Spatial-temporal variation and periodical change of streamflow and sediment discharge along the mainstream of the Yellow River during 1950-2013

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Structured abstract

Objectives Under the background of global climate change, the variations of streamflow and sediment discharge in the Yellow River would continue with the

human activities intensified and the ecological environment changed. To analyze the change degrees and reasons of the streamflow and sediment discharge as well as predict the future trends would be an urgent need to harness the Yellow River.

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 trend magnitude, abrupt changes and periodical variation of streamflow and sediment discharge at eight hydrological stations from 1950 to 2013 along mainstream of the Yellow River.

Results Over the past 64 years (1950-2013), the spatial distribution was "M" type of the annual average streamflow and a parabolic curve shape of annual average sediment discharge along the mainstream of Yellow River. The temporal variation showed an obvious decreasing trend of streamflow since 1990s and sediment discharge since 1980s. Many times cycle oscillations existed in streamflow and sediment discharge variation, led to an alternate change in the wet/dry periods and the high/low sediment periods.

Conclusions The climate changes contribution rates for streamflow and sediment discharge reduction were 17.0%-45.0% and 12.2%-50.3%, while human activities contribution rates were 55.0%-83.0% and 49.7%-87.8% in different regions of the Yellow River basin since 1970s, respectively. Therefore, human activities were the major causes of the significant decline in streamflow and 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 promote watershed management and sustainability in different regions of the Yellow River basin.

Abstract

The changes in streamflow and sediment discharge in the Yellow River basin have attracted great attention during the last half century. In this paper, the non-parametric Mann-Kendall test, Pettitt's test and wavelet transform were applied to detect the trends, abrupt changes and periodical variation of streamflow and sediment discharge at eight hydrological stations from 1950 to 2013 along mainstream of the Yellow River. Except Tangnaihai (TNH) and Lanzhou (LZ) stations, the annual average streamflow exhibited a significant decreasing trend and the transition year was found in 1985 at Toudaoguai (TDG), Longmen (LM), Tongguan (TG), Huayuankou (HYK), Aishan (AS) and Lijin (LJ) stations ($P < 0.01$). The annual average sediment discharge except TNH station also exhibited a significant decreasing trend, the transition year was found in 1979 at LZ, LM, TG and HYK stations and in 1985 for TDG, AS and LJ stations ($P < 0.01$). According to the Morlet wavelet analysis, many times cycle oscillations existed in streamflow and sediment discharge variation. In the near future, the wet/dry periods dividing points of streamflow were 2016, 2019, 2017, 2017, 2017, 2016, 2016 and 2016 at eight stations, while the high/low sediment periods dividing points of sediment discharge were 2015, 2016, 2016, 2016 and 2016 at TNH, LZ, TDG, AS and LJ stations and low/high sediment periods dividing points were 2014, 2015 and 2016 at LM, TG and LJ stations, respectively. Numerous studies concluded that human activity was the primary factor that caused the decrease in the streamflow and sediment discharge in the Yellow River. Reasonable and possible measures are needed for water resources optimization and sediment sustainable management in

different regions of the Yellow River basin.

Keywords: streamflow; sediment discharge; spatial-temporal variation; periodical change; Yellow River

1. Introduction

Water resource is the base of the life on earth and a major limiting factor for socio-economic development in the world (Miao and Ni, 2009). Meanwhile, sediment transportation from continents to oceans via rivers is one of the important processes regulating river-bank stabilization, soil formation, biogeochemical cycling of elements, crust 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 reducing, which will accelerate coastal erosion and a decrease in habitat and 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 researches focused on the periodic variation, oscillation and prediction of streamflow and sediment discharge in the river systems.

Many rivers across the world have experienced a significant streamflow and sediment load reduction over the last decades as well. Walling and Fang (2003) found that ca. 50% of the sediment load records showed the majority evidencing declining loads by assembling long-term records of annual sediment load for 145 major world's rivers (Walling and Fang, 2003). 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), while both annual sediment yield and runoff showed significant evidence of reduction in the 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 the tropical river basins, around 88% (62%) of the total 133 gauging stations showed decline in sediment loads in the monsoon (non-monsoon) season (Panda et al., 2011). Salmoral et al. (2015) demonstrated the upper Turia basin of Spain presented significant decreasing trends in streamflow (Salmoral et al., 2015). The mean annual flow has decreased 16.5% in the Columbia River at the Dalles (Naik and Jay, 2011). Since 1950, 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 display 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 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 95% confidence

level in the mainstream of the Yellow River from 1950 to 2009 (Liu et al., 2012a). Annual runoff at Lijin station forty kilometers far from the river mouth to the Bohai Sea showed a significant downward trend and declined by about 10.8 mm/10a (Wang et al., 2012). It was found that sediment loads in the middle and lower reaches also displayed a gradually decreasing trend from 1950 to 2007 and at Lijin station was only 0.15Gt/year (2000-2007), suggesting that the estuarine delta has been starved of sediment (Peng et al., 2010). The reduction of sediment load can directly impact on 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 whole Yellow River delta. Furthermore, reduced streamflow is the major concern in the Yellow River basin, which supplies large amount of fresh water for agriculture, industry, and 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 works on the discussions of water discharge and sediment load in big rivers, especially in the Yellow River basin, China. However, under the background of global climate change, the variations of streamflow and sediment discharge in the Yellow River would continue with the human activities intensified and the ecological environment changed. To analyze the change degrees and reasons of the streamflow and sediment discharge as well as predict the future trends would be an urgent need to harness the Yellow River. Meanwhile, the majority of papers

