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Key Points:

- Yangtze River system had been greatly impacted by TGD operation
- Hydrological behaviors had time and spatial shifts pre- and post-TGD filling
- The tributary and adjoining riparian lakes diminish the dam effects

Correspondence to:

Z. Dai,
zjdai@sklec.ecnu.edu.cn

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Linking Three Gorges Dam and downstream hydrological regimes along the Yangtze River, China

Xuefei Mei¹, Zhijun Dai¹, P. H. A. J. M. van Gelder², and Jinjuan Gao¹

¹State Key Laboratory of Estuarine and Coastal Research, East China Normal University, Shanghai, China, ²Faculty of Technology, Policy and Management, Delft University of Technology, Delft, Netherlands

Abstract The magnitude of anthropogenic influence, especially dam regulation, on hydrological system is of scientific and practical value for large river management. As the largest dam in the world by far, Three Gorges Dam (TGD) is expected to be a strong evidence on dam impacts on downstream hydrological regime. In this study, statistical methods are performed on the pre- and post-TGD daily hydrological data at Yichang, Hankou, and Datong stations to detect the daily, monthly, yearly, and spatial fluctuations in river hydrology along the Yangtze River during the period of 2000–2013. It is found that TGD makes a significant hydrological variation along the Yangtze River following the dam operation since 2003. Specifically, the daily discharge and water level are gathered to normal event ranges with less extreme events than before 2003. Both maximum and minimum daily water levels at the study stations have decreased due to TGD-induced riverbed incision. The operation of TGD shifts the maximum monthly discharge and water level from August to July at Yichang station. The significance of TGD effect on discharge and water level relationship presents spatial variation. The rating curves at upstream reach experience the most significant effects with a substantial upward shift, while those at lower reach only suggest slight modification. Of the potential drivers considered in this study, dam regulation is responsible for the changes in downstream river hydrology. Moreover, the tributary and adjoining riparian lakes of the Yangtze River contribute to weaken the effect of TGD on downstream hydrological behavior.

1. Introduction

The Earth system is experiencing significant changes with response to anthropogenic activities. As the main component of Earth system, rivers around the world are subjected to the regulation of 45,000 large dams since the 1930s [World Commission on Dams, 2000]. The research of dam-induced hydrological variation is of vital importance to study the influence of human activities on the Earth system [Postel *et al.*, 1996; Chao, 1995]. Common effects of dam on downstream area include the following: change in net water balance [Vörösmarty *et al.*, 1997], regulation of flow regime [McClelland *et al.*, 2004; Batalla *et al.*, 2004], modification of water level [Wang *et al.*, 2013; Lu and Siew, 2006], disruption of downstream sediment transport [Willis and Griggs, 2003; Topping *et al.*, 2000; Walling and Fang, 2003], change of channel morphology [Brandt, 2000; Batalla, 2003; Bondar and Blendea, 2000; Xu, 1996], and alteration of ecology [Koel and Sparks, 2002; Power *et al.*, 1996]. While the impacts of dam on river hydrology have received special attentions, relatively little knowledge is available on the detailed impacts associated with large dams in large rivers on the basis of daily information. Moreover, most previous studies focused on the influence of dam on the reach directly below the dam, without considering the basin-wide influences of dam within a river network.

Yangtze River, the longest river in Asia, was controlled by Three Gorges Dam (TGD, currently the world's largest dam) since 2003. More than 10 years of operation experience can provide enough actual information on the effects of TGD on downstream area. Although many studies have been undertaken since the operation of TGD [Dai *et al.*, 2008; Xu *et al.*, 2006b; Zhang *et al.*, 2008a; Dai *et al.*, 2010], few systematic analysis of river flow and water level has been made on multiple gauging stations along the Yangtze River. The related knowledge is of great significance for scientific research as well as water resources management. Moreover, there is a considerable need to update yearly knowledge on the downstream hydrology with response to TGD regulation.

This paper therefore systematically assesses the effects of TGD on the Yangtze River based on the latest daily discharge and water level records from 2000 to 2013. Specifically, differences in mean hydrological variables

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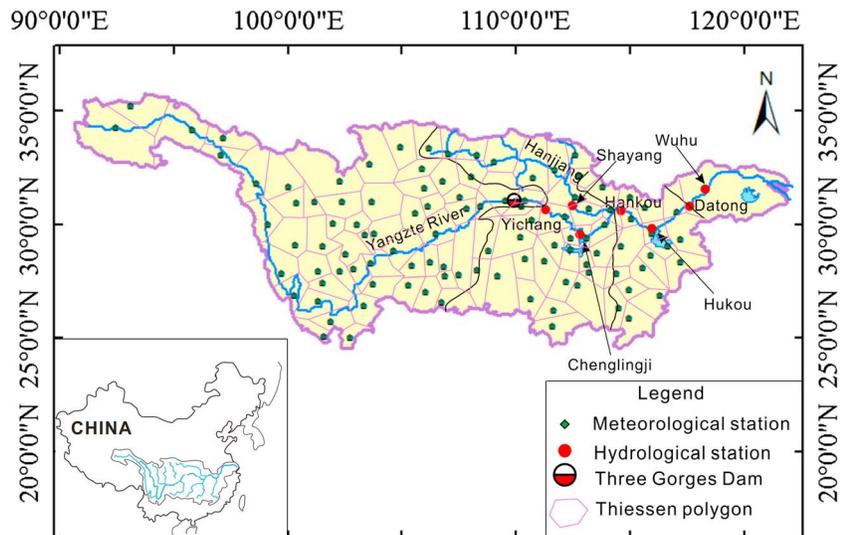


Figure 1. Map of the Yangtze River drainage basin with Thiessen polygons.

before and after reservoir filling are calculated on daily, monthly, and yearly basis for the upper, middle, and lower sections of the catchment. Meanwhile, extreme values are extracted to evaluate the influence of TGD on flood and drought events. Then rating curves are established to examine changes in the relationship between river discharge and water level. After that, the possible factors that may drive river hydrological variations are discussed.

