Chin. Geogra. Sci. 2017 Vol. 27 No. 2 pp. 325–336
doi: 10.1007/s11769-017-0866-x

Springer Science Press
www.springerlink.com/content/1002-0063

Change of Annual Extreme Water Levels and Correlation with River Discharges in the Middle-lower Yangtze River: Characteristics and Possible Affecting Factors

YE Xuchun[1, 2], XU Chong-Yu[3], LI Yunliang[2], LI Xianghu[2], ZHANG Qi[2]

(1. *School of Geographical Sciences*, *Southwest University*, *Chongqing* 400715, *China*; 2. *Key Laboratory of Watershed Geographic Sciences*, *Nanjing Institute of Geography and Limnology*, *Nanjing* 210008, *China*; 3. *Department of Geosciences*, *University of Oslo*, *Oslo* 0316, *Norway*)

Abstract: As one of the fastest developing regions in China, the middle-lower Yangtze River (MLYR) is vulnerable to floods and droughts. With obtained time series of annual highest water level (HWL), annual lowest water level (LWL) and the corresponding river discharges from three gauging stations in MLYR that covering the period 1987–2011, the current study evaluated the change characteristics of annual extreme water levels and the correlation with river discharges by using the methods of trend test, Mann-Whitney-Pettitt (MWP) test and double mass analysis. Major result indicated a decreasing/increasing trend for annual HWL/LWL of all stations in MLYR during the study period. A change point in 1999 was identified for annual HWL at the Hankou and Datong stations. The year 2006 was found to be the critical year that the relationship between annual extreme water levels and river discharges changed in the MLYR. With contrast to annual LWL in MLYR, further investigation revealed that the change characteristics of annual HWL were highly consistent with regional precipitation in the Yangtze River Basin, while the linkage with Three Gorges Dam (TGD) operation is not strong. Our observation also pointed out that the effect of serious down cutting of the riverbed and the enlargement of the cross-section area during the initial period of TGD operation caused the downward trend of the relationship between annual LWL and river discharge. Whereas, the relatively raised river water level before the flood season due to TGD regulation since 2006 explained for the changing upward trend of the relationship between annual HWL and river discharge.

Keywords: extreme water level; water level-discharge relationship; double mass analysis; Yangtze River

Citation: Ye Xuchun, Xu Chong-Yu, Li Yunliang, Li Xianghu, Zhang Qi, 2017. Change of annual extreme water levels and correlation with river discharges in the middle-lower Yangtze River: characteristics and possible affecting factors. *Chinese Geographical Science*, 27(2): 325–336. doi: 10.1007/s11769-017-0866-x

1 Introduction

The variability of flow in river channels has important influence on the health of regional ecology and the development of socioeconomic. However, the occurrence of some extreme water regime such as extreme high water level or extreme low water level in a river is easily to cause flood and drought events with varying degrees in a region. According to the exacerbation of climate change and human activities, atmospheric circulation and global hydrological cycle have been changed gradually during the past century (IPCC, 2013). One of the most potential consequences of global hydrological changes is that floods and/or droughts may occur at modified severity and frequency, causing considerable socioeconomic loss and extensive degradation of the

---

Received date: 2016-07-06; accepted date: 2016-11-09

Foundation item: Under the auspices of the Fund of Key Laboratory of Watershed Geographic Sciences, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences (No. WSGS2015003), Fundamental Research Funds for the Central Universities (No. XDJK2016C093), National Natural Science Foundation of China (No. 41571023)

Corresponding author: YE Xuchun. E-mail: yxch2500@163.com

© Science Press, Northeast Institute of Geography and Agroecology, CAS and Springer-Verlag Berlin Heidelberg 2017

aquatic ecosystem (Shankman *et al*., 2006; Bond *et al*., 2008; Li *et al*., 2013). Up to now, due to the frequent occurrence of floods and/or droughts within the context of global change, studies focusing on the occurrence and mechanism of world hydrological and meteorological extremes have become one of the most frontier scientific issues (Easterling *et al*., 2000; Milly and Wetherald, 2002; Alexander *et al*., 2006; Coumou and Rahmstorf, 2012).

The Yangtze River Basin belongs to subtropical monsoon climate, temporal and spatial distributions of the rain zone are closely related to monsoon activities and seasonal motion of subtropical highs (Jiang *et al*., 2006). As a prominent example of hydrological modifications according to global climate change, the Yangtze River, especially the middle-lower Yangtze River (MLYR) is experiencing frequent floods and droughts in recent decades. Most notably, the floods in the 1990s were much more frequent and severe than that in any other decades. Statistics indicate that the floods in the summers of 1998, 1996, and 1995 were the three most severe floods (in descending order) in the last five decades (Jiang and Shi, 2003). Since the last decade, remarkable hydrological changes in the MLYR were the frequent occurrences of seasonal hydrological droughts. For example, extremely low water levels below or close to the lowest historical water level were frequently observed in 2006, 2007, 2009 and 2011 in the Poyang Lake, the largest freshwater lake in China that connected to the MLYR (Min and Zhan, 2012).

Because the Yangtze River Basin, as one of the fastest developing regions in China, plays a significant role in the socioeconomic development of China, the frequent occurrence of floods and droughts has caused great concerns for local and the central governments (Lai *et al*., 2016; Mao *et al*., 2016; Li *et al*., 2016). These concerns have further elevated by the large water conservancy projects that have been or will be built in the upper reaches of the Yangtze River. For example, the operation of the Three Gorges Dam (TGD) in the Yangtze River since 2003 has altered the natural flow dynamics downstream (Lai *et al*., 2014; Mei *et al*., 2016; Yao *et al*., 2016). This regime change of downstream flow has significant impacts on fluvial processes, such as downstream river bed degradation (Li *et al*., 2009; Fang *et al*., 2012; Sun *et al*., 2012; Xu *et al*., 2016). In addition, these changes may further affect downstream large lake hydrological processes and the wetland ecosystems (Zhang *et al*., 2012; Wang *et al*., 2016). For this reason, a growing number of researchers are now studying the variation in hydrological parameters that reflect these human impacts in the region of MLYR (Guo *et al*., 2012; Zhang *et al*., 2012; Zhang *et al*., 2014; Lai *et al*., 2014; Li *et al*., 2015). However, to date, few studies focused on the temporal and spatial variability of the hydrological extremes in the MLYR (Zhang *et al*., 2006). Moreover, questions regarding the stationarity and change characteristics of the relationship between river extreme water levels and the corresponding discharges remain to be addressed. A better understanding of these changes is essential for assessing the impact of anthropogenic activities in this river system and for local water resources management as well as the natural hazards prevention. With this motivation, this study was designed to achieve the following objectives: 1) to analyze the change characteristics of annual extreme water levels in the MLYR since the end of 1980s; 2) to examine the changing relationship between annual extreme water levels and the corresponding river discharges, and 3) to evaluate the possible affecting factors to the above changes.

