Front. Earth Sci. 2019, 13(3): 510–522
https://doi.org/10.1007/s11707-018-0739-3

RESEARCH ARTICLE

Water level variation characteristics under the impacts of extreme drought and the operation of the Three Gorges Dam

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Abstract Under the influence of a climate of extreme drought and the Three Gorges Dam (TGD) operation, the water levels in the middle and lower reaches of the Yangtze River in 2006 and 2011 changed significantly compared with those in the extreme drought years of 1978 and 1986. To quantitatively analyze the characteristics of water level variations in 2006 and 2011, a new calculation method was proposed, and the daily water level and discharge from 1955–2016 were collected in this study. The findings are as follows: in 2006 and 2011, the water level in the dry season significantly increased, but that in the flood season obviously decreased compared with the levels in 1978 and 1986. Here, we described this phenomenon as "no low-water-level in dry season, no high-water-level in flood season". Based on the calculation method, the contributions of climate variability and the Three Gorges Dam operation to water level variations in the middle and lower reaches of the Yangtze River were calculated, and the contributions indicated that climate variability was the main reason for the phenomenon of "no low-water-level in dry season, no high-water-level in flood season" instead of flood peak reduction in the flood season and drought runoff implementation in the dry season, which are both induced by TGD.

Keywords water level, extreme drought climate, the Three Gorges Dam, the Yangtze River Basin

1 Introduction

Water level variations are closely related to navigation conditions, the location of water intakes, the stability of slopes and the growth of aquatic vegetation and animals. Many scholars have studied the patterns of water levels (Li et al., 2017; Lin et al., 2017) and its causes (Lin et al., 2011; Mei et al., 2018) and impacts (Fischer and Öhl, 2005). Some researchers have concentrated on the response of water level variations to climate variability (Gibson et al., 2006; Bian et al., 2010). For instance, Milano (Milano, 2012) predicted the influence of precipitation variations on water levels in the Des Prairies River based on Hec-Geo HMS, Hec-Geo RAS and River2D software. Xiao et al. (2018) analyzed evaporation and its effects on present, past, and future water levels in White Bear Lake. Wu et al. (2014) studied the effects of glacial melting on water levels, and the results show that glacial meltwater in a catchment contributes to the water level rise in Nam Co Lake. Some scholars have also focused on the effects of human activities on water level changes. Wu (2008) analyzed the effects of dredging activities and the Three Gorges Dam (TGD) on the water level of Poyang Lake. The influence of the Shuikou Reservoir on water level changes in the Minjiang River was analyzed by using a mathematical model (Yang et al., 2013). Wang et al. (2013, 2017) used the hydrological model PCR-GLOBWB and the stage-discharge rating curves to assess the influence of the TGD operation on the water level downstream the dam by comparatively quantifying the impacts of two major outcomes of TGD operation: (i) regulated Yangtze flow and (ii) concurrent channel erosion due to reduced sediment discharge. Particularly in Wang et al. (2017), the authors also considered the impacts of human water consumption. However, water level variations are affected by both climate variability and human activities, and because of this, the influence of these two factors on water levels have also been analyzed by many researchers (Hu and Wang, 2009). Lai et al. (2014) reconstructed the water level at Luoshan, Hankou, and Datong under the condition of non-TGD operation using a newly developed hydrodynamic model and suggested that the TGD operation significantly

Received February 26, 2018; accepted September 25, 2018

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decreased the water level in late September to November because of water impoundment and increased water level from April to early June due to the drawdown of the TGD water level, but the influence of riverbed scouring on water levels needs more detailed studies. However, under the combined influence of a climate of extreme drought and reservoir operation, fewer studies have focused on the hydrological processes in these conditions (Dai et al., 2008a). Some researchers have concentrated on the variability characteristics of organic carbon transport process (Yu et al., 2011), sediment (Yan et al., 2008; Dai et al., 2011), baseflow (Dai et al., 2010a), groundwater (Dai et al., 2010b), salinity (Dai et al., 2008b), and river-lake interactions (Dai et al., 2010c). Few studies are about the water level variation characteristics with the impacts of both extreme drought and reservoir operation. Dai et al. (2008a) analyzed the water level variation characteristics under the influence of extreme drought and the TGD operation in great detail, but the reasons for the variation characteristics needs to be further investigated.

Under the impacts of climate variability and human activities, river hydrology and morphology have changed, which further changed the relationship between runoff and water level (Dai et al., 1998; Mei et al., 2016). There is a general rule that riverbed erosion will occur and the elevation of a thalweg will decline after reservoir operations, and this phenomenon is quite normal in many rivers, including the Nile, Danube, Ebro, and Mississippi rivers (Dai and Liu, 2013) and 21 rivers in North America (Williams and Wolman, 1984). In 2003, TGD, the largest reservoir in the world, was constructed in the Yangtze River, which obviously reduced the river sediment load downstream of the dam and thus significantly changed the water level variation characteristics. During the period from October 2002 to October 2014, the incision of the thalweg downstream of the TGD within 410 km was up to 1.5 m due to the TGD operation (Yang et al., 2017a), which significantly reduced the water level under the same discharge. In addition, the variations in the runoff caused by the TGD can also have a significant impact on the water level variations. From January 1 to June 10, 2011, the total water volume supplemented by the TGD was up to 2.15×10^{10} m^3 to satisfy the needs of the ecological environment and to combat drought, which distinctly increased the water level downstream of the TGD. Thus, the water level variation characteristics become more complex under the effects of the riverbed evolution and discharge variations caused by the TGD operation. Apart from the influence of the TGD operation, the Yangtze River Basin suffered from extreme drought in 2006 and 2011. The annual average discharges at Datong Station (the control station of the mouth of the Yangtze River) were the lowest and the third lowest in history (1955–2017), respectively, which further changed the water level processes in the middle and lower reaches of the Yangtze River (MLRYR). Furthermore, based on the PRECIS climate model system, Zhang et al. (2006) concluded that extreme climate events, especially extreme precipitation events, will be more and more frequent in the Yangtze River Basin because of the warming environment.

The obvious fluctuation in water levels can significantly impact the ecological environment, shipping, and irrigation. Thus, based on insufficient research and the research significance, the purposes of this paper are as follows: (i) analyzing the changes in water level characteristics and their causes in 2006 and 2011, under the influence of the TGD operation and the climate of extreme drought; (ii) estimating the contributions of the TGD operation and climate variability on the water level variations downstream of the TGD. This research will be meaningful for optimizing reservoir operation rules and the distribution and management of water resources.

2 Study area and data collection

2.1 Study area

The Yangtze River originates from the Qinghai-Tibetan Plateau and flows into the East China Sea at a downstream distance of approximately 6300 km (Liu et al., 2007) and is divided by Yichang and Hukou into the upper reach, the middle reach and the lower reach (Han et al., 2017a) (Fig. 1(a)). The river is the largest in Asia in terms of discharge, and its runoff accounts for 35.1% of the total runoff in China (Cao et al., 2011). Owing to its abundant water resources, more than 45,694 reservoirs have been constructed since 1950, with a total capacity of up to 1.59×10^{11} m^3 (Li et al., 2011). In 2003, TGD, the largest reservoir in the world, was constructed in the upper reach of the Yangtze River, posing landmark impacts on riverbed evolution and the spatiotemporal distribution of water resources. In addition, there are two lakes (Dongting Lake and Poyang Lake) and a main tributary (Hanjiang River) in the middle and lower reaches. Six main hydrological stations on the mainstream of the Yangtze are involved in this study, including Yichang, Jianli, Chenglingji, Luoshan, Hankou, and Datong stations (as shown in Fig. 1(b)). Yichang and Datong are the control stations of the TGD outflow and the mouth of the Yangtze River, respectively. The supplement of runoff and sediment from Dongting Lake and Poyang Lake into the Yangtze River are gauged at the Chenglingji and Hukou stations, respectively.

