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ORIGINAL PAPER

Observed changes in hydrological extremes and flood disaster in Yangtze River Basin: spatial–temporal variability and climate change impacts

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Abstract The variation and tendency of hydrological extremes in the context of climate change have received extensive concern. However, there is still no clear understanding toward the evolution of hydrological extremes, and the impacts of climate change on flood disaster and risk have been explored very poorly. This study investigated the trends in flood-related variables of extreme precipitation, extreme river flow (1955–2012), and flood damages (1990–2014) in Yangtze River Basin. To further explore the impacts of climate change, the relations of changes in extreme river flow and precipitation were evaluated using wavelet transform analysis, and the trends in normalized flood damages were re-examined with the elimination of changes in exposure. The results showed that flood damages decreased significantly in the middle and lower reaches, while extreme precipitation and river flow still had increasing trends, indicating the potential of increasing flood risk. For upper basin, extreme precipitation increased significantly in the west and northeast part, while significant decreasing trends can also be found in the central part. The wavelet analysis revealed significant covarying relations for extreme discharge and precipitation, demonstrating the substantial influence of climate variability on extreme river flow. Meanwhile, the normalized flood damages showed increasing trend in Sichuan province, indicating significant climate change impacts on flood disaster. This study suggests the need for more effective measures to mitigate flood risk and better adaptation

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for climate change in Yangtze River Basin, especially in the middle and lower basin and northeast of the upper basin.

Keywords Hydrological extremes · Floods · Spatial–temporal variation · Climate change impact · Yangtze River Basin

1 Introduction

Climate change resulting from anthropogenic alterations in atmospheric composition is expected to intensify global water cycle, leading to the occurrence of more frequent extreme floods (IPCC 2013; Milly et al. 2002). Over recent decades, the evolution of hydrological regimes and the risk of extreme events in the context of climate change have become a global concern, especially in light of growing flood losses observed in many regions around the world and projected increasing frequency of extreme hydrological events in the future (Alfieri et al. 2015; Hirabayashi et al. 2013). With this regard, investigating spatial–temporal variation of hydrological extremes and the possible impacts of climate change would be a valuable effort, not only for flood risk reduction, but also as a justification for climate change adaptation.

Hydrological extremes usually refer to rainfall anomalies and extreme hydrological events including floods and droughts (Werner and Cannon 2016). Here, extreme precipitation and high river flow are mainly considered. During recent decades, a number of studies have evaluated the trends in extreme precipitation and river flow and explored their relationships with global climate change and variability. Among these, Alexander et al. (2006) presented a global picture of trends in extreme precipitation and found a widespread significant increase around the world. Xiao et al. (2017) analyzed the trends of ten extreme precipitation indices in China and examined their possible teleconnections with ocean–atmospheric modes. Kundzewicz et al. (2005) detected the trends in time series of annual maximum river flow on global scale and indicated a lack of ubiquitous growth of high flows worldwide. Madsen et al. (2014) presented a review of trend analysis of extreme precipitation and floods in Europe and concluded that a general increase in extreme precipitation was found in the summary of reported studies, whereas there were no clear indications of significant trends of extreme streamflow. Although extensively studied, the spatial–temporal patterns of hydrological extremes on either global or regional scale have not been well understood, and there is still no conclusive evidence for climate-related trend for hydrological floods, given the high complexity of flood hazard process and disaster dynamics (IPCC 2012).

Yangtze River is the longest river in China and the third longest in the world. The river basin plays a vital role in the development of Chinese economy and society, while also has suffered from frequent floods throughout history (Yu et al. 2009). Several previous studies have examined the spatial–temporal variation of extreme climatic and hydrological events in Yangtze River Basin. An increasing tendency for extreme precipitation and extreme river flow in the middle and lower basin of Yangtze River has been identified, indicating an increasing flood risk in these regions. However, distinct regional differences exist over the whole basin, and no consistent conclusions about changes in hydrological extremes for the upper basin have been made (Chen et al. 2014; Guo et al. 2013; Su et al. 2008; Zhang et al. 2008). More recently, Gao and Xie (2016) applied generalized extreme value distribution to fit extreme precipitation events and examined the changes in return values for two periods. Significantly positive trends were mainly detected in the vicinity of the mainstream and major tributaries as well as large lakes in their study. Guan et al. (2017) explored trends of daily precipitation and extremes in Yangtze River Basin and found a wetting tendency in the eastern Tibet Plateau besides the middle and lower basin. In general, previous studies addressing the variations of hydrological extremes in Yangtze River Basin primarily focused on either annual or seasonal variability of extreme precipitation, or part of the basin. There are relatively few researches of changes in extreme river flow and water level, and they are often studied separately with extreme precipitation. In addition, the changes of flood damages in Yangtze River Basin have seldom been studied, and the impacts of climate change on hydrological extremes and flood disaster remain unclear. In this regard, more comprehensive researches are still needed to fully characterize the variations and change relations of hydrological extremes in Yangtze River Basin, as well as the potential impacts of climate change.

Therefore, this study attempts to examine the spatial and temporal variations of hydrological extremes in Yangtze River Basin and explore potential impacts of climate change through synthetic evaluation of observed changes in multiple flood-related variables. Specifically, changes in extreme precipitation, river flow, water level, and flood damages were analyzed with particular attention to the evidence of climate change impacts. The article is organized as follows: Section 2 introduces the study area of Yangtze River Basin; Sect. 3 describes the data and the analysis methods used in this study; Sect. 4 presents the results of changes in extreme precipitation, discharge, water level, and flood damages; Sect. 5 provides a synthesis of the results and summarizes the main conclusions.

2 Study area

Yangtze River originates in the Qinghai–Tibet Plateau and flows eastwards to the East China Sea, with total length of about 6380 km (Fig. 1). Yangtze River Basin (YRB) has a total drainage area of about 1.8×10^6 km^2, which covers about one-fifth of China's mainland area. It can be divided into three parts according to the topography in different areas: the upper basin covers the area from the source region to Yichang; the middle basin encompasses the section from Yichang to Hukou; and the lower basin extends from Hukou to the estuary. In the lower basin, river flow is usually influenced by the sea tide and shows more complicated variability. Datong is the last station beyond this tidal influence. Eleven provincial administration units in China at least partly overlaps with the YRB, and four of them are almost entirely within the basin boundary. They are Sichuan, Chongqing, Hunan, and Hubei, which are located mainly in the upper and middle basins. They were chosen to evaluate the changes in flood damages considering the data availability and spatial integrity.