2 Materials and Methods

2.1 Study area

The Yangtze River is the largest river in China with a length of 6300 km and the basin covers an area of 1.8×10^6 km^2. The middle reach of the Yangtze River is defined between Yichang and Hukou (the conjunction of the Poyang Lake and Yangtze River), and down-river from Hukou is defined as the lower reach of the river (Fig. 1). In the middle reach of the Yangtze River, Hankou station is the most crucial gauging station that collects most of the inflows from the middle basin, such as the Hanhe River and the Dongting Lake basins. Due to the landward limit of the tidal river is located at Datong during the flood season, the gauging station was considered to be the outlet control station for the whole Yangtze River Basin.

As the Yangtze River receives large number of tributaries from the middle and downstream, river discharge increased dramatically. As shown in Table 1, among the three gauging stations, mean annual discharge at Yichang is 13 225.91 m^3/s, which is about 59.5% of the Hankou station and 46.7% of the Datong station.

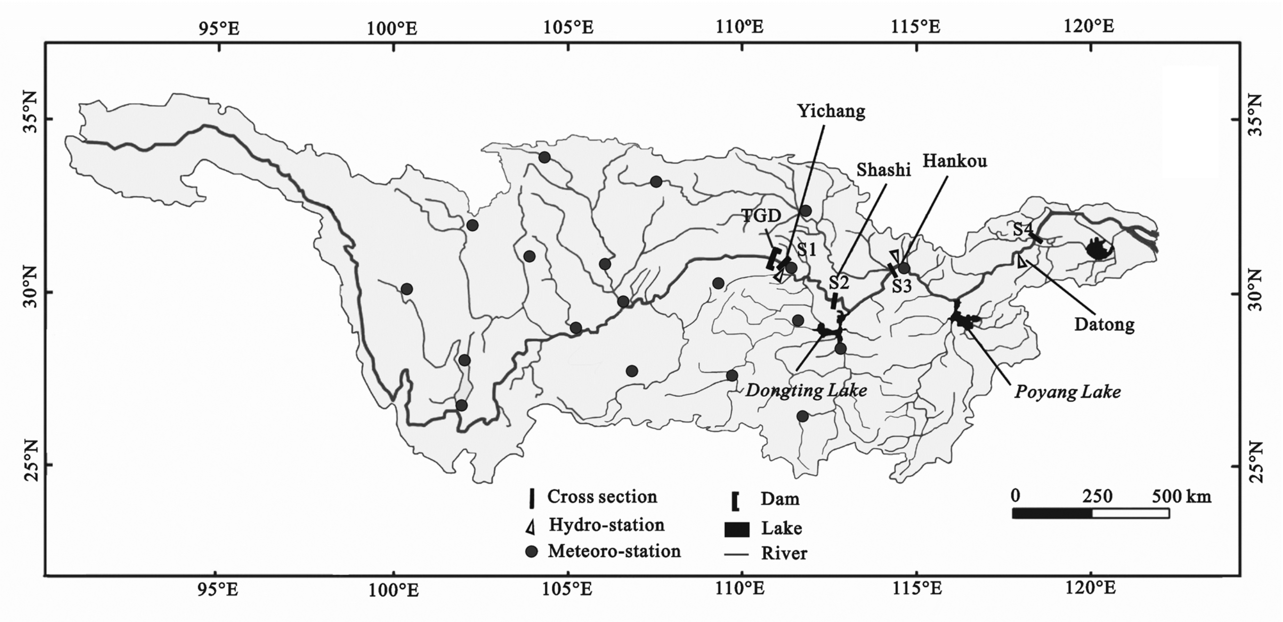

Fig. 1 Locations of the Yangtze River, the Three Gorges Dam (TGD) and hydrological and meteorological stations used in this study. S1–4 represents the number of the cross-section in the middle-lower Yangtze River

Table 1 Information of three gauging stations and hydrological features from 1987 to 2011

Gauging station	Location	Drainage area (10^4 km²)	Mean annual discharge (m³/s)	Mean annual water level (m)
Yichang	30°42′N, 111°17′E	100.55	13225.91	42.89
Hankou	30°35′N, 114°17′E	148.80	22204.04	19.12
Datong	30°46′N, 117°37′E	170.54	28328.53	8.62

2.2 Data and processing

In this study, data are composed of four groups. The first group includes daily discharge and water level of the Yangtze River measured at the three major gauging stations: Yichang, Hankou and Datong for the period 1987–2011. These hydrological data were quality controlled at the office of the Hydrological Bureau of the Yangtze River Water Resources Commission, China. The second group includes the four representative river cross-sections (S1, S2, S3, S4) located in the MLYR (Fig. 1). Among the four cross-sections, data from S1, S2 and S3 near Yichang, Shashi and Hankou, respectively, were collected from Bulletin of China River Sediment 2009 and 2010 which were surveyed intermittently between 1998 and 2010 (available on http://www.cjh.com.cn), while the data from cross-section S4 at Nanjing between 2002 and 2006 were obtained from published literatures (Dai and Liu, 2013). The third group includes daily discharge and water level from Three Gorges Dam (TGD) during 2003–2011, and the data were collected from the web of China Three Gorges Corporation (http://www.ctg.com.cn/inc/sqsk.php). The fourth group of data includes monthly precipitation from 19 representative meteorological stations that almost evenly distributed in the upper and middle reaches of the Yangtze River (Fig. 1). The data were downloaded from the web of China Meteorological Administration (http://data.cma.cn/site/index.html), and covered the period 1987–2011.

2.3 Methods

2.3.1 Trend test

The Mann-Kandell (MK) test (Kahya and Kalayci, 2004) is a rank-based non-parametric method which has been widely applied for trend detecting in hydro-climatic time series due to its robustness against the influence of abnormal data and especially its reliability for biased variables (Chen *et al.*, 2007; Zhang *et al.*, 2009; Ye *et al.*, 2013, 2014; Zhang *et al.*, 2014; Wei *et al.*, 2016; Yin *et al.*, 2016). According to the method, the null hypothesis of no trend is rejected if standardized statistics $|Z|\geq 1.64$ at 10% significance level and rejected if |Z|≥1.96 at 5% significance level. In order to calculate the change degree of the time series, Sen′s slope (Sen, 1968) of the hydrological variable was also calculated. Details about the method can be referred to the above mentioned literatures.

In addition, a combination of an ordinary linear regression model in the form of $\hat{y} = a + bt$ is also used to detect the long-term change trend. In this equation, a and b are the regression coefficients with a represents interception and b estimates the rate of change, t is an independent time variable, $\hat{y}$ is the dependent hydrological variable of time series. The significance of the linear trend is further estimated by t test (Zhang *et al*., 2006).

2.3.2 Mann-Whitney-Pettitt change point analysis

Mann-Whitney-Pettitt (MWP) change point analysis is a non-parametric test method, which was first proposed by Pettitt in 1979 (Pettitt, 1979). Due to clarity of physical meaning and simple calculation of this method, MWP test has been widely applied for change point detecting in hydrological or meteorological time series (Lin *et al*., 2008; Kundu *et al*., 2015). This method can give not only the occurrence time of the change point, but also the significance of the change point.

