© 2016 The Authors **Hydrology Research** | 47.S1 | 2016

Quantifying the effects of channel change on the discharge diversion of Jingjiang Three Outlets after the operation of the Three Gorges Dam

Yanyan Li, Guishan Yang, Bing Li, Rongrong Wan, Weili Duan and Zheng He

ABSTRACT

The Jingjiang Three Outlets (JTO) are the water-sediment connecting channels between the Yangtze River and the Dongting Lake. The discharge diversion of the JTO plays a dominant role in the flood control of the middle–lower Yangtze River, Dongting Lake evolution, and ecological environment. After the operation of the Three Gorges Dam (TGD), the river channels downstream experienced dramatic channel changes. To study the influences of the channel change on the discharge diversion, the authors analyzed the channel changes by water level–discharge rating curves and cross-sectional channel profiles in 1980–2014. Hence, changes in the water level with the same discharge and the decline of discharge diversion at the JTO were noted. Channel incision caused the water level with the same discharge to greatly decrease in the upper Jingjiang River. The water level with the same discharge significantly increased at the JTO as a result of the channel deposition. The channel changes contributed approximately 37.74% and 76.36%, respectively, to the amount and ratio of discharge diversion decreases after the TGD operation. The channel changes serve as the primary factor in facilitating the decrease in the discharge diversion ratio, but not the main factor for the decreased amount of the discharge diversion.

Key words | channel change, discharge diversion, Jingjiang Three Outlets, rating curve, Three Gorges Dam, Yangtze River

Yanyan Li
Guishan Yang (corresponding author)
Bing Li
Rongrong Wan
Weili Duan
Zheng He
State Key Laboratory of Lake Science and Environment,
Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences,
Nanjing 210008,
China
and
Key Laboratory of Watershed Geographic Sciences,
Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences,
Nanjing 210008,
China
E-mail: *gsyang@niglas.ac.cn*

INTRODUCTION

More than 47,000 large dams and 800,000 small dams have been constructed in river systems worldwide in the past few decades (Haghighi *et al.* 2014). Dam impoundment led to large amounts of sediment retention in reservoirs (Syvitski *et al.* 2005; Duan *et al.* 2015). The channels downstream of the dams also underwent erosion and morphological changes (Dai & Liu 2013; Csiki & Rhoads 2014). Channel changes can influence navigation management, ecosystems, and flood control and prevention. In recent years, the channel changes downstream of the dams and the homologous environmental effects have attracted extensive attention from the public and the science community (Hudson *et al.* 2008; Tealdi *et al.* 2011; Segura-Beltrán & Sanchis-Ibor 2013; Gao *et al.* 2015a).

Water level–discharge curves (rating curves) play an essential role in hydrology, i.e., in water resource management of river basins (Petaccia & Fenocchi 2015), as well as in flood risk and control assessment (Bormann *et al.* 2011). Rating curves are highly sensitive to channel changes (Jalbert *et al.* 2011), such that the rating curve shifts down or up, respectively, once the channel erodes or deposits. Long-term variations of the water level–discharge relationships can reflect the channel morphology changes (Zhang

This is an Open Access article distributed under the terms of the Creative Commons Attribution Licence (CC BY-NC-SA 4.0), which permits copying, adaptation and redistribution for non-commercial purposes, provided the contribution is distributed under the same licence as the original, and the original work is properly cited (http://creativecommons.org/licenses/by-nc-sa/4.0/).

doi: 10.2166/nh.2016.016

Downloaded from https://iwaponline.com/hr/article-pdf/47/S1/161/366949/nh047s10161.pdf
by guest
on 15 August 2018

et al. 2015). Therefore, rating curves can be used to detect the channel changes and homologous environmental effects in a river. Numerous approaches for studying rating curves can be found in the literature. Regression methods based on data-driven, non-parametric, and non-linear models are popularly used for rating curve construction and water discharge forecasting (Duan *et al.* 2013; Valipour *et al.* 2013; Wolfs & Willems 2014; Valipour 2015a, 2016). Regression models can provide accurate water discharge forecasting results. However, information on the channel morphology changes cannot be obtained. In recent years, the most commonly used method of the rating curve as a power-law function has been applied to detect the channel morphology changes (Wang *et al.* 2013; Zhang *et al.* 2015).

The Yangtze River is the largest river in the Asian Monsoon region and suffers from a combination of highly intensified human activities (Chen *et al.* 2014) and natural flow regime variability (Zhang *et al.* 2007). The occurrence of severe floods and droughts in the middle–lower Yangtze River has accelerated at an increasing rate, during the past few decades (Nakayama & Shankman 2013; Gao *et al.* 2014). The Three Gorges Dam (TGD) on the Yangtze River is the largest hydroelectric project in the world. The TGD impoundment in 2003 intercepted 65–85% of upstream sediments (Yang *et al.* 2014), thereby leading to downstream channel erosion, which reached 979 million m^3 in 2002–2010 (Lu *et al.* 2011). Long-distance channel incision occurred downstream (Dai & Liu 2013). The channel incision lessened the water level of the main river with the same discharge (Wang *et al.* 2013), and also directly altered complex river–lake relationships (e.g., Gao *et al.* 2014; Zhang *et al.* 2014a). The TGD operation decreased the magnitude of extreme flow in the summer season (Gao *et al.* 2013) and partially contributed to flood control. However, the frequency and timing of severe floods in the middle–lower Yangtze River are affected because of the channel incision caused by the TGD (Nakayama & Shankman 2013). The channel incision downstream of the TGD is mainly distributed along the main stream of the Yangtze River (Dai & Liu 2013). The lowering water level reduces the ability of the water discharge to transfer to the water diversion area. Channel changes caused a new water regime situation to appear in the middle–lower Yangtze River basin. Understanding the influences of channel change on the water regime situation is crucial for flood control, the management of the ecological environment and water resources in the Yangtze River basin. Therefore, quantitative assessments of the contribution of the channel changes to the water regime changes are urgently needed.

The Jingjiang Three Outlets (JTO), which form the main entrance of the water discharge of the Yangtze River entering the Dongting Lake, directly play a dominant role in flood control in the middle–lower Yangtze River, Dongting Lake evolution (Ding & Li 2011), and ecological environmental changes (Hu *et al.* 2015). During the flood season, the JTO recharge 20–30% of the main river water discharge (Lu *et al.* 2012), thereby reducing the flood pressure on the lower reaches. Meanwhile, the diverted discharge can relieve the lake droughts during the other seasons. After 2003, the amount of discharge diversion at the JTO significantly decreased (Lu *et al.* 2012). Chang *et al.* (2010) concluded that the TGD channel erosion at the main stream and the JTO jointly caused the decrease in the discharge diversion ratio, and then resulted in the amount of discharge diversion decreasing. However, Zhu *et al.* (2015) believed that the decreased ratio and amount of discharge diversion were mainly caused by the hydrological variations of the main stream. Previous studies still disagree on the degree to which channel changes affect the discharge diversion of the JTO. Therefore, figuring out the channel change characteristics and the contributions of the channel changes to the discharge diversion of the JTO is necessary. Specifically, this study has the following objectives: (1) to reconstruct the water level–discharge rating curves for detecting the river channel change characteristics and quantify the effect of the river channel changes on lowering the water level; (2) to establish equations on the discharge diversion and level difference of the Yangtze River and the JTO, thereby estimating the discharge diversion under no channel changes; and (3) to analyze the influence of the channel changes on the discharge diversion.

MATERIALS AND METHODS

Study area and data

The Jingjiang River is approximately 347 km long in the middle Yangtze River between Zhicheng and Chenglingji.