2. Study Area

As the third longest river in the world, the Yangtze River, extending from the Tibetan Plateau to eastern China, spans a total length of 6300 km and drains an area of 1,800,000 km² [Chen *et al.*, 2001]. Its annual flow stands at 951.3 km³. By convention, the Yangtze River basin is divided into three subbasins: the upper Yangtze River basin (from the source to Yichang), the middle Yangtze River basin (from Yichang to Hankou), and the lower Yangtze River basin (from Hankou to Datong) [Xu *et al.*, 2006a]. Datong is about 640 km away from the estuary. The reach between Datong and river mouth is defined as estuary reach because Datong is the upstream limit of tide influence [Dai *et al.*, 2011].

The upper Yangtze River extends 4504 km in length, drains 55% of total area, and contributes about 50% of the total discharge to the estuary. The middle watershed extends 955 km, accounts for 38% of total drainage area, and provides 30% of annual runoff. The lower catchment extends 338 km, covers 7% of total drainage area, and generates 20% of basin total discharge [Chen *et al.*, 2001; Zhang *et al.*, 2008b]. The hydrometric stations Yichang, Hankou, and Datong record the river runoff and water level of the upper, middle, and lower basin, respectively.

TGD, currently the world's largest dam, is 185 m high with a total volume storage of 39.3×10^9 m³ [Nilsson *et al.*, 2005; Yang *et al.*, 2007]. Located at the outlet of the upper Yangtze River, TGD was put into practice in 2003 and serves multipurpose, including flood control, navigation, and power generation [Hu *et al.*, 2009]. The location of the Yangtze River basin, TGD, hydrological stations, and meteorological stations with their associated Thiessen polygons are presented in Figure 1. Main characteristics of Yichang, Hankou, and Datong station are shown in Table 1.

The Yangtze River basin is affected by two independent types of climate: the Indian summer monsoon in the upper river and the East Asian summer monsoon in the middle-lower reach [Ding and Chan, 2005; Chen *et al.*, 2014]. The monsoon rainfall hits the southeast Yangtze coast in April and moves to the middle Yangtze in May and June and then to the upper Yangtze [Chen *et al.*, 2010]. The precipitation presents downward trend when it migrates from the lower Yangtze River to the upper region. The annual areal precipitation ranges from 859 mm in the upper reach to 1528 mm in the lower reach [Chen *et al.*, 2014].

Table 1. Main Characteristics of Yichang, Hankou, and Datong Stations

Station	Distance From the TGD	Annual Sediment (10 ⁸ t)	Annual Discharge (10 ⁸ m ³)
Yichang	37	5.01 (1950–2000)	4382 (1950–2000)
Hankou	688	4.04 (1954–2000)	7112 (1954–2000)
Datong	1177	4.33 (1950–2000)	9051 (1950–2000)

3. Data and Methods

3.1. Data Set

Daily discharge and water level record for Yichang, Hankou, and Datong stations along the Yangtze River are collected from the Changjiang Water Resources Commission, China (Figure 2) (available in www.cjh.com.cn). The time periods of the data cover 14 years, from 2000 to 2013. The observed daily precipitations over the same period for 106 meteorological stations are obtained from the National Climatic Centre of the Chinese Meteorological Administration (available in www.cdc.cma.gov.cn). The data qualities have been validated by the related institutes before being uploaded.

3.2. Methods

Since 14 years of information are too short to do hydrological forecasting, this study focuses on the systematic comparison of river flow and water level between predam and postdam periods. The statistical characters of the river hydrology are mainly analyzed with nonparametric Mann-Kendall (MK) test, grouped frequency statistics, and discharge-water level rating curves. The areal precipitations are obtained by Thiessen polygon method.

3.3. Trend Test

Many statistical tests can be employed to assess whether a time series displays significant increase or decrease that might indicate heterogeneity. Among them, the nonparametric Mann-Kendall (MK) test is the most popular one [Kendall, 1975; Yue et al., 2002].

The MK test is on the basis of the test statistic *S* defined as follows:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sgn}(x_j - x_i) \tag{1}$$

where *x_i* is the sequential data values and *n* is the length of the data set.

$$\text{sgn}(q) = \begin{cases} +1 & q > 0 \\ 0 & 0 \\ -1 & q < 0 \end{cases} \tag{2}$$

Mann [1945] documented that when *n* ≥ 8, the statistic *S* is an approximately normal distribution with the mean and variance as follows:

$$E(S) = 0; \tag{3}$$

$$\text{Var}(S) = \left[n(n-1)(2n+5) - \sum_{i=1}^n t_i(t_i-1)(2t_i+5) \right] / 18$$

where *t_i* is the number of records in the *i*th tied group.

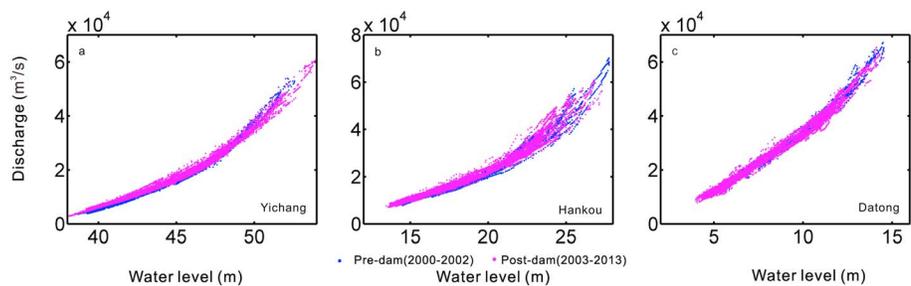


Figure 2. Annual water level versus discharge over 2000–2013.

The standardized test statistic Z is calculated by

$$Z_{MK} = \begin{cases} (S - 1)/\sqrt{\text{Var}(S)} & S > 0 \\ 0 & S = 0 \\ (S + 1)/\sqrt{\text{Var}(S)} & S < 0 \end{cases} \quad (4)$$

The null hypothesis, that there is no trend, is accepted at significant level of 0.05 if the standardized statistic Z is less than 1.96. A positive Z indicates an increase trend, while a negative one states a decrease trend.