2.3.3 Double mass analysis

Double mass analysis is a commonly used data analysis approach for investigating the behavior of records made of hydrological or meteorological data at a number of locations (Searcy and Hardison, 1960). Initially, the method was mainly applied in consistency examination and verification of hydrological and meteorological data, but it has been widely used in the investigation on the effects of human activities (such as water and soil conservation, reservoir construction and deforestation, etc.) on precipitation, runoff and sediment transportation in recent decades (Cluis, 1983; Zhang and Wen, 2002; Mu *et al*., 2007; Ma *et al*., 2012). The framework of double mass analysis in checking consistency of a hydrological or meteorological record is based on the hypothesis that each item of the recorded data is consistent. Commonly, when the compared variables are highly correlated and have proportional relationship, this method can give an accurate and useful result (Kohler, 1949).

Generally, the slope change point can be easily visually identified from double mass curve, but the result sometimes is subjectivity. In this study, in order to investigate the significance of the change point, the significant difference of linear trends before and after the change point is further examined by t test.

3 Results and Analyses

3.1 Characteristics of annual extreme water levels

Because the presence of serial correlation may lead to an erroneous rejection of the null hypothesis in trend analysis by MK test (Yue and Pilon, 2003; Villarini *et al*., 2009), autocorrelation analysis was made first for annual highest water level (HWL) and annual lowest water level (LWL) of the three hydro-stations, and no significant serial correlation was found in the data. The results of the MK test and the linear regression test are summarized in Table 2. The variations of annual HWL, LWL and the probabilities of change point by MWP analysis are plotted in Fig. 2. For each station, the results are described as follows.

Fig. 2a depicts the variation of annual HWL and LWL at Yichang station during the period 1987–2011. Maximum value of HWL (54.27 m) was observed in 1998, and the minimum value of LWL (38.11 m) was observed in 2003. Annual HWL shows a long-term decreasing trend, while annual LWL shows an increasing trend. The change degrees of annual HWL and LWL series are about –0.06 and 0.02 for β in MK test and –0.07 and 0.02 for b in the linear regression model (Table 2). However, both the tests indicate that the change trends of annual HWL and LWL are not significant at 0.1 level. The MWP analysis indicates that there is no change point can be found for both annual HWL and LWL series (Fig. 2b).

During the study period, the maximum value of annual HWL (29.43 m) at Hankou station was observed in 1998, and the minimum value of annual LWL (12.20 m) was observed in 1987. Similar to Yichang station, annual HWL of Hankou station also shows a decreasing trend, and annual LWL shows an increasing trend (Fig. 2c). The change degrees of annual HWL and LWL series are about –0.10 and 0.03 for β in MK test and –0.09 and 0.03 for b in the linear regression model (Table 2). MK test indicates that the decreasing trend of HWL is significant at the 0.1 level, but the increasing trend of LWL is not significant. However, both change trends of annual HWL and LWL are found to be significant at the

0.1 level by the linear regression test (Table 2). Different from Yichang station, annual HWL at Hankou station shows a significant change point in 1999 by the MWP analysis (Fig. 2d).

For Datong station, the maximum value of annual HWL (16.30 m) was observed in 1998 and the minimum value of LWL (3.58 m) was observed in 1987 during the past 25 years. Annual HWL shows a decreasing trend, and annual LWL shows an increasing trend (Fig. 2e). The change degrees of annual HWL and LWL series are about –0.09 and 0.01 for β in MK test and –0.09 and 0.02 for b in the linear regression model (Table 2). Both the tests indicate that the decreasing trend of HWL is significant at 0.05 level, but the increasing trend of LWL is not significant (Table 2). Same as the result of Hankou station, MWP analysis indicates that annual HWL at Datong station shows a significant change point in 1999, and no change point can be found for annual LWL (Fig. 2f).

In addition to the above analysis, one of the most notably characteristics of LWL variations in Fig. 2 is that the fluctuations of annual LWL series of all the three gauging stations were much minimized since 2004, which is much different from the large fluctuations before this year. However, same cases are not found for the fluctuations of annual HWLs. Reasons for this may be attributed to human regulations on river discharge and discussed later.

