Investigation of changes in the annual maximum flood in the Yellow River basin, China

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ABSTRACT

Flooding in the Yellow River basin (YRB) has changed significantly over the last few decades because of climate change and human activities. Determining how the flooding changed and identifying the main driving factors of flood change is crucial to flood risk assessment and water resources planning. However, few studies have been conducted, especially in the whole YRB. To fill this gap, we investigate the spatial and temporal change of the annual maximum flood (AMAXF) in the YRB using observed data from 32 key hydrological stations (including 15 mainstream stations and 17 tributary stations). The Mann–Kendall test combined with trend index method is used to evaluate the trend in precipitation and AMAXF. The trend results indicate the AMAXF over the whole basin is dominated by decreasing trends: 72% of the stations exhibit significant decreasing trends (at 0.1 significance level) and 22% of the stations show no significant decreasing trends in the AMAXF. Both flood trends and abrupt change time exhibit obvious regional differences: the flood decreases is more pronounced in the midstream basins than in the headwater of the basin; the abrupt changes mainly occurred in the early 1990s for the upper reaches, and in the late 1990s for the middle reaches. To investigate the causes of flood change, the trends of precipitation extremes are analyzed in relation to the trends of peak floods. The analysis reveals that the decreasing precipitation extremes only results in the AMAXF reduction in the upstream basin. The decreasing AMAXF in the midstream and downstream of the basin are mainly attributable to the impacts of human activities (mainly including dam construction and soil conservation practices). In general, anthropogenic impacts play an increasingly important role in the AMAXF changes in the YRB. According to the possible changes in forcing factors, the AMAXF over the whole basin is expected to further decrease in the near future. However, there are still large flood risks in the tributary basins due to the collapse of check dams caused by extreme storms.

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1. Introduction

Flooding is one of the most common hazards and causes property damage and deaths worldwide. The occurrence and variability of flooding is a complex and dynamic process and is affected by various factors, including extreme precipitation, land use practices, dam construction, vegetation properties and soil type. In recent decades, precipitation intensity, frequency and type has changed along with climate warming. Human activities have substantially altered the relationship between rainfall and runoff. The combination of climate change and human activities has caused

significant changes in flood trends in many regions around the world (Milly et al., 2008; Zhang et al., 2011b; Ishak et al., 2013). Changes in flood trends create challenges when assessing and managing flood risk. Understanding the spatial and temporal variability of flood trends is helpful for coping with the challenges.

Many studies have investigated the spatial and temporal variability of flood trends worldwide. Petrow and Merz (2009) analyzed the flood trends at 145 stations in Germany and found that flood magnitude increased at many stations. Cunderlik and Ouarda (2009) identified decreasing trends for the magnitudes of snowmelt flood in Canada over the past three decades. McCabe and Wolock (2002) revealed that few gauges had significant trends in flood magnitude in the United States. Kundzewicz et al. (2005) and Svensson et al. (2005) detected the trends in flood magnitudes on a global scale and concluded that flood magnitudes did not present

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significant trends globally. In these studies, the annual maximum flood (AMAXF) was used as the indicator for flood trend analyses (Adamowski and Bocci, 2001; Franks, 2002; Petrow and Merz, 2009; Bormann et al., 2011). The results of these studies showed that the changes of the AMAXF have regional differences.

The Yellow River is the second-longest river in China and the sixth-longest river in the world. It covers an area of approximately 742,443 km² and supports approximately 30% of China's population (McVicar et al., 2007; Xu et al., 2009a). The Yellow River is characterized by a high sediment load, accounting for approximately 6% of the global sediment discharge to the ocean (Milliman and Meade, 1983; Saito et al., 2001). Historically, the Yellow River was the one of the most flood-prone rivers in China. Frequent flood hazards in the Yellow River basin (YRB) have resulted in a large amount of deaths and property damage (Wang et al., 2007a). Over the last 50 years, the YRB has undergone unprecedented changes in land use. Numerous dams and reservoirs have been constructed to control floods and generate power. In addition, a series of soil conservation practices (SCP) have been implemented to reduce soil erosion (Huang and Zhang, 2004; Wang et al., 2006; Yang et al., 2008). The annual precipitation has also changed significantly in many sub-basins of the YRB (Xu et al., 2009a; Dong et al., 2011; Wang et al., 2012). As a result, significant changes in streamflow were observed in the YRB (Wang et al., 2006). Previous studies mainly focused on the changes in annual streamflow (Yang et al., 1998; Fu et al., 2004; Liu et al., 2008; Tang et al., 2008; Yang et al., 2009), while limited attention has been paid to flood trends. Studies about flood trends in the YRB focused on a single or a few gauges (Kang et al., 2001; Xu et al., 2009a; Yao et al., 2011). In this study, we investigate the spatial and temporal changes of the AMAXF for the whole YRB and analyze the reasons for the changes in floods.