2.2 Data collection

In this paper, daily water level and discharge data at the main hydrological stations in the Yangtze River Basin (Fig. 1(b)) were collected over the period from 1955 to

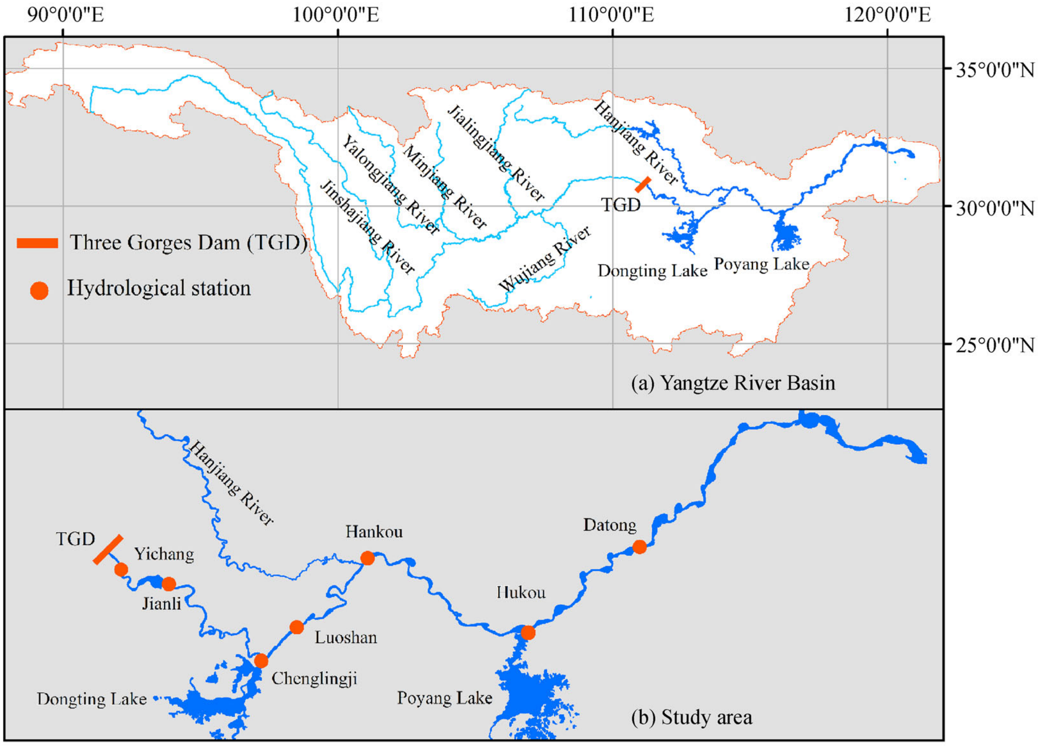

Fig. 1 (a) The geographical location of the Yangtze River Basin; (b) the location of the hydrological stations.

2016, referring to the CWRC (Ministry of Water Conservancy of China). The daily inflow discharge data of the TGD in 2006 and 2011 were obtained from China Three Gorges Corporation (http://www.ctg.hk/sxjt/sqqk/index.html). To study the water level variation patterns of the Yangtze River in 2006 and 2011, the hydrological data of 2006 and 2011 are compared with typical years, the extremely dry years of 1978 and 1986 (pre-TGD) (it is quite clear that the annual average discharge of these four extremely dry years at Datong were the lowest during the period from 1975–2012 (Fig. 2(b)), and the average annual precipitation in the Yangtze River Basin in 1978, 1986, and 2011 was also lowest during this period (Fig. 2(a))), the mean over the decade from 1955 to 2002 (pre-TGD), and the mean over the decade from 2003 to 2016 (post-TGD).

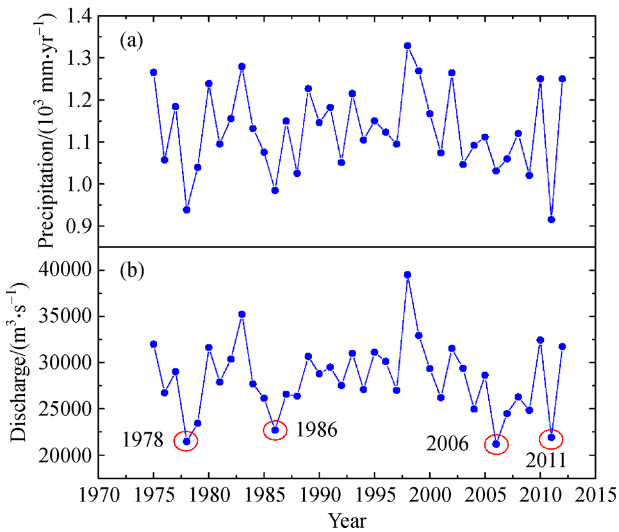

Fig. 2 Long-term variations in average annual precipitation in the Yangtze River Basin (a) (Dai et al., 2016a) and the annual average discharge at Datong station (b).

2.3 Method

Water level variations are affected by many factors, including climate variability, reservoir operation, backwater effect, irrigation and living water, human sand excavation and so on. It is obvious that it is almost impossible to calculate the contribution of each factor on water level variations. Thus, we only consider the impact of climate variability and TGD operation. Assuming that the annual average discharge and water level of the year N are Q_A and H_A, then the values of the year M ($M > N$) are Q_B and H_B after the effects of climate variability and human activity. We also assume that the influences of discharge changes and riverbed evolution changes on the water level are independent of each other, and thus the water level variation of the year M compared with the year N, namely ΔH , can be separated according to Fig. 3(a), and then the contributions of climate variability (R_N) and human activity (R_H) on water level changes can be calculated with Eqs. (1) and (2), respectively:

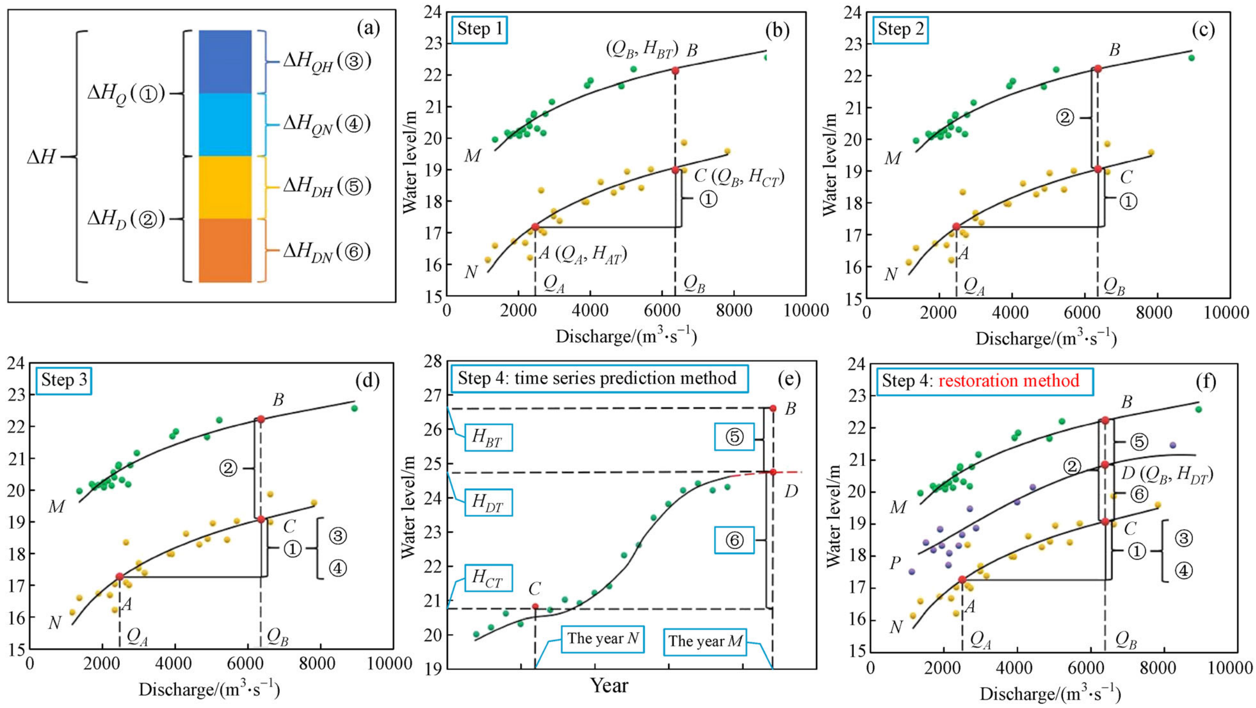

Fig. 3 Flow diagram of the calculation method. Note: *M*, *N*, and *P* are the fitting curves in the years *M*, *N*, and *P*, respectively.