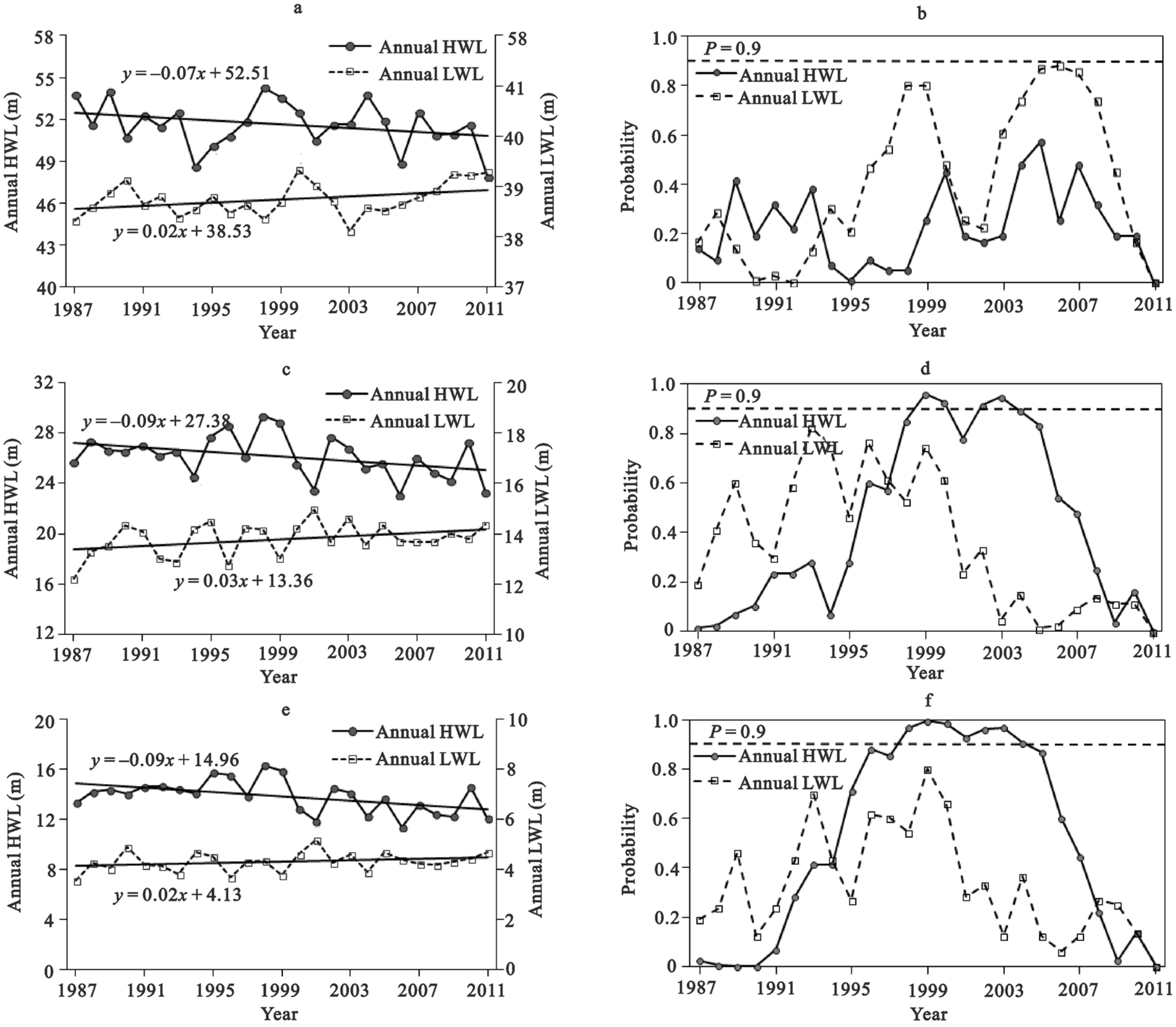

Fig. 2 Variations of annual highest water level (HWL) and lowest water level (LWL) and the probabilities of change point by Mann-Whitney-Pettitt analysis for the three hydro-stations: (a, b) Yichang station, (c, d) Hankou station and (e, f) Datong station. The horizontal dashed lines in the right graphs denote the 90% confidence interval

Table 2 Results of trend analysis for extreme water levels at three gauging stations

Station	Item	Mean (m)	MK test				Linear trend test			
			Z	β	Sig.	Trend	T	b	Sig.	Trend
Yichang	HWL	51.62	–0.96	–0.06	–	↓	–1.54	–0.07	–	↓
	LWL	38.74	1.78	0.02	–	↑	1.90	0.02	–	↑
Hankou	HWL	26.20	–1.92	–0.10	*	↓	–2.06	–0.09	*	↓
	LWL	13.79	1.59	0.03	–	↑	1.90	0.03	*	↑
Datong	HWL	13.84	–2.03	–0.09	**	↓	–2.64	–0.09	**	↓
	LWL	4.32	1.47	0.01	–	↑	1.42	0.02	–	↑

Note: 'HWL' indicates highest water level; 'LWL' indicates lowest water level; * denotes significance at 0.1 level; ** denotes significance at 0.05 level; '–' denotes no significant trend. '↓' indicates a decreasing trend while '↑' indicates an increasing trend

3.2 Relationship between annual extreme water level and river discharge

The change of river water level is the response of the change of river discharge. According to Pearson correlation analysis of annual HWLs, LWLs and their corresponding river discharges of the three hydro-stations, the result shows that the coefficients of all the stations are larger than 0.82. Further test indicates that all these linear relationships are significant at 0.01 level. In addition, the coefficients between annual HWLs and the corresponding river discharges are commonly higher than those between annual LWLs and corresponding river discharges. The reason for this is that the relationship between annual LWL and corresponding river discharge is more easily to be affected by the shape of river cross-section and river regulation.

With the context that annual HWLs, LWLs and their corresponding river discharges of the three gauging stations have strong linear correlation, we can then use the double mass analysis to test the potential change of these relationships. It is seen from Fig. 3 that the double mass curves of HWLs, LWLs and their corresponding discharges of the three gauging stations show a break in the slope of all the curves, and this break was occurred in the year 2006. The two sections of the curve before and after 2006 show a highly linear correlation (although slight deviate of the scatters can be found sometimes), but the slope obviously changed in this year. Further investigation from a t test for the two lines of the curve before and after 2006 indicates that the break of linear trends in 2006 of all the double mass curves of the three gauging stations is significant at the 0.01 level. Generally, Fig. 3 shows that an upward trend in the annual HWL in the double mass curve since 2006, while downward trend in the annual LWL can be noted. This result demonstrates that annual HWL has been raised given the same river discharge at the three gauging stations in the past several years, while annual LWL has been reduced. Furthermore, result from the Fig. 3 indicates that the change degree of annual LWL after 2006 is bigger than HWL of each gauging station seems to be diminished downstream the river.

4 Discussion

4.1 Impacts of precipitation

The Yangtze River Basin is located in the subtropical zone. Variations of river discharge and water level are mainly controlled by local precipitation conditions (Feng *et al.*, 2013). According to long term observations, annual highest river water level (or the maximum river discharge) and annual lowest river water level (or the minimum river discharge) mainly appeared in July/August and January/February, respectively. However, according to cross correlation analysis, river discharge in MLYR shows one month lag in response to precipitation of the upper and middle reaches of the Yangtze River Basin. Fig. 4 shows the precipitation of January–February and June–July in the upper and the middle reaches of the Yangtze River Basin. From which it is seen that precipitation of January–February and June–July in both the upper and the middle reaches of the Yangtze River Basin shows a decreasing trend. The decreasing trend of precipitation in June–July is consistent with the long-term decreasing trend of annual HWL in the middle and lower reaches of the Yangtze River. In addition, the obvious increasing trend of June–July precipitation followed by a decreasing trend before and after the end of 1990s (Fig. 4b), to a large extent, well explains the step change of HWL at Hankou and Datong in 1999. Previous studies indicated that the increased annual precipitation especially the wet season precipitation