The YRB is characterized by a subtropical and temperate climate. The annual mean temperature is 19 and 15 °C in the southern and northern parts, respectively (Zhang et al. 2008). The mean annual precipitation varies from 300–500 mm in the west to 1600–1900 mm in the southeast (Chen et al. 2014). The precipitation is mainly dominated by the Asian monsoon system, with the Indian monsoon mainly affecting the upper basin, and the East Asian summer monsoon influencing most of the mid-lower regions (Ding and Chan 2005). The monsoon system brings abundant precipitation during the summer and may cause persistent rainfall when the rain belt is suspended within the basin for several weeks. The heavy and long-lasting rainfall usually leads to frequent floods, especially in

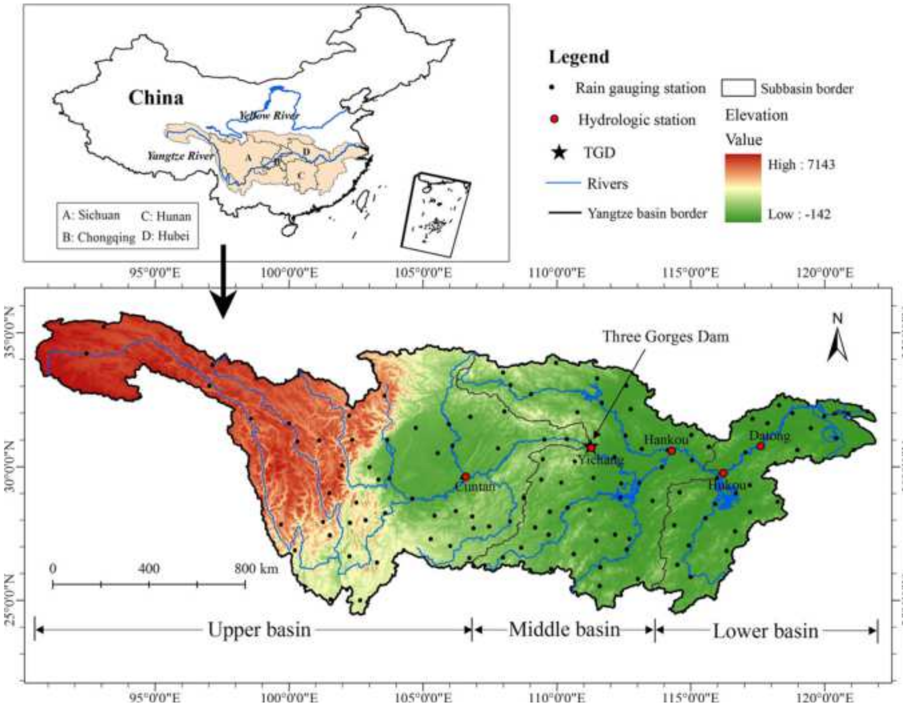


Fig. 1 Study area of Yangtze River Basin and the location of gauging stations

the mid-lower regions, which are highly populated and mainly occupied by flood-prone low flat plains.

3 Data and methods

3.1 Datasets

This study involves various datasets from different sources. The daily precipitation data from 130 rain-gauging stations were provided by the National Climate Center of the China Meteorological Administration. These stations were selected based on the criterion of relatively long observation series, and most of them cover the period from 1955 to 2014. The hydrological data of daily discharge and water level from the same period for Yichang, Hankou, and Datong stations were used to represent the upper, middle, and lower reaches of the river, respectively. As the Three Gorges Dam is located just upstream of Yichang station and has a direct influence on the flow regimes, data from the Cuntan station, another important station in the upper basin, were also used in this study. All these hydrological data were provided by the Changjiang Water Resources Commission (CWRC) of China. Both meteorological and hydrological data were carefully checked by the provider regarding data homogeneity and reliability before they were released, and the missing data were filled through a linear interpolation of nearby observations.

In this study, indices for extreme precipitation, river discharge, and water level were defined as annual maxima and also as statistics of extreme events based on percentiles, such as annual frequency and the mean intensity of the events. For extreme precipitation, annual maxima for both 1-day and 3-day accumulated precipitation were considered. Extreme precipitation for the upper, middle, and lower basins was calculated using the Thiessen polygon method to regionalize the data from rain-gauging stations within each area.

Historical flood damages data such as affected population and monetary economic loss from 1990 to 2014 for Sichuan, Chongqing (1998–2014), Hunan, and Hubei province were gathered from the Ministry of Civil Affairs of China, which is the designated government agency in charge of disaster management and relief in China. The corresponding socioeconomic data of population, GDP, were collected from the Provincial Statistical Yearbooks for the four provinces mentioned above.

3.2 Methods

3.2.1 Statistical methods for trend detection

Both parametric and nonparametric approaches were used in this study to detect trends in hydrological extremes. For the parametric method, the most common linear regression was used. Linear trends in the time series were estimated by ordinary least squares fitting (OLS), and the significance of the trends was assessed with the statistic t test.

For series that might be non-normally distributed, the rank-based nonparametric Mann–Kendall (MK) test was employed. This method is distribution-free and less sensitive to outliers than parametric statistics (Zhang et al. 2016). It has been widely used to examine trends in hydrometeorological time series (Du et al. 2013; Sang et al. 2014; Sayemuzzaman and Jha 2014; Basarin et al. 2016; Huang et al. 2016). To search for a monotonic trend, a standardized statistic Z is computed based on the rankings of data in the series, which is normally distributed under the null hypothesis of no trend. A significant upward (downward) trend is indicated by a positive (negative) Z with an absolute value greater than the critical value of $Z_{1-\alpha/2}$ at significance level of α.

It is well known that the original MK test is sensitive to autocorrelation. The existence of a positive serial correlation in the time series may increase the probability of rejecting null hypothesis and lead to inaccurate interpretation of the trends (Nalley et al. 2012). Therefore, the autocorrelation is first assessed before applying the MK test. If it is significant at 5% significance level, the modified Mann–Kendall (MMK) test proposed by Hamed and Rao (1998) would be applied instead.

3.2.2 Wavelet analysis

Wavelet transform is one of the most powerful mathematical methods that have been widely used in signal processing and time-series analysis. It provides a flexible way to reveal periodic features of a time series in different timescales by decomposing it into a time–frequency space (Torrence and Compo 1998). Unlike traditional Fourier transforms, wavelet transform allows high accurate capture of all frequencies within a given time series (Araghi et al. 2017) and therefore is suitable for the study of non-stationary, multi-scale geophysical processes (Grinsted et al. 2004).

Basically, the continuous wavelet transform (CWT) of a signal f is the convolution of f with a set of scaled and translated wavelets, given as:

$$W_f(a,\ b) = a^{-1/2}\int_{-\infty}^{+\infty} f(t)\psi^*\left(\frac{t-b}{a}\right)\mathrm{d}t \tag{1}$$

where $W_f(a,b)$ denotes the wavelet coefficient; ψ is the mother wavelet function, the asterisk denotes the complex conjugate; a, b are the scale and translation parameters. Here, the Morlet wavelet was chosen as the mother wavelet function.