2. Data and methods

2.1. Data

The runoff records at 32 key hydrological stations in the YRB were provided by the Yellow River Hydrological Bureau. Each

station has at least 50 years of hydrological data. 22 of 32 stations are located in the middle reaches of the Yellow River, historically flood-prone (Xu et al., 2009a). Detailed information about the stations is shown in Table 1. The daily precipitation records from 79 national meteorological stations in the YRB were collected from the China Meteorological Data Sharing Service System. The datasets were checked for completeness and consistency before trend analyses. The spatial distributions of the hydrological and meteorological stations are shown in Fig. 1.

2.2. Trend test method

In this study, the non-parametric Mann–Kendall (M–K) test (Mann, 1945; Kendall, 1975) combined with the trend index (TI) method (Kundzewicz et al., 2005; Svensson et al., 2005) are used for trend analyses. The M–K test has been commonly used for trend detection because of its robustness for non-normally distributed data (Yue et al., 2002; Hamed, 2008). However, using the M–K test, it is hard to reflect the trend magnitude of a time series. Therefore, the results of the M–K test are further stated using the TI method to obtain the trend magnitude of a time series (Kundzewicz et al., 2005), which is defined as:

$$TI = \begin{cases} 100 - p & \text{for positive trends} \\ -(100 - p) & \text{for negative trends} \end{cases} \quad (1)$$

where p is the significance level calculated by the M–K test. The value of TI is always between –100% and 100%. A positive value of TI indicates an upward trend, and a negative value indicates a downward trend. The larger the absolute value of TI, the stronger the trend magnitude (Kundzewicz et al., 2005). Compared to traditional methods, such as Sen's slope (Sen, 1968; Hirsch et al., 1982) and linear slope, the TI is not affected by the value of a time series and can better describe the relative change of a time series. Thus, it is widely used in meteorology and hydrology (Svensson et al., 2005; Hirsch and Ryberg, 2012).

Fig. 1. Location of the study area. The upper reach of the river is the region above Toudaoguai; the middle reach is the region from Toudaoguai to Huayuankou; the river reach below the Huayuankou is the lower reach of the Yellow River.

2.3. Abrupt change detection

The sequential version of the M–K test (Mann, 1945; Kendall, 1975) is used to analyze the abrupt change point of the AMAXF series. For the sequential time series $x_1, x_2, \dots, x_n$, m_i is the number of later terms in the series whose values exceed x_i . The M–K rank statistic d_k is calculated as follows:

$$d_k = \sum_{i=1}^k m_i \quad (2 \leq k \leq n) \quad (2)$$

The expected value $E(d_k)$ and variance $\text{Var}(d_k)$ are estimated as follows:

$$\begin{cases} E(d_k) = \frac{k(k-1)}{4} \\ \text{Var}(d_k) = \frac{k(k-1)(2k+5)}{72} \end{cases} \quad (2 \leq k \leq n) \quad (3)$$

The test statistic $U(d_k)$ is calculated using the following formula:

$$U(d_k) = \frac{d_k - E(d_k)}{\sqrt{\text{Var}(d_k)}} \quad (1 \leq k \leq n) \quad (4)$$

The terms of $U(d_k)$ ($1 \leq k \leq n$) constitute a forward sequence curve (C_1). The same method is then applied to the inversed series and obtains a backward sequence (C_2). The intersection of the C_1 and C_2 curves is regarded as the abrupt change point.

Table 1

Selected runoff gauges in the YRB; “M” indicates the mainstream gauge, “T” indicates the tributary gauge.