focused on the variation of runoff or sediment yield of the main sections or tributaries in the Yellow River basin, less analysis have been done on runoff and sediment changes along the mainstream of the Yellow River. Therefore, both streamflow and sediment discharge at eight gauging stations along the mainstream of the Yellow River were applied to analyze their spatiotemporal variation from 1950 to 2013. The objectives of the study were to 1) identify the spatial distribution and temporal variation of streamflow and sediment discharge, 2) predict the changing trends of streamflow and sediment discharge in the short term, and 3) discuss main reasons for the variation of streamflow and sediment discharge. The results of this study will be helpful to understand the detailed hydrological regime of streamflow and sediment discharge, and to provide a reference for watershed water resources planning and effective management in the Yellow River basin.

2. Study area and methods

2.1. 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 of higher than 5,000 m above the sea level, then flows eastward through Loess Plateau and North China Plain, finally enters into the Bohai Sea (Wang et al., 2013). The Yellow River basin is located between 96-119° E longitude and 32-42° N latitude, with a drainage area of 752,443km² and a length of 5,464 km passing through nine provinces and autonomous regions (Fig. 1) (Li et al.,

2009; Miao et al., 2011). According to geomorphological features, the river is usually divided into three reaches by Toudaoguai and Huayuankou stations, respectively (Liu et al., 2012a).

The mean annual precipitation and temperature of the Yellow River basin vary greatly in space and time. The mean annual precipitation increases from 368 mm in the upper reaches to 530 mm in the middle reaches and 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). 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 shortage has 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 “relatively clear water area”, contributing 56% of the total runoff. The middle reaches produce 42% of total basin runoff, and the lower reaches provide only 2% of total basin runoff (Liu et al., 2012a; Yang et al., 2010). Meanwhile, due to the river flowing through arid and semi-arid regions, the torrential rainfall and lack of natural vegetation against soil erosion by runoff, where have high potential for producing and exporting large quantities of sediment (Bracken and Kirkby, 2005; Zuazo et al., 2012). And the average annual erosion rate has reached 2,480t/km² for the entire Yellow River Basin in 1989, which

is the highest of any major river system and is famous for the large 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 7,767.4t/(km²•a) in 1951-1969 to 980.5t/(km²•a) in 2000-2010 (Jiao et al., 2014).

[Insert Fig. 1 about here]

Fig. 1 The Yellow River Basin and spatial distribution and temporal variation of streamflow and sediment discharge in the 8 stations along the mainstreams of Yellow River

Note: TNH: Tangnaihai station, LZ: Lanzhou station, TDG: Toudaoguai station, LM: Longmen station, TG: Tongguan station, HYK: Huayuankou station, AS: Aishan station, LJ: Lijin station.

2.2. Data

Annual streamflow and sediment discharge records at eight representative gauging stations (Tangnaihai, Lanzhou, Toudaoguai, Longmen, Tongguan, Huayuankou, Aishan and Lijin stations, abbreviated to 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), and the detailed information about the eight hydrological stations show in Table 1.

[Insert Table 1 about here]

3. Methodology

3.1. Trend test

The Mann-Kendall nonparametric test (Mann, 1945; Kendall, 1975) was used to test the temporal trend in steamflow and sediment load time series from 1950 to 2013. For a given time series $X(x_1, x_2, \dots, x_n)$, namely the null hypothesis H_0 was independent and random variables of identical distribution, the statistic S was calculated as:

$$S = \sum_{i=2}^n \sum_{j=1}^{i-1} \text{sgn}(x_i - x_j) \text{ and } \text{sgn}(x_i - x_j) = \begin{cases} 1 & x_j > x_i \\ 0 & x_j = x_i \\ -1 & x_j < x_i \end{cases} \quad (1)$$

Where S is approximately normally distributed, the average is zero. So the variance was calculated as follows:

$$\text{Var}(S) = \frac{n(n-1)(2n+5)}{18} \quad (2)$$

The standardized statistics Z is:

$$Z = \begin{cases} \frac{S-1}{\sqrt{\text{Var}(S)}} & S > 0 \\ 0 & S = 0 \\ \frac{S+1}{\sqrt{\text{Var}(S)}} & S < 0 \end{cases} \quad (3)$$

For a given confidence level α , if $|Z| \geq Z_{1-\alpha/2}$, a trend exists and the null hypothesis H_0 is rejected. A positive Z value indicates an increasing trend, and a negative Z value indicates a decreasing trend. And the trend magnitude is estimated using Sen's estimator of slope (β) and the absolute value of the slope reflected the rate of change, a nonparametric method proposed by Sen (1968).

