The variation and influencing factors of the runoff and sediment entering sea in the Yellow River

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Abstract. This paper analyzes the trend of runoff and sediment entering the Bohai Sea using the streamflow and sediment data of the Yellow River estuary hydrological station. The results show that runoff and sediment into sea in the Yellow River both reduce in the recent 60 years, there is significant positive correlation between the two. And the influencing factors of runoff and sediment are also researched, it is found that there is no significant correlation between runoff and precipitation, or between sediment and precipitation. The increase of the water intake quantity from the river is the main reason of runoff reduction entering the sea. And soil and water conservation measures and water storage projects result in the decrease of sediment in the river estuary.

1. Introduction
The sediment discharge of rivers into the sea is an important manifestation of the surface process and an important part of global change research. At present, the researches on the generation and transportation of river sediments and the response of estuary delta to the change of sediment load has become an important aspect of earth system science study. The long sequence records of river water and sediment flux shows that both the annual sediment transportation and runoff of many rivers in the world is unstable. The sediment concentration of the Yellow River is highest among all the rivers in the world. From June 1855, the Yellow River flows into the Bohai Sea, and the river has been affecting the modern Yellow River Delta since then. The amount of water and sediment entering the lower reaches of the Yellow River has continued to decrease since the 1970s due to the influence of watershed factors and human activities. Especially in the past 10 years, the reduction has been more severe, which resulted in a sharp decrease in the amount of water inflow to the Yellow River estuary. In sequence, it greatly impacts the interaction between sea and land, the dynamic condition, ecology system and environment. Numerous studies have shown that several important factors affecting the flow of the Yellow River into the sea include climate change (e.g. temperature, precipitation) and large-scale human activity disturbances (e.g. reservoirs, soil and water conservation measures, and sediment control engineering)(Wang et al., 2010, Wu et al., 2004). Therefore, it is essential to research the change trend of the discharge and sediment into the sea of the Yellow River in the past 60 years, and preliminarily analyse the reasons, which is benefits to manage the water resources, sediment, the coast and estuary delta in the Yellow River Basin.

2. Data source and analysis method

2.1. Data source
The Lijin hydrological station is the last important hydrological station before the Yellow River flow into the Bohai Sea. The water extraction below the Lijin station is relatively little, so the runoff and sediment amount of the station is generally used as the water flow and sand flux into the sea of the Yellow River. In this paper, the measured runoff and sediment discharge in the Lijin hydrological station is used as the measured runoff and sediment load of the Yellow River entering into the sea. The measured runoff and measured sediment load in Lijin Station from 1952 to 2014 are derived from *the Sediment Bulletin in the Yellow River Basin* (Yellow River Conservancy Commission, 2014). The annual average precipitation amount from 1961 to 2013 in the Yellow River Basin is weighted by precipitation data of 70 meteorological stations in the basin, and the precipitation data is acquired from *the Surface Climate Data Collection in China* from the website of the China Meteorological Administration.

2.2. Analysis method

The Mann-Kendall rank correlation test (M-K method) is a non-parametric statistical test method, which is commonly used to evaluate the time series trend of climatic elements and also utilized in trend studies of long serial hydrological sediment processes. The advantage of the M-K method is that the sample does not need to follow a certain distribution law, is not interfered by a few abnormal values, and is more suitable for typical variables and ordinal variables (Yue et al., 2002). This method is known for its wide application range, less artificial and high degree of quantification (Shi et al., 2014). Therefore, this paper uses the M-K rank correlation test to analyze the trend of the Yellow River's runoff and sediment flow sequence.

3. Changes in the runoff and sediment entering into the sea

3.1. Changes in the runoff and sediment entering into the sea

The annual runoff and sequence from 1952 to 2014 of the Lijin Hydrological Station in the Yellow River is analysed by M-K trend method. The results show that the M-K test statistic $U_F^k$ of the measured runoff and sediment amount into the sea is -5.88 and -6.55, and the both pass the test when $\alpha$ is equal to 0.01 ($U_{0.01}=2.58$). The result indicates that the measured runoff and sediment amount into the sea of the Yellow River both have significant decreasing tendency. In recent years, Chinese scholars have carried out mutation analysis on the runoff and sediment time sequence of the Yellow River, and put forward that the 1968 (1969), 1985, 1996, and 2007 were the points of abrupt change in the runoff and sediment amount into the sea (Ren et al., 2014). According to the mutation points, the sequence of runoff and sediment in the Yellow River is divided into five stages including Stage I (1952-1969), Stage II (1970-1985), Stage III (1986-1996), Stage IV (1997-2007), Stage V (2008-2014), which is shown as Figure 1 and Figure 2. The average annual runoff and sediment amount in the five stages all significantly decreased. From the Stage I to the Stage V, the average annual runoff decreased from 48.91 billion cubic meters to 18.42 billion cubic meters, and the average annual sediment volume decreased from 1200 million tons to 130 million tons. Among the years, the amount of sediment entering into the sea in 2014 was only 30 million tons, and the amount is only 4 percent of the average annual sediment.

