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Study of the Three Gorges Dam's Impact on the Discharge of Yangtze River during Flood Season after Its Full Operation in 2009

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Abstract: The impact of the Three Gorges Dam (TGD) on the discharge after its first operation in 2003 has drawn much attention. Most of the existing research focuses on the TGD's impact after its initial operation in 2003. However, the water level first reached the TGD's maximum water level, 175 m, in September 2009. In this paper, to quantify the TGD's impact during flood season after its full operation in 2009, we created a hydrological model to reconstruct the daily discharge unregulated by the TGD from 2003 to 2018 at the five stations downstream from the TGD. The TGD had an impact on the maximum 1-day discharge and maximum 30-day runoff and the coefficient of variation of the daily discharge, but it had less impact on the flood season runoff and the coefficient of skewness of the daily discharge. Additionally, the TGD was only responsible for 18.3% of the change in the maximum 1-day discharge at the Datong station, which is 1123 km downstream from the TGD. Moreover, the TGD had limited impact on the discharge after its initial operation in 2003, but the impact of the TGD on discharge increased after its full operation in 2009. This study helps to show the TGD's impact on the discharge of the Yangtze River from the Yichang station (43 km downstream from the TGD) to the Datong station.

Keywords: hydrological regime; Three Gorges Dam; flood season; hydrological modelling

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1. Introduction

Since the beginning of the historical record, the development of human society has been plagued by floods and droughts [1,2]. Fortunately, the construction of many large dams and reservoirs has helped human societies resist the flood and drought disasters [3,4]. According to admittedly incomplete statistics, as of April 2020, there were 58,713 large reservoirs in the world [5]. However, the operation of reservoirs can also introduce problems for water resources and human society [6–8]. It is always important to evaluate dams and reservoirs for humans and ecosystems.

The Three Gorges Dam (TGD), one of the largest hydropower plants in the world and one of the largest projects ever built in China, draws much research attention. In recent years, with the accumulation of operational data of the TGD, relevant studies on the impact of the TGD on the Yangtze Basin have gradually progressed. Before the completion and operation of the TGD, the streamflow in the middle reaches of the Yangtze River showed an upward trend and there was a consistent increase in water level from the upper to the lower reaches of the river [9]. However, before and after the completion of the TGD, the precipitation in the Yangtze Basin did not change significantly, so changes in the discharge of Yangtze River were mainly due to the operation of the TGD and other human activity [10–13]. After the completion of the TGD, the impact of the TGD on the lower reaches of the Yangtze River was multifaceted [14–17]. On the one hand, the impoundment of the TGD has significantly changed the annual patterns of water discharge in the lower reaches of the Yangtze River, resulting in significant changes in high flows and low flows [18,19]. Among them, the annual maximum discharge decreased significantly, while the annual minimum discharge increased significantly [20]. The discharge also increased in early summer but decreased in early autumn [21]. On the other hand, the impoundment of the TGD has also had a great impact on the water level in the lower reaches of the Yangtze River [22]. Wang et al. found that, after the impoundment of the TGD, the annual water levels of 15 gauging stations in the lower reaches of the Yangtze River had decreased by 3.9–13.5% due to the scouring of the riverbed, with the water levels declining significantly in autumn and rising significantly in winter and spring [23]. Furthermore, after the operation of the TGD began, when the downstream channel was at a low water level, the water level decreased at a given discharge compared with that before the completion of the TGD. In contrast, when the downstream channel was at a high water level, the water level rose at the same discharge compared with that before the completion of the TGD [24].

The TGD has also exerted a certain degree of influence on the runoff of the Yangtze River. For instance, the amount of water was reduced during the flood period, and the annual patterns of runoff have also changed dramatically, which has significantly reduced the frequency of flood disasters in the lower reaches of the Yangtze River [25,26]. These changes in water level, discharge, and runoff in the lower reaches of the Yangtze River are closely related to the operational rules of the TGD [27]. It is precisely because the TGD stores water in early autumn and releases water in winter and spring that the hydrological characteristics of the lower reaches of the Yangtze River have changed as described above [28,29].