3.4. Grouped Frequency Distribution

Grouped frequency distribution is suggested when a large number of continuous variables are needed to be analyzed, which groups the values into intervals according to their amplitude and assigns each interval a frequency. The grouped frequency can be expressed by two types of form: relative frequency and relative cumulative frequency.

The relative frequency is defined as follow:

$$PF = n_i/n \quad (5)$$

where n_i is the number of records that occurs in a certain class and n is the total number of data.

The relative cumulative frequency is set as quotient between the sum of all the classes that is smaller or equal to the one under consideration and the total number of observations.

3.5. Rating Curves

An exponential curve can be obtained by plotting the daily discharge against the daily water level for a study station. The power-type equation is used in the present paper to simulate the relationship between discharge and water level along the Yangtze River [Pappenberger *et al.*, 2006; Kim *et al.*, 2014].

$$Q = a(h - h_0)^b \quad (6)$$

where Q is the stream discharge, m^3/s ; H is the water level, m ; h_0 is the water level corresponding to zero discharge, m ; and a and b are parameters that represent geometrical characteristics of the cross section.

The datum correction h_0 is a nominal value and not physically ascertainable.

In order to calculate parameters a and b , logarithmic form of the power-type equation is derived as

$$\log(Q) = \log(a) + b \log(h - h_0) \quad (7)$$

Thus, the discharge and water level series flow a liner relationship on the double log scale. The coefficients a and b are estimated by the least squares method in this study.

3.6. Thiessen Polygon Method

As a classical weighted mean method, Thiessen polygon method transfers the observed point precipitation into areal average precipitation by the following functions [Fielder, 2003]:

$$P = \sum_{i=1}^n w_i P_i \quad (8)$$

$$w_i = A_i/A \quad (9)$$

where P is areal average precipitation, mm ; P_i is point precipitation, mm ; w_i is Thiessen weight; A_i is area represented by the station, m^2 ; A is total watershed area, m^2 ; and N is the total number of precipitation stations over the basin.

4. Result

4.1. Grouped Frequency Distribution of Daily Discharge and Water Level

To understand the preliminary characteristics of the hydrological patterns in the Yangtze River catchment, statistical parameters, including the mean value, standard deviation (SD), and variation coefficient (Cv), for the predam and postdam daily data series at the gauging stations are obtained by the moment method,

Table 2. Hydrological Variables for the Three Stations Over the Period of 2000–2013^a

Station	Indicator	Predam (2000–2002)			Postdam (2003–2013)		
		Mean	SD	Cv	Mean	SD	Cv
Yichang	Discharge	13,500	9,920	0.73	12,400	8,770	0.69
	Water level	43.16	3.48	0.08	42.38	3.29	0.07
Hankou	Discharge	22,800	12,230	0.53	21,000	10,750	0.50
	Water level	19.43	3.44	0.18	18.68	3.16	0.17
Datong	Discharge	28,900	13,130	0.45	26,400	11,110	0.43
	Water level	8.71	2.58	0.30	8.16	2.34	0.29

^aMean: mean value of the indicator; SD: standard deviation; and Cv: coefficient of variation.

shown in Table 2. Comparing with that of predam period, all the statistical parameters of postdam discharge suggest decreases over the Yangtze River. The changes of water level coincide with those of discharge.

Grouped frequency analysis is further applied to the daily discharge and water level to discern the occurrence possibilities of discharge and water level for various intervals, as show in Figure 3. The contribution of each month to each hydrological interval is illustrated in the figure as well. Here the class interval for water discharge and water level is set as 5000 m³/s and 1 m, respectively. At Yichang station, the discharge mainly occurs in the range of 5000–10000 m³/s (be composed of January–May and October–December), which accounts for 34% in the predam period. The regulation of TGD makes the distribution of discharge more centralized. The range of 5000–10,000 m³/s (be composed of January–May and August–December) is still the largest component in the postdam period, and its percentage increases to 43% (Figures 3a and 3d). The same situation occurs in the water level series. The proportion of dominant water level (39–40 m) increases from 26% (be composed of January–April and December) to 31% (be composed of January–May and November–December) as a result of dam regulation (Figures 3g and 3j). On the other hand, the occurrence probabilities of great events present decline trends. For example, the proportions of extreme discharge (>50,000 m³/s) and water level (>50) fall from 1.3% to 0.4% and from 7% to 4%, respectively. At Hankou station, the daily streamflow occurs mainly in the range of 10,000–15,000 m³/s with a percentage of 26% (be composed of January–May and November–December), which increases to 30% in response to dam regulation (be composed of January–May and October–December) (Figures 3b and 3e). The pattern of water level suggests larger variation as a result of dam regulation. In the predam period, the ranges of 16–17 m (be composed of January–May and November–December) and 22–23 m (be composed of May–November) are the largest components for daily water level with ratios of 12% and 11%, respectively. The dominant components shift to the ranges of 14–15 m (be composed of January–March, May, and October–December) and 15–16 m (be composed of January–May and October–December), with the occurrence possibilities of 15% and 14% following the dam regulation (Figures 3h and 3k). It is shown that 23% of daily water level locates in the dominant classes during 2000–2002, which increases to 29% during 2003–2013. As a result, the ratios of extreme events reduce. At Datong station, the primary components of daily discharge for predam and postdam periods are intervals of 10,000–15,000 m³/s (be composed of January–March and December for predam period and be composed of January–May and October–December for postdam period) and 15,000–20,000 m³/s (be composed of January–May and November–December for predam period and be composed of January–May and September–December for postdam period) (Figures 3c and 3f). The sum of their percentage increases from 32% to 42% in response to the construction of TGD. The grouped frequency distribution suggests 5–6 m (be composed of January–March and December for predam period and be composed of January–May and October–December for postdam period) and 6–7 m (be composed of January–May and November–December for predam period and be composed of January–May and September–December for postdam period) as the dominant components of daily water level (Figures 3i and 3l). The change of their total percentage is similar with that of discharge: increases from 29% to 33%. The growing proportion of normal values can be explained by the disappearance of some maximum records. For instance, the percentages of great discharge (>55,000 m³/s) and water level (>13 m) in the predam period are around 7% (be composed of June–September) and 13% (be composed of July and August), which decreases to 3% (be composed of June–September) and 7% (be composed of July and August) respectively following TGD regulation.