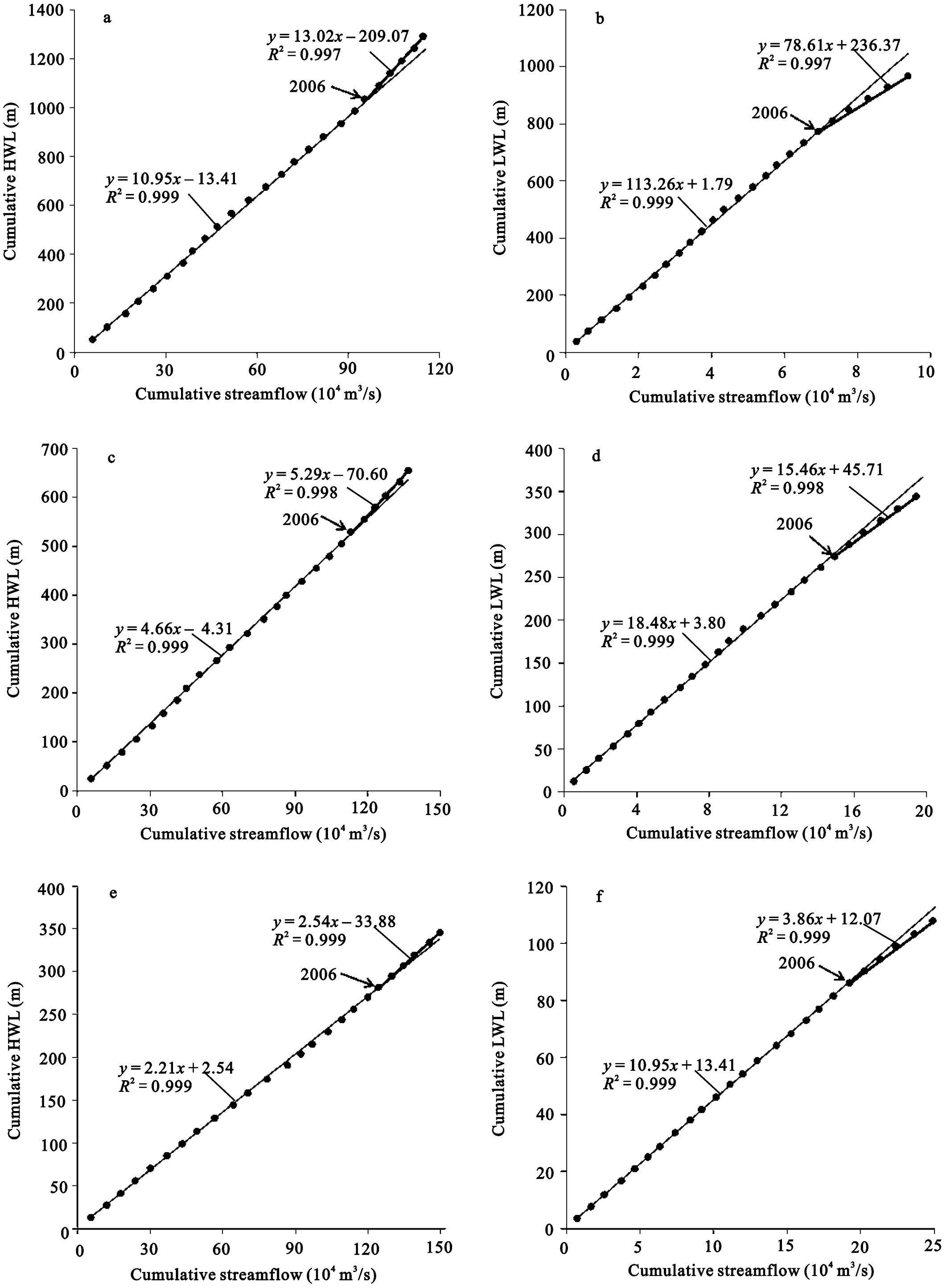

Fig. 3 Double mass analysis of HWLs, LWLs and corresponding river discharges of the three gauging stations: (a, b) Yichang station, (c, d) Hankou station and (e, f) Datong station

in the Yangtze River Basin in the 1990s was caused by the southward shift of the major rain bands in eastern China (Hu and Feng, 2001). Similarly, with the coming of drought episode in Yangtze River Basin in the 2000s, wet season precipitation decreased significantly, and so did the river discharge and water level.

However, the decreasing trend of precipitation in January–February (Fig. 4) can not explain the increasing

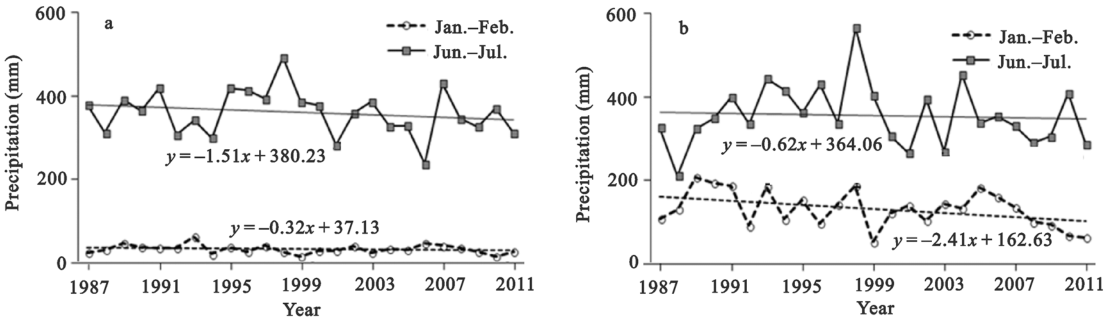

Fig. 4 Precipitation of January–February and June–July in the upper (a) and the middle reaches (b) of the Yangtze River Basin

trend of the annual LWL in recent years. Especially, the minimized fluctuation and slight increase of annual LWL of the three gauging stations in the last several years were much different from the remarkable decrease of January–February precipitation in the upper and middle reaches of Yangtze River Basin. This result may suggest an obvious regulation effect of water conservancy project in the Yangtze River.

4.2 Potential linkage with the TGD

The TGD is located approximately 45 km upstream of the Yichang gauging station (Fig. 1b). The development of the TGD proceeded through four stages: the coffer dam stage (2003), the initial stage (2006), the pilot stage (2008) and the normal operation stage (2010) (http://www.ctgpc.com.cn/en/). Since 2010, the monthly water level of the reservoir has been regulated following the normal water impounding and releasing rules of the dam.

Flood control during the wet season and increasing discharge during the dry season to ensure adequate navigation conditions are the two basic functions of the TGD. Fig. 5 shows the water level variations of the reservoir and corresponding regulation of river discharges since the operation of TGD. Under the normal water storage condition, volume of reservoir after the operation of TGD is about 3.93×10^{10} m^3, of which 1.65×10^{10} m^3 is considered to be a regulating storage volume. Therefore, there is no doubt that the TGD plays an important role on reducing extreme flood peaks and raising extreme low water levels in the MLYR. According to the operating mode, the TGD makes three major changes in the river discharge pattern over an annual cycle: an obvious increase in January–March, May– early June and a decrease in September–October. Due to the huge flood storage function, the TGD may play an important promotion on the decreasing trend of annual HWL during the study period. However, in consideration of the variation of regional precipitation and the start of TGD operation, there is no strong linkage can be observed between the change characteristics of annual HWL in MLYR and the effect from this great water conservancy project.

Affected by the TGD regulation during the dry season, the fluctuation of annual LWL since 2004 diminished a lot. Furthermore, due to the rising water level of the reservoir and the encounter of frequent seasonal hydrological droughts in the MLYR since 2003 characterized by extremely low water levels in some large lakes, the TGD increased its water releasing in recent years. Compared to its prior state, statistical result indicates that the TGD makes an average increase of water discharge of 1437.93m^3/s in December–February during the period 2003–2011. With regard to the long term decreasing regional precipitation, it can be concluded that the inconsistent increasing trend of annual LWL series as compared with precipitation in the same period was mainly caused by the increased release of TGD during dry season in recent several years.