$$R_N = \frac{|\Delta H_{DN}| + |\Delta H_{QN}|}{|\Delta H_{DN}| + |\Delta H_{DH}| + |\Delta H_{QH}| + |\Delta H_{QN}|}, \quad (1)$$

$$R_H = \frac{|\Delta H_{DH}| + |\Delta H_{QH}|}{|\Delta H_{DN}| + |\Delta H_{DH}| + |\Delta H_{QH}| + |\Delta H_{QN}|}, \quad (2)$$

where ΔH_Q denotes the water level changes caused by discharge variations, ΔH_D represents the water level changes induced by riverbed evolution, ΔH_{QH} is the water level variation caused by discharge changes resulting from human activity, ΔH_{QN} denotes the water level variation caused by discharge changes resulting from climate variability, ΔH_{DH} represents the water level variation caused by riverbed evolution resulting from human activity, and ΔH_{DN} is the water level variation caused by riverbed evolution resulting from climate variability.

However, it is difficult to separate ΔH_{DN}, ΔH_{DH}, ΔH_{QH}, and ΔH_{QN} from ΔH , which is the main reason why it is hard to quantify the individual impact of the human activity and climate variability on the water level variation. To solve this problem, a new calculation is proposed as follows:

Step 1 (Fig. 3(b)): calculation of water level variation (ΔH_Q, namely, ①) caused by discharge changes (ΔQ):

$$\Delta Q = Q_B - Q_A, \quad (3)$$

$$\Delta H_Q = H_{CT} - H_{AT}, \quad (4)$$

where H_{AT} and H_{CT} denote the water level under the condition of Q_A and Q_B, respectively (Fig. 2(b)), which can be calculated using the fitting curves of *N* years.

Step 2 (Fig. 3(c)): calculation of water level variation (ΔH_D, namely, ②) under the same discharge (Q_B). Note: the water level variation under the same discharge, namely, ΔH_D, is caused by the riverbed evolution. If the measured water level variation of year *M* compared with that of year *N*, namely, ΔH, is approximately equal to the theoretical water level variation **(**ΔH_T, Eqs. (6) and (7)**)**, then it suggests that the results of this calculation method show good agreement with the actual situation, following:

$$\Delta H_D = H_{BT} - H_{CT}, \quad (5)$$

$$\Delta H_T = \Delta H_Q + \Delta H_D, \quad (6)$$

$$\Delta H \approx \Delta H_T, \quad (7)$$

where H_{BT} denotes the water level under the condition of Q_B (Fig. 2(b)), which can be calculated with the fitting curves of *M* years.

Step 3 (Fig. 3(d)): the discharge variation ((ΔQ)) can be divided into two different aspects: ΔQ_H (induced by human activity, such as reservoir operation) and ΔQ_N (caused by climate variability). Therefore, the corresponding ΔH_Q can also be split into ΔH_{QH} (③) and ΔH_{QN} (④) based on Eqs. (8) and (9), respectively:

$$\Delta H_{QH} = \frac{\Delta Q_H}{\Delta Q} \cdot \Delta H_Q, \quad (8)$$

$$\Delta H_{QN} = \frac{\Delta Q_N}{\Delta Q} \cdot \Delta H_Q. \tag{9}$$

Step 4 (Figs. 3(e) and 3(f)): ΔH_D can also be separated into ΔH_{DH} (⑤) and ΔH_{DN} (⑥) by adopting the time series prediction method or the restoration method:

Time series prediction method (Fig. 3(e)): based on the varying tendency of a variable over time, an effective prediction method, such as the arithmetic average method, moving average method, or trend extrapolation method, will be selected to build a mathematical model to predict the developing trend of the variable (Simon et al., 2004). This method is widely applied to hydrological forecasts (Deng et al., 2015), but it is only applied to the variable that has an obvious change rule with time. The basic mathematical model is as follows:

$$H_{t+h} = f(H_{t-i}, H_{t-i+1}, ..., H_{t-1}, H_t) + h \cdot e_{t+h}, \tag{10}$$

where H_{t+h} denotes the predicted value of the prediction period of $t+h$; $f(H_{t-i}, H_{t-i+1}, ..., H_{t-1}, H_t)$ represents the estimated function; h is the prediction step; and e_{t+h} denotes the random noise.

The application of this method to this study: based on the fitting curves of water level and discharge during different years, the water levels under the same discharge (Q_B), namely, $(H_{t-i}, H_{t-i+1}, ..., H_{CT}, ..., H_{t-1}, H_t)$, are calculated. Then, according to the variation characteristics of the values over time, the suitable prediction method (in this study, the arithmetic average method and the calculation formula Eq. (11) is chosen to predict the water level (H_{DT}) under the condition of Q_B in the year P (assuming that the human activity did not happen during the year M, and thus here we describe this year as the year P). Therefore, ΔH_{DN} and ΔH_{DH} can be calculated by Eqs. (12) and (13):

$$H_{DT} = \frac{H_{t-i} + H_{t-i+1} + ... + H_t}{t+1}, \tag{11}$$

$$\Delta H_{DN} = H_{DT} - H_{CT}, \tag{12}$$

$$\Delta H_{DH} = \Delta H_D - \Delta H_{DN}. \tag{13}$$

Restoration method (Fig. 3(f)): if the values $(H_{t-i}, H_{t-i+1}, ..., H_{CT}, ..., H_{t-1}, H_t)$ do not have significant variation characteristics with time, we can choose the restoration method. Based on hydrological and topographic data, the discharge and water level in the year P can be restored by adopting a one-dimensional unsteady flow and sediment transport model, which allows us to draw the fitting curve of P. Thus, based on the fitting curves of M, N, and P, ΔH_D can be divided into ΔH_{DN} and ΔH_{DH}.

3 Results

3.1 Effects of the TGD operation on runoff and sediment

The operation rules of the TGD are flood peak reduction in the flood season (FPRF) and drought runoff implementation in the dry season (DRID) (Figs. 4(a) and 4(b)). In the flood season, the upstream flood peak is decreased to alleviate the pressure of downstream flood prevention, and the runoff is supplemented to dramatically relieve downstream drought conditions in the dry season (Han et al., 2017b; Yang et al., 2017b). Because of this, the maximum discharge shows a distinct downward trend, and the minimum discharge shows a significant increasing trend relative to the predam period (Fig. 4(c)). According to Fig. 4(d), it is clear that the sediment discharge at Yichang saw a significant decline after the opening of the TGD, which caused riverbed erosion downstream of the TGD (Han et al., 2017c). Because of this, the water level at the same discharge showed a significant decline, especially during the dry season (Zhu et al., 2017).