$$\beta = \text{median} \left(\frac{x_i - x_j}{i - j} \right) \text{ for } i > j \quad (4)$$

3.2. Abrupt change analysis

The Pettitt test (Pettitt, 1979) was applied to identify the turning points in

streamflow and sediment discharge at the eight stations. The method uses a version of the Mann-Whitney statistic $U_{t,n}$, it includes two parts $x_1, x_2, \dots, x_t$ and $x_{t+1}, x_{t+2}, \dots, x_n$ from a given time series $X(x_1, x_2, \dots, x_n)$. The test statistic $U_{t,n}$ is expressed as:

$$U_{t,n} = U_{t-1,n} + \sum_{j=1}^n \text{sgn}(x_t - x_j) \text{ for } t = 2, \dots, n \quad (5)$$

$$K_n = \max_{1 \leq t \leq n} |U_{t,n}| \quad (6)$$

Where the $\text{sgn}(x_t - x_j)$ function is the same as mentioned in the Mann-Kendall test. The statistic K_n denoted the most significant change point at t place corresponding to the $|U_{t,n}|$ reaches the maximum value, and the associated probabilities used in the significance test was given as:

$$P \cong 2 \exp \left\{ -6 \left(k_n \right)^2 / \left(n^3 + n^2 \right) \right\} \quad (7)$$

3.3. Wavelet analysis

The complex Morlet wavelet was used to analyze the periodicity and variation tendency in streamflow and sediment discharge at the eight stations. The wavelet function is the key to the wavelet analysis. The Morlet wavelet is given information of the phase and amplitude, and a phase difference of $\pi/2$ in the real part and imaginary part can eliminate false oscillation so that the results more accurate (He et al., 2013). The complex Morlet wavelet $\psi(t)$ and wavelet variance $Var(a)$ were defined as:

$$\psi(t) = e^{ict} e^{-t^2/2} \quad (8)$$

$$Var(a) = \sum \left(W_f \right)^2(a, b) \quad (9)$$

Where c is a constant, i denotes imaginary part. The main period of time series is

obtained by wavelet variance $Var(a)$. The first peak value has strongest oscillation, it is used to analyze the average period and oscillation variation for streamflow and sediment discharge in mainstream. The second and third peak values correspond to the second and third main periods.

4. Results

4.1. Spatial distribution

Over the past 64 years (1950-2013), the spatial distribution of the annual average streamflow along the mainstream of Yellow River was “M” type. The annual average streamflow increased from 20.15km^3 at TNH station to 28.89km^3 at LZ station, and decreased to 21.39km^3 at TDG station. Subsequently, there was a significant increase from TDG station to a maximum value of 37.47km^3 at HYK station. Then, the average annual streamflow decreased to 30.45km^3 at LJ station. The streamflow showed a continuous increasing trend from TNH station to LJ station in the 1960s, while the streamflow in the other five decades (1950-1959 and 1970-2013) were similar to the average annual streamflow (Fig. 2).

[Insert Fig. 2 about here]

Fig.2 Variation of the streamflow and sediment discharge at the eight hydrological stations in the Yellow River during different decades

The streamflow mainly comes from the upstream of Lanzhou station, accounting for approximately 64.2% of total amount in the Yellow River basin (1950-2013). The streamflow of above TNH station accounted for 69.76% of the total inflow water at LZ station. In the region between LZ and TDG stations, the mean annual consumed

water was 7.51km^3 , accounting for 25.98% of the total amount at LZ station. The streamflow was 16.09km^3 in the middle reaches, with the TDG-LM, LM-TG and TG-HYK sections accounted for 29.97%, 49.50% and 20.52%, respectively. In the lower reaches between HYK and LJ stations, the mean annual consumed water was 7.02km^3 , in which HYK-AS and AS-LJ sections accounted for 50.95% and 49.05%. The streamflow was mainly from the area above TNH station, TNH-LZ section, TDG-LM section, LM-TG section and TG-HYK section, accounting for 44.81%, 19.42%, 10.72%, 17.71% and 7.34% of the total inflow water, respectively. Therefore, the area above LZ station in the upper reaches and the TDG-TG section in the middle reaches were the main sections of the inflow water along the mainstream of the Yellow River.

The average annual streamflow exhibited a decreasing trend in the mainstream of the Yellow River during 1950-2013. The rates of decline ranged from -0.26mm/a at TNH station to -6.78mm/a at LJ station, the decreasing trend for streamflow increased in the downstream direction (Table 2).

[Insert Table 2 about here]

The spatial distribution of the average annual sediment discharge (1950-2013) was in a parabolic curve shape in the mainstream of Yellow River. The average annual sediment discharge increased from 0.01Gt at TNH station to 1.01Gt at TG station, subsequently reduced to 0.71Gt at LJ station. The spatial distribution of the sediment discharge in the six decades was in the same trend as the annual average value (1950-2013), respectively (Fig. 2).