Station	Longitude	Latitude	Series	Drainage area (km ²)	M/T
Jimai	99.64	33.78	1958–2010	45,019	M
Maqu	102.10	33.98	1959–2010	86,048	M
Tangnaihai	100.15	35.50	1956–2010	121,972	M
Minhe	102.80	36.33	1955–2010	15,342	T
Lanzhou	103.82	36.07	1956–2010	222,551	M
Qingtongxia	106.00	37.90	1956–2010	275,010	M
Shizuishan	106.78	39.15	1956–2010	309,146	M
Bayingaole	107.02	40.19	1973–2010	314,000	M
Sanhuhekou	108.46	40.37	1955–2010	347,909	M
Toudaoguai	111.07	40.27	1954–2010	367,898	M
Huangfu	111.08	39.28	1954–2010	3175	T
Qiaotou	111.13	38.93	1956–2010	2854	T
Wenjiachuan	110.77	38.47	1954–2010	8645	T
Gaojiachuan	110.48	38.25	1955–2010	3253	T
Linjiaping	110.87	37.67	1954–2010	1873	T
Wupu	110.72	37.45	1954–2010	433,514	M
Dingjiagou	110.25	37.55	1959–2010	23,422	T
Baijiachuan	110.42	37.23	1956–2010	29,662	T
Ganguyi	109.80	36.67	1954–2010	5891	T
Danling	110.72	36.45	1955–2010	3992	T
Longmen	110.58	35.67	1956–2010	497,552	M
Hejin	110.80	35.57	1954–2010	38,728	T
Jingcun	108.13	35.00	1960–2010	40,281	T
Xianyang	108.7	34.32	1954–2010	46,827	T
Huaxian	109.76	34.59	1955–2010	106,498	T
Zhuangtou	109.83	35.00	1955–2010	25,154	T
Tongguan	110.30	34.62	1954–2010	682,144	M
Sanmenxia	111.37	34.82	1954–2010	688,421	M
Heishiguan	112.93	34.72	1954–2010	18,563	T
Wushe	113.17	35.07	1950–2010	12,880	T
Huayuankou	113.65	34.92	1952–2010	730,036	M
Lijin	118.30	37.52	1950–2010	751,869	M

3. Results

3.1. Trend analysis and abrupt change detection

AMAXF at 23 out of 32 stations exhibits significant decreasing trends at the 5% significant level, accounting for 72% of the total number of the stations (Fig. 2a). Seven stations display no significant decreasing trends, and two stations have no significant increasing trends. Overall, the AMAXF over whole basin is dominated by decreasing trends. For the spatial variation, the AMAXF decreased significantly in the midstream and downstream basins, decreased slightly but not significantly in the headwater of the basin. Additionally, the decrease magnitudes in the mainstream stations are larger than those in the tributary stations: 80% (12/15) of the mainstream stations are characteristic by significant decreasing trends, while 65% (11/17) of the tributary stations exhibit significant decreasing trends. The changes in the AMAXF at eight representative stations are shown in Fig. 3. Abrupt change detection indicates that abrupt changes occurred in 21 out of 32 stations. Among the 21 stations, 19 stations have one abrupt change and two stations have two abrupt changes (Fig. 2b). The occurrence time of abrupt change has spatial and temporal differences in the YRB. Most of the abrupt changes in the upper reaches occurred in the early 1990s, while the abrupt changes in the middle reaches occurred mainly in the late 1990s. In addition, the occurrence times of abrupt changes at the tributary stations are more scattered than those from the mainstream stations.

3.2. Reasons for the decreases in the AMAXF in the YRB

Changes in extreme precipitation and land use/cover changes (LUCC) are regarded as two main contributors to changes in floods worldwide (Douglas et al., 2000; Jain and Lall, 2000; Pinter et al., 2006; Cunderlik and Ouarda, 2009). In this study, we investigate the impacts of extreme precipitation changes and human activities on the changes in the AMAXF in different regions of the YRB.

3.2.1. Impacts of changes in extreme precipitation on flooding

The floods in the Yellow River basin are usually caused by one day or several consecutive days of heavy rainfall (Ran et al., 2000; Yao et al., 2011). We referred to the 27 core climate extreme indices recommended by World Meteorological Organization (Zhang et al., 2011a) and chose the Rmax-1day and R20 as the two indices of extreme precipitation to analyze the changes in precipitation extremes. Rmax-1day is defined as the annual maximum daily precipitation and the R20 is defined as the number of days with daily precipitation totals above or equal to 20 mm. We evaluated trends of Rmax-1day and R20 over two time periods (1960–2011 and 1990–2011) and found inconsistent trends for the two periods (Fig. 4). During the period from 1960 to 2011, the spatial distribution characteristics of trends in the two indices are similar. Both indices have nonsignificant decreasing trends at most stations. The two indices in the upper and lower reaches feature mixed negative and positive trends, whereas in the middle regions are dominated by negative trends (Fig. 4a and b). The 1990–2011 trends show differences from the trends of 1960–2011. Two indices over the whole basin are dominated by nonsignificant positive trends. The two indices in the upper reaches present nonsignificant positive trends at most stations, and in the middle and lower reaches are characterized by mixed negative and positive trends (Fig. 4c and d).