3.2 Water level variation characteristics

Flow regulations at the TGD implement flood peak reduction in the flood season and drought runoff implementation in dry season (DRID), which has a leveling effect on the water level in the MLRYR (Dai et al., 2016b; Kuang et al., 2017). As shown in Fig. 5, the C_v and R values from 2003 to 2016 (post-TGD) are significantly smaller than that of the period from 1955 to 2002 (pre-TGD), which may suggest that the discrete level of the water level in the downstream reservoir decreased due to the TGD operation. Before the TGD construction, the C_v and R in the extremely dry years of 1978 and 1986 are slightly smaller than that from 1955 to 2002 as a whole. Under the effects of both the TGD operation and extreme drought, C_v and R are smallest compared with those in typical years, implying that the water level variation in 2006 and 2011 was the smoothest. This obvious and special phenomenon can be described as “no low-water-level in dry season, no high-water-level in flood season” (NLD-NHF).

3.2.1 Water level during the dry season

In the dry season, the monthly average water levels in the MLRYR in 2006 and 2011 all showed a notable upward trend compared to the extreme drought years of 1978 and 1986 (the brown oval in Fig. 6). As shown in Table 1, it is noticeable that the average water level of the six hydrological stations in the dry season in 1978 and 1986 showed a remarkable decline in comparison to 1954–2002 (pre-TGD), with the maximum reduction being up to 1.4 m, while the values in 2006 and 2011 did not change substantially compared with 2003–2016 (post-TGD), and the variations were between −0.5 m and 0.4 m. In conclusion, the distinct and special phenomenon of “no low-water-level in dry season” (NLD) occurred in 2006 and 2011.

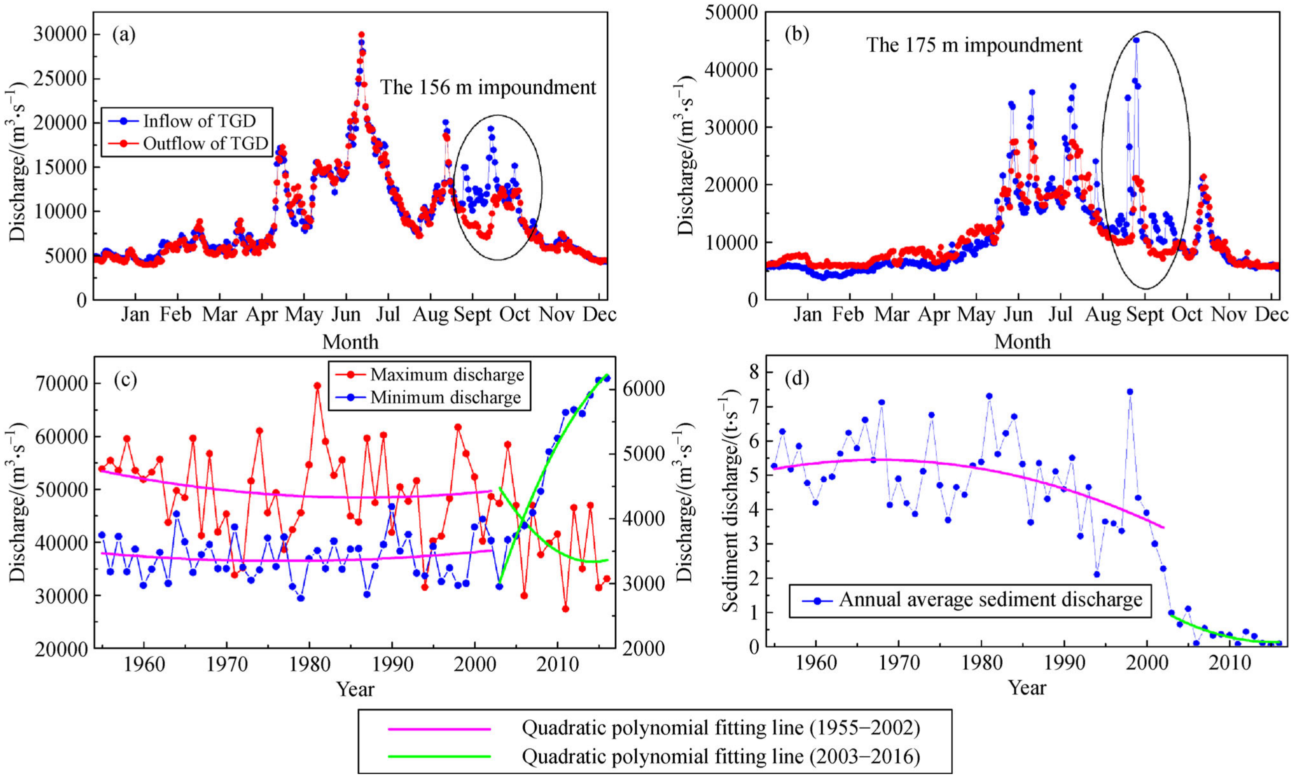

Fig. 4 Variations in discharge and sediment before and after the operation of the TGD. (a) and (b) The inflow and outflow of TGD in 2006 and 2011, respectively; (c) the maximum and minimum discharges at Yichang during the period from 1955–2016; (d) the sediment discharge at Yichang from 1955 to 2016.

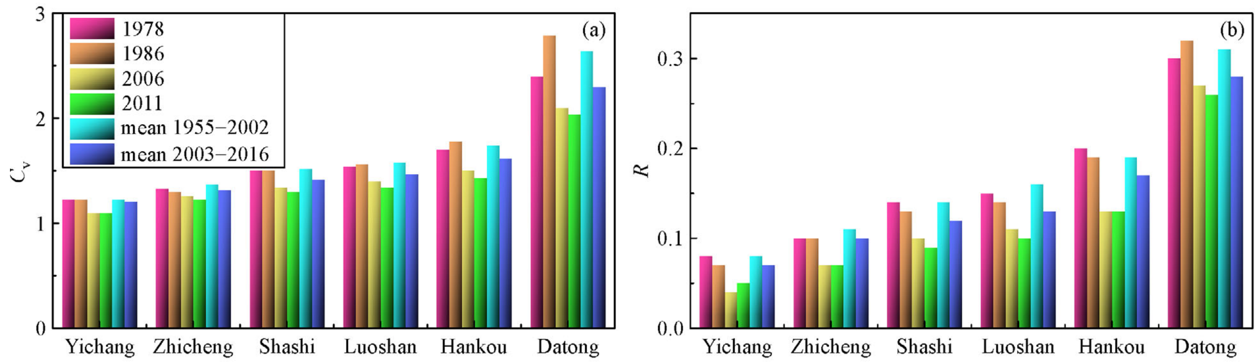

Fig. 5 Statistical parameters of C_v (a) and R (b) at each hydrological station. Note: C_v is the coefficient of variation of the monthly average water level; R is the ratio of the maximum monthly average water level to the minimum; the values of R and C_v stand for the degree of dispersion of the water level.

3.2.2 Water level during the flood season

In the flood season, compared with 1978 and 1986, the monthly average water level in the MLRYR in 2006 and 2011 showed a significant decrease (the pink oval in Fig. 6). Furthermore, the average water levels during the flood season at Yichang and Jianli in 2006 both dropped to the lowest point on record (1955–2016), and the four other stations in 2011 also dropped to the lowest on record (Table 1). It is noteworthy that the decreasing values of the average water level in 2006 and 2011 were between 1.8 m and 2.7 m, compared to 2003–2016. More importantly, the maximum reduction of the average water level in 2006 and 2011 was up to 3.6 m, in contrast to the extreme drought years of 1978 and 1986. Therefore, the phenomenon of "no high-water-level in flood season" (NHF) is an obvious variation in the water level characteristics in the MLRYR in 2006 and 2011.