Based on the CWT, we used the cross wavelet transform (XWT) and wavelet coherence (WTC) in this study to analyze the associations between extreme precipitation and river flow. The XWT reveals the areas in time–frequency space where the two series show high correlation, and the WTC further quantifies the degree of correlation. The WTC coefficient is similar to a correlation coefficient and is defined as:

$$R_n^2 = \frac{\left|S\left(s^{-1}W_i^{XY}(s)\right)\right|^2}{S\left(s^{-1}|W_i^X(s)|^2\right)\cdot S\left(s^{-1}|W_i^Y(s)|^2\right)} \tag{2}$$

$$W_i^{XY} = W_i^X W_i^{Y*} \tag{3}$$

where S is a smoothing operator; $W_i^X(s)$ and $W_i^Y(s)$ are wavelet transforms of time series X and Y for the scale of s, and $W_i^{XY}(s)$ is the XWT of the two series; * denotes complex conjugation.

3.2.3 Flood loss normalization

The damage caused by flood is a direct proxy of flood disaster and risk. It provides a straightforward way to view the impacts of climate change. Barredo (2009) developed a framework for flood loss normalization and assessed the normalized flood losses in Europe after the adjustment of changes in population, wealth, and inflation. Here, the normalization refers to the adjustment of flood loss series through eliminating the effects of time-variant socioeconomic factors to make it comparable over time. The ultimate goal for normalization is to evaluate the trend of losses that could be attributed to anthropogenic climate change as if all the floods happened in the same socioeconomic context. Similar approaches had been used by some other studies and applied to other types of hazards (Neumayer and Barthel 2011; Pielke et al. 2008).

In this study, we introduced the normalization scheme developed by Barredo (2009) and applied it to flood damage records of the four provinces mentioned above. Specifically, the normalization equations used in this study for flood-affected population and economic loss are defined as:

$$\mathrm{AP}_{2014} = \mathrm{AP}_i \times \frac{P_{2014}}{P_i} \tag{4}$$

$$L_{2014} = L_i \times \frac{I_{2014}}{I_i} \times \frac{\mathrm{GDP}_{2014}}{\mathrm{GDP}_i} \tag{5}$$

where AP_i and L_i are the nominal affected population and economic loss of floods in year i, respectively; AP_{2014} and L_{2014} are the corresponding normalized affected population and economic loss if the floods in year i happened in 2014; I_{2014} and I_i are the deflator factors in 2014 and year i, respectively; GDP_{2014} and GDP_i are the gross domestic product adjusted at a comparable price in 2014 and year i, respectively; P_{2014} and P_i are the total population in 2014 and year i, respectively.

4 Results

4.1 Spatial and temporal variations of extreme precipitation

Spatial–temporal variations of extreme precipitation for individual stations as well as for the upper, middle, and lower regions of Yangtze River Basin were investigated using the MK test. Figure 2 shows the spatial distribution of trends for six extreme precipitation indices for all stations in the basin. Significant increasing trends in annual maximum daily precipitation were mainly found in the north of the mid-lower basin and the west of the upper basin, while significant decreasing trends were mainly observed in the central part of the upper basin (Fig. 2a). Annual maximum 3-day precipitation had a similar pattern of trends while with less significant stations (Fig. 2b). For extreme precipitation events exceeding the 95th percentile, significant increasing trends of annual frequency were detected for nine stations in the northwest and southeast of the mid-lower basin, and seven stations in the west of the upper basin, while significant decreasing trends were mainly found in the central and southern parts of the upper basin, and the rest of the basin was characterized with insignificant trends in frequency (Fig. 2c). The intensity of extreme precipitation exceeding the 95th percentile showed a different pattern of changes, with significant increasing trends detected for three stations in the south of the mid-lower basin and six stations scattered in the upper basin (Fig. 2e). For even more extreme events that

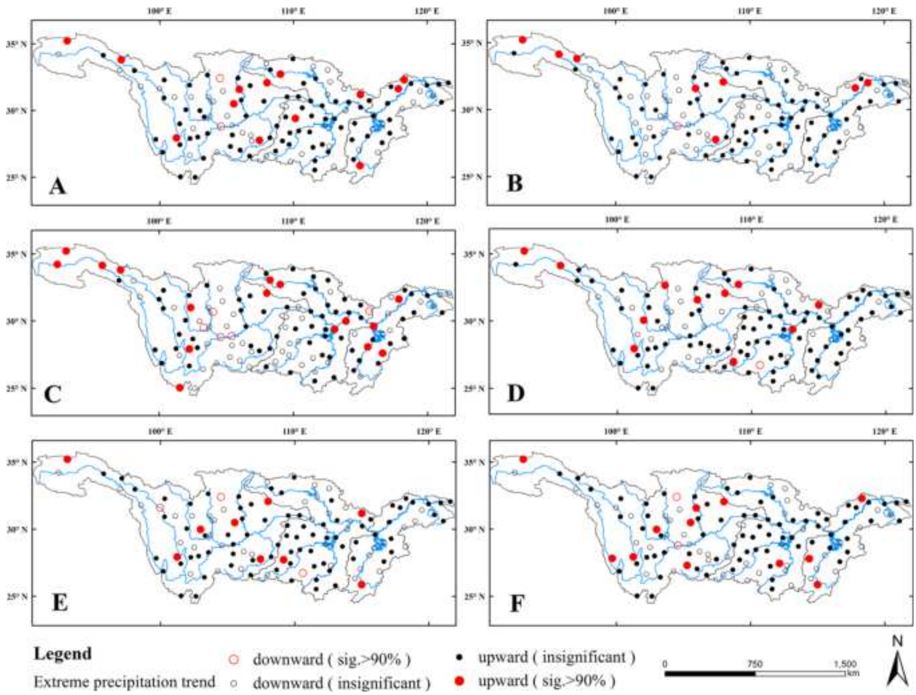


Fig. 2 MK test for extreme precipitation trends for each station in the Yangtze River Basin. **a** Annual maximum daily precipitation; **b** annual maximum 3-day precipitation; **c** annual frequency of extreme precipitation exceeding 95th percentile; **d** annual frequency of extreme precipitation exceeding 99th percentile; **e** annual mean intensity of extreme precipitation exceeding the 95th percentile; **f** annual mean intensity of extreme precipitation exceeding the 99th percentile

exceed the 99th percentile, there were less stations with decreasing trends, and the changes in annual frequency and intensity are dominated with increasing trends, especially significant increasing trends in the upper basin (Fig. 2d, f).