In the upper reaches (above Tangnaihai station), the impacts of human activities are limited (Zheng et al., 2009). The change in extreme precipitation is considered to be the main driving factor of flood change. The AMAXF and extreme precipitation demonstrate

Fig. 2. Trend of AMAXF (a) and abrupt change (b) for 32 key runoff stations, 1960–2010. Abrupt change year has been simplified as 98 for 1998, 01 for 2001.

consistent trend over the two periods in this region (Figs. 4 and 5). In the middle YRB, however, the changes in the AMAXF are inconsistent with changes in extreme precipitation in the period of 1990–2010. Two indices of extreme precipitation are dominated by nonsignificant increase trends (Fig. 4c and d), whereas the AMAXF still present significant decreasing trends at most stations (Fig. 5). The inconsistent changes between extreme precipitation and the AMAXF indicate that decreasing trends in the AMAXF are mainly caused by human activities rather than extreme precipitation in the middle YRB.

3.2.2. Impacts of large reservoirs on AMAXF reduction

The construction of reservoirs is the most direct way to reduce peak discharge during flood season (Wang et al., 2006). Since the 1950s, more than 3100 reservoirs have been built in the YRB, with a total storage capacity of 57.4 km³, which is approximately equal to the mean annual natural discharge of the YRB (Li and Yang, 2004; Wang et al., 2006). Reservoirs with larger storage capacities have more obvious effect on peak flow reduction. By the end of 2010, nine reservoirs along the Yellow River had storage capacities greater than 1.0 km³, of which four have a storage capacity greater than 5.0 km³. The four large reservoirs are Liujiaxia (LJX), Longyangxia (LYX), Sanmenxia (SMX) and Xiaolangdi (XLD), and the spatial distribution of the

four reservoirs is shown in Fig. 6. These large dams have significantly changed the downstream flood processes. The impacts can be reflected by the ratio (RA) between the AMAXF at a downstream station and the AMAXF at the upstream station of the reservoir.

The RA exhibited a significantly decreasing trend since the LJX reservoir opened in 1968 (Fig. 7). Abrupt change at the Lanzhou station and at several downstream gauges most likely resulted from the dam operation at the two reservoirs (Fig. 4). Thus, the operation of large dams in the headwater of the river is the major cause of the AMAXF reduction for the gauges below dams. The impacts of dams on downstream floods are gradually weakened with increasing distance from the dams.

The other two large reservoirs, SMX and XLD, are located in the river segment between Tongguan to Huayuankou (Fig. 6). They play a vital role in reducing the flood risk in downstream regions (Yang et al., 2008). The SMX reservoir was completed in 1960 with a storage capacity of 9.7 km³ (YRCC, 2008). The SMX reservoir resulted in severe sediment deposition and was forced to operate at a low storage level in flood seasons since 1962 to balance the sediment inflow and outflow (Wang et al., 2005, 2007b). During operation, the flood control function of the dam was weakened. There is no noticeable decrease in the RA since the operation of the SMX reservoir (Fig. 7b).

Fig. 3. The change of the AMAXF at eight representative stations.

Since the operation of the XLD reservoir in 2001, the Yellow River Conservancy Commission (YRCC) had the ability to regulate water-sediment to reduce the sediment siltation on the downstream riverbed and reservoirs. Water-sediment regulation is a reservoir operation scheme that releases the water storage in XLD, SMX and other small reservoirs to generate “man-made flood” to scour the riverbed (Ran et al., 2000; Li and Sheng, 2011). From 2002 to 2010, more than 10 water-sediment regulation schemes were conducted and resulted in a significant increase in the AMAXF for the downstream gauges of the dam since 2002 (Fig. 7b). The function of the XLD reservoir was to reduce peak flow, but there has not been a large flood since completion of the reservoir, so its role has not been fully demonstrated. According to the original design, however, the dam can increase the flood return period downstream from less than 100 years–500 years.