Downloaded from https://iwaponline.com/hr/article-pdf/47/S1/161/366949/nh047s10161.pdf
by guest
on 15 August 2018

The river flows through the Jianghan and Dongting Lake plains. Three diversion branches at Songzikou, Taipingkou, and Ouchikou are located in the upper Jingjiang Reach, which links the Yangtze River with the Dongting Lake (Figure 1). These branches usually divert water from the main stream during flood seasons, but are normally dry during non-flood seasons (Xia *et al.* 2014). Zhicheng is the control hydrological station of the upper Jingjiang Reach. Xinjiangkou and Shadaoguan, Mituosi, and Ouchi (kang) and Ouchi (guan) are the control hydrological stations at Songzikou, Taipingkou, and Ouchikou, respectively. The mean annual runoff volumes of Songzikou, Taipingkou, and Ouchikou in 1955–2008 were 404.6×10^8, 155.2×10^8, and 305.4×10^8 m^3, respectively. Human activities, including construction of the lower Jingjiang cut-off project and operation of the Gezhouba Dam, have influenced the JTO discharge diversion since the 1950s (Zhu *et al.* 2015). All data are obtained from the Bureau of Hydrology, Changjiang Water Resources Commission, China. These data include daily water level and discharge data at Zhicheng in 1980–2014 as well as daily water level and discharge data in 1980–2012 and 1980–2014, respectively, at the Xinjiangkou, Shadaoguan, Mituosi, Ouchi (kang), and Ouchi (guan) hydrological stations. The annual channel cross sections at Zhicheng and the JTO are determined to analyze riverbed scouring and silting. However, the use of cross-section data in different channels in the following analysis may be based on different years, because of the fixed cross-section position that has changed in some river channels. More than 90% of the total discharge diversion is delivered from May to October. Accordingly, the discharge from November to April is not considered in this study. The water level elevation and cross-sectional data are corrected to the 85 Yellow Sea elevation.

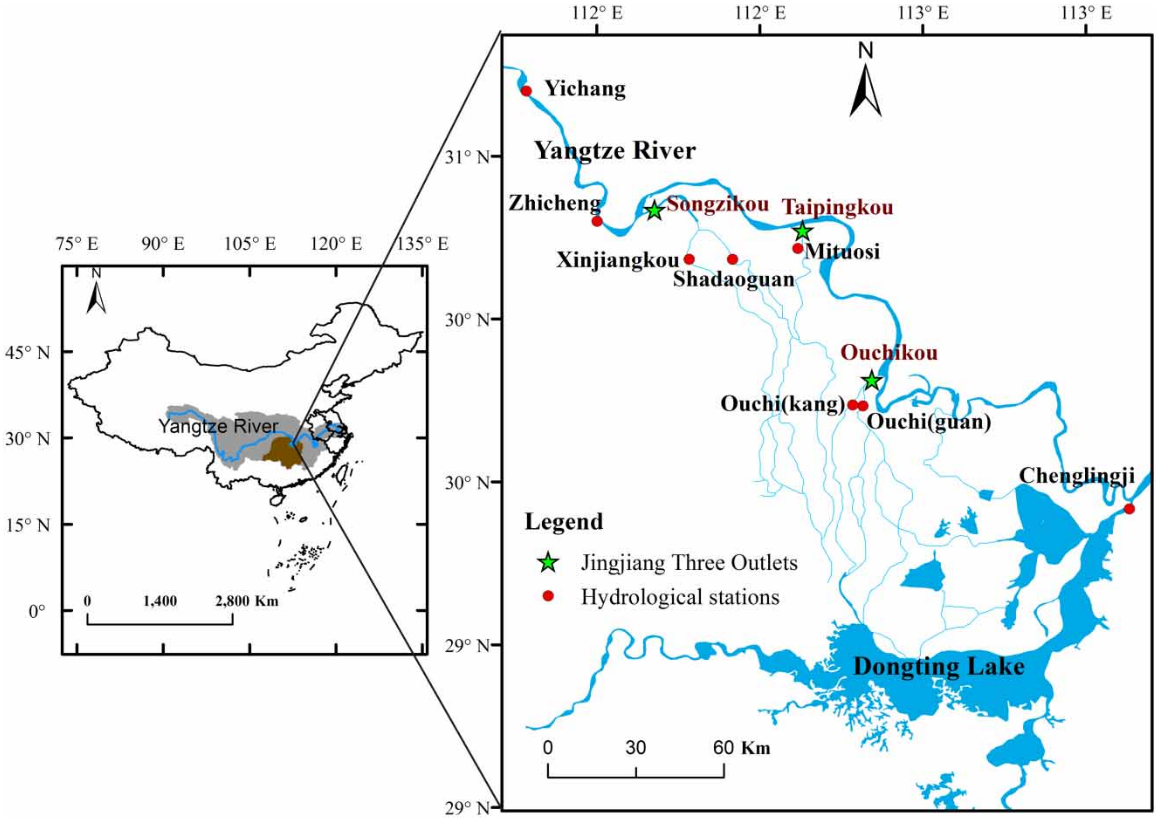

Figure 1 | Geophysical location of the JTO in the Yangtze River basin. Zhicheng is the control hydrological station of the Jingjiang Reach. The Yangtze River diverts discharge to the Dongting Lake by the JTO channels.

Downloaded from https://iwaponline.com/hr/article-pdf/47/S1/161/366949/nh047s10161.pdf
by guest
on 15 August 2018

Water level–discharge rating curve

The power law function approach for the rating curve is based on the Manning equation (Leon *et al.* 2006). The approach uses a one-to-one mapping of the river water level to the discharge estimates (Wolfs & Willems 2014) as follows:

$$Q = a(H - h_0)^b \tag{1}$$

where Q is the discharge (m^3/s), H is the water level (m), a and b are the empirical parameters, and h_0 is the water level at zero flow (datum correction) (m). This equation can be transformed by logarithms to the following form:

$$\log Q = \log a + b \log (H - h_0) \tag{2}$$

where the parameter range of h_0 is not less than the bottom elevation and not more than the water stage (Zhang *et al.* 2015). First, the entire range of the possible h_0 values is explored by increments of 0.01 m. Parameter h_0 is given an a value. The a and b coefficients are observed by Equation (2). The root-mean-square error (RMSE) is calculated from the observed discharge and the estimated discharge using Equation (3) (Leon *et al.* 2006). h_0 is determined by the smallest value as follows by checking all of the RMSE values:

$$\text{RMSE} = \sqrt{\frac{\sum (Q_{mes} - Q_{cal})^2}{n}} \tag{3}$$

where Q_{mes} is the observed flow in the gauge case, Q_{cal} is the rated flow, and n is the number of measurements.

The water level–discharge rating parameters can be related to the physical characteristics of the river channel. a is a scaling factor that encompasses the section width, local bottom slope, and Manning coefficient (Valipour 2012, 2015b; Khasraghia *et al.* 2015). b includes the river bank geometry, particularly the departure from the vertical banks (Leon *et al.* 2006). h_0 is connected to many factors that affect the rating curve (Jalbert *et al.* 2011).

Mann–Kendall test for trend change analysis

The non-parametric Mann–Kendall (MK) test is used to analyze the trend variations of the water level–discharge rating parameters. The MK test is based on the correlation test between the ranks of observations and their time sequence (Mann 1945; Kendall 1975). The test statistic for a time series ($x_1, x_2, x_3, \ldots, x_n$) is given as follows:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}(x_j - x_i) \tag{4}$$

where x_i and x_j are the data values at times i and j, respectively. n is the data set record length, and

$$\operatorname{sgn}(x_j - x_i) = \begin{cases} +1 & \text{if} \quad (x_j - x_i) > 0 \\ 0 & \text{if} \quad (x_j - x_i) = 0 \\ -1 & \text{if} \quad (x_j - x_i) < 0 \end{cases} \tag{5}$$

$$Var(S) = \frac{\left[n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(t_i - 1)(2t_i + 5)\right]b}{18} \tag{6}$$

where m is the number of tied groups; t_i is the number of data in the tied group. The standard normal variable Z is computed from Equation (7) as follows:

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{Var(S)}}, & \text{if} \quad S > 0 \\ 0, & \text{if} \quad S = 0 \\ \dfrac{S-1}{\sqrt{Var(S)}}, & \text{if} \quad S < 0 \end{cases} \tag{7}$$

The positive Z values indicate increasing trends, whereas the negative Z values show decreasing trends. The null hypothesis of the absent trend is rejected if $|Z| > 1.96$ at the 0.05 significance level and rejected if $|Z| > 2.58$ at the 0.01 significance level.

