge during 2006-2015, respectively (Table 2). During 2006-2015, the impact of precipitation was responsible for 25.4% and 11.5% of the runoff and sediment discharge decrease, respectively; while the effects of human activities were responsible for 74.6% and 88.5% of the runoff and sediment discharge decrease, respectively. Human activities were the main driving factor for the runoff and sediment discharge
changes in the Xiliugou Basin.

Table 2 Attribution of the changes in runoff and sediment discharge in the Xiliugou Basin during 2006-2015

| Hydrological features | \( W_0 \) | \( W_1 \) | \( W_2 \) | \( \Delta W \) | \( \Delta W_P \) | \( \Delta W_H \) | \( \Delta W_P (%) \) | \( \Delta W_H (%) \) |
|-----------------------|---------|---------|---------|---------|---------|---------|---------|---------|
| Runoff (10^4 m^3)     | 3057    | 2541    | 1026    | 2031    | 516.2   | 1514.8  | 25.4    | 74.6    |
| Sediment discharge (10^4 t) | 419.2  | 376.9   | 51.9    | 367.3   | 42.2    | 325.1   | 11.5    | 88.5    |

5. Conclusions
The runoff and sediment discharge in the Xiliugou Basin showed a significant decreasing trend from 1960 to 2015, and the change point for runoff and sediment discharge was around 2005. The hydrological modeling method was employed to quantitatively assess the attribution of precipitation and human activities to runoff and sediment discharge changes in the Xiliugou Basin for the period of 2006-2015. The results showed that human activities was the main driving factor for the runoff and sediment discharge change, which accounted for 74.6% and 88.5% of the runoff and sediment discharge reduction, respectively. Precipitation was responsible for 25.4% and 11.5% of the runoff and sediment discharge reduction, respectively.

Acknowledgments
This research was financially supported by the National Key R&D Program of China (2017YFC0403600, 2016YFC0402400), and Special purpose of Science and Technology Development Fund of Yellow River Institute of Hydraulic Research (HKY-HKF-2019-05).

References
[1] Guangyao, G., Bojie, F., Jianjun, Z., Ying, M., & Murugesu, S. (2018). Multiscale temporal variability of flow-sediment relationships during the 1950s–2014 in the loess plateau, china. Journal of Hydrology, 563: 609-619.
[2] Ahn, K. H., Yellen, B., & Steinschneider, S. (2017). Dynamic linear models to explore time-varying suspended sediment-discharge rating curves. Water Resources Research, 53(6): 4802-4820.
[3] Zheng, M., Yang, J., Qi, D., Sun, L., & Cai, Q. (2012). Flow–sediment relationship as functions of spatial and temporal scales in hilly areas of the Chinese Loess Plateau. CATENA, 98: 29-40.
[4] Liu T., Zhang S. F., Liu S. X. (2007). Primary analysis of the relationship between storm runoff and sediment yield in Ten-watershed – A case study in Xiliu Brook. Journal of Water Resources & Water Engineering, 18(3): 18-21. (in Chinese)
[5] Lei C. M., Li Z., Guo S. M. (2017). Analysis of August 17, 2016 storm flood in Xiliugou River Basin of the Yellow River in 2016. Yellow River, 39(11): 63-65. (in Chinese)
[6] Liu, C. M., Xia J. (2004). Water problems and hydrological research in the Yellow River and the Huai and Hai River basins of China. Hydrological Processes, 18(12): 2197-2210.
[7] Li X. Y., Liu X. Y., Li Z. (2016). Effects of rainfall and underlying surface on sediment yield in the main sediment-yielding area of the Yellow River. Journal of Hydraulic Engineering, 47(10): 1253-1259 (in Chinese).