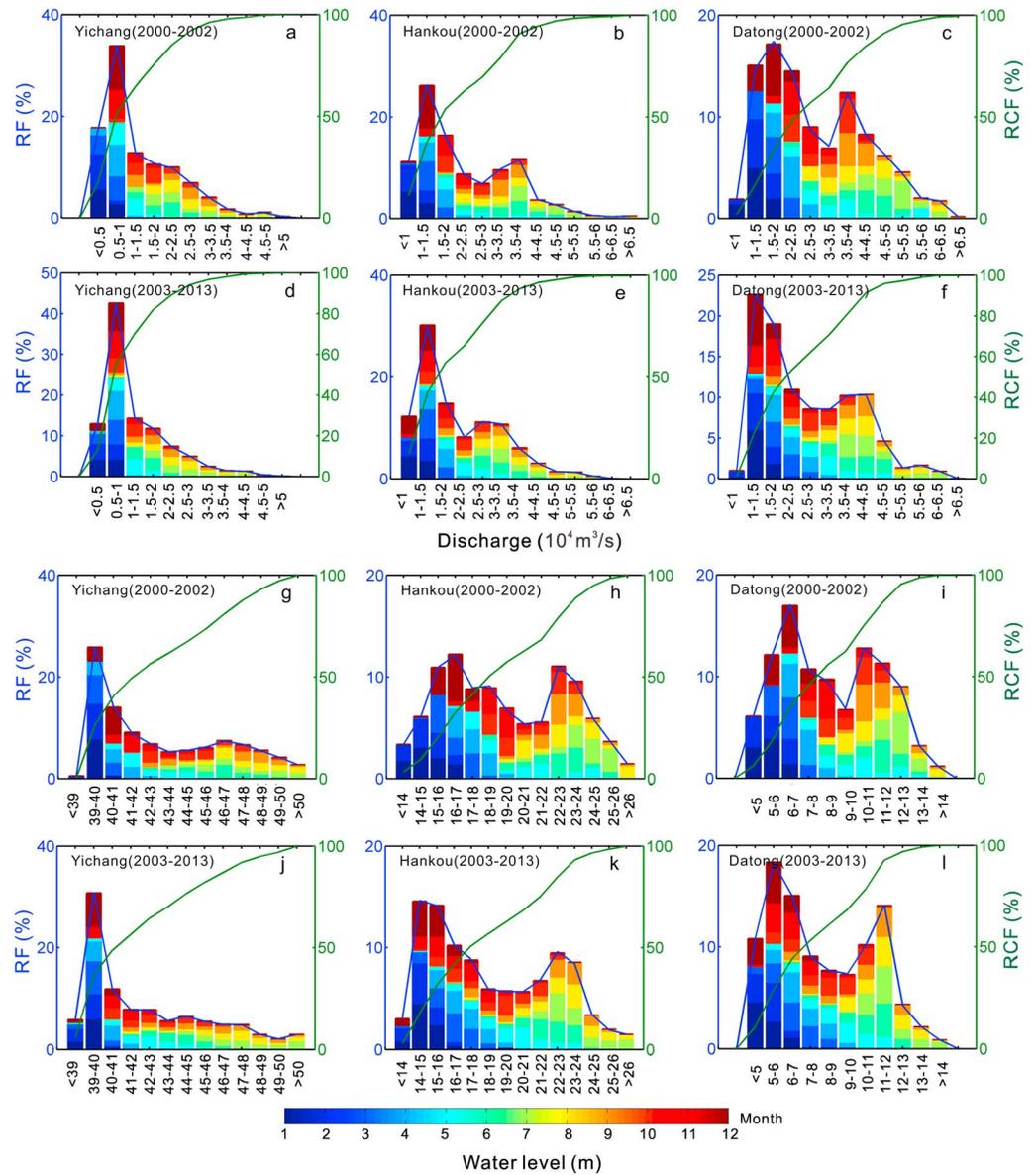


Figure 3. Occurrence probability of discharge and water level at gauging stations (RF: relative frequency; RCF: relative cumulative frequency).

Taken all together, TGD controls the downstream events by increasing the proportion of normal events (spreading over a longer time period) and decreasing the proportion of extreme events (spreading over a shorter time period).

4.2. Extreme Discharge and Water Level

One immediate consequence of dam on downstream hydrology is to prevent or relieve extreme event [Magilligan et al., 2003; Graf, 2006]. The hydrological behaviors of floods and droughts in the Yangtze River basin that downstream of TGD are illustrated in terms of daily and monthly variables.

The maximum and minimum daily hydrological records are analyzed first to reflect the influence of TGD on extreme events. As Figure 4 suggests, TGD regulates the downstream flood behavior by decreasing the magnitude of flow peak; however, the three stations suggest different degrees of modification. Specifically, Yichang station, the one closest to TGD suggests the most significant downward trend in annual maximum discharge by passing the significant level of 0.05 in the MK test (Figure 4a). The discharge series at Hankou