3.2. Relationship between the runoff and sediment entering the sea

In order to analyze the relationship between annual runoff and sediment discharge, the principle of maximizing the square of correlation coefficient is used to choose the linear regression equation for fitting the relationship from linear, power, exponential, lognormal, polynomial and other regression equations. The relationship between the annual runoff and sediment amount into the sea of the Yellow River was fitted as follows: $S= 0.2485R - 0.8243 \ (r^2=0.66)$. 

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Figure 1. Change of runoff flowing into the sea from 1952 to 2014 in the Yellow River.

Figure 2. Change of sediment entering into the sea from 1952 to 2014 in the Yellow River. Where \( S \) represents the annual sediment discharge, \( R \) represents the annual runoff, and \( r \) represents the correlation coefficient. It can be seen from the above equation that the annual sediment load and annual runoff are positively correlated, and the correlation is very high, which indicates that the sediment flowing into the sea of the Yellow River decreases with the reduction of runoff.

Table 1. The runoff and sediment discharge in the Lijin hydrological station of the Yellow River

| Stage        | Runoff | Sediment discharge |
|--------------|--------|--------------------|
| 1952-1969    | 48.91  | 1.2                |
| 1970-2014    | 21.78  | 0.48               |
| 1986-2014    | 15.62  | 0.27               |
| 2000-2014    | 16.14  | 0.14               |
| 2008-2014    | 18.42  | 0.13               |

In order to further analyze the variation range of runoff and sediment transport in the Yellow River, some researchers have standardized the both and analyzed the slope of the change. It is found that the slope of the sediment transport is larger than the runoff (Xu, 2004, Liu et al., 2005). This paper further compares the rate of change of the runoff and the sediment into the sea in each stage, as shown in Table 1. After 1986, the change rate of the average annual sediment into the sea of the Yellow River is greater than that of runoff into the sea. Especially after 2000, the change rate of the average annual
sediment discharge exceeds the change rate of the average annual runoff more than 20 percent. It shows that the annual sediment reduction of the Yellow River into the sea is significantly greater than that of the annual runoff.

4. Influencing factors

4.1. Impact of climate change

Previous studies have shown that the annual average evaporation change has little correlation with the change of the runoff and sediment into the sea in the Yellow River. But the annual average precipitation in the basin is decreasing, and it is an important influencing factor to reduce of runoff and sediment amount into the sea (Dai et al., 2007). In this paper, the M-K nonparametric test is carried out on analyzing the variation trend of the annual average precipitation sequence from 1960 to 2013 in the Yellow River Basin. The statistic is only -0.02, which doesn’t pass the significance test, indicating that the annual average precipitation sequence has no significant reduction trend. The findings are inconsistent with the results of the previous researches. The main reason is that the data sequence of the previous studies is end around 2004. But in the 10 years from 2004 to 2013, the annual average precipitation in the basin has increased, which has affected the overall trend from 1960 to 2013.

In contrast, the runoff and sediment transportation entering the sea from 1960 to 2013 showed a significant trend of decreasing. Moreover, the correlation coefficient between precipitation and runoff is 0.411, and the correlation coefficient between precipitation and sediment transportation is 0.375. It shows there is no obvious correlation between precipitation and runoff, and similarly between precipitation sediment. Therefore, from the change trend and correlationship, it indicates that the precipitation has no dominant influence on the runoff and sediment transportation changes. Especially in the past 10 years, with more significant impact of human activities, the role of precipitation is even weaker.

\[ y = -0.158x + 445.68 \]
\[ R^2 = 0.0016 \]

![Figure 3](image-url)

Figure 3. The change of annual average precipitation from 1961 to 2014 in the Yellow River Basin.

4.2. Impact of water withdrawal

Economic and social water consumption is the main impacting factor to the reduction of runoff in the Yellow River. After the 1950s, the population and irrigated area of the Yellow River Basin increased sharply. The population increased from 41 million people in 1953 to 114 million people in 2010. The effective irrigation area increased from 0.8 million hectare to 59.0 million hectare between 1949 and 2010 (Peng, 2011). The expanded population and irrigated area directly led to the increasement of water withdrawal. From 1963 to 1968, the annual water intake from the Yellow River was 16.07 billion cubic meters, and it increased to 34.3 billion cubic meters between 1997 and 2009. And nearly
at the same time, the measured runoff entering into the sea decreased rapidly. Water withdrawals accounts for 22.5 percent of runoff into the sea from 1963 to 1968, and the ratio heightened to 75.3 percent from 1997 to 2009. So increased water withdrawals is the main reason of the massive reduction of runoff into the sea.