Pettitt test for abrupt change analysis

The non-parametric Pettitt test (Pettitt 1979) is used to determine the abrupt change of the rating curve parameters at Zhicheng station. The method uses a version of the Mann–Whitney statistic $U_{t,n}$ including two parts ($x_1, x_2, x_3, \ldots, x_t$ and $x_{t+1}, x_{t+2}, x_{t+3}, \ldots, x_T$) from the same population. The test statistic $U_{t,n}$ is computed as follows:

$$U_{t,T} = \sum_{i=1}^{t} \sum_{j=1}^{T} \operatorname{sgn}(x_t - x_j) \quad \text{for} \quad t = 2, \ldots, n \tag{8}$$

Downloaded from https://iwaponline.com/hr/article-pdf/47/S1/161/366949/nh047s10161.pdf
by guest
on 15 August 2018

The most significant change-point is found where the value of $|U_{t,T}|$ is the largest:

$$K_T = \max|U_{t,T}| \tag{9}$$

The associated probabilities (p value) used in the significance testing are as follows:

$$p \cong 2\exp\left\{-\frac{6(K_T)^2}{T^3+T^2}\right\} \tag{10}$$

The null hypothesis is rejected once the p value is less than the specific significance level (e.g., 5% in this study). In other words, a significant change point exists.

Commonly, climatic and hydrologic series may generally display serial autocorrelation. Many studies have indicated that the serial autocorrelation may alter the MK and Pettitt test results. To eliminate the effect of a serial autocorrelation on the MK and Pettitt test, the 'Trend-Free-Pre-Whitening' procedure was applied in this study (Yue *et al.* 2002).

Equations to estimate the effects of channel changes on the discharge diversion at the JTO

The amount of discharge diversion at the JTO is affected by many factors, such as the relative position between the diversion entrance and the main stream, river regime variations of the main stream, and scouring and silting changes of the diversion channel. Among these factors, the level differences between the water level at the main stream and the riverbed elevation at the JTO were closely related to the amount of discharge diversion (Lu *et al.* 2012).

The water level–discharge relationships and cross-sectional channel profiles remained steady in 1994–2002 at the five control stations of the JTO (Figures 2 and 3). Therefore, the correlation equations are established between the amount of discharge diversion and the level differences based on data observed in the pre-TGD decade (1994–2002):

$$Q_X = 0.5392(L_Z-30.326)^3+10.168(L_Z-30.326)^2 + 34.942(L_Z-30.326)+701.93\,,\quad R^2=0.99,\quad P<0.001 \tag{11}$$

$$Q_S = -0.7898(L_Z-30.114)^3+47.071(L_Z-30.114)^2 - 565.83(L_Z-30.114)+1912.4,\quad R^2=0.99,\quad P<0.001 \tag{12}$$

$$Q_M = 0.336(L_Z-32.017)^4-14.011(L_Z-32.017)^3 + 217.77(L_Z-32.017)^2-1250.2(L_Z-32.017) + 2359.7,\quad R^2=0.98,\quad P<0.001 \tag{13}$$

$$Q_{Ok} = 0.1744(L_Z-30.778)^3-0.0221(L_Z-30.778)^2 - 29.322(L_Z-30.778)+143.49,\quad R^2=0.95,\quad P<0.001 \tag{14}$$

$$Q_{Og} = 1.3959(L_Z-25.818)^3-17.536(L_Z-25.818)^2 - 103.31(L_Z-25.818)+1397,\quad R^2=0.96,\quad P<0.001 \tag{15}$$

where Q_X, Q_S, Q_M, Q_{Ok}, Q_{Og} are the amount of discharge diversion at Xinjiangkou, Shadaoguan, Mituosi, Ouchi (kang), and Ouchi (guan), respectively; L_Z is the water level of the main stream at Zhicheng.

The regression equations were used to predict the amount of discharge diversion of the same series (1994–2002) and to test the predicted precision. A comparison between the estimated and observed values in 1994–2002 confirms that the estimated daily discharge diversion is consistent with the observed values at the five control stations of the JTO (Figure 4). Thereafter, the equations of the pre-TGD were used to predict the amount of discharge diversion under no channel changes for the post-TGD period and to quantify the impact of the river channel changes on the amount of discharge diversion. The difference between the observed and estimated discharge diversions is attributed to the channel changes.

RESULTS AND DISCUSSION

Variability of water level–discharge rating curves

The trend and abrupt changes of the water level–discharge rating parameters at Zhicheng during 1980–2014 were calculated by the MK and Pettitt tests (Table 1). $\log a$ and h_0

Downloaded from https://iwaponline.com/hr/article-pdf/47/S1/161/366949/nh047s10161.pdf
by guest
on 15 August 2018

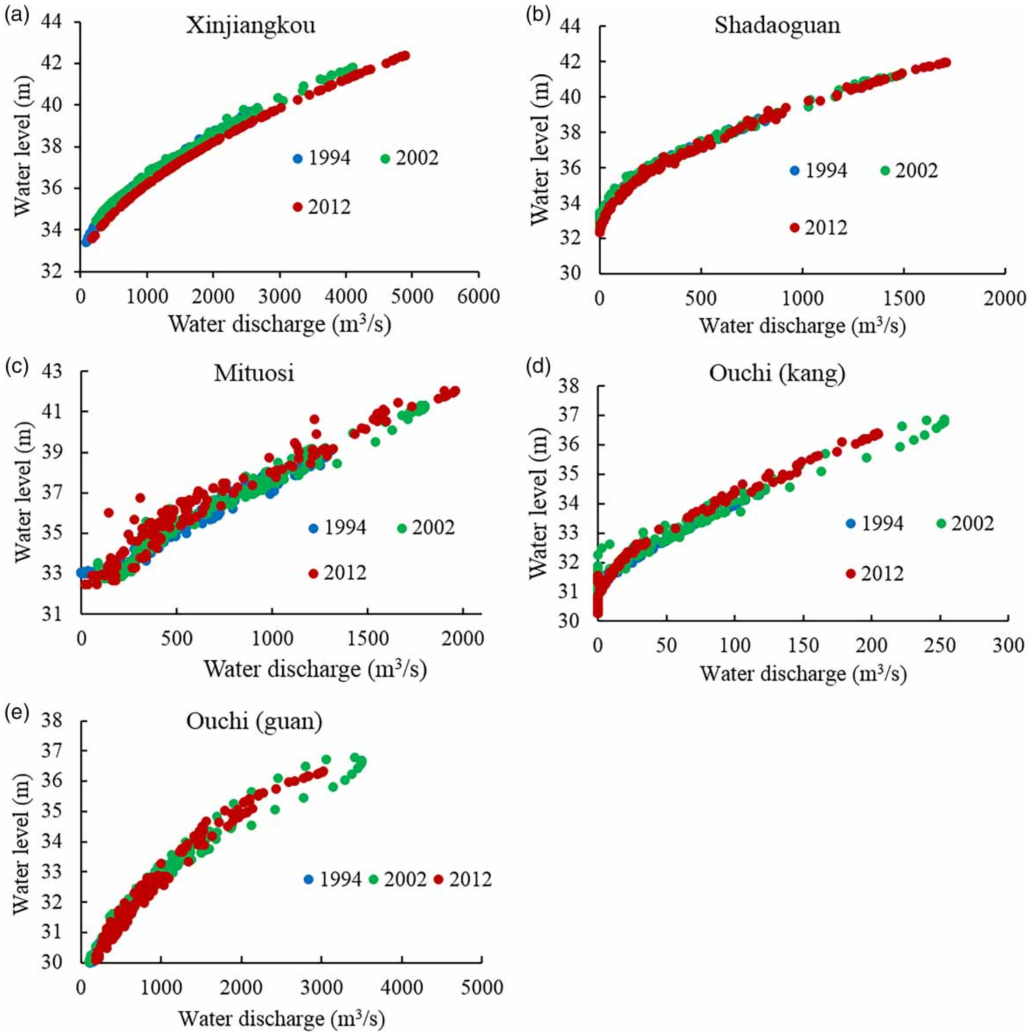

Figure 2 | Water level–discharge rating curves at the five control stations of the JTO in 1994–2012. (a) Xinjiangkou, (b) Shadaoguan, (c) Mituosi, (d) Ouchi (kang), and (e) Ouchi (guan).

show increasing trends with the 99% confidence level, whereas b displays a decreasing trend at the same confidence level. The parameters $\log a$, b and h_0 all display an abrupt change point in 1993 with the 95% confidence level. The parameter changes indicate that the river width–depth ratio dramatically decreased and the river channel depth increased during 1980–2014. The river channel morphology exhibits drastic changes.