The average annual sediment discharge was 0.10Gt in the upper reaches, where the area above TNH station, TNH-LZ section and LZ-TDG section accounted for 11.87%, 46.52% and 41.60%, respectively. The sediment discharge was 0.75Gt in the middle reaches, and TDG-LM and LM-TG sections accounted for 77.82% and 42.94%, respectively. However, there was sediment deposition at TG-HYK section, accounting for 20.77% of the total in the middle reaches. The amount of sediment deposition was 0.15Gt in the lower reaches, HYK-AS and AS-LJ sections accounted for 82.10% and 17.60%, respectively. In addition, the mean annual inflow sediment was 1.01Gt, the mean annual sediment deposition was 0.30Gt, and the average annual sediment discharge into the sea was 0.71Gt. Thus, the inflow sediment was mainly from TDG-LM section and LM-TG section, accounting for 57.94% and 31.97%, respectively.

The Mann-Kendall test showed that sediment discharge at 7 stations undergone a significant downward trend ($p < 0.01$) since 1950 except TNH station. The average decreasing rate ranged from -0.015t/a at LZ station to -0.244t/a at TG station (Table 2).

4.2. Temporal variation

In general, the relatively high annual streamflow at TNH and LZ stations were found in 1980s, while it occurred in 1960s at the other six stations. This suggested that water resources experienced different wet/dry periods due to climate condition. The streamflow anomalies since 1990s were negatives, which ranged from -164.90 to -25.57 in 1990-1999 and from -139.77 to -4.37 in 2000-2013 at eight stations,

respectively (Table 3). The results showed that streamflow had an obvious decreasing trend since 1990s.

The sediment discharge peak value were found at TNH in 1980s and at TDG station in 1960s, while it occurred in 1950s at the other six stations. Since 1980s, the sediment discharge anomalies were negatives, which varied from -2.30 to -0.04 in 1980-1989 except TNH station, from -3.22 to -0.01 in 1990-1999 and from -7.49 to -0.03 in 2000-2013 at the eight stations, respectively (Table 3). Overall, the sediment discharge had a significant decreasing trend since 1980s.

[Insert Table 3 about here]

The Pettitt's test results for detecting the change points in annual streamflow and sediment discharge of the eight stations were shown in Table 4. Except for TNH and LZ stations, the transition year of annual streamflow was in 1985 for the other six stations ($P < 0.01$). No changing point was detected in annual sediment discharge at TNH station while the transition year was found in 1979 at LZ, LM, TG and HYK stations and in 1985 at TDG, AS and LJ stations with a significance level of 99%.

[Insert Table 4 about here]

Compared to the pre-change period, the reduction rate of streamflow at TDG, LM, TG, HYK, AS and LJ stations were 34.13%, 37.19%, 39.94%, 42.10%, 52.91% and 62.51%, respectively; while the average reduction rate of annual sediment discharge at LZ, TDG, LM, TG, HYK, AS and LJ stations were 72.38%, 68.56%, 66.53%, 61.38%, 63.35%, 71.77% and 74.51%, respectively (Table 5). Overall, the sediment reduction rate was much larger than the reduction rate in streamflow.

[Insert Table 5 about here]

4.3. Periodical change

According to the Morlet wavelet analysis, average period and wet-dry transition feature, there were *circa* eight-cycle oscillations with 9-year average period at TNH station, the periods of 2013-2016 and 2017-2020 would be in the wet and dry periods, respectively. At LZ station, there are *circa* three-cycle oscillations with 20-year average period. The period of 2011-2019 would be in the wet period, while 2020-2028 would be in the dry period. In the middle reaches, there were *circa* four-cycle oscillations with 16-year average period at TDG, LM and TG stations, the streamflow would be in the wet and dry periods during 2010-2017 and 2018-2025, respectively. In the lower reaches, there were *circa* six-cycle oscillations with 11-year average period at HYK, AS and LJ stations, and the streamflow would be in the wet and dry periods in 2012-2016 and 2017-2021, respectively (Fig. 3).

[Insert Fig. 3 about here]

Fig. 3 The wavelet coefficient diagram of the first main period for streamflow

The wavelet coefficient diagram of the first main period for sediment discharge series was more complicated compared with streamflow (Fig. 4). At TNH station, there were *circa* seven-cycle oscillations with 9-year average period, it would be in the high sediment and low sediment periods during 2012-2015 and 2016-2019, respectively. There were *circa* seven-cycle oscillations with 10-year average period at LZ station, the period of 2012-2016 and 2017-2021 would be in the high sediment and low sediment periods. At TDG station, there were *circa* four-cycle oscillations with

16-year average period, it would be in the high sediment and low sediment periods in 2009-2016 and 2017-2024, respectively. There were *circa* five-cycle oscillations with 12-year average period at LM, TG and HYK stations, the periods of 2009-2014, 2010-2015 and 2011-2016 would be in the low sediment periods, while 2015-2020, 2016-2021 and 2017-2022 would be in the high sediment periods, respectively. At AS and LJ stations, there were *circa* six-cycle oscillations with 11-year average period, the sediment discharge would be in the high sediment and low sediment periods in 2012-2016 and 2017-2021, respectively.