4.3. Impact of soil and water conservation
Since 2010, there 225.6 thousand km² of water and soil loss area has been controlled, and more than 90 thousand warping dams and a large number of small water storage and soil conservation projects have been built. As a result, the underlying surface of the Loess Plateau has undergone tremendous changes. In 2013, the vegetation coverage of the Loess Plateau reached 59.6 percent. The water production and sediment yield conditions in the basin have undergone qualitative changes, which directly led to significant reduction in the amount of water and soil entering the Yellow River. The average reduction of soil entering the Yellow River is about 400 million tons. According to estimates, the sediment reduction by engineering measures such as warping dams and reservoirs accounts for about 47 percent of the total sediment reduction. And the sediment reduction by ecological measures such as forests and grasses accounts for about 30 percent of the total reduction (Chen et al., 2012). In sequence, the reduction of water and soil entering the Yellow River has greatly reduced the runoff and sediment measured flowing into the sea.

4.4. Impact of reservoir filling
Since 2013, there 28 water conservancy projects have been built or under construction in main stream of the Yellow River, with a total storage capacity of 69.4 billion cubic meters. At the same time, there more than 2.6 thousand large, medium and small reservoirs have been built in the tributaries of the Yellow River, with a total storage capacity of more than 13 billion cubic meters. Among them, there are four large reservoirs such as Sanmenxia Reservoir, Liujiaxia Reservoir, Longyangxia Reservoir and Xiaolangdi Reservoir, which play a vital role in regulating runoff and hindering sediment in the basin. The sum of the capacity of Sanmenxia Reservoir, Liujiaxia Reservoir, Longyangxia Reservoir is 40 billion cubic meters, and their water storage accounts for about 70 percent of the average annual natural runoff of the Yellow River (Jiang et al., 2013).

The Sanmenxia Reservoir, Liujiaxia Reservoir, Longyangxia Reservoir and Xiaolangdi Reservoir were respectively built up in September 1960, October 1968, October 1986 and October 1999. After the reservoirs were completed, the downstream runoff all significantly declined. The starting time of storing water of Liujiaxia Reservoir and Longyangxia Reservoir was 1968 and 1986 respectively. The adjusting water and sediment experiment of Xiaolangdi Reservoir was carried out in 2002. These years coincide with the break points of the sequence of the measured runoff flowing into the sea, which indicates that the construction of the water conservancy project has an important impact on the change of the runoff entering the sea in the Yellow River.

The Sanmenxia Reservoir and Xiaolangdi Reservoir locate in the middle reaches and downstream of the Yellow River, which has an important impact on the evolution of downstream river channel, the ability of flood discharge and sediment transportation, and changes of the runoff and sediment flowing into the sea. Since 1960, 70 percent of sediment intercepted by reservoirs in the Yellow River Basin has been intercepted in the Sanmenxia Reservoir and Xiaolangdi Reservoir. And the Sanmenxia Reservoir controls 89 percent and 98 percent of the water and sediment discharge in the lower reaches of the Yellow River. From 1960 to 2014, the Sanmenxia Reservoir accumulated 6.347 billion tons and the annual sediment deposition is 117.5 million tons.

The Xiaolangdi Reservoir impounded water in October 1999. Most of the sediment discharging through the reservoir was intercepted in the reservoir. The siltation of the reservoir should be compensated from the scouring of the downstream river channel. However, the ratio of the siltation amount of Xiaolangdi Reservoir to the amount of scouring the river downstream channel is two, which is seriously unbalanced. From October 1997 to October 2014, the cumulative sediment deposition was
3.085 billion tons, and the siltation in the reservoir accounted for about 80 percent of the total sediment discharge. And it indirectly leads to the reduction of soil entering the sea in the Yellow River.

5. Conclusion
(1) The measured amount of runoff and sediment entering the Bohai Sea in the Yellow River decreased significantly from 1952 to 2014. According to the break point, the sequence of runoff and sediment can be divided into five stages. Both of the average annual runoff and average annual sediment discharge of the five stages obviously declined.

(2) There was significant positive correlation between the measured runoff and sediment entering the sea in the Yellow River, and the reduction of sediment transportation is affected by runoff. However, the change extent of sediment is significantly greater than that of annual runoff. Especially after 2000, the changing rate of average annual sediment transportation exceeded the average annual runoff by more than 20 percentage.

(3) There was no significant reduction in the average annual precipitation of the Yellow River Basin from 1960 to 2014. And the correlation of precipitation with the measured runoff and sediment entering the sea was not obvious, which indicated that the impact of precipitation variation on the runoff and sediment into the sea was limited.

(4) The increasement of water withdrawal from the river is the main reason for the decrease of the runoff entering the sea in the Yellow River. Soil and water conservation measures and water conservancy projects such as reservoirs are the main factors for the reduction of sediment flowing into the sea.

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