The $\log a$, b, and h_0 changes are relatively small, while the rating curves are kept steady in 1994–2002 compared with the other periods (Figure 5). A series of projects have been performed since 1989 to expedite the soil and water conservation in the upper reaches of the Yangtze River and to ensure safe TGD operation. After 1994, the project gradually expanded to the middle reaches (Dai & Lu 2014), increased the vegetation cover by 23% (Xu & Milliman 2009), and stabilized the source of the river channel sediment. Sand extraction has been banned in the Yichang–Jiangkou reach of the Yangtze River since 1988 (Duan 2012). The Gezhou Dam of the run-of-river reservoir located in the main stream of the Yangtze River 38 km below the TGD was partly used in 1981 (Li *et al.* 2011). Channel erosion/accretion has attained a balance since the early 1990s (Bulletin of Yangtze River Sediment 2000). The channel morphology achieved the corresponding adjustment and maintained a dynamic equilibrium during 1994–2002

Downloaded from https://iwaponline.com/hr/article-pdf/47/S1/161/366949/nh047s10161.pdf
by guest
on 15 August 2018

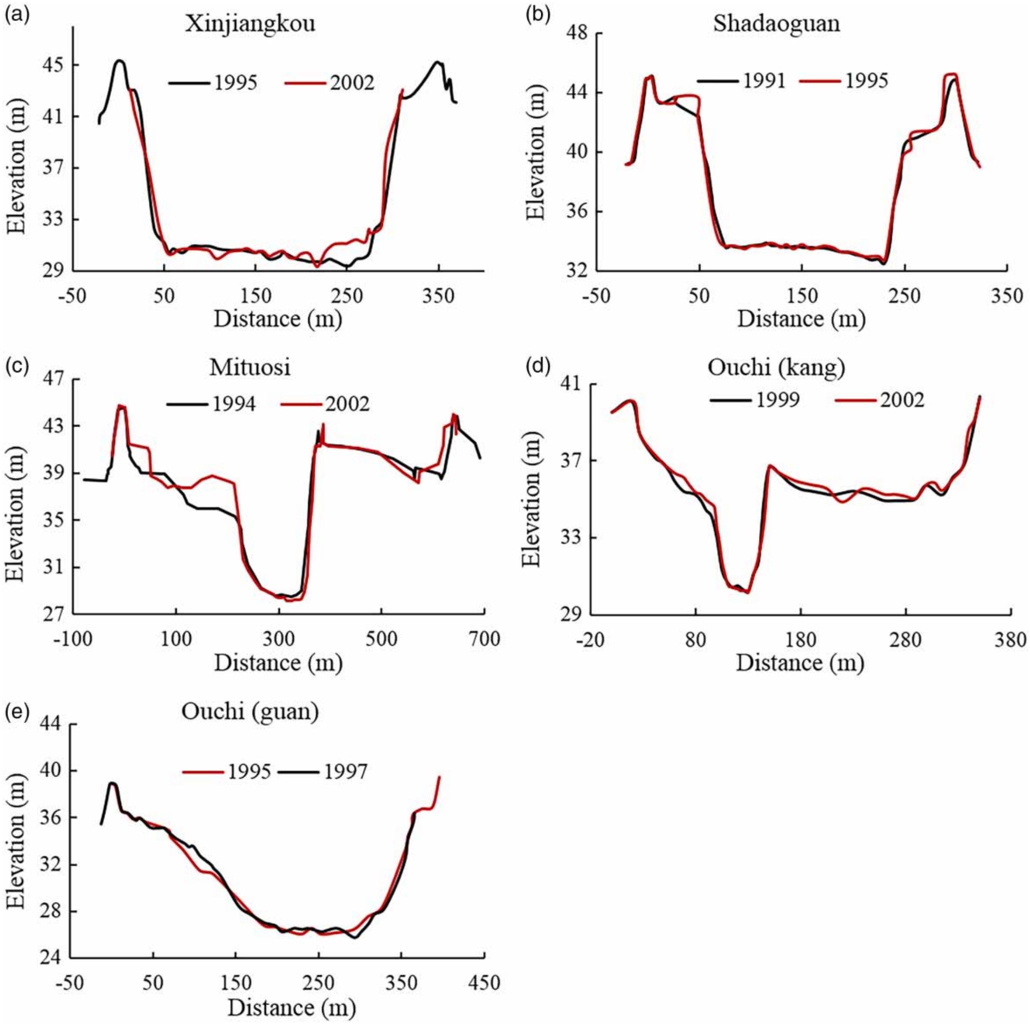

Figure 3 | Cross-sectional channel profiles of the five control stations of the JTO. (a) Xinjiangkou, (b) Shadaoguan, (c) Mituosi, (d) Ouchi (kang), and (e) Ouchi (guan).

under the influence of climate and human activities (Figure 6).

Normally, the relationship between the water level and the discharge gradually varies under natural conditions (Zhang *et al.* 2015). However, the parameter changes are remarkable after 2003. The rating curves move downward when the discharge is less than 30,000 m^3/s (Figure 6(a)). The channel at the main stream significantly erodes after the TGD operation (Figure 6(b)). Most sediments are trapped in the TGD, and the downstream channel erosion is severe (Yang *et al.* 2014), particularly in the Yichang–Chenglingji reach, after the TGD operation. The average channel erosion depth reaches 2.1 m in the Yichang–Zhicheng reach and 1.1 m in the Jingjiang reach (Lu *et al.* 2011), thereby resulting in a significant water level decrease with the same discharge (Figure 6(a)). Not all of the channel changes of the post-TGD period can be attributed to the TGD. However, many studies have found that the TGD operation is the main driver for the channel change (Dai & Liu 2013). Accordingly, 65–85% of the changes are attributed to the TGD (Yang *et al.* 2014).

Effect of river channel changes on lowering water level

The stable water level–discharge rating curve during 1994–2002 would appropriately estimate the water level under no channel changes after 2003 (Figure 6(a)). The relationship between the water level and the discharge in

Downloaded from https://iwaponline.com/hr/article-pdf/47/S1/161/366949/nh047s10161.pdf
by guest
on 15 August 2018