Although existing studies have analyzed the impact of TGD on the Yangtze River from different time scales and different methods, many studies are based on observed discharge series [10,18,24,28], and few studies develop hydrological models to reconstruct the daily discharge unaffected by the TGD or mainly focus on a single gauging station [14,22,27,30], especially the Yichang gauging station, which is only 43 km downstream from the TGD. Moreover, most of them take 2003 as the dividing line for analyzing TGD's impact before and after its operation [15,16,20,31]. In fact, the TGD was initially put into operation by filling the reservoir to a water level of 135 m in June 2003, but the water level reached 175 m in September 2009 [27], which is the TGD's maximum water level.

This study aimed to assess the TGD's impact on the discharge of Yangtze River during the flood season (from May to October) after it began to be fully operational in 2009. A hydrological model based on the Xin'anjiang rainfall–runoff model and the Muskingum routing model was created to reconstruct the daily discharge unaffected by the TGD at the five gauging stations downstream from the TGD from 2003 to 2018. Data on 29 years (1990–2018) of daily discharge of six gauging stations on the mainstream of the Yangtze River and 29-year (1990 to 2018) daily precipitation and evaporation data from 206 meteorological stations in the Yangtze Basin were used to drive the hydrological model. As the Yichang gauging station is only 43 km downstream from the TGD and there is no large tributary or large lake between the TGD and the Yichang gauging station (see Figure 1 and Table 1), it is assumed that the Yichang gauging station is completely controlled by the TGD, and the analysis of this station was used as the standard for assessing the TGD's impact on the other four gauging stations downstream from the TGD. Additionally, to assess the TGD's impact during flood season, the maximum 1-day discharge, the maximum 30-day runoff, the flood season runoff, the coefficient of variation (C_v), and the coefficient of skewness (C_s) during flood season were analyzed.