Result from the double mass analysis indicates that annual LWL has been reduced given the same river

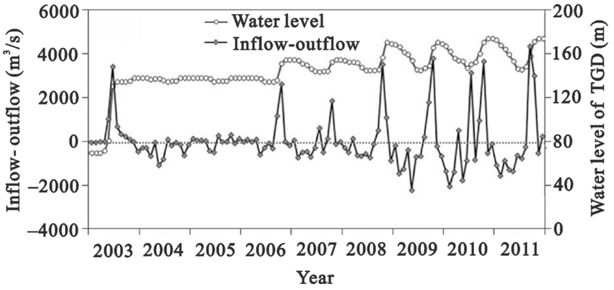

Fig. 5 Water level variations and the corresponding differences between inflow and outflow of the TGD from 2003–2011

discharge at the three gauging stations since 2006; reasons for this should be attributed to the change of morphology of riverbed section since the operation of TGD. Previous studies have pointed out a serious riverbed erosion and corresponding declining water level in the MLYR since the operation of TGD (e.g., Zhang *et al*., 2010; Chen *et al*., 2011), although deposition may also exist at some river sections (e.g., Fang *et al*., 2012). Fig. 6 displays the changes at four selected cross-sections (S1–4) near the reference gauging stations. It is visible from the figure that serious down cutting of the riverbed and enlargement of the cross-section area have occurred at the four cross-sections. However, with the down cutting of the riverbed, all the riverbanks are basically stable. Statistical result indicates that the thalweg depths between Yichang and Shashi lowered significantly after the initial impoundment of TGD in 2003. The deepest down cutting could reach –12 m, and the average down cutting was –2.5 m (Dai and Liu, 2013). Riverbed erosion was obviously weakened since 2006 (see S1, S3 in Figs. 6a, c). Dai and Liu (2013) revealed that suspended sediment discharge and suspended sediment content in MLYR have been reduced significantly since TGD operation in 2003 and reach the minimum in 2006. In addition, Fig. 6 also reveals that the enlargement of the cross-sectional area was mainly restricted in the lower part of the river section, such as < 40 m in S1 (Fig. 6a), < 15 m in S3 (Fig. 6c) and < 5 m in S4 (Fig. 6d). These elevation limited areas are just comparable with the averaged annual LWL of the gauging stations (for example, the averaged annual LWL is 38.74 m at Yichang, 13.79 m at Hankou, and 4.32 m at Datong). It is known that under the conditions of small river discharge, changes of river cross-sections (such as riverbed erosion) will have relatively big influence on water level variations. Therefore, due to the serious down cutting of the riverbed and the enlargement of the cross-section area, it is easy to understand why significant downward trend appeared in the double mass curve of the annual LWL and its corresponding discharge of the three gauging stations.

Generally, serious down cutting of the riverbed and the enlargement of cross-sectional area may also have the same effect on annual HWL as that on the change of the relationship between annual LWL and its corresponding discharges, even though the relative changes of river section area are not that obvious at high water levels. However, our observation rejects this hypothesis. Actually, things are not that simple. According to the principle of river flood wave movement, the curve of relationship between water level and river discharge during a flood event is like a loop (Huang, 2009). The

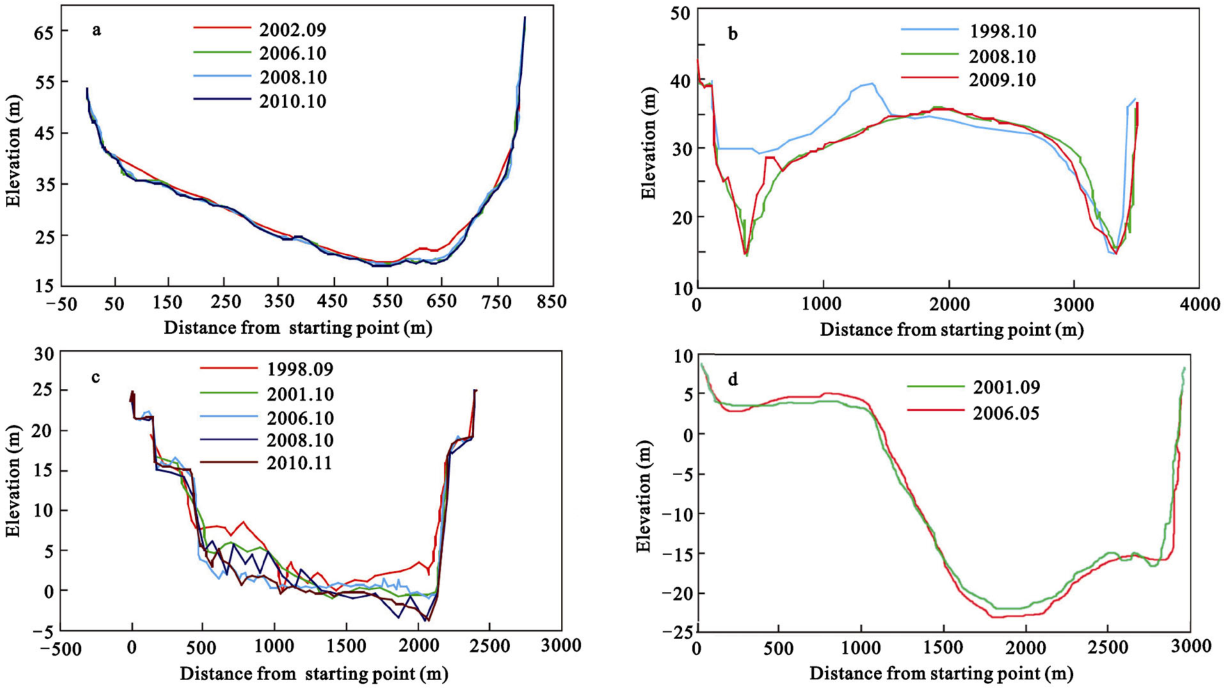

Fig. 6 Changes of cross-sections at four locations in the middle-lower Yangtze River

lower and upper parts of the loop may represent the raising and recession stages of a flood event. The deviation of the relationship is not only affected by the velocity of catchment flood routing, but also affected by initial stable water level of the river (Huang, 2009). Since the operation of TGD, river discharge has been increased from April to early June, the months before the flood season is coming, for the purpose of increasing the reservoir's storage for flood mitigation generated by heavy upstream summer rainfall. It is hypothesized that the increased discharge may raise the river water level in MLYR, especially in May, and this has been proved by previous studies (e.g., Guo *et al*., 2012; Zhang *et al*., 2012; Lai *et al*., 2014). On this basis, the raised initial stable river water level before the flood season will definitely cause a relatively increased water level given the same river discharge during the flood season. In other words, the changed annual pattern of flow regime due to the regulation of TGD is the main reason for the relative raising of annual HWL for the same river discharge, with comparison to the case of no TGD effect. In addition, due to water recharge of many tributaries downstream TGD, the effect of TGD regulation on mainstream gradually weakened (Guo *et al*., 2012), and therefore the change degree of the correlation between annual extreme water levels and river discharges diminished downstream the river.