[Insert Fig. 4 about here]

Fig. 4 The wavelet coefficient diagram of the first main period for sediment discharge

5. Discussion

A number of studies have addressed impacts of climate change and human activities on the hydrological cycle (Gao et al., 2013; Gao et al., 2011; Miao et al., 2011; Miao et al., 2010a; Wang et al., 2012; Zhang et al., 2012). Climate change usually influences streamflow and sediment discharge change periodically and long lastingly, while human activities impact on streamflow and sediment discharge variation suddenly and directionally (Miao et al., 2010a). Understanding the impacts of climate variation and human activity on the hydrological regime and sediment dynamics is useful for developing effective conservation strategies in the Yellow River basin (Gao et al., 2010).

5.1. Impacts of climate changes on streamflow and sediment discharge variation

Precipitation and temperature are the two dominant climatic factors, which directly influence the streamflow in the mainstream of the Yellow River basin. The streamflow was positively correlated with the precipitation and negatively correlated with the temperature in the mainstream of Songhua River basin (Miao et al., 2010a). A similar situation also appeared in the Yellow River Basin, the significant positive correlation ($R = 0.7014$, $P < 0.01$) between precipitation and streamflow and negative correlation ($P < 0.01$) between streamflow and temperature were found in the whole Yellow River (Miao and Ni, 2009). The investigation from the Yellow River suggested that annual precipitation decreased by 11.7mm/10a and annual temperature had an average increasing rate of 0.31°C/10a in 1961-2005, which is consistent to the trend of global warming with the increase rate of 0.24°C/10a (Huang et al., 2009). This trend of precipitation and temperature variation was expected to continue in the near future of the whole Yellow River Basin (Liang et al., 2010). It was showed changes in precipitation caused reductions in runoff of about 3%, 17% and 9% at LZ, HYK and LJ stations in 1950-2008, respectively (Wang et al., 2012). Wang et al. (2007) estimated that the decrease in precipitation accounted for 30% of the sediment discharge decrease at HYK station in 1969-2005 (Wang et al., 2007), while Peng et al. (2010) showed the precipitation decrease accounted for 20% of the sediment discharge reduction above HYK station during 1979-2007 (Peng et al., 2010). Precipitation and temperature had 8-12 and 10-13 year periods, which were similar to the average periods 9-16 year for streamflow (except LZ station) and sediment discharge in our study. Therefore, the trend variation of precipitation and temperature

accelerated streamflow and sediment discharge reduction in the Yellow River. Since 1970s, the climate changes contribution rates for streamflow and sediment discharge reduction were 17.0%-45.0% and 12.2%-50.3% in different regions of the Yellow River basin, respectively (Table 6).

The headwater catchment above TNH station is regarded as the “water tower” of the whole Yellow River Basin and play a vital role in meeting downstream water resources requirements (Zheng et al., 2007; Zheng et al., 2009). In our study, the streamflow of the Yellow River is mainly from the area above TNH station (44.81%) and TNH-LZ section (19.42%) in the upper reaches. However, eco-environmental degradation in the source region of the Yellow River, including the temporal-spatial changes of water environment, deglaciation, permafrost reduction, vegetation degeneracy and desertification, led to land capacity decreasing and river disconnecting during the last half century (Feng et al., 2006). There has been a warm and dry tendency in the headwater catchment above LZ station during 1960-2001, which may result in further reduction of streamflow and sediment discharge (Zhao et al., 2008). Approximately 90% of the sediment is derived mainly from the middle reaches (Peng et al., 2010), which is consistent with our research that the sediment discharge is derived mainly from the TDG-TG section in the middle reaches, accounting for 90.99% of the average total inflow sediment (1950-2013). The annual precipitation showed a remarkable downward trend in the middle Yellow River with declines of 8.8mm/10a from 1950 to 2008 (Wang et al., 2012). Compared to 1956-1959, the mean annual runoff reduced by 3.2%, 11.2%, 5.9% and 12.7% due to

the decreases in precipitation and increases of temperature in the four decades from the 1960s to 1990s for the whole middle Yellow River, respectively (Shi et al., 2013). Gao et al. (2011) estimated the climate change contribution rate was 28.0% and 12.2% for the streamflow and sediment discharge reduction from 1980s to 2008 in the middle reaches of the Yellow River (Table 6) (Gao et al., 2011). In the lower reaches, the zero-flow phenomenon appeared frequently since 1970s (Tang et al., 2008; Tang et al., 2013). Owing to sediment deposition, the riverbed has risen significantly and the lower reach of the Yellow River was widely known as a “hanging river” (Wang and Li, 2011). The annual precipitation decreased 9.8mm/10a in the lower reaches from 1950 to 2008, while streamflow declined by about 10.8mm/10a at LJ station (Wang et al., 2012). In general, the climate changes contribution rate was less than 50% for streamflow and sediment discharge reduction in majority studies of the Yellow River basin.