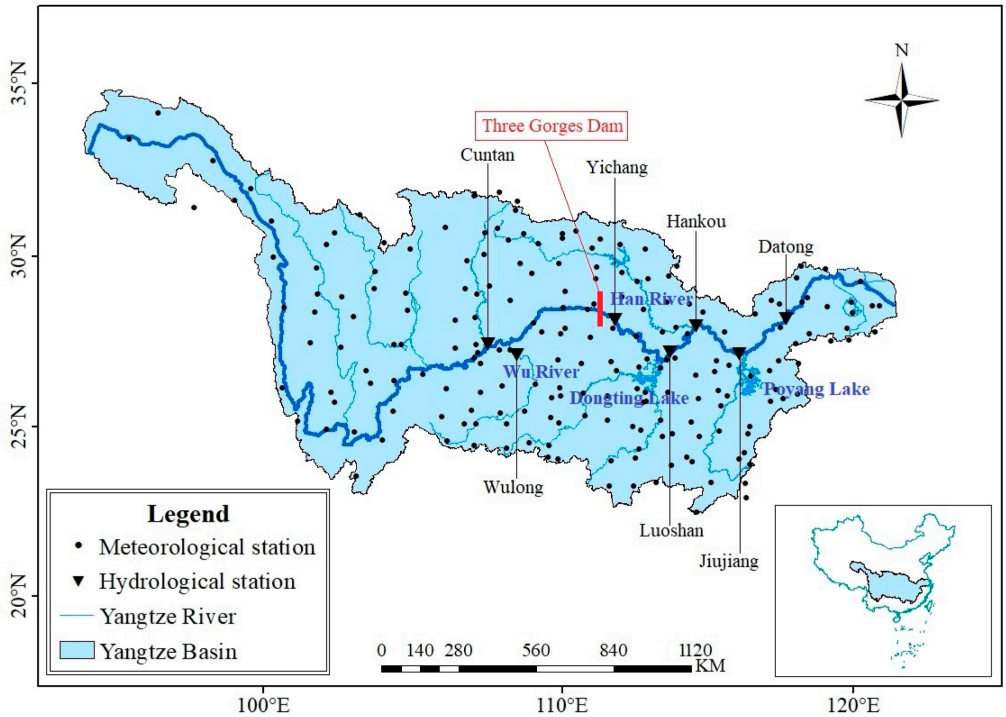

Figure 1. Map showing locations of the Yangtze River (blue thick line), 7 gauging stations (black triangle points), 206 meteorological stations (black circle points), and the Three Gorges Dam (TGD).

Table 1. The distances of the gauging stations from the TGD (km) and their drainage area (km^2). A negative distance value indicates that the gauging station is located upstream from the TGD, and a positive value indicates the gauging station is located downstream from the TGD. (* Wulong gauging station is located on the Wu River, a tributary of the Yangtze River).

Station	Cuntan	Wulong *	Yichang	Luoshan	Hankou	Jiujiang	Datong
Distance	−597	−543	43	452	643	877	1123
Area	866,559	83,035	1,005,501	1,294,911	1,488,036	1,759,349	1,705,383

2. Study Area and Data

2.1. Study Area

The Yangtze River is the longest river in China and is the third longest river in the world, extending from the Tibetan Plateau to Eastern China, spanning a total length of 6300 km and draining an area of 1,800,000 km^2. The Yangtze River basin is divided into three sections: the upper reaches (from the source to Yichang), the middle reaches (from Yichang to Hankou), and the lower reaches (from Hankou to Datong) [20].

2.2. Data

Daily discharge data of the Yangtze River in this study were measured at Cuntan, Wulong, Yichang, Luoshan, Hankou, Jiujiang, and Datong from 1990 to 2018, for a total of 29 years. The locations of these gauging stations are shown in Figure 1. These quality-controlled hydrological data were provided by the Hydrological Bureau of the Yangtze River Water Resources Commission in Wuhan, China. These daily discharge data were used to examine variations in the discharge of the Yangtze River before and after the TGD operation.

The quality-controlled daily precipitation data and daily evaporation data from 206 weather stations across the Yangtze Basin were obtained from the National Meteorological Information Center in China for 1990–2018. These precipitation data and evaporation data were used to drive the hydrological model as input data.

In addition, the distance of the gauging stations from the TGD and the drainage area of these gauging stations (see Table 1) were obtained from the hydrological yearbook published by the Ministry of Water Resources of the People's Republic of China.

3. Methods

3.1. The Xin'anjiang Rainfall–Runoff Model

The Xinanjiang model is a rainfall–runoff, distributed, basin model for use in humid and semi-humid regions [32–35]. The evapotranspiration component is represented by a model of three soil layers. Runoff production occurs on the repletion of storage to capacity values that are assumed to be distributed throughout the basin. Runoff concentration to the outflow of each sub-basin is represented by a unit hydrograph or by a lag and route technique. The damping or routing effects of the channel system connecting the sub-basins are represented by Muskingum routing.

3.2. The Muskingum Routing Model

The Muskingum method of natural streamflow routing is a widely used hydrologic method for routing flood waves in rivers and channels [36]. The overall stream-flow routing procedure is based on the hydrologic continuity equation, which is written as follows:

$$I - Q = \frac{dW}{dt} \tag{1}$$

where I = inflow; Q = outflow; W = channel storage; t = time.

Channel storage is modeled by linear form as follows:

$$W = K[xI + (1-x)Q] \tag{2}$$

where K = storage constant; x = dimensionless weighting factor.

The Muskingum routing model is given as follows:

$$Q_2 = C_0 I_2 + C_1 I_1 + C_2 Q_1 \tag{3}$$

where $C_0 = \frac{0.5\Delta t - Kx}{0.5\Delta t + K - Kx}$; $C_1 = \frac{0.5\Delta t + Kx}{0.5\Delta t + K - Kx}$; $C_2 = \frac{-0.5\Delta t + K - Kx}{0.5\Delta t + K - Kx}$.