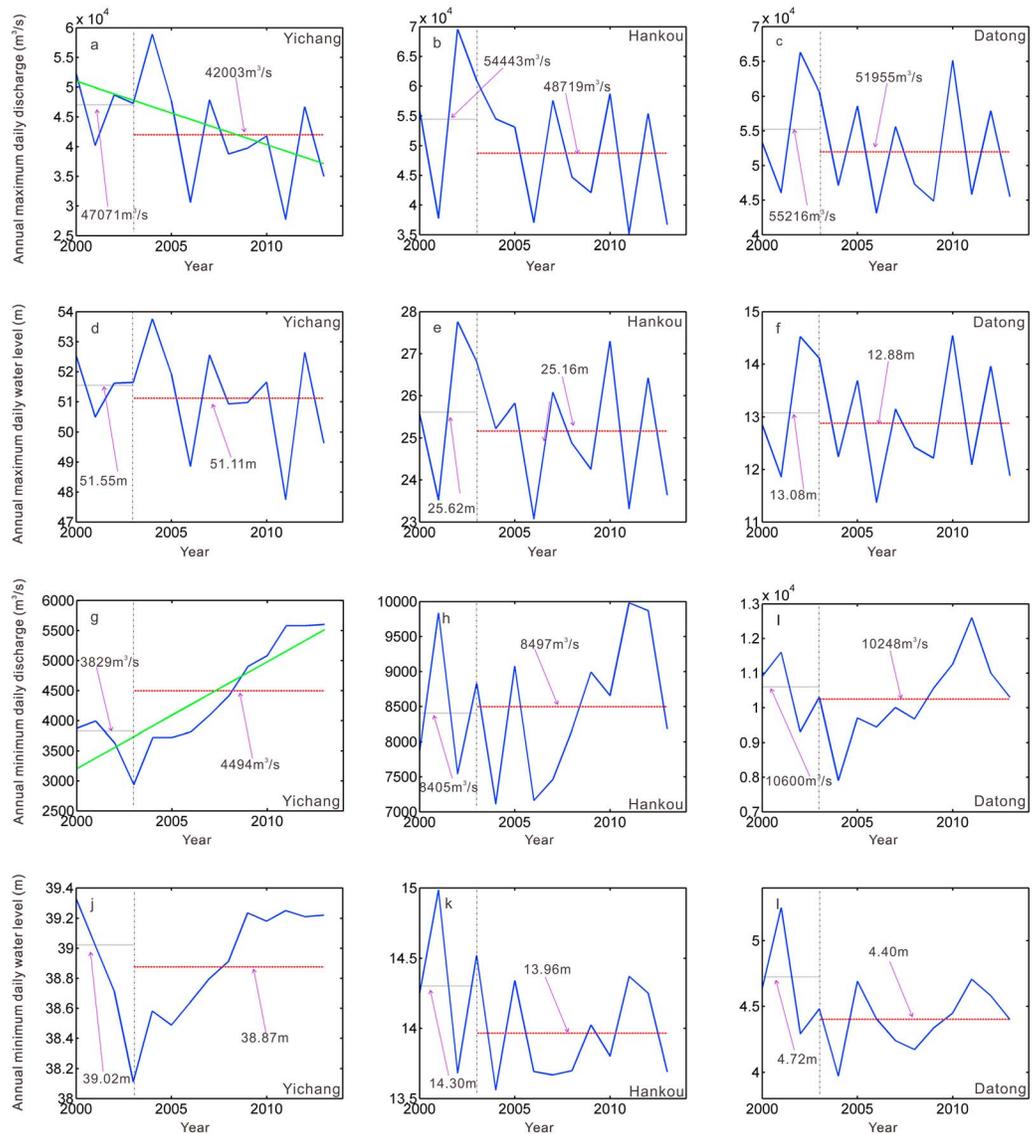


Figure 4. Annual extreme series at gauging stations with dotted line showing the year of dam construction.

and Datong station also indicate declining tendencies, but they are not accepted at 5% significant level by MK test (Figures 4b and 4c). The annual minimum discharge records show various trends in response to dam control in the Yangtze River. At Yichang station, the annual minimum discharge presents prominent upward during 2000–2013 (Figure 4g). The drought conditions at Hankou and Datong, on the other hand, are not alleviated effectively (Figures 4h and 4i). The mean annual minimum discharges at Hankou and Datong fluctuate around $8451 \text{ m}^3/\text{s}$ and $10,428 \text{ m}^3/\text{s}$, respectively, without clear differences. The extreme water level series present consistent trends of variations along the Yangtze River. It is noted that both the maximum water level and the minimum water level series at the three stations present reductions in consequence of TGD regulation.

The effects of TGD on monthly hydrological variables are illustrated in Figure 5. Operation of TGD has a strong effect on monthly flow fluxes over the Yangtze River. In general, control of flow during flood season decreases the high discharge, while releases of water from the reservoir during dry season increase the low discharge. However, the water level series present different tendencies, both high and low water levels suggest decline tendencies, which are coincide with the extreme daily water level variables. Take Hankou as an example, the maximum monthly water discharge over the predam period averages $40,466 \text{ m}^3/\text{s}$, suggesting a downward since TGD was put into operation, with an average of $37,454 \text{ m}^3/\text{s}$. Instead, TGD raises the minimum monthly

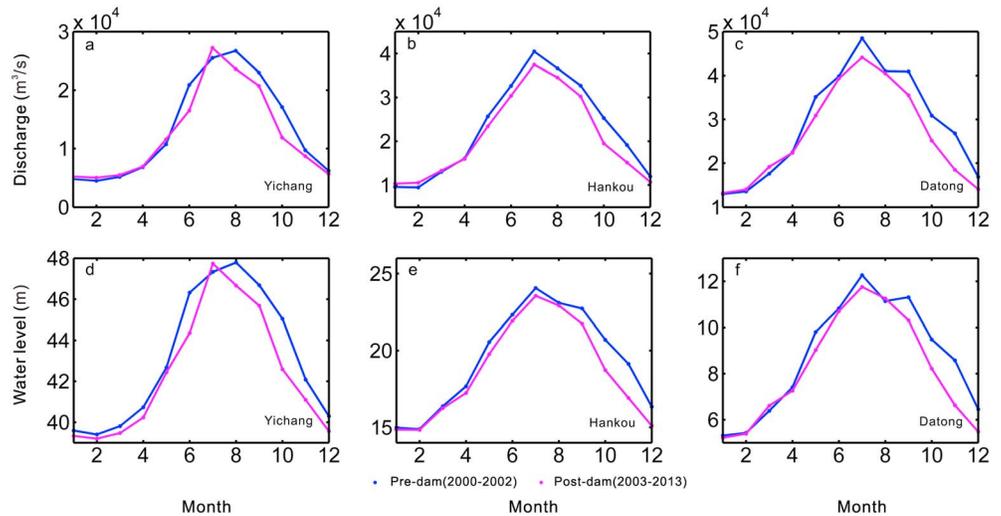


Figure 5. Monthly mean discharge and water level over the Yangtze River.

water discharge from 9539 m³/s to 10,289 m³/s (Figure 5b). On the other hand, the maximum monthly water level decreases from 24.06 m to 23.55 m, and the minimum monthly water level decreases from 14.98 m to 14.85 m in response to TGD regulation (Figure 5e).