To reveal the contribution of extreme rainfall events to annual total precipitation, the proportion of extreme precipitation was further analyzed along with their temporal trends. It can be seen that extreme precipitation in the central part of the upper basin had the highest proportion, taking 41 and 15% of annual total precipitation for extreme events exceeding the 95th and 99th percentiles, respectively. Meanwhile, the lowest proportion was found in the west of the upper basin, reaching 24 and 6%, respectively. Moreover, the MK test revealed widespread significant increasing trends for extreme precipitation proportion in the west and northeast of the upper basin and northwest of the middle basin.

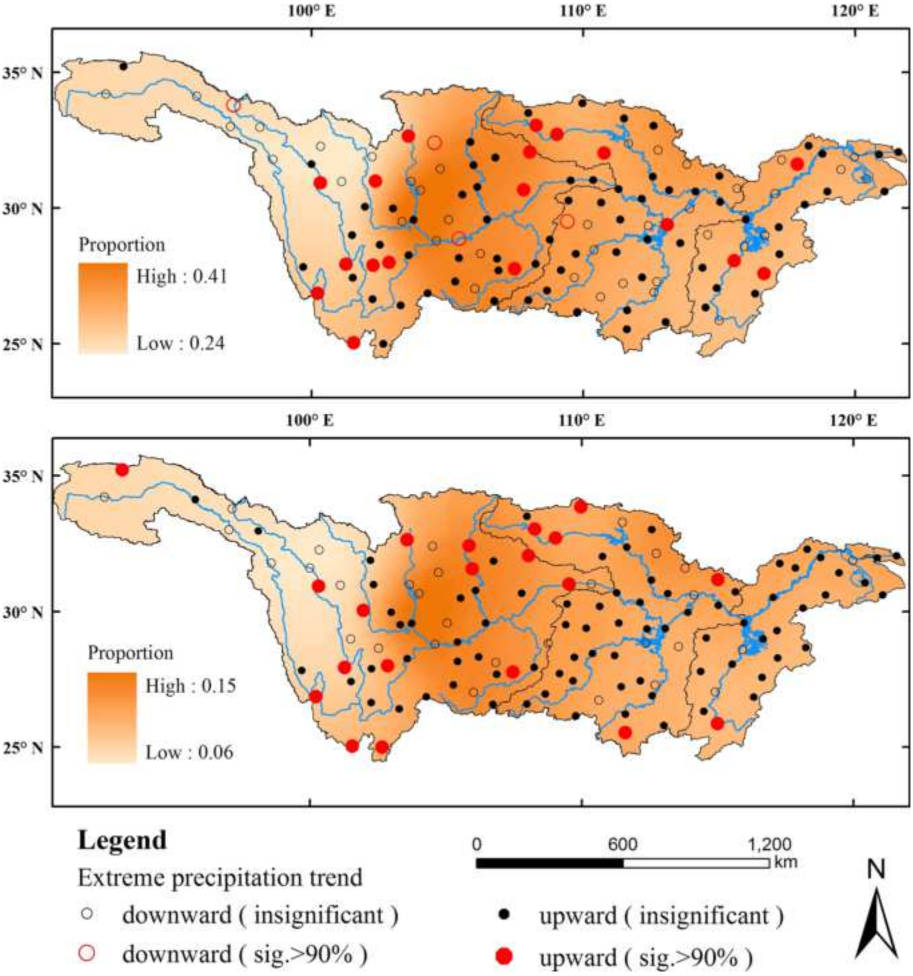


Fig. 3 Average proportion of extreme precipitation to annual total precipitation in Yangtze River Basin and MK test for the trends of changes in the proportion (upper: extreme events exceeding the 95th percentile; lower: extreme events exceeding the 99th percentile)

Only four stations in the upper and middle basins were found with significant decreasing trends (Fig. 3).

In addition to the analyses for individual stations, interannual and decadal variations of extreme precipitation for upper, middle, and lower basins of Yangtze River were also investigated. As shown in Fig. 4, annual maximum precipitation in all three regions showed a significant increasing trend (at $\alpha < 0.1$ level), and the linear changes are 0.12, 0.17, and 0.22 mm/yr for upper, middle, and lower basins, respectively. For middle and lower basins, annual maximum precipitation increased from 1960s to 1990s and then decreased slightly in 2000s, while the peak value for annual maximum precipitation in the upper basin was found in 1980s. For the frequency of extreme precipitation exceeding 95th percentile, the upper basin showed a significant increasing trend (at $\alpha < 0.01$ level) and decadal increase was evident from 1960s to 2000s, while the trends in middle and lower basins were not significant and the frequency increased from 1960s to 1990s and decreased afterward.

Figure 5 shows the temporal variations of mean intensity and total amount of extreme precipitation events exceeding the 95th percentile for the upper, middle, and lower basins. The upper basin showed significant increasing trends in both extreme indices, and the upward trends in recent years were particularly evident. The total amount of extreme precipitation increased significantly at $\alpha < 0.05$ level in the lower basin, while the mean

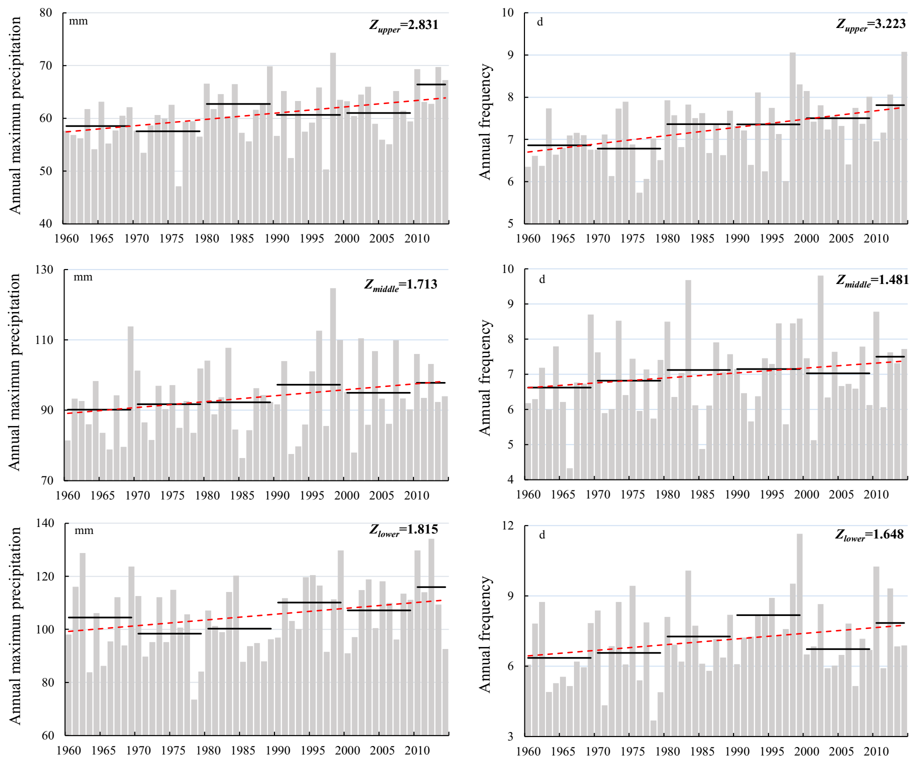


Fig. 4 Interannual and decadal variations and trends for annual maximum daily precipitation (left) and annual frequency of extreme precipitation events (right) for upper, middle, and lower basins (2010–2014 were excluded in decadal analysis as the series were not long enough)