3.3. The Hydrological Model for Reconstructing the Discharge Unaffected by the TGD

After the operation of the TGD, gauging stations downstream from the TGD, such as the Yichang gauging station, are affected by the TGD. As the Cuntan gauging station and Wulong gauging station are located on the tail of the Three Gorges Region (see Figure 1), they can be assumed to be unaffected by the TGD [27]. The observed daily discharge of the Cuntan and Wulong gauging station was used as inflow data in this hydrological model to remove the effect of the TGD and reconstruct the discharge.

In this hydrological model [27], daily discharge can be reconstructed by using a linear combination as follows:

$$Q_r = Q_{up} + Q_{LIW} + Q_{RIW} \tag{4}$$

where Q_r is the reconstructed discharge of the gauging station unaffected by the TGD; Q_{up} is the discharge routing from the upstream gauging station; Q_{LIW} and Q_{RIW} are the interval discharge between two gauging stations in the left bank and right bank of the Yangtze River, respectively.

To obtain Q_r, Q_{up} is simulated using the Muskingum routing model; Q_{LIW} and Q_{RIW} are simulated using the Xin'anjiang rainfall–runoff model. A flowchart is shown in Figure 2. To reconstruct the discharge of the Yichang gauging station, first, the observed daily discharge of the Cuntan and Wulong gauging station is processed by the Muskingum routing model to obtain Q_{up}. The observed daily meteorological data is processed by the Xin'anjiang rainfall–runoff model to obtain Q_{LIW} and Q_{RIW}. Finally, Q_r, the reconstructed daily discharge of the Yichang gauging station unaffected by the TGD, can be calculated by the formula. Similarly, the reconstructed daily discharge of the Luoshan gauging station can be calculated in the same way using the reconstructed daily discharge of the Yichang gauging station as inflow. The reconstructed daily discharge of the Hankou, Jiujiang, and Datong gauging stations can also be calculated in the same way.

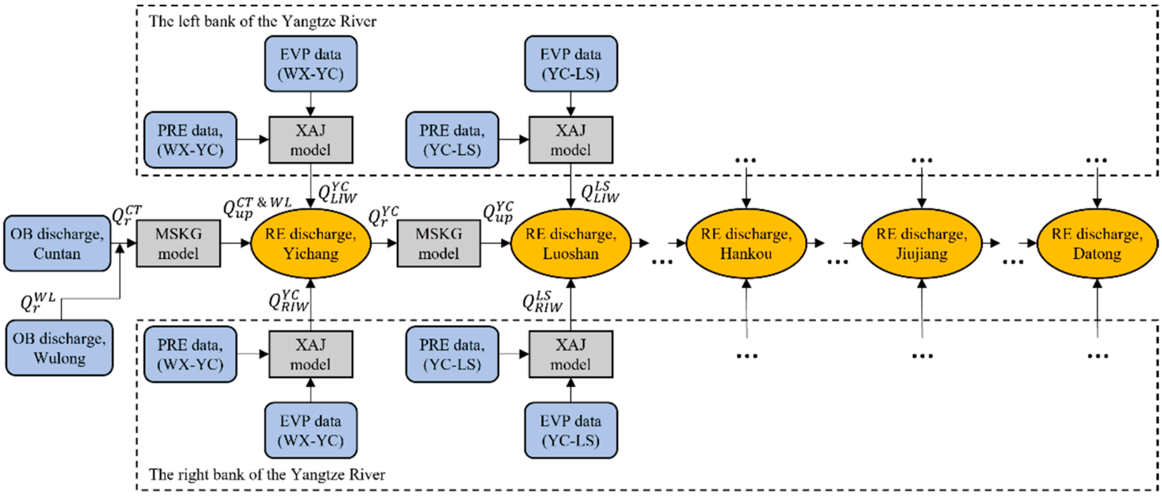

Figure 2. Flowchart of reconstructed discharge modeling in the downstream from the TGD. CT: Cuntan, WL: Wulong, YC: Yichang, LS: Luoshan, HK: Hankou, JJ: Jiujiang, DT: Datong, OB: observed, RE: reconstructed, XAJ model: Xin'anjiang model; MSKG model: Muskingum routing model.