It should be noted that the maximum monthly discharge and water level at Yichang station occur in August in predam period, which shifts to July in postdam period (Figures 5a and 5d). This situation has not been observed in the middle and lower reaches of the Yangtze River.

4.3. Discharge-Water Level Relationship Variation

The variations of river discharge and water level due to TGD regulation further change the relationship between the two indicators. As Figure 2 suggested, the discharge-water level points for Yichang and Hankou are allocated to two distinct groups, while that of Datong have no obvious stratification. Therefore, discharge-water level rating curves are established for the three gauging stations to detect patterns in the discharge and water level relationship along the Yangtze River (Figure 6).

It is shown that the dam effect fades from the upper to the lower reach as the distance between the gauging station and dam increases. Specifically, the stage-discharge variation is most significant at Yichang (the nearest gauging station below the dam), where the rating curve has a clear upward shift from predam period to postdam period (Figure 6a). Hankou (in the middle reach) is less sensitive to the dam operation (Figure 6b). The predam and postdam rating curves at Datong almost overlap without apparent change (Figure 6c).

5. Discussion

The hydrological characteristic along the Yangtze River is a rather complex process in response to various factors, including precipitation variation, dam regulation, and the peculiar geographical characteristic of Yangtze River itself. It is necessary to distinguish the influence of each factor on the river hydrology.

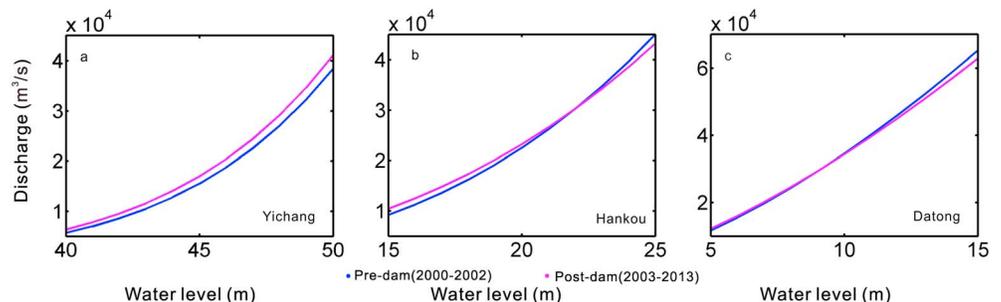


Figure 6. The relationship between river discharge and water level.

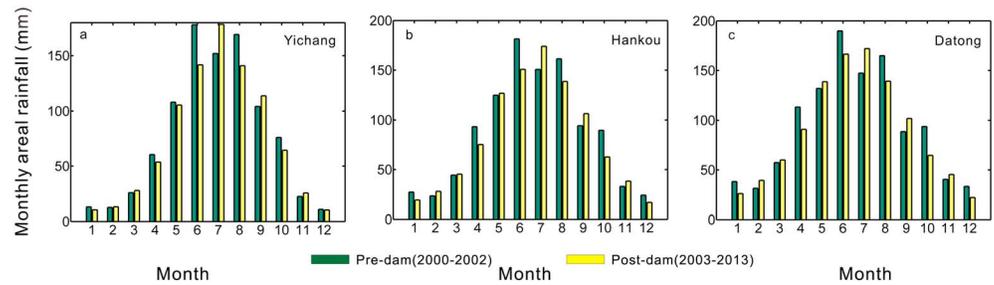


Figure 7. Mean monthly rainfall over the period 2000–2013.

5.1. Precipitation Variation

The Yangtze River is dominated by the monsoon activity, which therefore is a potential driver of river hydrology variations [Jiang *et al.*, 2006]. Comparisons of predam and postdam monthly areal precipitation characteristics are presented in Figure 7. It is shown that the three stations follow similar patterns of changes in precipitation. Compared with predam period, the postdam precipitation series suggest slight decreases, which are not strong enough to support the great changes in runoff series as mentioned in section 4. In addition, compared with predam period, the time of maximum monthly precipitation during postdam period delays from June to July, which is inconsistent with those of runoff series, especially for Yichang station, where the time of maximum monthly runoff moves from August to July. Therefore, the strong changes in the river runoff cannot be explained by areal precipitation, and other factors exist to result in runoff variations along the Yangtze River.

5.2. Dam Regulation

TGD affects the downstream hydrology through two ways: flow regulation and sediment transport, which influence the downstream discharge and water level, respectively [Xu *et al.*, 2008; Wang *et al.*, 2013]. Here the influences of TGD on downstream water level are further discussed by studying the water level differences between study years and reference year under the same discharge level. In the current paper, the year 2000 is selected as reference year, while the postdam period during 2003–2013 is set as study years. The water level differences between study years and reference year at various discharge levels are shown in Figure 8. Regression analysis is used to quantify the temporal pattern of water level difference, which is expressed with solid line if the correlation coefficient between the mathematical model and data set is strong ($R > 0.7$). From low- to high-flow scenarios, clear decline can be found in the low-flow and normal flow scenarios during 2003–2013. The high-flow scenario, on the other hand, presents homogeneous status without significant gradient patterns. Therefore, the effects of TGD on downstream water levels are much stronger in dry season than flood season. The significant reduction in water level can be explained by TGD-induced riverbed erosion along the downstream river from TGD [Dai and Liu, 2013].