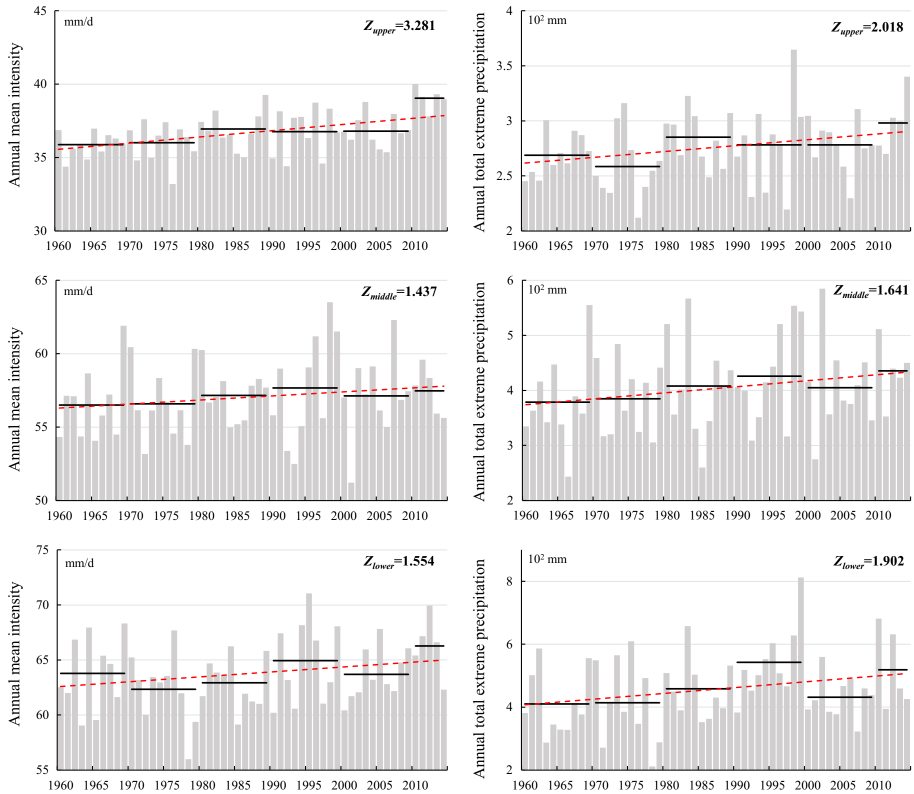


Fig. 5 Interannual and decadal variations and trends for annual mean intensity (left) and annual total amount of extreme precipitation (right) for upper, middle, and lower basins (2010–2014 were excluded in decadal analysis as the series are not long enough)

intensity did not show any significant trend, even at $\alpha < 0.1$ level. Meanwhile, no significant trends in either intensity or total amount could be detected for the middle basin. On decadal scale, the variability for the intensity of extreme precipitation was quite small in all basins, while the total amount increased from 1960s to 1990s and declined significantly in 2000s in middle and lower basins and changed slightly in upper basin.

In general, the aforementioned results coincide with the findings of previous studies that examined trends in extreme precipitation in this region (Su et al. 2008; Zhang et al. 2008); however, more significant changes have been found in our study as the data series were expanded to more recent years, especially the increasing trends in the upper basin, which were consistent with several severe floods and landslides occurring in the upper basin in recent years (Liu and Xu 2016; Liu et al. 2017), while were not detected in previous studies.

4.2 Observed changes in extreme river flow and water level

For extreme river flow and water level, changes in annual maxima and frequency of extreme events exceeding the 95th percentile were studied for four hydrological stations located in different parts of Yangtze River (Cuntan, Yichang in the upper stream; Hankou in the middle stream; Datong in the lower stream, see Fig. 1). Considering the fact that the Three Gorges Dam (TGD, completed in 2003) might have a great influence on flow regimes downstream, we analyzed two data series for each station: one covers the entire period up to 2012, and the other ends in 2002. This discrimination enables a comparison of impacts from both climate variability and major human activity.

The results of MK test for extreme discharge and water level are summarized in Table 1. Viewing from the entire period, decreasing trends could be observed in Cuntan station and most of them were significant at $\alpha < 0.1$ level. The shortening of the time series did not bring any consistent changes as it is located upstream of the TGD and may have very limited influence from the dam. For Yichang station, all indices for extreme water level and annual maximum discharge for entire period were found to decrease significantly at $\alpha < 0.05$ level, while the frequency of extreme discharge decreased insignificantly. All the decreasing trends became more significant after the construction of the dam. For Hankou and Datong stations, significant increasing trends could be detected at $\alpha < 0.05$ level in all extreme indices before 2003; however, these trends became insignificant when the post-TGD period was included.

The regression *t* test revealed similar results in terms of linear trends in extreme discharge and water level. As shown in Fig. 6, annual maximum discharge and water level decreased at Cuntan and Yichang stations, and construction of the TGD intensified the decreasing trend at Yichang station. Meanwhile, significant increasing trends in extreme discharge and water level were found for data series before 2003 at Hankou and Datong stations in the middle and lower basins ($\alpha < 0.05$). When the influence of TGD was considered using the entire period data series, all these increasing trends became insignificant ($\alpha > 0.1$). A comparison with previous studies (Xiong and Guo 2004; Zhang et al. 2006) indicates similar changing patterns of extreme discharge and water level in Yangtze River Basin with decreasing trends in the upper stream and increasing trends in the middle and lower stream.

4.3 Relations between changes in extreme river flow and extreme precipitation

To further explore the response of extreme river flow to extreme precipitation, the covarying relationships between changes in annual maximum discharge and maximum precipitation at Cuntan, Yichang, Hankou, and Datong stations were investigated using cross wavelet transform (XWT) and wavelet coherence (WTC) analysis.