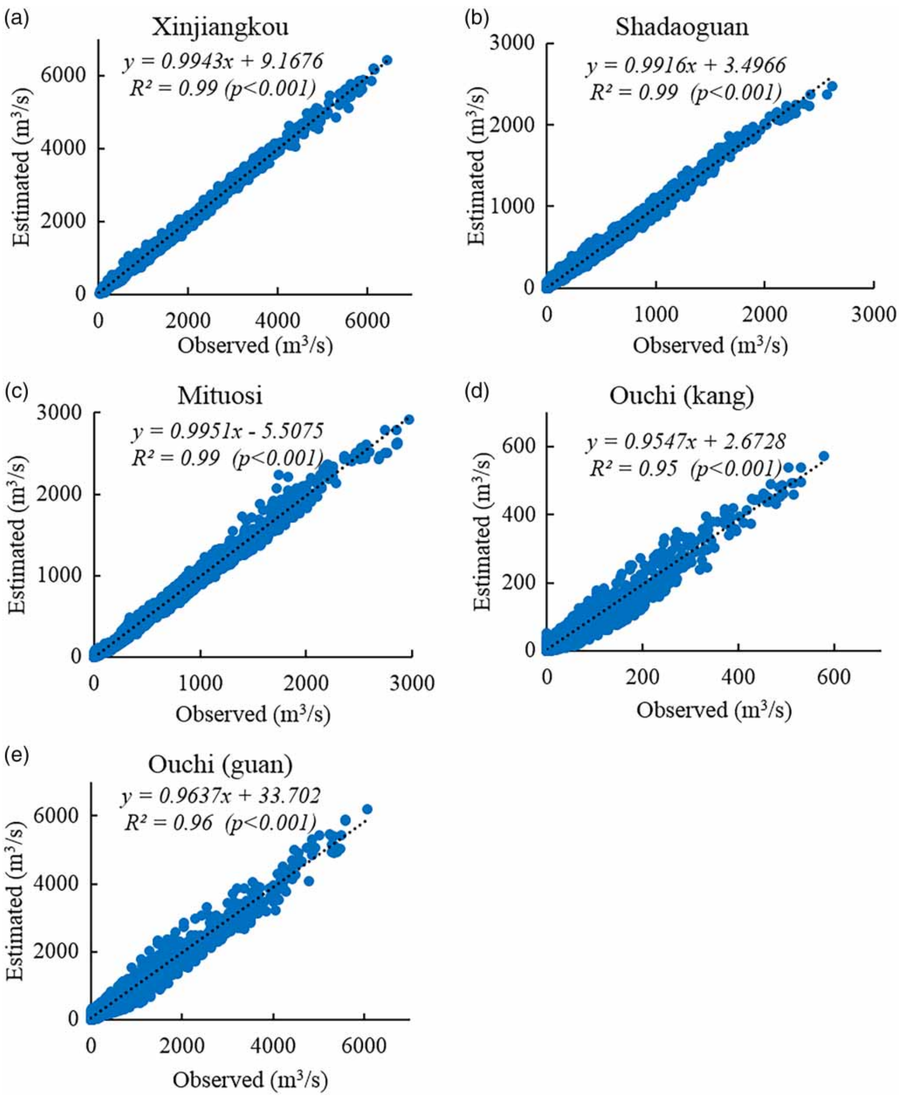

Figure 4 | Observed and estimated daily discharge at the five control stations of the JTO in 1994–2002. (a) Xinjiangkou, (b) Shadaoguan, (c) Mituosi, (d) Ouchi (kang), and (e) Ouchi (guan).

Table 1 | Results of the MK and Pettitt tests for the rating parameters

		MK test		Pettitt test	
Parameter	**Data periods**	***Z***	**Trend**	**Change point**	***p***
$\log a$	1980–2014	5.04**	Increasing	1993	0.004**
b	1980–2014	−5.01**	Increasing	1993	0.004**
h_0	1980–2014	4.596**	Decreasing	1993	0.013*

*Significant at $p < 0.05$.

**Significant at $p < 0.01$.

1994–2002 is obtained by a regression analysis (Figure 6(a)).

$$L = 6\times10^{-14}Q^3 - 8\times10^{-9}Q^2 + 0.0005Q + 33.893 \qquad (16)$$

where L is the water level (m) and Q is water discharge (m^3/s).

The regression equations were used to predict the water level of the same series (1994–2002) and to evaluate the reliability of the predicted results using this method. The comparison between the estimated and observed values in

Downloaded from https://iwaponline.com/hr/article-pdf/47/S1/161/366949/nh047s10161.pdf
by guest
on 15 August 2018

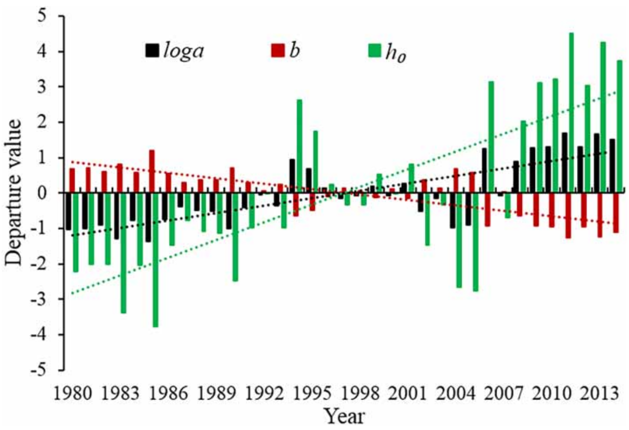

Figure 5 | Departure value of the water level–discharge rating parameters at Zhicheng in 1980–2014.

1994–2002 indicates that the estimated water level explains 98.41% of the observed water level variance within the 99.99% confidence level (Figure 7). Therefore, the daily water levels under no channel changes after 2003 at Zhicheng can be calculated using regression Equation (16).

Figure 8 reveals the effects of the river channel changes on lowering the water level with the same discharge at Zhicheng in 2003–2014. The observed daily water levels at the same discharge are lower than the estimated values from May to October. The channel incision causes the water levels to decline by 0.12–0.80 m. The channel erosion is mainly observed in the middle and low water levels (Figure 6-(b)), and causes different amplitudes in different months (Figure 8). The channel changes at the low and middle water levels result in an obvious decline in water level. Meanwhile, the drops at the high water levels are relatively small.

Effect of the river channel changes on the amount of discharge diversion

The estimated daily water levels of the post-TGD at Zhicheng under no channel changes are expressed in Equations (11)–(15). Therefore, the daily discharge diversion in 2003–2014 without the channel changes is estimated (Figure 9). The observed discharges at the five control stations are lower than the estimated values. The channel changes cause the amount of discharge diversion at the five control stations to decrease by 2.89%, 4.14%, 18.83%, 39.99%, and 16.32%.

The various outlets present distinct reductions in discharge diversion (Figure 9) because of the channel morphology at the different outlets, which exhibits different change patterns (Figure 2). The water level with the same discharge at Xinjiangkou decreases from 2003 to 2012, which indicates channel erosion (Figure 2). By contrast, the rating curves remain relatively stable at Shadaoguan, which suggests no obvious channel changes. The rating curves for Mituosi, Ouchi (kang), and Ouchi (guan) dramatically shift upward because of channel deposition. The results suggest that the deposition of the diversion channels under the same main stream conditions aggravates the reduction of the water-level differences between the main stream and the JTO and leads to a decrease in discharge diversion. The erosion relieves the reduction of the water-level differences and increases the discharge diversion.

The comparison of the estimated and observed values in 2003–2014 shows that the channel changes cause the total

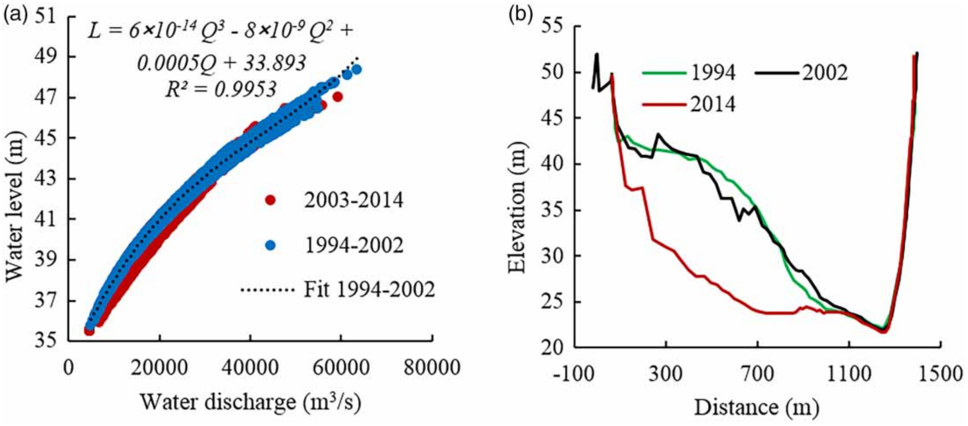

Figure 6 | Water level–discharge rating curves (a) and cross-sectional channel profiles (b) at Zhicheng in 1994–2014.

Downloaded from https://iwaponline.com/hr/article-pdf/47/S1/161/366949/nh047s10161.pdf
by guest
on 15 August 2018

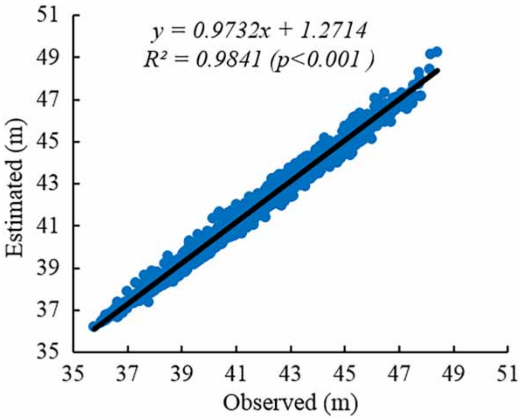

Figure 7 | Comparison of the estimated and observed water levels during training period of 1994–2002 at Zhicheng.