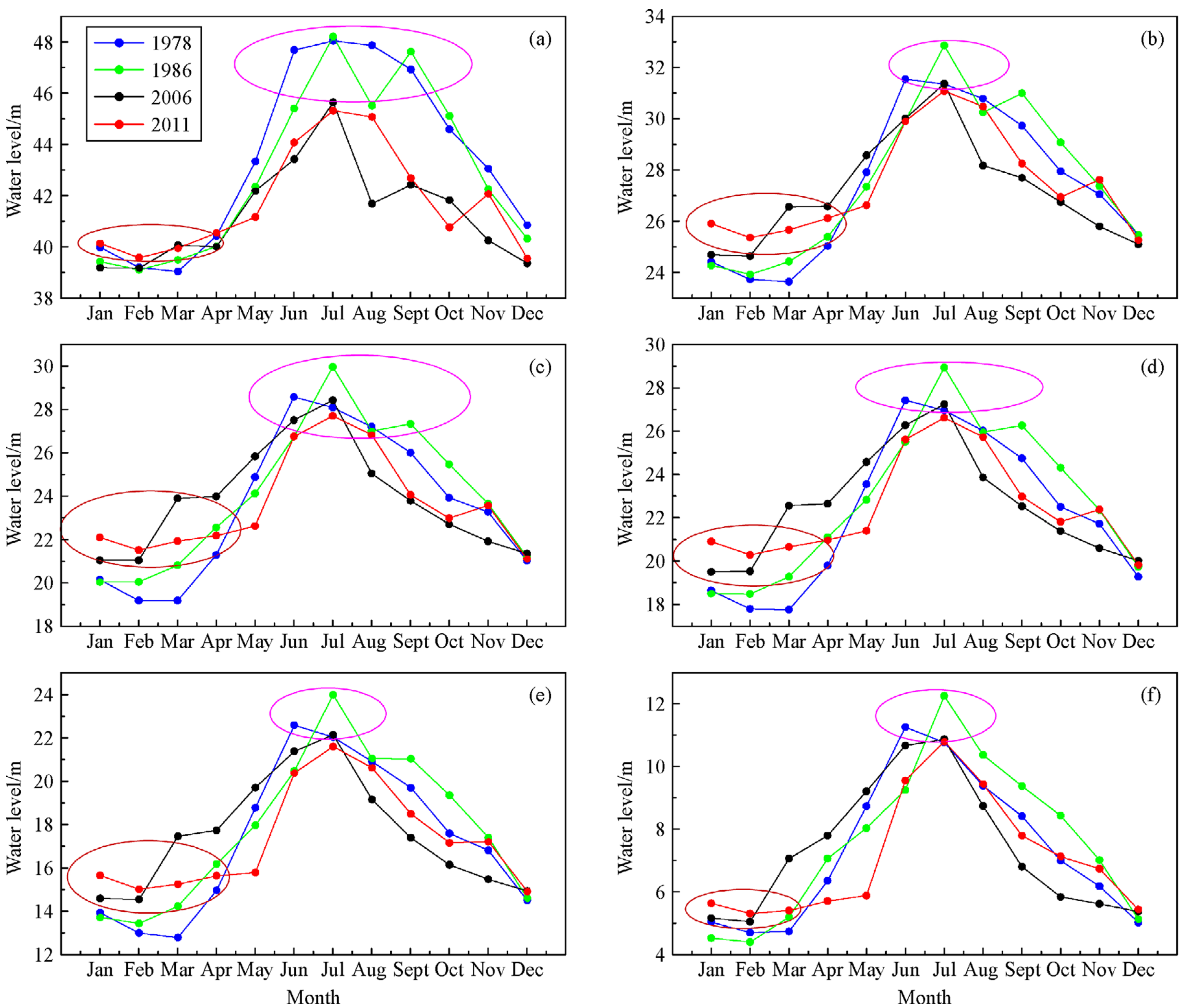

Fig. 6 The monthly average water level at six hydrological stations. (a) Yichang; (b) Jianli; (c) Chenglingji; (d) Luoshan; (e) Hankou; and (f) Datong.

Table 1 Average water level (m) during the dry and flood seasons

City	1978		1986		1955–2002		2006		2011		2003–2016	
	Flood season	Dry season	Flood season	Dry season	Flood season	Dry season	Flood season	Dry season	Flood season	Dry season	Flood season	Dry season
Yichang	46.40	40.30	45.70	40.00	46.70	40.70	42.80	40.00	43.10	40.30	44.90	39.90
Jianli	29.89	24.90	30.10	25.10	31.10	25.80	28.76	25.60	28.80	26.00	30.70	25.80
Chenglingji	26.45	20.68	26.80	21.30	27.90	21.50	25.54	22.21	25.10	22.10	27.70	22.30
Luoshan	25.22	19.18	25.70	19.90	26.90	20.20	24.32	20.83	24.00	20.90	26.70	21.00
Hankou	20.30	14.30	20.70	14.90	22.20	15.70	19.30	15.90	19.00	15.60	21.50	15.90
Datong	9.30	5.20	9.60	5.50	11.10	6.20	8.60	6.10	8.40	5.70	10.40	6.20

4 Discussion

Datong is situated at the mouth of the Yangtze River, which means that its annual runoff represents the total water resources of the Yangtze River Basin. Interestingly, although the annual runoff values at Datong in the extreme drought years of 1978, 1986, 2006, and 2011 were almost the same (6.76×10^{11} m^3, 7.14×10^{11} m^3, 6.67×10^{11} m^3, 6.88×10^{11} m^3, respectively), the distinct and peculiar phenomenon of “NLD-NHF” in the MLRYR occurred in 2006 and 2011, under the effects of the TGD operation and extreme drought, instead of taking place in 1978 and 1986.

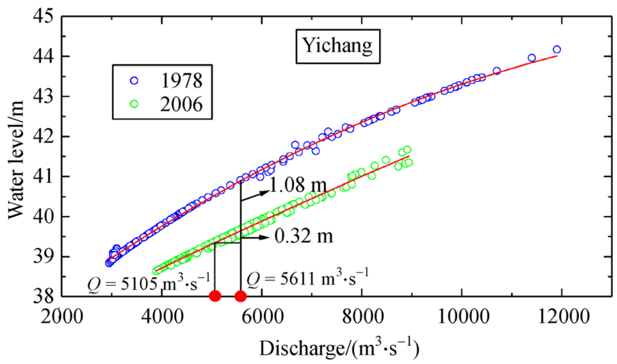

Fig. 7 The fitting curve of water level and discharge at Yichang in the 1978 and 2006 dry season.

The water level at Yichang is more seriously affected by the TGD operation than the other five stations, because Yichang is the control station of the TGD outflow and has the smallest distance to the TGD. In contrast, the water level at Datong is most seriously affected by climate variability because Datong is the control station of the mouth of the Yangtze River and is the farthest from the TGD. In addition, the annual runoff at Datong in 2006 and 2011 are the most similar to the value in 1978. Thus, based on the proposed calculation method, the water level and discharge data in 1978, 2006, and 2011 at Yichang and Datong were chosen to analyze the main reasons for the phenomenon, which are highly typical and representative.