[Insert Table 6 about here]

5.2. Impacts of human activities on streamflow and sediment discharge variation

Human activities are the primary factors that caused the decrease in the streamflow and sediment load in the Yellow River. Since 1970s, human activities played a dominant role in streamflow and sediment discharge reduction and the contribution rates were 55.0%-83.0% and 49.7%-87.8% in different regions of the Yellow River basin, respectively (Table 6). Wang et al. (2013) showed most of the reduction in runoff was caused by human activities, which contributed to 83% of the reduction in

runoff during 1970-2008 in the Yellow River basin (Wang et al., 2012). Miao et al. (2011) showed human activities directly responsible for 55% and 54% of the reductions in streamflow and sediment discharge in the whole Yellow River basin in the 21st century. Soil conservation practices and sediment retention within reservoirs contribute 40% and nearly 30% of the decrease of sediment discharge in the Yellow River (Peng et al., 2010; Wang et al., 2007).

In the upper reaches, Liujiaxia reservoir was completed in 1968, trapping sediment from the upper reaches (Peng et al., 2010). The commencement joint operations of Liujiaxia and Longyangxia reservoirs in 1985 with a total storage capacity 30.4km^3 , which trapped further most of sediment from the upper reaches and regulating water into the downward reaches. The abrupt change of streamflow at TDG, LM, TG, HYK, AS and LJ stations and sediment discharge at TDG, AS and LJ stations in the mainstream of the Yellow River in the year 1985 coincided well with the operation of reservoirs. After 1986, the streamflow and the peaks of sediment discharge decreasing dramatically due to the entrapment of sediment by the reservoirs (Wang et al., 2007). Moreover, land use change is responsible for more than 70% of the streamflow reduction in the 1990s in the headwaters above TNH station (Zheng et al., 2009). Since 2000, the annual average extracted water was 13.05km^3 , the annual average consumed water was 9.39km^3 and the annual average extracted sediment was 0.03Gt in Ningxia-Inner Mongolia irrigation districts at LZ-TDG section. As a result, the operation of reservoirs, agricultural irrigation, land use change and channel deposition played important roles in the reduction of streamflow and sediment discharge in the

uppers reaches.

The middle reaches pass the Loess Plateau, which is characterized the fragile ecological environment and severe soil loss. Since 1950s, a number of soil conservation measures have been implemented on the Loess Plateau, including terraces, check dams, reservoirs, afforestation and planting grass, etc. Over the past 50 years, about 110,000 check dams have been built on the Loess Plateau and approximately 21 billion m³ of sediments have been captured by these dams (Jin et al., 2012). According to the data of soil and water conservation measures between TDG and TG station in the middle reaches, the terrace, forests, pasture and check-dam from 530km², 1,966 km², 415 km² and 36 km² in 1959 increased to 28,540 km², 58,614 km², 14,073 km² and 1,310 km² in 2006, respectively (Zhao et al., 2014). Soil and water conservation practices were effective from the late 1970s, have caused streamflow and sediment discharge reduction and abrupt change of sediment discharge (1979) at LZ, LM, TG and HYK stations in the Yellow River (Gao et al., 2010; Zhao et al., 2014). Sanmenxia and Xiaolangdi reservoirs were completed in 1960 and 1999, which led to a notable decrease of sediment load in the lower reaches. The streamflow and sediment discharge observed at HYK station were significantly affected by construction of reservoirs in the middle reaches (Ma et al., 2012; Miao et al., 2010b; Peng et al., 2010). Up to 2010, approximately 19.3Gt and 21.0Gt of sediment has been trapped by reservoirs and check dams in the Yellow River basin (Ran et al., 2013). In particular, after the “Grain for Green” project implemented in 1999, the streamflow and sediment discharge decreased more significantly. Compared

to the average value in 1950-1999 in our study, the streamflow decreased by 1.93%-52.07%, while the sediment discharge decreased by 30.66%-90.15% in 2000-2013 at the eight stations. Gao et al. (2011) estimated that the average human activities contribution rate was 72.0% and 87.8% for the streamflow and sediment discharge reduction in the middle reaches of the Yellow River (Gao et al., 2011).

Sedimentation is a major problem in the lower reaches of the Yellow River (Xu and Cheng, 2002). The amount of sediment deposition was 0.15Gt in the lower reaches in our study from 1950 to 2013, while Peng and Chen (2009) [56] showed the usage of water and sediment for industry and agriculture were 25.16km³ and 0.24Gt in 1950-2005, respectively. Meanwhile, Water-Sediment Regulation Project was initiated in 2002 by the YRCC, and the total inflow water into the lower reaches was 50.91km³ and the sediment erosion in the downstream channel was 0.39Gt of the Yellow River by 2011. Since the 1950s, the lower reaches have experienced three times of alternating siltation and scouring in response to the change of streamflow and sediment discharge influenced by human activities (Liu et al., 2012b). Yu et al. (2011) indicated that the evolution of shoreline and change of area of the Yellow River Delta are directly affected by the dramatic reduction of streamflow and sediment discharge, which are closely related human activities in Yellow River basin from 1976 to 2009 (Yu et al., 2011). In the lower reaches, the changes in runoff and sediment transport have been dramatically influenced by human activities, such as reservoir construction and the introduction of soil and water conservation programs in the sub-watershed of the upper and middle reaches, the increase in industrial and agricultural water

consumptions and the implementation of the Water-Sediment Regulation Project in the lower reaches of the Yellow River.