The cross wavelet spectrum from XWT can indicate areas in time–frequency space where two time series show high correlation. Further, the wavelet coherence coefficient measures the degree of correlation of the two series in the time–frequency domain, which is similar to a correlation coefficient and the value falls between 0 and 1. It can be observed from Fig. 7 that most arrows in the significant area (within solid black lines) of the spectral plots point right for all the four stations, indicating consistent in-phase relations between the series of extreme precipitation and discharge. For Cuntan and Yichang stations, significant common power could be found at 2- to 4- and 7- to 9-year period during 1975–1985 from cross wavelet spectrum, and the WTC revealed wider areas with significant coherence: The coefficients were on average greater than 0.8 at 1- to 4- and 7- to 11-year period from 1970s to 1990s. For Hankou station, significant common power and high coherence were mainly observed at 7- to 10-year period during 1985–1995 and 2- to 5-year period during 1995–2005. For Datong station, there was a small area with significant common power of 2- to 4-year periodicity during 1992–2002, while the wavelet

Table 1 MK test for extreme discharge and water level in four selected stations for the entire time series (ZMK-2012) and the series before 2003 (ZMK-2002)

Station	Extreme discharge				Extreme water level			
	Annual maxima		Annual frequency		Annual maxima		Annual frequency	
	$Z_{MK\text{-}2012}$	$Z_{MK\text{-}2002}$	$Z_{MK\text{-}2012}$	$Z_{MK\text{-}2002}$	$Z_{MK\text{-}2012}$	$Z_{MK\text{-}2002}$	$Z_{MK\text{-}2012}$	$Z_{MK\text{-}2002}$
Cuntan	− 1.655*	− 2.040**	− 1.708*	− 1.212	− 1.572	− 2.125**	− 1.996**	− 1.496
Yichang	− 3.055**	− 1.695*	− 1.720*	− 1.051	− 2.746**	− 2.102**	− 2.680**	− 2.160**
Hankou	1.150	2.586**	0.812	2.109**	1.274	2.641**	1.459	2.577**
Datong	0.489	2.430**	0.726	2.211**	0.750	2.513**	1.301	2.779**

*Significant level $\alpha < 0.1$, **significant level $\alpha < 0.05$

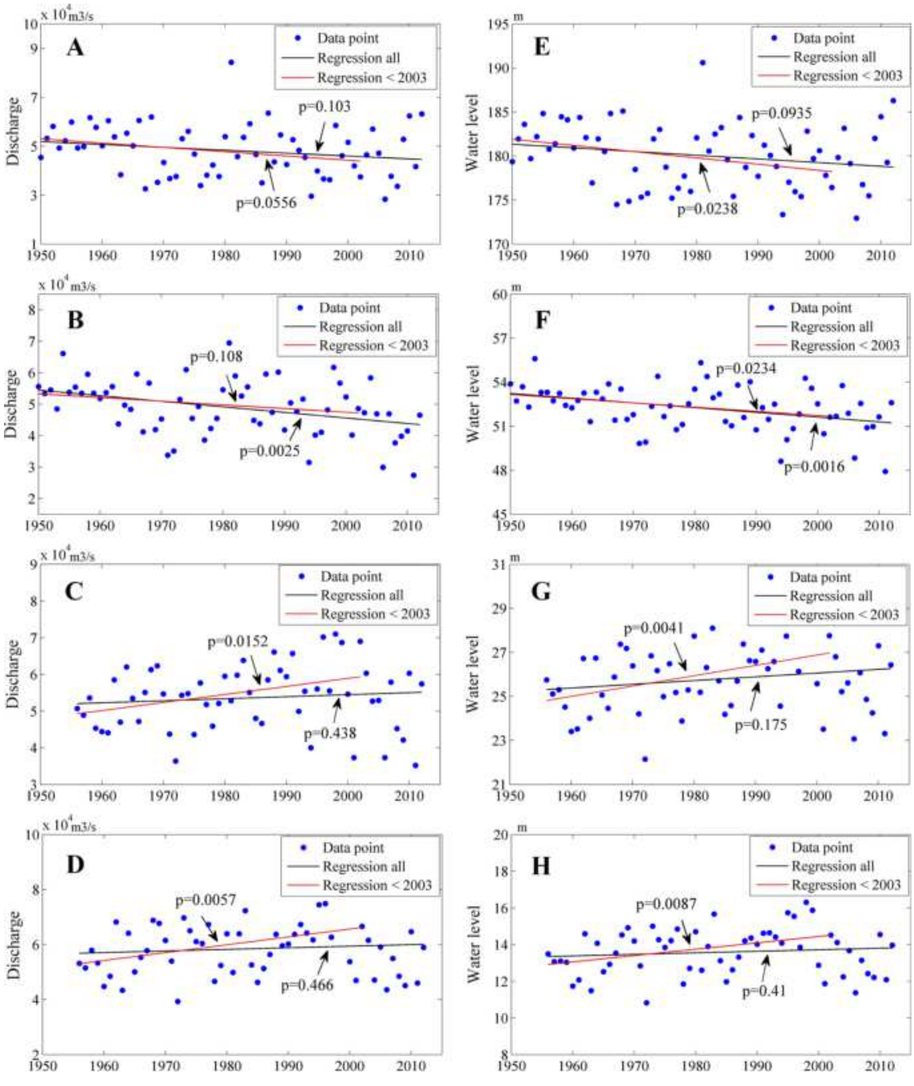
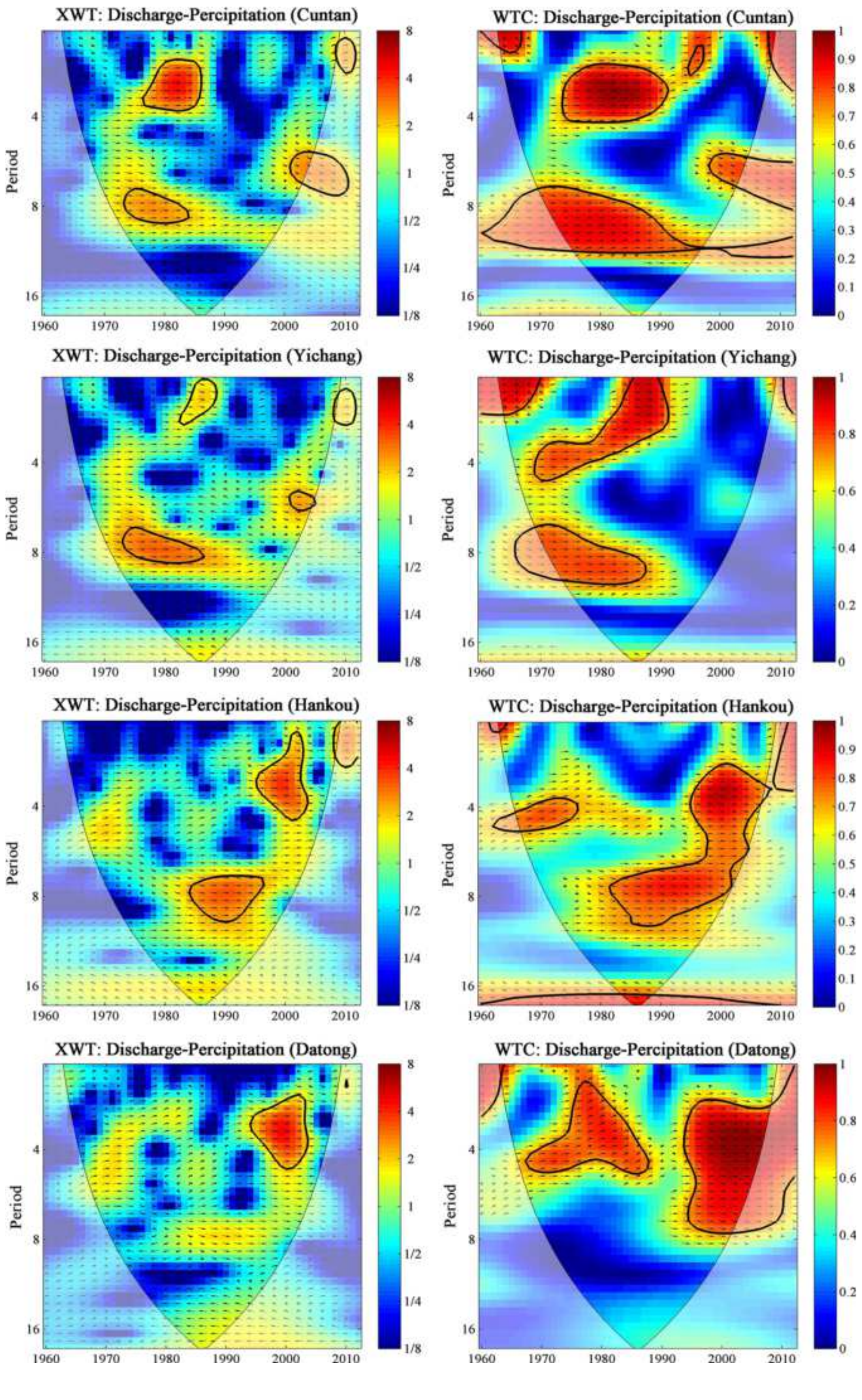