In summary, the hydrological model for a single gauging station's discharge reconstruction requires a total of 16 parameters, including 2 parameters for the Muskingum routing model and 14 parameters for the Xin'anjiang rainfall–runoff model. These model parameters are calibrated by a genetic algorithm [37]. The Nash efficiency coefficient (NSE) is employed to assess the performance of the hydrological model as follows:

$$NSE = 1 - \frac{\sum_{i=1}^{N} \left(Q_i' - Q_i\right)^2}{\sum_{i=1}^{N} \left(Q_i - \overline{Q}\right)^2} \tag{5}$$

where Q_i' (i = 1, 2, . . . , N) is the simulated daily discharge; Q_i (i = 1, 2, . . . , N) is the observed daily discharge; N is the length of daily discharge; $\overline{Q}$ is the mean of the observed daily discharge.

4. Results

4.1. Reconstructing the Flow Downstream the TGD

The hydrological model showed satisfactory performance in simulating the daily discharge downstream from the TGD (see Figures 3–5).

The Nash efficiency coefficient (NSE) of the Yichang gauging station during the calibration period (1 May 1990–31 December 1999) was 0.993. The NSE of the Luoshan gauging station during the calibration period was 0.981. The NSE of the Hankou gauging station during the calibration period was 0.983. The NSE of the Jiujiang gauging station during the calibration period was 0.979. The NSE of the Datong gauging station during the calibration period was 0.973. In summary, the NSEs of the five gauging stations downstream from the TGD during the calibration period were above 0.970 (see Figure 3 and Table 2).

Additionally, the NSE of the Yichang gauging station during the validation period (1 January 2000–31 December 2002) was 0.992. The NSE of the Luoshan gauging station during the validation period was 0.978. The NSE of the Hankou gauging station during the validation period was 0.978. The NSE of the Jiujiang gauging station during the validation period was 0.964. The NSE of the Datong gauging station during the validation period was

0.963. In summary, the NSEs of the five gauging stations downstream from the TGD during the calibration period were above 0.960 (see Figure 4 and Table 2).

Moreover, the NSEs of the five gauging stations during the initial operation of the TGD period (2003–2008) and full operation of the TGD period (2009–2018) were obviously different (see Table 2). The average of the NSEs of the five gauging stations during the initial operation of the TGD period was 0.937, but that of the five gauging stations during the full operation of the TGD period was 0.838. This strengthens the argument that 2009 should be taken as the dividing line for analyzing the TGD's impact before and after its full operation.

The NSEs of the five gauging stations downstream from the TGD during the calibration period and the validation period were all above 0.960. This hydrological model can thus well simulate the Yangtze River's daily discharge.