The altered streamflow and sediment discharge regime in the Yellow River has a series of geological and ecological implications to the coastal environment (shrinking delta plain, altering sediment dispersal mechanism, restricting plume extent near the river mouth, less sediment reaching the deeper shelf environment, changing fate of the fluvial sediments, and altering ecological environment in the Bohai sea) and is mainly a consequence of anthropogenic interventions including water and soil conservation in the Loess Plateau, increasing water consumption, channel deposition and the multiple dam effects (Yu et al., 2013). Thus, the planning and management strategy of streamflow and sediment discharge in different sections along the Yellow River still need further investigation.

6. Conclusion

In our study, the Mann-Kendall test, Pettitt's test and wavelet transform were applied to detect the trends, abrupt changes and periodical variation of streamflow and sediment discharge at eight hydrological stations from 1950 to 2013 along mainstream of the Yellow River. The streamflow was derived mainly from the area above LZ station (64.23%) and the LM-TG section (17.71%), while the main source region of the sediment discharge was the TDG-TG section (89.91%). The annual average streamflow (except TNH and LZ stations) and sediment discharge (except TNH station) exhibited a significant decreasing trend ($P < 0.01$). Except for TNH and LZ stations, the transition year of annual streamflow was in 1985 for the other six stations

($P < 0.01$). The transition year of annual sediment discharge was detected in 1979 for the LZ, LM, TG and HYK stations, and in 1985 for TDG, AS and LJ stations with a significance level of 99%, while TNH station did not exist a change point.

In the near future, the wet/dry periods dividing points of streamflow were 2016, 2019, 2017, 2017, 2017, 2016, 2016 and 2016 at eight stations, while the high/low sediment periods dividing points of sediment discharge were 2015, 2016, 2016, 2016 and 2016 at TNH, LZ, TDG, AS and LJ stations and low/high sediment periods dividing points were 2014, 2015 and 2016 at LM, TG and LJ stations, respectively.

The climate changes contribution rates for streamflow and sediment discharge reduction were 17.0%-45.0% and 12.2%-50.3%, while human activities contribution rates were 55.0%-83.0% and 49.7%-87.8% in different regions of the Yellow River basin since 1970s, respectively. Therefore, human activities were the major causes of the significant decline in streamflow and 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 promote watershed management and sustainability in different regions of the Yellow River basin.

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Table 1 The location and data series of the hydrological stations

Hydrological station	Longitude	Latitude	Reaches	Drainage area (km ²)	Streamflow (10 ⁸ m ³)	Sediment discharge (10 ⁸ t)
TNH	100°09′	35°30′	Upper reach	121,972	201.53 (1950-2013)	0.12 (1956-2013)
LZ	103°49′	36°04′	Upper reach	222,551	288.90 (1950-2013)	0.60 (1950-2013)
TDG	111°04′	40°16′	End of Upper reach	367,898	213.85 (1950-2013)	1.02 (1950-2013)
LM	110°35′	35°40′	Middle reach	497,552	262.06 (1950-2013)	6.87 (1950-2013)
TG	111°06′	34°43′	Middle reach	682,166	341.69 (1950-2013)	10.10 (1950-2013)
HYK	113°40′	35°54′	End of Middle reach	730,036	374.71 (1950-2013)	8.54 (1950-2013)
AS	116°15′	36°15′	Lower reach	749,136	338.93 (1950-2013)	7.33 (1951-2013)
LJ	118°15′	37°29′	Lower reach	751,869	304.49 (1950-2013)	7.07 (1950-2013)

Table 2 Mann-Kendall trend analysis for streamflow and sediment discharge

Station	Annual runoff			Annual sediment load		
	Z statistic	Sig. level	Sen's slope (β)	Z statistic	Sig. level	Sen's slope (β)
TNH	-0.75	ns	-0.258	-0.01	ns	0
LZ	-0.65	ns	-0.295	-6.17	**	-0.015
TDG	-3.70	**	-1.672	-5.27	**	-0.021
LM	-5.06	**	-2.666	-9.01	**	-0.165
TG	-5.64	**	-3.828	-6.67	**	-0.244
HYK	-5.42	**	-4.436	-6.18	**	-0.235
AS	-5.60	**	-5.785	-6.58	**	-0.221
LJ	-6.00	**	-6.775	-6.59	**	-0.216

A negative indicates a decreasing trend

** significant at $P = 0.01$; ns: not significant at $P \leq 0.1$.

Table 3 The variation of streamflow and sediment discharge anomalies in six decades from 1950 to 2013