Fig. 6 Linear regression for annual maximum discharge at Cuntan (**a**), Yichang (**b**), Hankou (**c**), and Datong (**d**) stations and that for annual maximum water level at Cuntan (**e**), Yichang (**f**), Hankou (**g**), and Datong (**h**) stations: the red and black lines represent regression lines for the time series ending in 2002 and 2012, respectively

coherence was significant for much larger area: at 2- to 5-year period during 1970–1985 and at 2- to 8-year period during 1995–2005.

The cross wavelet transform and wavelet coherence analysis indicated widespread significant correlation relationship between extreme river flow and precipitation, demonstrating that although major human activities like the construction of the Three Georges Dam may have great effects on flow regimes of the downstream river, the variations of extreme river flow in the main stream of Yangtze River still coincided with the variability of extreme precipitation in the long term.


XWT: Discharge-Percipitation (Cuntan)
WTC: Discharge-Percipitation (Cuntan)
XWT: Discharge-Percipitation (Yichang)
WTC: Discharge-Percipitation (Yichang)
XWT: Discharge-Percipitation (Hankou)
WTC: Discharge-Percipitation (Hankou)
XWT: Discharge-Percipitation (Datong)
WTC: Discharge-Percipitation (Datong)
Period
1960 1970 1980 1990 2000 2010

◀**Fig. 7** Cross wavelet transforms (left) and wavelet coherence (right) for annual maximum precipitation and discharge at Cuntan, Yichang, Hankou and Datong stations. Arrows show the phase relationship between the two series. The arrows pointing left (right) means anti-phase (in-phase) relationship. Solid black lines indicate 5% significance level; light black line indicate the area influenced by edge effects

4.4 Changes in observed and normalized flood damages

To reveal changes in historical flood damages, annual economic loss and affected population from recorded floods for four provinces within Yangtze River Basin are plotted in Fig. 8 along with their linear trends. With regard to economic loss, significant increasing trends can be observed in upstream provinces of Sichuan and Chongqing, while it decreased insignificantly in Hunan and showed almost no trend in Hubei. For affected population, it is clear that the number of people affected from flooding decreased significantly in Hunan and Hubei with average decreasing rates of 61.09 and 40.82 million people per year, respectively. For upstream provinces, affected population increased slightly in Sichuan and decreased weakly in Chongqing.

The original nominal flood damages of economic loss and affected population were further normalized to eliminate the influence of changes in socioeconomic factors. For flood economic losses, significant decreasing trends could be found in Hunan and Hubei after normalization, and the significant increasing trends of original records were replaced by significant decreasing trend and no trend in Chongqing and Sichuan, respectively. This suggests that changes in inflation and GDP had been the main factors contributing to the variation of nominal economic losses, especially for Chongqing and Sichuan. For affected population, the normalization did not bring much difference and the overall trends were similar to the original nominal records: It decreased insignificantly in Chongqing and significantly in Hunan and Hubei, while still increased slightly in Sichuan (Fig. 9). It is worth noting that the investments and improvements in flood defense and protection measures were not considered in the normalization process; therefore, the weak increasing

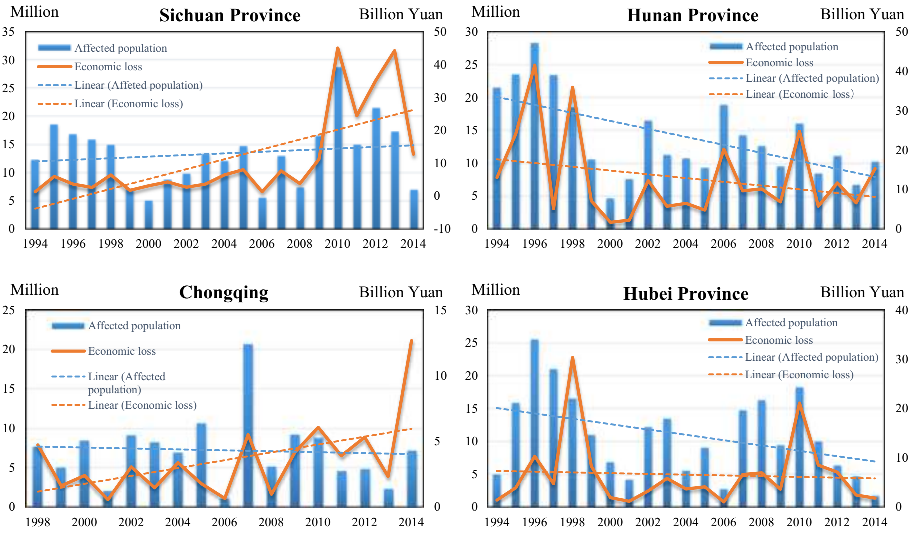


Fig. 8 Time series of nominal flood economic losses and affected population along with their linear trends for four provinces in the Yangtze River Basin: Sichuan, Chongqing, Hunan, and Hubei