4.1 Factors of NLD

In the 2006 dry season, the average inflow discharge was up to 5870 $m^3 \cdot s^{-1}$, and the outflow discharge (Yichang, 5611 $m^3 \cdot s^{-1}$) showed no obvious variation because of the weak influence of DRID (in Fig. 4(a), the daily inflow and outflow discharges in the 2006 dry season are approximately the same), which is approximately 506 $m^3 \cdot s^{-1}$ larger than the value in 1978 (Fig. 9). Based on the calculation method, the rising average water level induced by the increasing average discharge at Yichang was 0.32 m (Fig. 7). As shown in Fig. 8, it is quite clear that the reach between Yichang and Zhicheng was under scouring conditions (Fig. 8(b)), and the thalweg elevation in the reach shows a significant decreasing trend after the opening of the TGD (Fig. 8(c)). Based on the statistics, the average elevations of the thalweg in this reach decreased by 2.3 m and 2.05 m during the periods of 2002–2008 and 2008–2013, respectively. Because of this, the water level at Yichang under the same discharge also shows a downward trend (Fig. 8(a)). Compared with the level in 1978, the reduction in the average water level at Yichang in 2006 caused by riverbed erosion was up to

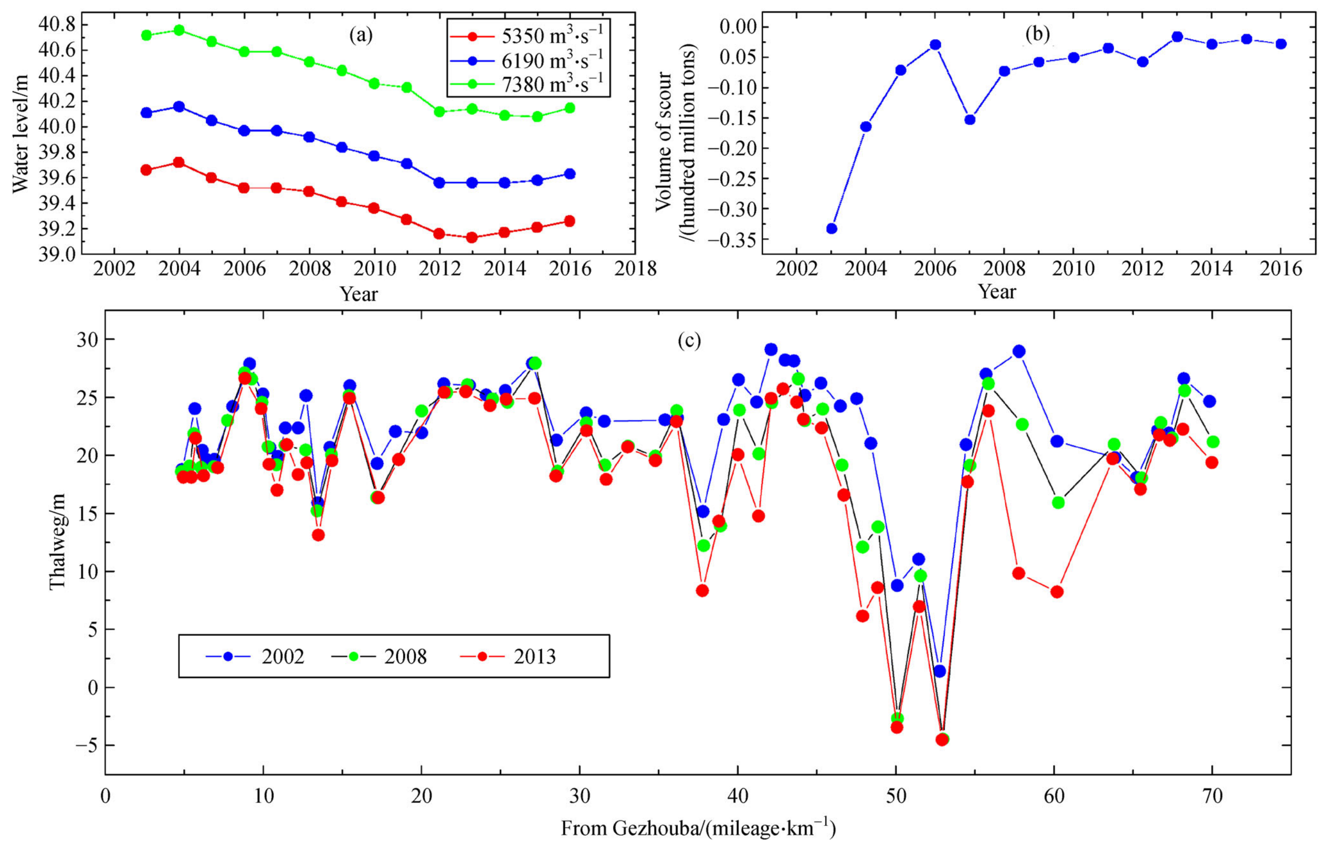

Fig. 8 (a) The time-series graph of the water level at Yichang under the same discharge; (b) the volume of scour after the TGD operation (Yichang-Zhicheng); and (c) downstream thalweg elevation before and after the construction of the TGD (Yichang-Zhicheng).

1.08 m (Fig. 7 and Fig. 10(a)). Thus, under the effects of both discharge variation and riverbed evolution, the theoretical average water level reduction (ΔH_T) in 2006 was 0.76 m compared to 1978, which is the same as the measured average water level variation (ΔH). In addition, the same conclusion that the theoretical water level variation was approximately equivalent to the measured water level changes can also be drawn based on the data in Table 2, which satisfies Eq. (7). This shows that the results of the calculation method were in accordance with actual facts. In conclusion, the decreasing average water level caused by riverbed erosion was partly offset by the rising average water level caused by the rising average inflow discharge, which resulted in the phenomenon of "NLD" at Yichang in 2006, and the effects of DRID were small. As shown in Fig. 9, the confluence of tributaries and lakes between Yichang and Datong in 2006 was increased by 2741 $m^3 \cdot s^{-1}$ compared to 1978, which further led to a significant increase in the average discharge at Datong during the dry season. Thus, the rising average water level at Datong caused by the increasing average discharge was up to 0.81 m, while the decline of average water level induced by riverbed erosion was only 0.14 m (Fig. 10(a)). Therefore, the decline of water level induced by riverbed erosion was totally offset by the increasing average water level induced by the abundant inflow of the TGD and the

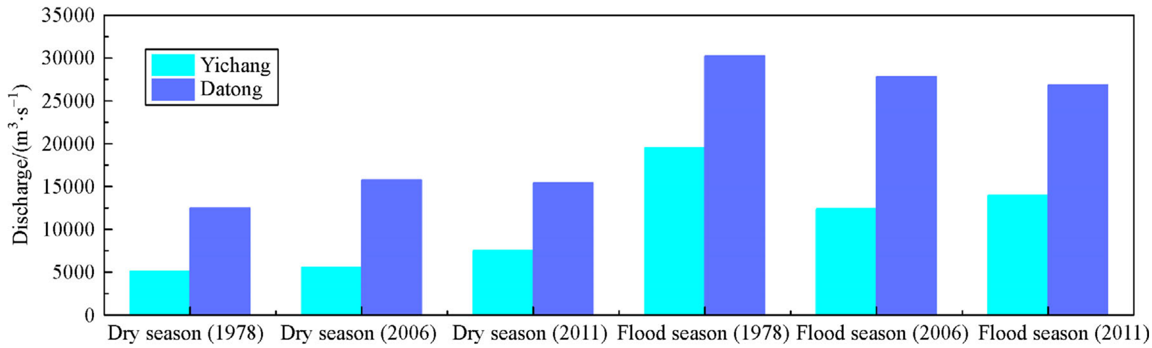

Fig. 9 The average discharge during the dry and flood seasons.