3.2.3. The impacts of soil conservation practices (SCP) on flood reduction

The middle reaches of the Yellow River pass through the Loess Plateau, which is a major sediment source for the river.

Approximately 90% of the total river sediment comes from this region (Milliman et al., 1987; Tang et al., 2008; Yang and Liu, 2011). Soil and water loss caused serious degradation of the eco-environment in the Loess Plateau, and led to sediment siltation on the downstream riverbed and reservoirs. Since the late 1970s, numerous SCP (e.g., afforestation, grass-planting, level terraces and check dam) have been implemented to reduce soil erosion and improve the environment (Hassan et al., 2008; Zhang et al., 2008; Li et al., 2010). The percentage of SCP areas accounting for the total soil erosion area in the middle YRB has increased from 13.2% in 1978 to 41.1% in 1997 (Gao et al., 2011). A nationwide ecological recovery program, the “Grain for Green Project” (GGP) began in 1999, which has greatly increased the vegetation coverage in the Loess Plateau (Fig. 8 and Table 2). The SCP can effectively reduce the runoff and sediment generation by intercepting precipitation, increasing water infiltration and delaying surface runoff (Huang and Zhang, 2004; Valentin et al., 2008; Miao et al., 2011). Some studies indicated that the increasing SCP were mainly responsible for the peak flow reduction in major tributaries of the middle YRB (Xu and Chen, 2000; Kang et al., 2001; Ran et al., 2004).

Fig. 4. Trend of extreme precipitation over the Yellow River basin.

Fig. 5. Trend of the AMAXF in 1990–2010.

To quantitatively assess the effects of SCP on reducing peak flow since the implication of GPP, we analyzed the relationship between the AMAXF and corresponding areal precipitation in two representative sub-basins in the middle YRB (Fig. 9). Under similar areal precipitation, the differences in AMAXF before and after the implication of GPP are considered approximately as the AMAXF changes caused by SCP. The results indicate that approximate 20%–80% reduction in AMAXF can be attributed to the impacts of SCP. As the vegetation coverage increases, the effects of SCP on reducing peak flows are likely more significant. Moreover, the results of abrupt change detection further reveal that abrupt changes are likely to be associated with the SCP implementation (Fig. 2b).

4. Discussion

4.1. Possible future changes in flood in the YRB

Changes in extreme precipitation and human activities are the two main factors altering flood characteristics. Changes in floods in the near future are mainly dependent on the changes in the two factors. Based on the trends of the two factors, the AMAXF is likely to further decrease in the YRB. First, with increasing vegetation coverage, the SCP will have more significant influences on reducing peak flow. Second, with the increasing energy demand, China would develop hydropower in the YRB (Kahrl, 2012; Li and Wang,

Fig. 6. Reservoirs with storage capacity exceeding $1.0 \times \text{km}^3$ in the YRB. The two numbers in parentheses denote storage capacity of reservoir and the year of completion, respectively. Triangles represent hydrological stations.

Fig. 7. Variations of the RA before and after the reservoir began operating. The RA is the ratio of the AMXF between the downstream gauge and the upstream gauge of the reservoir; black dashed lines are the year the reservoir began operating; red dashed lines represent the average RA of the corresponding period. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2012; Zhou et al., 2012). As a result, a large number of hydropower projects would be constructed on the Yellow River (Huang et al., 2006). These projects can reduce floodwater during flood seasons. Finally, although many studies indicated that future precipitation in the YRB is projected to increase according to the outputs of various general circulation models (GCMs) (Zhang et al., 2006; Shi et al., 2009; Xu et al., 2011; Li et al., 2012; Sun et al., 2012), considerable uncertainties exist in the GCMs. It is hard to offset the reduction effects of human activities on flooding, even if an increasing trend is present for future extreme precipitation. Therefore, human activities are still a major driving factor for the future change in the AMAXF in the YRB.

4.2. Facing decreasing peak flow in the YRB, should we revise the flood design criteria of hydraulic structures to reduce cost?

The designed flood estimations are the basis for building flood protection measures and performing integrated flood management to protect people's lives and property (Rogger et al., 2012). An underestimation of flood risk may result in damage, whereas an overestimation can increase the design costs. Traditionally, flood estimations and flood designs are generally based on the

assumption that the flood regime is stationary (Petrow and Merz, 2009; Luo et al., 2012). The assumption has been questioned recently because of the natural climate variability and the potential influence of human activities on the hydrological cycle (Milly et al., 2008). Many studies have emphasized the need to take non-stationary time series into consideration for designing flood estimations (Strupczewski et al., 2001; Cunderlik and Burn, 2003; El Adlouni et al., 2007; Leclerc and Ouarda, 2007).