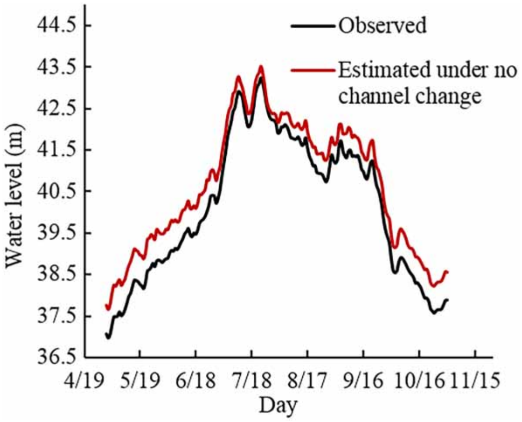

Figure 8 | Effects of the river channel changes on lowering water level with the same discharge at Zhicheng during 2003–2014.

discharge diversion to decrease by 326.78 m^3/s (Figure 10). The observed amount of discharge diversion in 2003–2014 decreases by 865.89 m^3/s (Figure 10) compared with that in 1994–2002; only 37.74% of which can be attributed to the channel changes. Nearly 62.26% of the amount of discharge diversion decrease should be attributed to the hydrological variations of the main stream. The streamflow changes in the Yangtze River are mainly the result of spatial and temporal distribution of precipitation (Chen *et al.* 2014). Precipitation exhibited a significantly increasing trend and was the most abundant during the 1990s, but exhibited a significantly decreasing trend during the 2000s (Zhao *et al.* 2015). Meanwhile, the seasonal precipitations show that the spring and autumn seasons exhibit a decreasing trend, whereas the summer and winter seasons show an increasing trend (Zhang & Cong 2014b). In addition, the inner-annual water discharge and impounding of the TGD affect the streamflow distribution in the wet and dry seasons (Gao *et al.* 2013). Therefore, the reduction and seasonal changes in precipitation and reservoir operations alter the amount of discharge diversion in the wet and dry seasons. The amount of discharge diversion would probably change further under the reduction and seasonal changes in precipitation, and the reservoir operation. Therefore, further study is needed to explore the specific influences of hydrological variation on the discharge diversion.

At the same time, the amount of discharge diversion accounts for approximately 31% of the total discharge into the Dongting Lake (Liu *et al.* 2011), which is closely related to the water level and area variations of the lake. Thus, the changes in the amount of discharge diversion would significantly influence the lake ecosystem. Therefore, further work should be conducted to detect the corresponding influences of hydrological alteration on the lake ecosystem.

Effect of the river channel changes on the discharge diversion ratio

Table 2 shows the discharge diversion ratio of the main stream at Zhicheng to the JTO from 1994 to 2014. The discharge diversion ratio at the JTO can reflect the interactive strength between the Yangtze River and the Dongting Lake. The observed total discharge diversion ratio is 17.31% and 15.11% in 1994–2002 and 2003–2014, respectively. The estimated total discharge diversion ratio under no channel changes is 16.79% in 2003–2014. The observed total discharge diversion ratio in 2003–2014 decreases by approximately 2.20% compared with that in 1994–2002. The channel changes reduce the total decrease of the discharge diversion ratio to 1.68% (Table 2), which is nearly 76.36% of the total decrease of the discharge diversion ratio in 2003–2014. This result reveals that the channel changes are the major factor that affects the decrease of the discharge diversion ratio after the TGD operation. This result is also consistent with the perspectives obtained from several previous studies (Chang *et al.* 2010; Lu *et al.* 2012).

Downloaded from https://iwaponline.com/hr/article-pdf/47/S1/161/366949/nh047s10161.pdf
by guest
on 15 August 2018

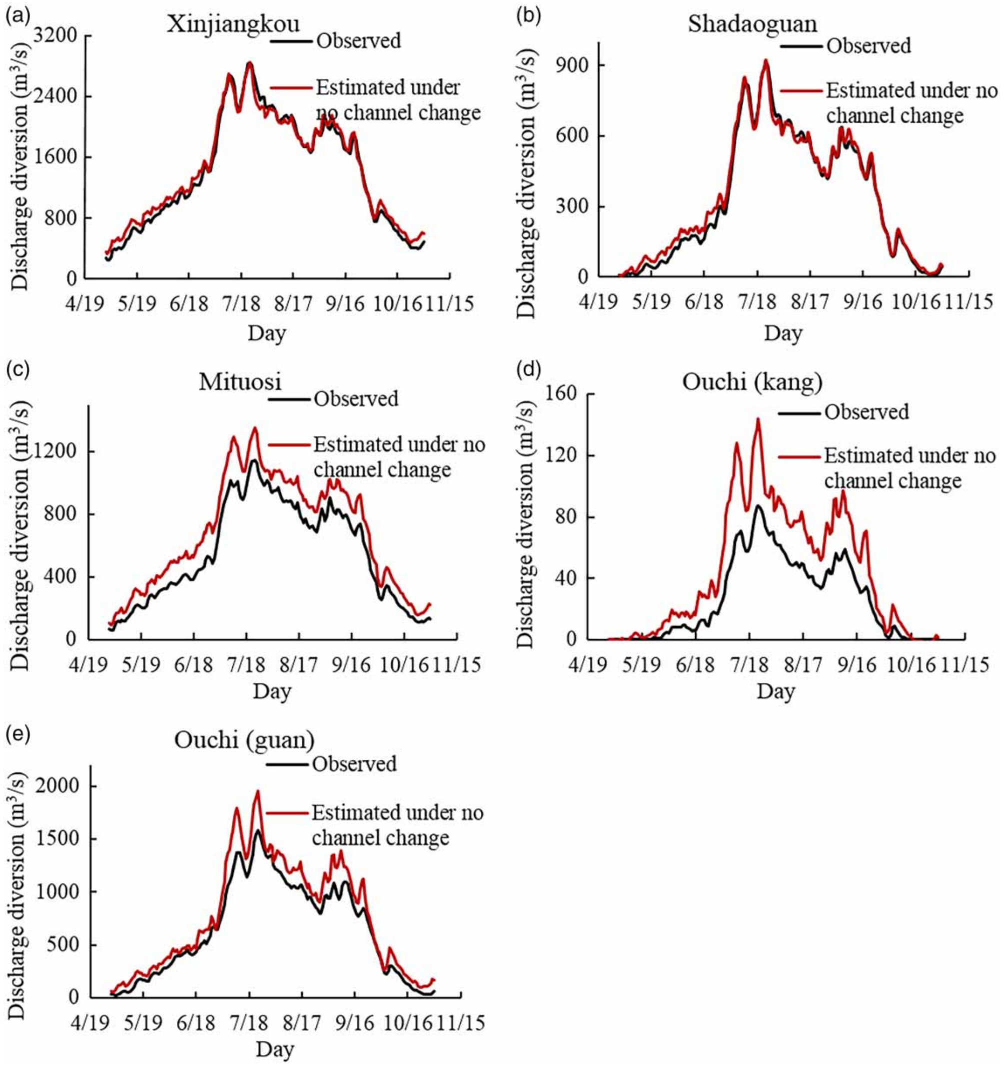

Figure 9 | Effects of the river channel changes on the amount of discharge diversion at the JTO during 2003–2014.

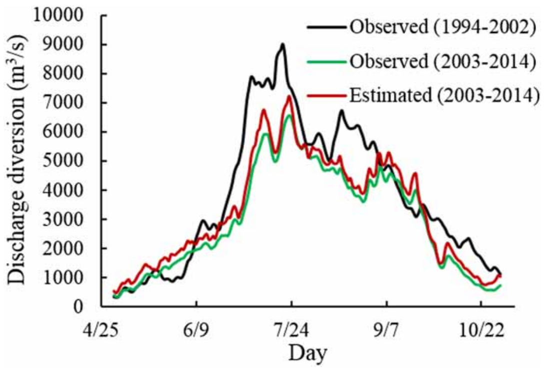

Figure 10 | Amount of discharge diversion at the JTO in different periods. 'Estimated' represents the discharge diversion under no channel change.

The changes in the discharge diversion ratio at different control hydrological stations display different amplitudes (Table 2). The channel changes in 2003–2014 result in average reductions of discharge diversion ratios of 2.58%, 4.76%, 23.84%, 69.23%, and 20.06% in comparison with the observed discharge diversion ratio.