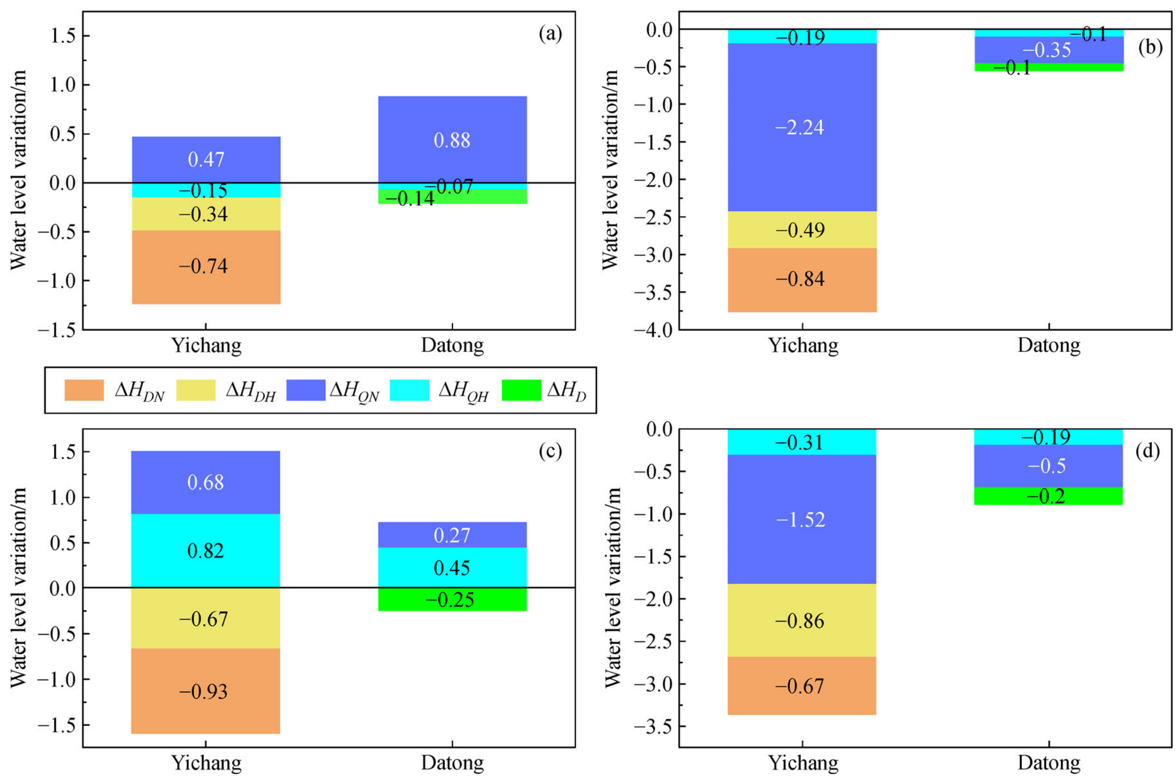

Fig. 10 The values of the average water level changes in 2006 and 2011 caused by each factor compared with 1978. Dry season (a) and flood season (b) in 2006; dry season (c) and flood season (d) in 2011.

rich implement of tributaries and lakes, and thus the average water level at Datong in 2006 shows an obvious increase compared with that in 1978, which corresponds to the phenomenon of "NLD".

In the 2011 dry season, the average inflow discharge of the TGD was also up to 6397 $m^3 \cdot s^{-1}$, combined with the significant effects of DRID (see Fig. 4(b), wherein the daily outflow discharge was obviously larger than the daily inflow discharge in the 2011 dry season), and thus the average outflow discharge (Yichang) further increased to 7475 $m^3 \cdot s^{-1}$, with approximately 2370 $m^3 \cdot s^{-1}$ more than the value in 1978 (Fig. 9). Therefore, the increasing average water level at Yichang caused by the rising average discharge was up to 1.5 m, and the falling average water level induced by riverbed erosion was 1.6 m, compared to 1978 (Fig. 10(c)). Thus, under the combined effects of discharge variations and riverbed evolution, the theoretical average water level reduction (ΔH_T) in 2011 was only 0.1 m (the measured average water level variation was 0 m). In conclusion, the reduction in the average water level caused by riverbed erosion was offset by the increasing average water level induced by the rising average inflow discharge and DRID, which caused the phenomenon of "NLD" at Yichang in 2011. Based on Fig. 9, the confluence of tributaries and lakes in 2011 was increased by 519 $m^3 \cdot s^{-1}$ compared to 1978, which further led to an increase of the average discharge at Datong. Thus, the increasing average water level caused by the rising average discharge was up to 0.72 m, while the decreasing average water level induced by riverbed erosion was only 0.25 m. Therefore, the phenomenon of "NLD" occurred at Datong in 2011.

4.2 Factors of NHF

In the flood season, the average inflow discharge was only 12,945 $m^3 \cdot s^{-1}$ and 14,916 $m^3 \cdot s^{-1}$ in 2006 and 2011, respectively, and the average outflow discharge (Yichang) further decreased to 12,387 $m^3 \cdot s^{-1}$ and 13,991 $m^3 \cdot s^{-1}$, respectively, due to the influence of FPRF, and thus the decreasing values were up to 7123 $m^3 \cdot s^{-1}$ and 5519 $m^3 \cdot s^{-1}$, respectively, compared to 1978 (Fig. 9). Therefore, the reductions in the average water level caused by the decline of the average discharge were up to 2.43 m and 1.83 m at Yichang in 2006 and 2011, respectively. Furthermore, the declines in the average water level induced by riverbed erosion were also up to 1.33 m and 1.53 m, respectively (Figs. 10(b) and 10(d)). In conclusion, the obvious decreases in average inflow discharge, FPRF and riverbed erosion caused the phenomenon of "NHF" at Yichang in 2006 and 2011.

Although the quantity of tributaries and lakes in 2006 and 2011 increased by 4669 $m^3 \cdot s^{-1}$ and 2108 $m^3 \cdot s^{-1}$, respectively, in contrast to 1978 (Fig. 9), the reductions in the average discharge at Yichang were so large that the average discharge at Datong also showed a significant decline. As a result, the decreases in the average water level induced by the decreases in average discharge were up to 1.18 m and 0.69 m at Datong in 2006 and 2011, respectively. In addition, the reductions in the average water levels caused by riverbed erosion were 0.08 m and 0.2 m (Figs. 10(b) and 10(d)). In conclusion, the obvious declines in the average discharge at Yichang and riverbed erosion were the reasons for the phenomenon of "NHF" at Datong in 2006 and 2011.

4.3 Estimating the contributions of the TGD operation and climate variability

Based on these calculations, the average water level changes during the dry season in 2006 caused by the increase of average inflow discharge and DRID were 0.47 m (ΔH_{QN}) and −0.15 m (ΔH_{QH}), respectively (as shown in Fig. 10(a)). Combined with the fitting curves of water level and discharge during the 1978 and 2006 dry seasons, the average water level under the same discharge at Yichang decreased by 1.08 m (ΔH_D) compared with that in 1978. To separate ΔH_{DN} and ΔH_{DH} from ΔH_D, the time series prediction method was selected in step 4 of the calculation method. Thus, the average water level under the same discharge (Fig. 11(a)) was calculated based on the fitting curves of each year during the period from 1976–2002 (pre-TGD), which had a significant decline from 1976 to 1986 while remaining almost the same from 1987 to 2002. This result is consistent with the existing research: from 1976 to 1986, the water level during the dry season decreased significantly under the same discharge (Yang et al., 2009), while the counterpart between 1987 and 2002

Table 2 Contributions of climate variability and TGD operation on water level changes

Item	2006				2011			
	Dry season		Flood season		Dry season		Flood season	
	Yichang	Datong	Yichang	Datong	Yichang	Datong	Yichang	Datong
ΔH_T	−0.76	0.67	−3.76	−0.55	−0.10	0.47	−3.33	−0.89
ΔH	−0.76	0.68	−3.54	−0.56	0.00	0.50	−3.30	−0.90
R_N	71%	93%	82%	78%	56%	62.5%	66%	72%
R_H	29%	7%	18%	22%	44%	37.5%	34%	28%