Time	Streamflow anomalies (10 ⁸ m ³)							
	TNH	LZ	TDG	LM	TG	HYK	AS	LJ
1950-1959	-13.23	28.70	29.65	59.14	90.51	109.29	105.57	176.01
1960-1969	15.07	-55.00	53.79	74.94	109.41	131.29	166.27	196.71
1970-1979	2.51	14.58	16.67	22.51	15.66	6.02	5.68	6.73
1980-1989	40.21	44.97	25.08	13.58	27.56	38.36	-0.91	-18.81
1990-1999	-25.57	-27.12	-57.62	-64.92	-93.18	-119.85	-151.28	-164.90
2000-2013	-13.55	-4.37	-48.30	-74.90	-107.11	-117.95	-123.00	-139.77
Time	Sediment discharge anomalies (10 ⁸ t)							
	TNH	LZ	TDG	LM	TG	HYK	AS	LJ
1950-1959	-0.05	0.75	0.51	5.02	7.51	6.61	5.83	6.12
1960-1969	-0.00	0.39	0.80	4.44	4.07	2.59	3.79	3.82
1970-1979	0.00	-0.02	0.13	1.81	3.08	3.80	2.41	1.91
1980-1989	0.08	-0.19	-0.04	-2.17	-2.30	-0.73	-0.36	-0.69
1990-1999	-0.01	-0.38	-0.61	-1.75	-2.20	-1.78	-3.05	-3.22
2000-2013	-0.03	-0.39	-0.57	-5.25	-7.26	-7.49	-5.73	-5.67

Table 4 Abrupt change years detected by the Pettitt test for streamflow and sediment discharge

Station	Abrupt change year		Station	Abrupt change year	
	Streamflow	Sediment discharge		Streamflow	Sediment discharge
TNH	no	no	TG	1985*	1979*
LZ	no	1979*	HYK	1985*	1979*
TDG	1985*	1985*	AS	1985*	1985*
LM	1985*	1979*	LJ	1985*	1985*

*Significant at $P = 0.01$, others all significant at $P = 0.05$.

Table 5 Result of the Pettitt method for abrupt changes in streamflow and sediment discharge in the Yellow River

Streamflow (10^8 m^3)	TNH	LZ	TDG	LM	TG	HYK	AS	LJ
Pre-change	-	-	251.39	312.99	414.05	459.32	441.02	419.10
Post-change	-	-	165.58	196.58	248.67	265.93	207.67	157.13
Change (%)	-	-	-34.13	-37.19	-39.94	-42.10	-52.91	-62.51
Sediment discharge(10^8 t)	TNH	LZ	TDG	LM	TG	HYK	AS	LJ
Pre-change	-	0.97	1.46	10.63	14.99	12.87	10.77	10.49
Post-change	-	0.27	0.46	3.56	5.79	4.72	3.04	2.67
Change (%)	-	-72.38	-68.56	-66.53	-61.38	-63.35	-71.77	-74.51

Table 6 The human activities and climate changes contribution rate for streamflow and sediment discharge reduction

Streamflow (%)		Study area	Periods	References
Human activities	Climate changes			
83.0	17.0	Yellow River basin	1970-2008	(Wang et al., 2012)
72.0	28.0	TDG-HYK section in the MRYP	1986-2008	(Gao et al., 2011)
55.0	45.0	Yellow River basin	2000-2008	(Miao et al., 2011)
73.8	26.2	HYRB (above TNH station)	1991-2000	(Zheng et al., 2009)
57.0	43.0	TDG-HYK section in the MRYP	1990-2000	(Liu and Zhang 2004)
62.0	38.0	HYRB (above TNH station)	1991-2004	(Kuang and Zhang 2008)
76.5	23.5	TDG-HYK section in the MRYP	1997-2006	(Yao et al. 2013)
65.7	34.3	Kuye River in the MRYP	1980-2006	(Liang et al., 2013)
Sediment discharge (%)		Study area	Periods	References
Human activities	Climate changes			
70.0	30.0	HYK station	1969-2005	(Wang et al., 2007)
87.8	12.2	TDG-HYK section in the MRYP	1982-2008	(Gao et al., 2011)
54.0	46.0	Yellow River basin	2000-2008	(Miao et al., 2011)
55.4	44.6	TDG-LM section in the MRYP	1980-2006	(Yue et al., 2014)
80.0	20.0	HYK station	1979-2007	(Peng et al., 2010)
81.0	19.0	Yellow River basin	1979-2008	(Mu et al., 2012)
49.7	50.3	TDG-HYK section in the MRYP	1997-2006	(Yao et al. 2013)

Note: MRYP: the middle reaches of the Yellow River, HYRB: The headwaters of the Yellow River Basin.

Figure captions:

Fig. 1 The Yellow River Basin and spatial distribution and temporal variation of streamflow and sediment discharge in the 8 stations along the mainstreams of Yellow River

Note: TNH: Tangnaihai station, LZ: Lanzhou station, TDG: Toudaoguai station, LM: Longmen station, TG: Tongguan station, HYK: Huayuankou station, AS: Aishan station, LJ: Lijin station.

Fig.2 Variation of the streamflow and sediment discharge at the eight hydrological stations in the Yellow River during different decades

Fig. 3 The wavelet coefficient diagram of the first main period for streamflow

Fig. 4 The wavelet coefficient diagram of the first main period for sediment discharge