Overall, the analysis shows that the channel changes have not yet significantly affected the discharge diversion ratio. However, channel erosion and incision downstream of the TGD are expected to continue to occur in the foreseeable future (Gao *et al.* 2015b, 2015c), thereby further lowering the water level with the same discharge. The channel

Downloaded from https://iwaponline.com/hr/article-pdf/47/S1/161/366949/nh047s10161.pdf
by guest
on 15 August 2018

Table 2 | Comparison of the observed and estimated discharge diversion ratios in 2003–2014

	Xinjiangkou (%)		**Shadaoguan (%)**		**Mituosi (%)**		**Ouchi (kang) (%)**		**Ouchi (guan) (%)**		**Total (%)**	
Year	**Obs**	**Est**	**Obs**	**Est**	**Obs**	**Est**	**Obs**	**Est**	**Obs**	**Est**	**Obs**	**Est**
1994–2002	**7.46**	**7.46**	**1.90**	**1.89**	**3.51**	**3.46**	**0.26**	**0.26**	**4.19**	**4.18**	**17.31**	**17.26**
2003	7.34	7.94	2.04	2.22	3.09	3.76	0.21	0.31	3.81	4.73	16.50	18.96
2004	7.52	7.74	1.83	1.82	3.18	3.69	0.15	0.22	3.32	4.01	16.00	17.49
2005	8.22	8.00	2.18	2.09	3.43	3.78	0.20	0.28	3.90	4.53	17.94	18.68
2006	5.14	5.76	0.53	0.63	1.73	2.30	0.02	0.04	1.46	1.84	8.89	10.57
2007	7.64	7.75	1.89	2.02	3.04	3.59	0.18	0.28	3.72	4.43	16.46	18.08
2008	7.31	7.64	1.72	1.82	2.86	3.60	0.12	0.22	3.39	3.95	15.41	17.22
2009	6.89	7.54	1.62	1.75	2.84	3.52	0.11	0.21	3.05	3.83	14.51	16.85
2010	7.87	7.78	1.93	1.95	3.30	3.68	0.18	0.25	4.07	4.22	17.35	17.88
2011	6.23	6.47	0.95	1.08	1.94	2.83	0.03	0.10	1.87	2.59	11.02	13.07
2012	8.35	8.08	2.10	2.16	3.12	3.83	0.18	0.29	3.94	4.67	17.70	19.05
2013	7.10	7.34	1.49	1.64	2.45	3.41	0.06	0.19	2.76	3.61	13.85	16.19
2014	7.49	7.88	1.90	1.95	2.67	3.76	0.10	0.24	3.56	4.20	15.71	18.03
2003–2014	**7.26**	**7.45**	**1.68**	**1.76**	**2.81**	**3.48**	**0.13**	**0.22**	**3.24**	**3.89**	**15.11**	**16.79**

'Obs' represents the actual discharge diversion ratio. 'Est' represents the discharge diversion ratio under no channel change.

deposition at the JTO entrance will also continue to occur (Lu *et al.* 2012). In the future, the discharge diversion ratio may inevitably decrease, which could increase the flood pressure of the lower reaches during the flood season. Thus, the flood diversion program downstream of the Yangtze River should be considered.

CONCLUSIONS

This study aims to detect the responses of the discharge diversion at the JTO to the significant channel changes that occurred at the main stream and the JTO after the TGD operation. The major findings are as follows:

(1) The channel morphology changed tremendously based on the rating curves and cross-sectional channel profile analysis after the TGD operation. The channel incision at Zhicheng resulted in a significant decline of water level with the same discharge. By contrast, the channel deposition at the JTO caused the water level to rise with the same discharge.

(2) Only 37.74% of the amount of discharge diversion decrease was attributed to the channel changes in 2003–2014. The hydrological variations of the main stream are the dominant factor in decreasing the amount of discharge diversion after the TGD operation.

(3) The discharge diversion ratio decreased by 2.20%, nearly 76.36% of which was attributed to the channel changes after the TGD operation. The channel changes were the primary factor in facilitating the discharge diversion ratio decrease. The discharge diversion ratio will inevitably further reduce in the near future with the continuous channel erosion at the main stream and the channel deposition at the JTO. This result will potentially increase the flood pressure for the lower reaches in the flood season. Hence, the flood diversion program downstream of the Yangtze River should be considered.

ACKNOWLEDGEMENTS

This work is supported by the National Key Basic Research Program of China (973 Program) (2012CB417006) and the National Natural Science Foundation of China (No. 41571107 and No. 41601041). We thank Prof. J. H. Gao for his detailed and helpful comments on the manuscript.

Downloaded from https://iwaponline.com/hr/article-pdf/47/S1/161/366949/nh047s10161.pdf
by guest
on 15 August 2018

We also gratefully acknowledge the constructive and valuable comments of two anonymous reviewers who have helped to improve the quality of this manuscript.

REFERENCES

Bormann, H., Pinter, N. & Elfert, S. 2011 Hydrological signatures of flood trends on German rivers: flood frequencies, flood heights and specific stages. *J. Hydrol.* **404**, 50–66.

Bulletin of Yangtze River Sediment 2000 Press of Ministry of Water Resources of the People's Republic of China.

Chang, J., Li, J. B., Lu, D. Q., Zhu, X., Lu, C. Z., Zhou, Y. Y. & Deng, C. X. 2010 The hydrological effect between Jingjiang River and Dongting Lake during the initial period of Three Gorges Project operation. *J. Geogr. Sci.* **20** (5), 771–786.

Chen, J., Wu, X. D., Finlayson, B. L., Webber, M., Wei, T. Y. & Li, M. T. 2014 Variability and trend in the hydrology of the Yangtze River, China: annual precipitation and runoff. *J. Hydrol.* **513**, 403–412.

Csiki, S. & Rhoads, B. L. 2014 Influence of four run–of–river dams on channel morphology and sediment characteristics in Illinois, USA. *Geomorphology* **206**, 215–229.

Dai, S. B. & Lu, X. X. 2014 Sediment load change in the Yangtze River (Changjiang): a review. *Geomorphology* **215**, 60–73.

Dai, Z. J. & 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). *J. Hydrol.* **480**, 10–18.

Ding, X. W. & Li, X. F. 2011 Monitoring of the water–area variations of Lake Dongting in China with ENVISAT ASAR images. *Int. J. App. Earth. Obs.* **13**, 894–901.

Duan, G. W. 2012 *Study on the Different Computation Patterns on Riverbed Erosion and Deposition Amount*. PhD Dissertation, Wuhan University, Wuhan (in Chinese with English abstract).

Duan, W. L., Takara, K., He, B., Luo, P. P., Nover, D. & Yamashiki, Y. 2013 Spatial and temporal trends in estimates of nutrient and suspended sediment loads in the Ishikari River, Japan, 1985 to 2010. *Sci. Total Environ.* **461**, 499–508.

Duan, W. L., He, B., Takara, K., Luo, P. P., Nover, D. & Hu, M. C. 2015 Modeling suspended sediment sources and transport in the Ishikari River basin, Japan, using SPARROW. *Hydrol. Earth Syst. Sci.* **19**, 1293–1306.

Gao, B., Yang, D. W. & Zhao, H. B. 2013 Impact of the Three Gorges Dam on flow regime in the middle and lower Yangtze River. *Quatern. Int.* **304**, 43–50.

Gao, J. H., Jia, J. J., Kettner, A. J., Xing, F., Wang, Y. P., Xu, X. N. & Yang, Y. 2014 Changes in water and sediment exchange between the Changjiang River and Poyang Lake under natural and anthropogenic conditions, China. *Sci. Total. Environ.* **481**, 542–553.

Gao, J. H., Xu, X. N., Jia, J. J., Kettner, A. J., Xing, F., Wang, Y. P., Yang, Y., Zou, X. Q., Gao, S., Qi, S. H. & Liao, F. Q. 2015a A numerical investigation of freshwater and sediment discharge variations of Poyang Lake catchment, China over the last 1000 years. *The Holocene* **25** (9), 1470–1482.

Gao, J. H., Jia, J. J., Kettner, A. J., Xing, F., Wang, Y. P., Li, J., Bai, F. L., Zou, X. Q. & Gao, S. 2015b Reservoir-induced changes to fluvial fluxes and their downstream impacts on sedimentary processes: the Changjiang (Yangtze) River, China. *Quatern. Int.* (in press).