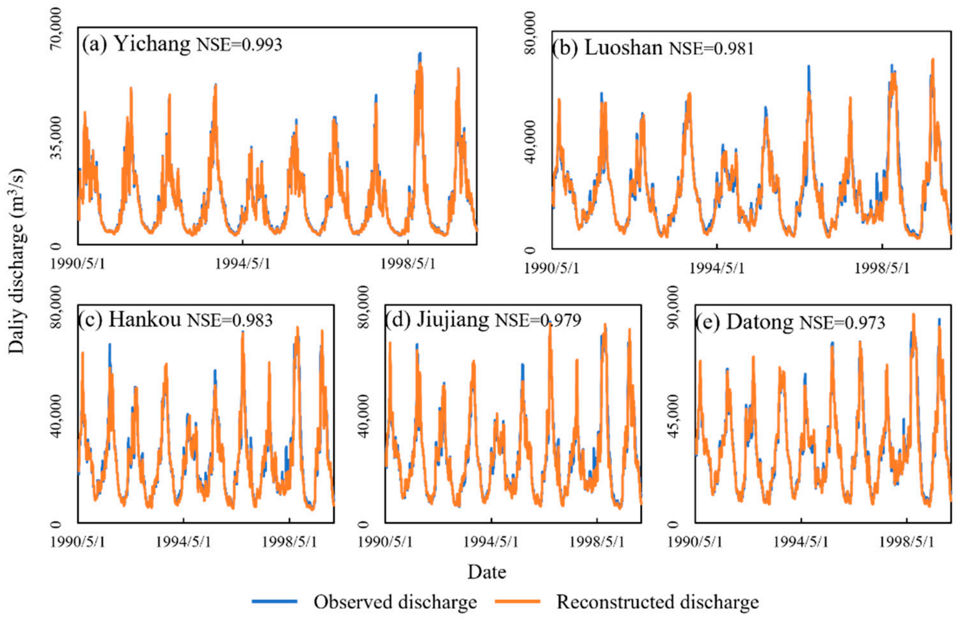

Figure 3. Calibration period from 1 May 1990 to 31 December 1999.

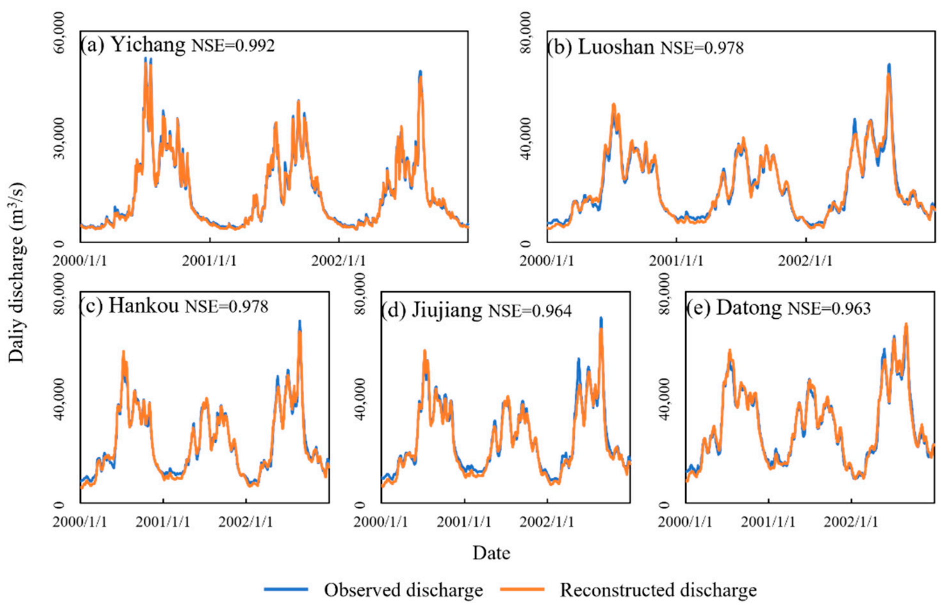

Figure 4. Validation period from 1 January 2000 to 31 December 2002.