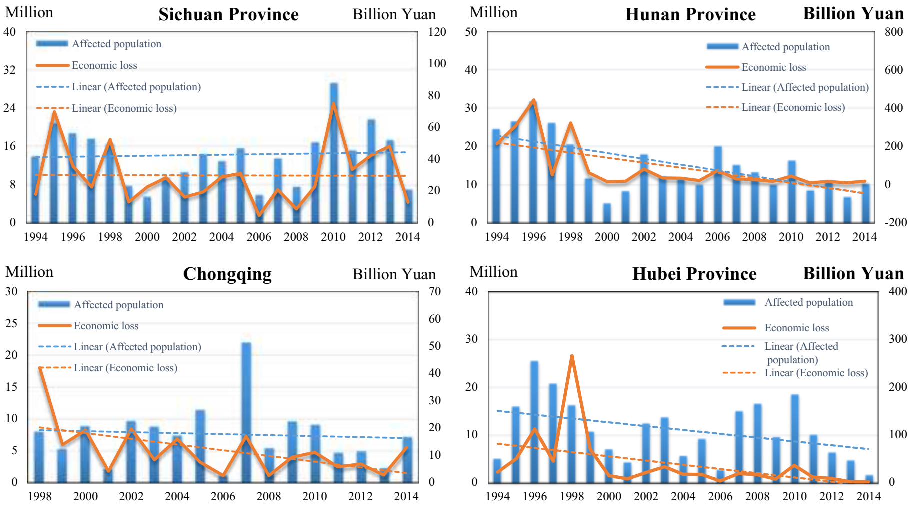


Fig. 9 Time series of normalized flood economic losses and affected population and their linear trends for four provinces in Yangtze River Basin: Sichuan, Chongqing, Hunan, and Hubei

trend in normalized affected population in Sichuan province, which can be attributed to anthropogenic climate change, was actually underestimated. This provides a notable evidence for climate change impacts on flood disaster in the upper basin of Yangtze River.

5 Conclusion and discussion

The variation and tendency of hydrological extremes in the context of climate change have great impacts on global and regional flood risk and have received extensive concern worldwide. This study investigated the trends in extreme precipitation, river flow, water level, and flood damages in Yangtze River Basin and further explored potential impacts of climate change with evidence from in-depth analyses of the observed changes. It provides a holistic assessment of historical variations of hydrological extremes in Yangtze River Basin and has implications for policy makers to advance climate change adaptation and flood risk reduction.

The results showed that extreme precipitation increased significantly at some stations in the middle and lower basins of Yangtze River, while the overall trends for some indices were not significant. In the upper basin, significant increasing trends were observed for the whole area, but the pattern of changes was quite complex: Generally, they increased significantly in the west and northeast part, while significant decreasing trends were also found in the central part. For extreme river discharge and water level, significant increasing trends can be detected at Hankou and Datong stations in the middle and lower basins, while opposite trends were evident for Cuntan and Yichang stations in the upper basin. Meanwhile, the Three Gorges Dam had remarkable impacts on river flow downstream, making the increasing trends less significant for Hankou and Datong stations and strengthening the decreasing trends at Yichang station. It is worth noting that the decreasing trends for extreme river flow at Cuntan and Yichang stations did not contradict with the overall increasing trends for extreme precipitation in the upper basin, as the increasing trends were mainly found in the northeast tributaries and the source region, and the mainstream and the central part of the upper basin were still dominated with decreasing trends. For historical flood damages, significant increasing trends in economic losses were detected in Chongqing and Sichuan, while they decreased slightly in Hunan and Hubei. No significant trends were found in affected population for upstream province of Chongqing and Sichuan, while they decreased significantly in Hunan and Hubei province.

To explore the impacts of climate change on extreme floods, the relations of changes in extreme river flow and extreme precipitation were further investigated using wavelet transform analysis. The results revealed significant covarying relationships between extreme precipitation and extreme discharge at various timescales, demonstrating the substantial influence of precipitation variability on extreme streamflow oscillation, in spite of the great impact of major human activities on river flow regimes. In addition, historical flood damages were normalized to remove the influence of changes in GDP and population and the trends were re-examined. The results indicated predominant contribution of growing exposure in flood damage trends, while the weak increasing trend after normalization in Sichuan province still provided evidence of climate change impacts.

In summary, significant regional differences exist for hydrological extremes and flood risk in Yangtze River Basin. For middle and lower reaches, there were widespread increasing trends for extreme precipitation, while most of the trends were not significant, and because of the improvements in flood defense system in the main stream and around important cities, flood damages decreased significantly. However, extreme river flow still increased in the middle and lower reaches, even after the construction of the Three Gorges Dam, highlighting the needs of sustained efforts to prepare and adapt for extreme floods in the future. For the upper basin, special attention should be given to the northeast mountainous area, where extreme precipitation increased significantly and recurrent flash floods and landslides from heavy rainfall have brought severe and increasing flood damages. More effective measures to protect from floods and reduce the vulnerability are urgently needed.

Flood disaster is a complex system that embraces extreme hydrometeorological hazard and the exposure. The evolution of flood disaster depends on the interaction of multiple factors in the atmospheric, terrestrial, and socioeconomic systems (Kundzewicz et al. 2010). The complexity in flood system signifies the need for integrated multi-disciplinary research to assess climate change impacts. This study presents a constructive endeavor to synthesize the analyses from different aspects, while the effort is still challenged by several limitations and uncertainties. Spatial–temporal variations of hydrological extremes were investigated, while the underlying mechanism needs more profound examination, which would be particularly important for robust projection of future changes. In addition, vulnerability is an important and integrated concept for disaster risk; however, it is difficult to be fully quantified and measured and thus not considered in this study. A better understanding toward the evolution of flood risk and the impacts of climate change requires the incorporation of vulnerability assessment in loss analysis and emphasizes the importance of documenting vulnerability characteristics over time. We propose these as necessary future work.

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