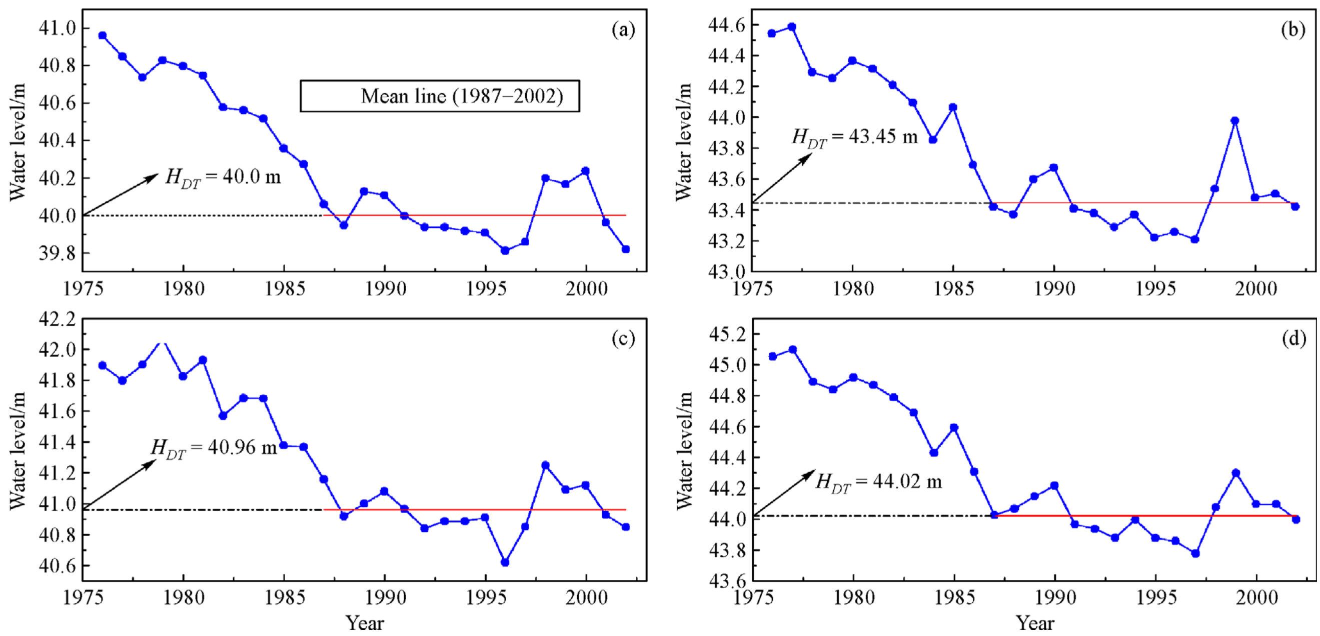

Fig. 11 The average water level under the same discharge at Yichang during the period from 1976–2002. (a) The average discharge during the dry season in 2006 (5617 $m^3 \cdot s^{-1}$) is regarded as the same discharge; (b) the average discharge during the flood season in 2006 (12,388 $m^3 \cdot s^{-1}$) is regarded as the same discharge; (c) the average discharge during the dry season in 2011 (7475 $m^3 \cdot s^{-1}$) is regarded as the same discharge; and (d) the average discharge during the flood season in 2011 (13,991 $m^3 \cdot s^{-1}$) is regarded as the same discharge.

was basically unchanged due to the stable riverbed in the Yichang reach (Xu, 2013; Dai et al., 2005). Therefore, based on the water level variation characteristics under the same discharge in the dry season from 1987–2002, the arithmetic average method (one of the time series prediction methods) was chosen to predict the water level H_{DT} under the condition of non-TGD in the 2006 dry season (Eq. (11), Fig. 11(a)), and thus, ΔH_{DN} and ΔH_{DH} were −0.74 m and −0.34 m, respectively based on Eqs. (12) and (13) (Fig. 10(a)). Based on the calculated values of ΔH_{QN}, ΔH_{QH}, ΔH_{DN}, and ΔH_{DH}, the contributions of climate variability (R_N) and DRID (R_H) on the average water level variation at Yichang in the 2006 dry season were 71% and 29%, respectively (Table 2). Similarly, the contributions of climate variability and DRID were 56% and 44% at Yichang in the 2011 dry season, respectively. At Datong, the reductions in the average water level caused by riverbed erosion were only 0.14 m and 0.25 m during the 2006 and 2011 dry seasons, respectively, which can be ignored. Therefore, the contributions of climate variability and DRID were 93% and 7%, respectively, at Datong in 2006, and the values in 2011 were 62.5% and 37.5%, respectively. Clearly, climate variability was the main reason for the water level variation (namely, the phenomenon of “NLD”) in the MLRYR in dry season in 2006 and 2011 compared to 1978, instead of DRID induced by the TGD operation.

In the flood season, the average water level under the same discharge also did not change significantly at Yichang during the period from 1987–2002 because of the stable riverbed in the Yichang reach (Figs. 11(b) and 11(d)). Thus, the arithmetic average method was also selected, and finally the contributions of climate variability and FPRF at Yichang in the 2006 flood season were 82% and 18%, and the figures in 2011 were 66% and 34%. At Datong, the average water level changes caused by riverbed erosion were only 0.1 m and 0.2 m in 2006 and 2011, respectively, and thus the effects of riverbed erosion can also be neglected. Therefore, the contributions of climate variability and FPRF at Datong in the 2006 flood season were 78% and 22%, respectively, and the values in 2011 were 72% and 28%. In conclusion, climate variability was still the dominant reason for water level changes (namely, the phenomenon of “NHF”) in the MLRYR in the 2006 and 2011 flood seasons, in contrast to 1978, instead of FPRF caused by the TGD operation. More importantly, many researchers have predicted that the precipitation during the dry season will increase in the Yangtze River Basin and precipitation during the flood season will decrease (Sun et al., 2013; Zeng et al., 2013; Gu et al., 2015). Obviously, the special phenomenon of “NLD-NHF” may become more and more frequent in the future. Therefore, the calculated contributions will be practically significant to optimize reservoir operation rules and water resource management.

5 Conclusions

Under the impacts of both extreme drought and the TGD operation, the water level variation characteristics in the MLRYR in 2006 and 2011 were significantly changed in contrast with the extreme drought years of 1978 and 1986, even if the total water resources of the Yangtze River Basin in these four years were almost the same. Based on the daily discharge data and water levels from 1955–2016, the characteristics of water level changes in 2006 and 2011 can be described as follows:

1) In the dry season, the average water level in the MLRYR in 2006 and 2011 did not change significantly compared with 2003–2016, but it had an obvious increase relative to 1978 and 1986. Here, we call this phenomenon "no low-water-level in dry season". In the flood season, the average water level at Yichang and Jianli in 2006 and at Chenglingji, Luoshan, Hankou, and Datong in 2011 all dropped to the lowest in recorded history (1955–2016). This condition can be described as "no high-water-level in flood season".

2) During the dry season, the reduction of the average water level caused by riverbed erosion in the MLRYR in 2006 and 2011 was offset by the rising average water level from the higher inflow of the TGD and the higher confluence of tributaries and lakes caused by climate variability, which led to the phenomenon of "no low-water-level in dry season".

3) In the flood season, the significant decline of the average water level induced by the scarce inflow of TGD and FPRF in the MLRYR in 2006 and 2011, combined with riverbed erosion, all led to the occurrence of "no high-water-level in flood season".

4) Based on the proposed new method, the contributions of climate variability and TGD operation on the water level changes in the MLRYR in 2006 and 2011 were calculated relative to 1978. The conclusion is that climate variability was the main reason for the water level variation in the MLRYR (namely, "no low-water-level in dry season, no high-water-level in flood season"), instead of DRID and FPRF, which are both induced by TGD.

Acknowledgements This research was supported by the National Science and Technology Support Program of China (2012BAB04B04), the National Basic Research Program of China (No. 2010CB429002), Open Research Fund Program of State Key Laboratory of Water Resources and Hydropower Engineering Science (2016HLG02), and National Key Research and Development Program of China (2016YFC0402106). We also highly appreciate the valuable insights from the reviewers.

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