5.3. Lakes and Lateral Tributary

As Figure 6 suggests, the rating curves at Yichang station present significant shift following the dam construction; however, the effect is limited at Datong. This phenomenon can be explained by the extra inflows from the reach between Yichang and Datong, including Dongting Lake, Hanjiang River, and Poyang Lake. The contributions of lakes and lateral tributary to the Yangtze River in predam and postdam periods are compared in Table 3. Here Chenglingji (CLJ), Shayang (SY), and Hukou (HK) represent the runoff from Dongting Lake, Hanjiang River, and Poyang Lake to the Yangtze River, respectively. The precipitations over Dongting Lake, Hanjiang River, and Poyang Lake are measured at Yueyang, Jinzhou and Ganjiang, respectively. The study period is reduced to 2001–2010 due to data loss at Shayang.

Comparing with predam period, the discharge from CLJ to the Yangtze River decreases by 23% (from 13,300 m³/s to 10,200 m³/s) and 14% (from 5100 m³/s to 4400 m³/s) in flood season and dry season, respectively. On the other hand, the flow from SY to the Yangtze River increases by 100% (from 1100 m³/s to 2200 m³/s) and 38% (from 800 m³/s to 1100 m³/s) in flood season and dry season, respectively. The runoff from HK to the Yangtze River reduces by 28% (from 6700 m³/s to 4800 m³/s) in flood season and increases by 5% (from 4200 m³/s to 4400 m³/s) in dry season. Meanwhile, both Dongting Lake and Poyang Lake suggest reductions in precipitation,

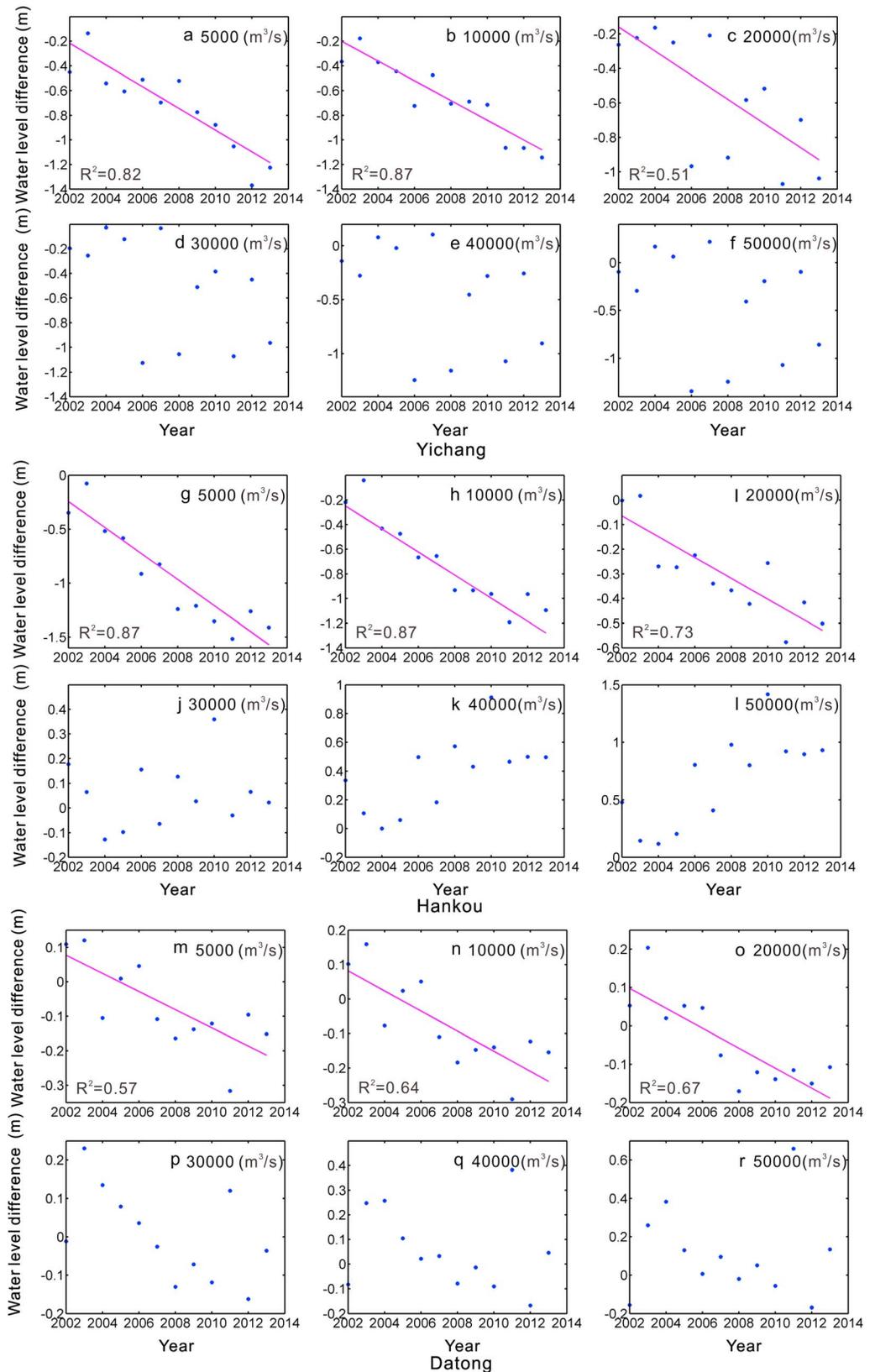


Figure 8. Water level variation under different discharge levels at gauging stations.

Table 3. Runoff Contributions of Dongting Lake, Hanjiang River, and Poyang Lake to the Yangtze River^a

Station		Flood Season (May–October)			Dry Season (November–April)		
		2001–2002	2003–2010	Change	2001–2002	2003–2010	Change
DT	P	50	39	–22%	40	30	–27%
	Q	13,300	10,200	–23%	5,100	4,400	–14%
HR	P	37	38	4%	29	17	–41%
	Q	1,100	2,200	100%	800	1,100	38%
PL	P	63	40	–37%	35	31	–1%
	Q	6,700	4,800	–28%	4,190	4,350	4%

^aDT: Dongting Lake; HR: Hanjiang; PL: Poyang Lake; P: precipitation (mm); Q: discharge (m³/s).

while Hanjiang River receives more precipitation in flood season and less precipitation in dry season after TGD was closed. It is shown that Dongting Lake, Hanjiang River, and Poyang Lake supply more water to the Yangtze River than they get from the precipitation as compared to predam period in dry season, which effectively weakens the effect of TGD on downstream hydrology regime.