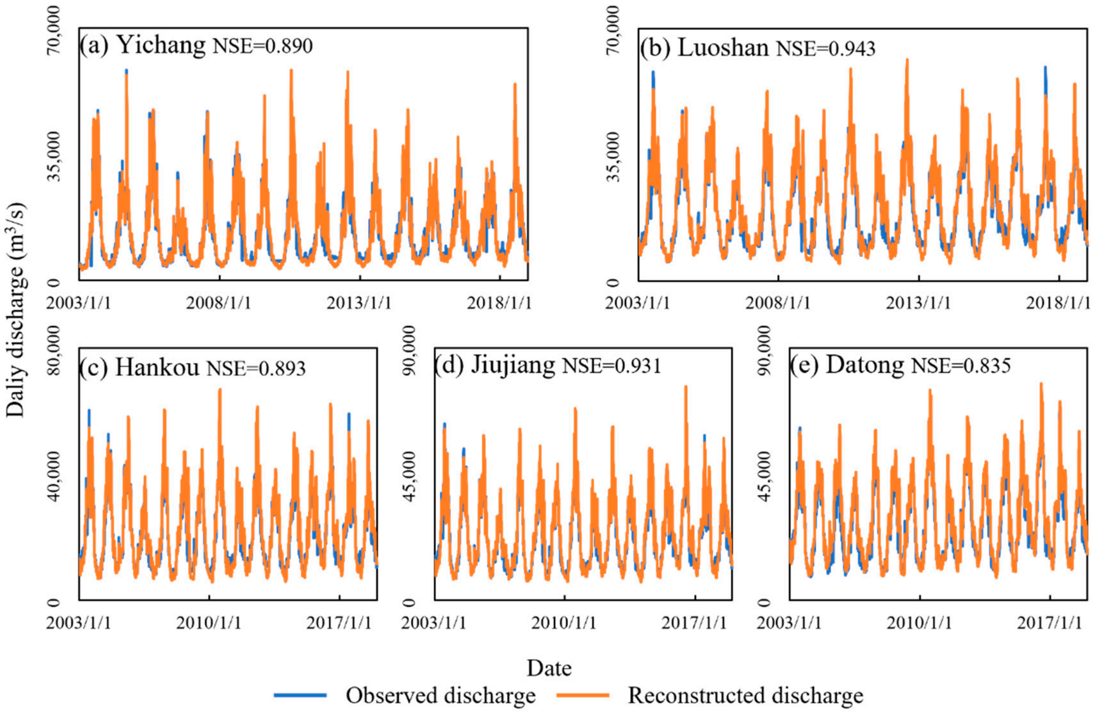

Figure 5. Simulation period from 1 January 2003 to 31 December 2018.

Table 2. The Nash efficiency coefficient (NSE) of different gauging stations during different periods. Calibration period: 1990–1999; validation period: 2000–2002; simulation period: 2003–2018; initial operation of the TGD period: 2003–2008; full operation of the TGD period: 2009–2018.

Period	Yichang	Luoshan	Hankou	Jiujiang	Datong	Average
1990–1999	0.993	0.981	0.983	0.979	0.973	0.982
2000–2002	0.992	0.978	0.978	0.964	0.963	0.975
2003–2018	0.890	0.943	0.893	0.931	0.835	0.898
2003–2008	0.953	0.942	0.952	0.944	0.895	0.937
2009–2018	0.838	0.867	0.852	0.832	0.801	0.838

4.2. Quantifying the TGD's Impact on the Discharge of the Yangtze River during Flood Season

According to the documents published by the China Meteorological Administration, flood season in Yangtze River starts in May and ends in October every year [38]. To quantify the TGD's impact on the discharge of Yangtze River during flood season, it is necessary to contrast the reconstructed daily discharge with the observed daily discharge from different aspects. Therefore, the maximum 1-day discharge, maximum 30-day runoff, flood season runoff, C_v, and C_s are analyzed in this paper.

The TGD's impact on the four gauging stations downstream of the Yichang gauging station is the difference between the reconstructed discharge and the observed discharge at the Yichang gauging station that routed to these stations by the Muskingum model.

In addition to the TGD's impact, there are other impacts on the four gauging stations downstream of the Yichang gauging station. The other impacts include the impacts of the regulation and storage of lakes, reservoirs, and other human activity, such as the Dongting Lake, Poyang lake, Danjiangkou Reservoir, and other reservoirs that are downstream of the TGD. The other impact is the difference between the total impact and the TGD's impact. In addition, the total impact is the difference between the reconstructed discharge and the observed discharge at these stations.