Gao, J. H., Jia, J. J., Wang, Y. P., Yang, Y., Li, J., Bai, F., Zou, X. & Gao, S. 2015c Variations in quantity, composition and grain size of Changjiang sediment discharging into the sea in response to human activities. *Hydrol. Earth Syst. Sci.* **19**, 645–655.

Haghighi, T. A., Marttila, H. & Kløve, B. 2014 Development of a new index to assess river regime impacts after dam construction. *Glob. Planet. Chang.* **122**, 186–196.

Hu, Y. X., Huang, J. L., Du, Y., Han, P. P., Wang, J. L. & Huang, W. 2015 Monitoring wetland vegetation pattern response to water–level change resulting from the Three Gorges Project in the two largest freshwater lakes of China. *Ecol. Eng.* **74**, 274–285.

Hudson, P. F., Middelkoop, H. & Stouthamer, E. 2008 Flood management along the lower Mississippi and Rhine rivers (The Netherlands) and the continuum of geomorphic adjustment. *Geomorphology* **101**, 209–236.

Jalbert, J., Mathevet, T. & Favre, A. C. 2011 Temporal uncertainty estimation of discharges from rating curves using a variographic analysis. *J. Hydrol.* **397**, 83–92.

Kendall, M. G. 1975 *Rank Correlation Methods*. Griffin, London, UK.

Khasraghia, M. M., Sefidkouhia, M. A. G. & Valipour, M. 2015 Simulation of open- and closed-end border irrigation systems using SIRMOD. *Arch. Agron. Soil. Sc.* **61** (7), 929–941.

Leon, J. G., Calmant, S., Seyler, F., Bonnet, M. P., Cauhope, M., Frappart, F., Filizola, N. & Fraizy, P. 2006 Rating curves and estimation of average water depth at the upper Negro River based on satellite altimeter data and modeled discharges. *J. Hydrol.* **328**, 481–496.

Li, Q. F., Yu, M. X., Lu, G. B., Cai, T., Bai, X. & Xia, Z. Q. 2011 Impacts of the Gezhouba and Three Gorges reservoirs on the sediment regime in the Yangtze River, China. *J. Hydrol.* **403**, 224–233.

Liu, K. B., Chong, Z. T. & Luan, Z. Y. 2011 Runoff from Yangtze River into Dongting Lake though four inlets. *J. Hydroelectric Eng.* **30** (5), 16–19 (in Chinese with English abstract).

Lu, J. Y., Yue, H. & Wang, J. 2011 The analysis on reservoir sediment deposition and downstream river channel scouring after impoundment and operation of TGP. *Eng. Sci.* **9** (3), 113–120.

Lu, J. Y., Yao, S. M., Shao, X. J. & Zhang, X. B. 2012 *Response Process of Downstream River–Lake Relation after the Early Operation of the Three Gorges Project*. Science Press, Shanghai (in Chinese).

Mann, H. B. 1945 Nonparametric tests against trend. *Econometrica* **13**, 245–259.

Downloaded from https://iwaponline.com/hr/article-pdf/47/S1/161/366949/nh047s10161.pdf
by guest
on 15 August 2018

Nakayama, T. & Shankman, D. 2013 Impact of the Three–Gorges Dam and water transfer project on Changjiang floods. *Glob. Planet. Chang.* **100**, 38–50.

Petaccia, G. & Fenocchi, A. 2015 Experimental assessment of the stage–discharge relationship of the Heyn siphons of Bric Zerbino dam. *Flow. Meas. Instrum.* **41**, 36–40.

Pettitt, A. 1979 A non-parametric approach to the change-point problem. *Appl. Stat.* **28** (2), 126–135.

Segura-Beltrán, F. & Sanchis-Ibor, C. 2013 Assessment of channel changes in a Mediterranean ephemeral stream since the early twentieth century. The Rambla de Cervera, eastern Spain. *Geomorphology* **201**, 199–214.

Syvitski, J. P. M., Vörösmarty, C. J., Kettner, A. J. & Green, P. 2005 Impact of humans on the flux of terrestrial sediment to the global coastal ocean. *Science* **308**, 376–380.

Tealdi, S., Camporeale, C. & Ridolfi, L. 2011 Modeling the impact of river damming on riparian vegetation. *J. Hydrol.* **396**, 302–312.

Valipour, M. 2012 Comparison of surface irrigation simulation models: full hydrodynamic, zero inertia, kinematic wave. *J. Agr. Sci.* **4** (12), 68–74.

Valipour, M. 2015a Long-term runoff study using SARIMA and ARIMA models in the United States. *Meteorol. Appl.* **22**, 592–598.

Valipour, M. 2015b Surface irrigation simulation models: a review. *Int. J. Hydrol. Sci. Tech.* **5** (1), 51–70.

Valipour, M. 2016 Optimization of neural networks for precipitation analysis in a humid region to detect drought and wet year alarms. *Meteorol. Appl.* **23**, 91–100.

Valipour, M., Banihabib, M. E. & Behbahani, S. M. R. 2013 Comparison of the ARMA, ARIMA, and the autoregressive artificial neural network models in forecasting the monthly inflow of Dez dam reservoir. *J. Hydrol.* **476**, 433–441.

Wang, J. D., Sheng, Y. W., Gleason, C. J. & Wada, Y. 2013 Downstream Yangtze River levels impacted by Three Gorges Dam. *Environ. Res. Lett.* **8**, 044012.

Wolfs, V. & Willems, P. 2014 Development of discharge-stage curves affected by hysteresis using time varying models, model trees and neural networks. *Environ. Modell. Softw.* **55**, 107–119.

Xia, J. Q., Zong, Q. L., Deng, S. S., Xu, Q. X. & Lu, J. Y. 2014 Seasonal variations in composite riverbank stability in the Lower Jingjiang Reach, China. *J. Hydrol.* **519**, 3664–3673.

Xu, K. H. & Milliman, J. D. 2009 Seasonal variations of sediment discharge from the Yangtze River before and after impoundment of the Three Gorges Dam. *Geomorphology* **104**, 276–283.

Yang, S. L., Milliman, J. D., Xu, K. H., Deng, B., Zhang, X. Y. & Luo, X. X. 2014 Downstream sedimentary and geomorphic impacts of the Three Gorges Dam on the Yangtze River. *Earth. Sci. Rev.* **138**, 469–486.

Yue, S., Pilon, P., Phinney, B. & Cavadias, G. 2002 The influence of autocorrelation on the ability to detect trend in hydrological series. *Hydrol. Process.* **16**, 1807–1829.

Zhang, X. Y. & Cong, Z. T. 2014b Trends of precipitation intensity and frequency in hydrological regions of China from 1956 to 2005. *Glob. Planet. Chang.* **117**, 40–51.

Zhang, Q., Xu, C. Y., Jiang, T. & Wu, Y. J. 2007 Possible influence of ENSO on annual maximum streamflow of the Yangtze River, China. *J. Hydrol.* **333**, 265–274.

Zhang, Q., Ye, X. C., Werner, A. D., Li, Y. L., Yao, J., Li, X. H. & Xu, C. Y. 2014a An investigation of enhanced recessions in Poyang Lake: comparison of Yangtze River and local catchment impacts. *J. Hydrol.* **517**, 425–434.

Zhang, W., Wang, W. G., Zheng, J. H., Wang, H. G., Wang, G. & Zhang, J. S. 2015 Reconstruction of stage–discharge relationships and analysis of hydraulic geometry variations: the case study of the Pearl River Delta, China. *Glob. Planet. Chang.* **125**, 60–70.

Zhao, Y. F., Zou, X. Q., Gao, J. H., Xu, X. W., Wang, C. L., Tang, D. H., Wang, T. & Wu, X. W. 2015 Quantifying the anthropogenic and climatic contributions to changes in water discharge and sediment load into the sea: a case study of the Yangtze River, China. *Sci. Total. Environ.* **536**, 803–812.

Zhu, L. L., Chen, J. C., Yuan, J. & Dong, B. J. 2015 Study on variation trends of flow diversion from Jingjiang River to Dongting Lake. *J. Hydroelectric Eng.* **34** (2), 103–111 (in Chinese with English abstract).

First received 4 January 2016; accepted in revised form 9 May 2016. Available online 5 July 2016

Downloaded from https://iwaponline.com/hr/article-pdf/47/S1/161/366949/nh047s10161.pdf
by guest
on 15 August 2018