5 Conclusions

The current study analyzed the change characteristics of annual extreme water levels and correlation with river discharges in the middle-lower Yangtze River, and investigated the possible affecting factors. During the study period of 1987–2011, annual HWLs of the three gauging stations in MLYR were found to show a decreasing trend, while annual LWLs show an increasing trend. A major change point in 1999 was identified for annual HWL at Hankou and Datong stations, and the year 2006 was observed to be the critical year that the relationship between annual extreme water levels and river discharges changed in the MLYR. The changed characteristics of annual HWL in MLYR were highly consistent with regional precipitation in the upper and middle reaches of Yangtze River Basin, while the linkage with TGD operation is not strong. However, the TGD regulation has altered the long-term change trend of annual LWL in MLYR, especially since 2004, by increasing discharge during the dry season in recent years. The major driving factors for the changing relationship between annual extreme water levels (HWL and LWL) and river discharges are different. The effect of serious down cutting of the riverbed and the enlargement of the cross-section area during the initial period of TGD operation should be responsible for the downward trend of the relationship between annual LWL and corresponding river discharge. Whereas, the enlarged regulation function and the relatively raised river water level before the flood season according to the second phase of water impoundment of TGD since 2006 would be an important promotion for the changing upward trend of the relationship between annual HWL and correspondding river discharge.

The study also raises concerns that are relevant to hydrological extremes in those large river basins under global changes. Apart from the climate changes, human activities, especially large water conservancy project will exert significant impacts on temporal and spatial variability of streamflow regime, fluvial processes and consequently will influence hydrological extremes. Because TGD increases river discharge in the dry season to ensure adequate navigation conditions, historically extreme low water or discharge in the MLYR will no longer appear. However, the changing upward trend of the relationship between annual HWL and river discharge may increase the regional risk of flood disasters downstream under certain conditions. Furthermore, as affected by global climate change, the uneven distribution of regional precipitation in the Yangtze River Basin may be aggravated. Therefore, an integrated research strategy to address the regional climate change and operation of TGD is essential for the mitigation and prevention against the risk of hydrological disasters in the MLYR.

References

Alexander L V, Zhang X, Peterson T C *et al*., 2006. Global observed changes in daily climate extremes of temperature and precipitation. *Journal of Geophysical Research Atmospheres*, 111(D5): 1042–1063. doi: 10.1029/2005JD006290

Bond N R, Lake P S, Arthington A H, 2008. The impacts of drought on fresh water ecosystems: an Australian perspective. *Hydrobiologia*, 600(1): 3–16. doi: 10.1007/s10750-008-9326-z

Chen H, Guo S L, Xu C-Y *et al*., 2007. Historical temporal trends of hydroclimatic variables and runoff response to climate variability and their relevance in water resource management in the Hanjiang basin. *Journal of Hydrology*, 344(3): 171–184. doi: 10.1016/j.jhydrol.2007.06.034

Chen Z Y, Wang Z H, Finlayson B *et al*., 2011. Implications of flow control by the Three Gorges Dam on sediment and channel dynamics of the middle Yangtze (Changjiang) River, China. *Geology*, 38 (11): 1043–1046. doi: 10.1130/G31271.1

Cluis D A, 1983. Visual techniques for the detection of water quality trends: double-mass curves and CUSUM functions. *Environmental Monitoring and Assessment*, 3(2): 173–184. doi: 10.1007/BF00398846

Coumou D, Rahmstor F S, 2012. A decade of weather extremes. *Nature Climate Change*, 2(7): 491–496. doi: 10.1038/nclimate 1452

Dai Z, Liu J T, 2013. Impacts of large dams on downstream fluvial sedimentation: An example of the Three Gorges Dam (TGD) on the Changjiang (Yangtze River). *Journal of Hydrology*, 480(4): 10–18. doi: 10.1016/j.jhydrol.2012.12.003

Easterling D R, Meehl G A, Parmesan C *et al*., 2000. Climate extremes: observations, modeling, and impacts. *Science*, 289(5487): 2068–2074. doi: 10.1126/science.289.5487.2068

Fang H W, Han D, He G J *et al*., 2012. Flood management selections for the Yangtze River midstream after the Three Gorges Project operation. *Journal of Hydrology*, 432–433(8): 1–11. doi: 10.1016/j.jhydrol.2012.01.042

Feng Yawen, Ren Guoyu, Liu Zhiyu *et al*., 2013. Rainfall and runoff trends in the Upper Yangtze River. *Resources Science*, 35(6): 1268–1276. (in Chinese)

Guo H, Hu Q, Zhang Q *et al*., 2012. Effects of the Three Gorges Dam on Yangtze River flow and river interaction with Poyang Lake, China: 2003–2008. *Journal of Hydrology*, 416–417: 19–27. doi: 10.1016/j.jhydrol.2011.11.027

Hu Q, Feng S, 2001. Southward migration of centennial scale variations of drought/flood in eastern China and western United States. *Journal of Climate*, 14: 1323–1328. doi: 10. 1175/1520-0442(2001)014<1323:ASMOCS>2.0.CO;2

Huang Xiquan, 2009. *Hydrology*. Beijing: Higher Education Press, 130–165. (in Chinese)

IPCC, 2013. *Climate Change 2013*: *the Physical Science Basis*. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. UK, Cambridge: Cambridge University Press.

Jiang Tong, Shi Yafeng, 2003. Global warming and its consequences in Yangtze River floods and damages. *Advances in Earth Science*, 18(2): 277–284. (in Chinese)

Jiang T, Zhang Q, Zhu D M *et al*., 2006. Yangtze floods and droughts (China) and teleconnections with ENSO activities (1470–2003). *Quaternary International*, 144(1): 29–37. doi: 10.1016/j.quaint.2005.05.010

Kahya E, Kalayci S. 2004. Trend analysis of streamflow in Turkey. *Journal of Hydrology*, 289(1): 128–144. doi: 10.1016/ j.jhydrol.2003.11.006

Kohler M A, 1949. On the use of double-mass analysis for testing the consistency of meteorological records and for making required adjustments. Bulletin of the American Meteorological Society, 30: 188–189.