Facing the decreasing AMAXF in the YRB, should we revise the flood design criteria to reduce cost? We think that it is not wise to do that due to some potential flood risks in the YRB. First, although the dams along the river can effectively reduce the downstream flood risk with large water storage capacities, the storage capacities of these large reservoirs are continuously shrinking because of severe sediment deposition. The XLD reservoir, for example, had a volume of accumulated sediment up to 2.58 km^3 from 1999 to 2009 (Wang et al., 2011), implying that the reservoir had lost approximately one fifth of its initial water storage capacity by the 11th year. The flood control ability of a dam would be weakened with increasing sediment deposition. Second, the check dams, as temporary structures, are mainly made of cheap and accessible materials such as loess, rocks, and sandbags in the Loess Plateau. More

Fig. 8. Land use map of the middle reach of the Yellow River in 1998 (a) and 2010 (b). (Luo et al., 2014).

Table 2
Area of soil conservation practices in Tongdaoguai–Longmen sub-basins.

Year	Area of soil conservation practices (km ²)				
	Level terrace	Afforestation	Grass-planting	Check dam	Total
1959	331	1513	357	28	2229
1969	1060	3140	383	121	4704
1979	2130	7730	730	364	10,954
1989	3020	12,070	1680	515	17,285
1999	3466	15,391	3209	486	22,552
2006	4597	26,160	5673	666	37,096

Data source: Ran et al. (2000) and Yao et al. (2011).

than half of check dams were constructed before the 2000s (Fig. 10). After many years of erosion and siltation, these old check dams are easily destructible by heavy rainfall. Some studies indicated that the check dams could reduce effectively the normal flood but not

extreme flood (Kang et al., 2001; Zhang et al., 2004; Chen et al., 2005). Once the dam collapses, the flood flows rapidly and returns to the previous state before implementing the SCP. A case can be identified in the flood observation records of the Yanchuan station in Qinjianhe River (Fig. 11). In July 2002, unusually heavy rainfall occurred in the upper basin and resulted in a severe flooding. The peak flow in Yanchuan station reached to 5540 m³/s, which is the second largest flood of record. More than 80 check dams were destroyed during the flooding event (Chen et al., 2005), which aggravated considerably the flood magnitude and offset the effect of other SCP on reduction of flooding. Finally, numerous studies reported that the rainfall extremes have increased around the world (Alexander et al., 2006; Allan and Soden, 2008; Liu et al., 2009; Sun and Ao, 2013). Extreme precipitation events are likely to increase in the YRB according to multiple GCMs projections (Xu et al., 2009b; Li et al., 2012; Wu et al., 2015).

Fig. 9. Relationship between AMAXF and corresponding areal precipitation at Wenjiachuan and Baijiachuan stations.

Fig. 10. Number of new check dams built from 1950s to 2000s.

Fig. 11. (a) Changes of the AMAXF at Yanchuan station. Dashed lines represent the average AMAXF. (b) Relationship between AMAXF and corresponding areal precipitation at Yanchuan station.

5. Conclusions

In this study, we investigated the spatial and temporal variations of flood in the YRB and analyzed the natural/anthropogenic influences on flood trends. The AMAXF series from 32 key gauging stations over the YRB were chosen as the flood indicator for trend

analyses. The results showed that most (72%) gauging stations show significant downward trends in the AMAXF, especially for mainstream gauges in the middle and lower reaches of the river. The decreasing flooding in the YRB is caused by many factors, including reduction in heavy rainfall, dam construction and soil conservation practices, which are considered to be the three main factors. Contribution analyses reveal that decreasing flooding is mainly caused by precipitation reduction in river source regions, dam construction in the region from Lanzhou to Toudaoguai, and the implementation of SCP in tributary regions from Toudaoguai to Tongguan. For these mainstream gauges below Tongguan, the causes of flood reduction are more complex, involving the joint effects of multiple factors. Overall, human activities play an increasing role in stream extreme change in the YRB. Flood in the near future is likely to further reduction because of the changes of various driving factors. However, flooding hazards may still frequently occur, particularly in tributary regions of the river. Further research should be performed to investigate the flood trends using more flood indices and gauges to better understand the change of flood characteristics in the basin.

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