6. Further Discussion

6.1. The Influence of Data Length on Trend Analysis

A number of investigations have been carried out to evaluate the hydrological variability along the Yangtze River. For example, Zhang *et al.* [2006] evaluated the maximum water level and streamflow data from the main hydrological stations during 1865–2000 along the Yangtze River and pointed out that the streamflow at middle Yangtze River suggested a significant upward trend. Chen *et al.* [2002] analyzed the minimum water level at the Datong station over the period of 1850–1999 and indicated a decreasing trend in the Yangtze River. Compared with the former researches, this paper indicates different hydrological changes along the Yangtze River. It should be noted that the results of Zhang *et al.*, Chen *et al.*, and the current paper are obtained from different lengths of data set, which indicates that the length of data set may influence the final results. Here the water level series at Yichang are taken as an example to analyze the influence of data length on trend results (shown in Figure 9). The annual maximum water level and mean water level present downward trends during 1950–2013. The series follow the same tendencies during 2000–2013 but indicate much larger slopes. The minimum water level at Yichang suggests declining trend during 1950–2013 but presents contrary trend during 2000–2013. It means that the long predam records affect and even inverse the trend test results at Yichang station. Consequently, it is not reasonable to discuss the influence of TGD on the downstream hydrological processes through long data sets while the TGD was put into practice in 2003.

6.2. The Influence of TGD on River Estuary

Aside from remit the threats of extreme flood and drought, dam regulation may affect the interaction between river and ocean and the physical environment of the river estuary by changing the natural flow cycles [Le *et al.*, 2007; Humborg *et al.*, 2006; Morais *et al.*, 2009].

Yangtze Estuary is a typical tidal-controlled estuary and receives a huge tidal volume from the sea [Dai *et al.*, 2011]. The tidal limit is located in Datong in dry season and in Wuhu in flood season, which is largely dependent on the volume of freshwater resisting the ocean water. As Figure 3 indicated, TGD changes the natural flow patterns at Datong station by decreasing maximum flows and increasing minimum flows. It is

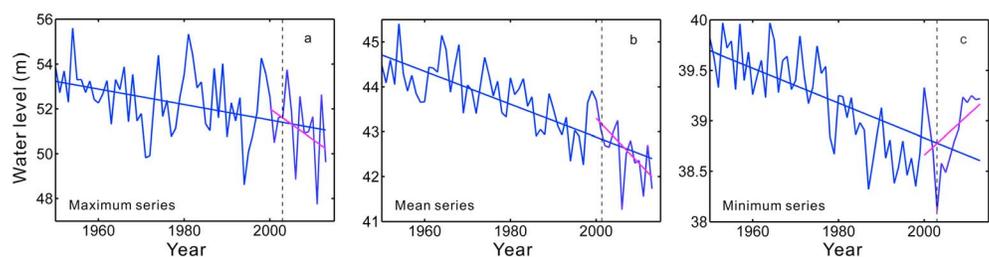


Figure 9. Trend analysis with various water level lengths at Yichang station.

reasonable to make the assumption that TGD modifies the flow regimes of river estuarine area as well, which may further alter water salinity and significantly affect the distribution of estuarine organisms. Moreover, the variation of flow cycle can change the dynamic conditions and sediment transport routes in the river estuary, which may modify delta erosion/accumulation regime [McManus, 2002; Dai et al., 2014].

7. Conclusion

Dam regulation can significantly affect the river hydrology. A temperate and spatial depiction of the downstream hydrological variations below TGD is present in this paper. The detailed hydrological dynamics of the Yangtze River are analyzed using discharge and water level records from three gauging stations along the mainstream: Yichang, Hankou, and Datong, which represent the upper, middle, and lower reach, respectively. The main results are drawn as follows:

1. TGD centralizes the grouped frequency distributions at Yichang, Hankou, and Datong by different degrees. (a) Yichang: the intervals 5000–10,000 m³/s and 39–40 m are the dominant components for discharge and water level; their proportions increase from 34% (be composed of January–May and October–December) to 43% (be composed of January–May and August–December) and from 26% (be composed of January–April and December) to 31% (be composed of January–May, November, and December), respectively. (b) Hankou: the interval 5000–10,000 m³/s is the dominant component for discharge; its proportion increases from 26% (be composed of January–May, November, and December) to 30% (be composed of January–May and October–December); meanwhile, the dominant water level intervals move from 16–17 m (be composed of January–May, November, and December) and 22–23 m (be composed of May–November) to 14–15 m (be composed of January–March, May, and October–December) and 15–16 m (be composed of January–May and October–December); their total percentage increases from 23% to 29%. (c) Datong: the intervals 10,000–20,000 m³/s and 5–7 m are the dominant components for discharge and water level; their proportions increase from 32% (be composed of January–May and November–December) to 42% (be composed of January–May and September–December) and from 29% (be composed of January–May and November–December) to 33% (be composed of January–May and September–December), respectively.
2. TGD controls the downstream extreme events by decreasing the maximum discharge and increasing the minimum discharge. However, both maximum and minimum water levels at the three stations have decreased in response to TGD-induced channel erosion. Moreover, TGD changes the monthly hydrological patterns at Yichang station, where the time of maximum monthly discharge and water level is shifted from August to July.
3. The relationships between discharge and water level along the Yangtze River are disturbed by dam operation. Spatial variability in rating curves is observed among Yichang, Hankou, and Datong. The station closest to the dam presents the most significant variations.
4. The river hydrology along the Yangtze River is mainly controlled by TGD, while the precipitation variability has little influence on water discharge. In addition, the lakes and lateral tributary diminish the dam effects.

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