Kundu S, Khare D, Mondal A *et al*., 2015 Analysis of spatial and temporal variation in rainfall trend of Madhya Pradesh, India (1901–2011). *Environmental Earth Sciences*, 73(12): 8197–8216. doi: 10.1007/s12665-014-3978-y

Lai X J, Liang Q H, Huang Q *et al*., 2016. Numerical evaluation of flow regime changes induced by the Three Gorges Dam in the Middle Yangtze. *Hydrology Research*, in press. doi: 10. 2166/nh.2016.158

Lai X, Jiang J, Yang G *et al*., 2014. Should the Three Gorges Dam be blamed for the extremely low water levels in the middle-lower Yangtze River? *Hydrological Processes*, 28(1): 150–160. doi: 10.1002/hyp.10077

Li F, Qin X, Xie Y *et al*., 2013. Physiological mechanisms for plant distribution pattern: responses to flooding and drought in three wetland plants from Dongting Lake, China. *Limnology*, 14(1): 71–76. doi: 10.1007/s10201-012-0386-4

Li J, 2009. Scientists line up against dam that would alter protected wetlands. *Science*, 326(5952): 508–509. doi: 10.1126/science.326_508

Li X H, Yao J, Li Y L *et al*., 2016. A modeling study of the influences of Yangtze River and local catchment on the development of floods in Poyang Lake, China. *Hydrology Research*, in press. doi: 10.2166/nh.2016.198

Li Y L, Zhang Q, Werner A D *et al*., 2015. Investigating a complex lake-catchment-river system using artificial neural networks: Poyang Lake (China). *Hydrology Research*, 46(6): 912–928. doi: 10. 2166/nh.2015.150

Lin X D, Zhang Y L, Yao Z J *et al*., 2008. The trend on runoff variations in the Lhasa River Basin. *Journal of Geographical Sciences*, 18(1): 95–106. doi: 10.1007/s11442-008-0095-4

Ma Xinping, Bai Hongying, Hou Qinlei *et al*., 2012. Runoff change of Bahe River basin in Qinling mountains and its influencing factors. *Resources Science*, 34(7): 1298–1305. (in Chinese)

Mao J Q, Zhang P P, Dai L Q *et al*., 2016. Optimal operation of a multi-reservoir system for environmental water demand of a river-connected lake. *Hydrology Research*, in press. doi: 10. 2166/nh.2016.043

Mei X, Dai Z, Wei W *et al*., 2016. Dams induced stage-discharge relationship variations in the upper Yangtze River Basin. *Hydrology Research*, 47(1): 157–170. doi: 10.2166/nh.2015.010

Milly P C, Wetherald R T, Dunne KA *et al*., 2002. Increasing risk of great floods in a changing climate. *Nature*, 415(6871): 514–517. doi: 10.1038/415514a

Min Qian, Zhan Lasheng, 2012. Characteristics of low-water changes in Lake Poyang during 1952–2011. *Journal of Lake Sciences*, 24(5): 675–678. (in Chinese)

Mu Xingmin, Chille Basang, Zhang Lu *et al*., 2007. Impact of soil conservation measures on runoff and sediment in Hekou-Longmen region of the Yellow River. *Journal of Sediment Research*, (2): 36–41. (in Chinese)

Pettitt A N, 1979. A non-parametric approach to the change point problem. *Applied Statistics*, 28(2): 126–135. doi: 10.2307/

2346729

Searcy J K, Hardison C H, 1960. Double-mass Curves. U.S. *Geological Survey Water Supply Paper*.1541–B.

Sen P K, 1968. Estimates of the regression coefficient based on Kendall's Tau. *Journal of the American Statistical Association*, 63: 1379–1389. doi: 10.2307/2285891

Shankman D, Keim B D, Song J, 2006. Flood frequency in China's Poyang Lake region: trends and teleconnections. *International Journal of Climatology*, 26(9): 1255–1266. doi: 10.1002/joc.1307

Sun Z D, Huang Q, Opp C *et al*., 2012. Impacts and implications of major changes caused by the Three Gorges Dam in the middle reach of the Yangtze River, China. *Water Resources Management*, 26(12): 3367–3378. doi: 10.1002/joc.1307

Villarini G, Serinaldi F, Smith AJ *et al*., 2009. On the stationarity of annual flood peaks in the continental United States during the 20th century. *Water Resources Research*, 45(8): W08417. doi: 10.1029/2008WR007645

Wang X L, Xu L G, Wan R R, 2016. Comparison on soil organic carbon within two typical wetland areas along the vegetation gradient of Poyang Lake, China. *Hydrology Research*, in press. doi: 10.2166/nh.2016.218

Wei Q, Sun C H, Wu G H *et al.*, 2016. Haihe River discharge to Bohai Bay, North China: trends, climate, and human activities. *Hydrology Research*, in press. doi: 10.2166/nh.2016.142

Xu X L, Li Y L, Li X H, 2016. Evaluating the influence of water table depth on transpiration of two vegetation communities in a lake floodplain wetland. *Hydrology Research*, in press. doi: 10.2166/nh.2016.011

Yao J, Zhang Q, Li Y L, 2016. Hydrological evidence and causes of seasonal low water levels in a large river–lake system: Poyang Lake, China. *Hydrology Research*, in press. doi: 10. 2166/nh.2016.044

Ye X C, Li X H, Liu J *et al*., 2014. Variation of reference evapotranspiration and its contributing climatic factors in the Poyang Lake catchment, China. *Hydrological Processes*, 28: 6151–6162. doi: 10.1002/hyp.10117

Ye X C, Zhang Q, Liu J *et al*., 2013. Distinguishing the relative impacts of climate change and human activities on variation of streamflow in the Poyang Lake catchment, China. *Journal of Hydrology*, 494: 83–95. doi: 10.1016/j.jhydrol.2013.04.036

Yin Y X, Xu C-Y, Chen H S *et al.*, 2016. Trend and concentration characteristics of precipitation and the related climatic teleconnections from 1982 to 2010 in the Beas River basin, India. *Global and Planetary Change*, 145: 116–129. doi: 10.1016/j. gloplacha.2016.08.011

Yue S, Pilon P, 2003. Interaction between deterministic trend and autoregressive process. *Water Resources Research*, 39(4), 1077. doi: 10.1029/2001WR001210.

Zhang Q, Li L, Wang Y G *et al*., 2012. Has the Three-Gorges Dam made the Poyang Lake wetlands wetter and drier? *Geophysical Research Letters*, 39(20): L20402. doi: 10.1029/ 2012GL053431

Zhang Q, Liu C L, Xu C-Y *et al*., 2006. Observed trends of annual maximum water level and streamflow during past 130 years in the Yangtze River Basin, China. *Journal of Hydrology*, 324(1): 255–265. doi: 10.1016/j.jhydrol.2005.09.023

Zhang Q, Ye X C, Werner A D *et al.*, 2014. An investigation of enhanced recessions in Poyang Lake: Comparison of Yangtze River and local catchment impacts. *Journal of Hydrology*, 517: 425–434. doi: 10.1016/j.jhydrol.2014.05.051

Zhang S R, Lu X X, 2009. Hydrological responses to precipitation variation and diverse human activities in a mountainous tributary of the lower Xijiang, China. *Catena*, 77(2): 130–142. doi: 10.1016/j.catena.2008.09.001

Zhang Xinbao, Wen Anbang, 2002. Variations of sediment in upper stream of Yangtze River and its tributary. *Journal of Hydraulic Engineering*, (4): 56–59. (in Chinese)

Zhang Zheng, Yang Shilun, Li Peng, 2010. Quantifying the Influence of Water Impoundment Phases I and II of the Three Gorges Reservoir on Downstream Suspended Sediment Flux. *Acta Geographica Sinica*, 65(5): 623–631. (in Chinese)