4.2.1. The Maximum 1-Day Discharge during Flood Season

As shown in Figure 6, the reconstructed maximum 1-day discharge of these five gauging stations is obviously larger than the observed maximum 1-day discharge after the full operation of the TGD, which means maximum 1-day discharge fell after the full operation of the TGD. The difference between the reconstructed discharge data and the observed discharge data is also different at different gauging stations. As the distance from gauging station to the TGD becomes longer, the difference is gradually larger.

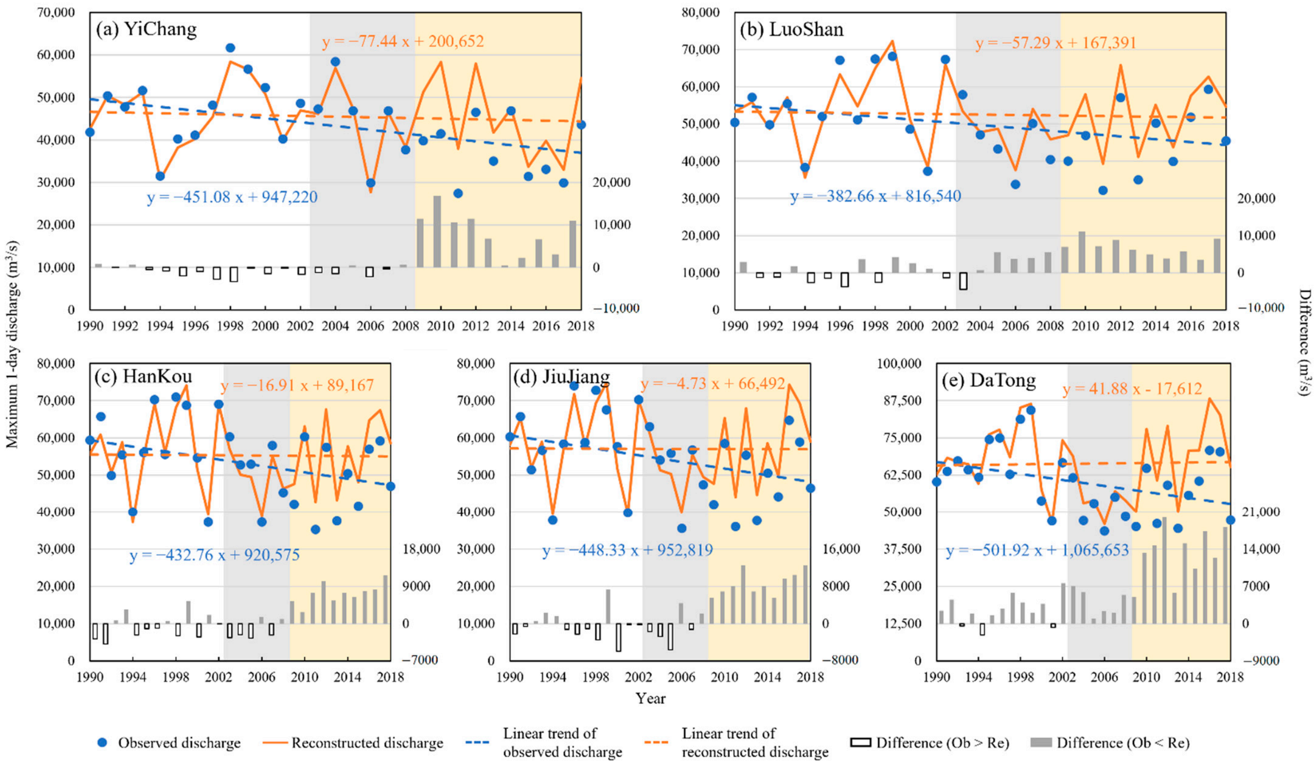

Figure 6. Analysis of the maximum 1-day discharge during flood season in the five gauging stations (the grey zones denote the initial operation period of the TGD from 2003 to 2008, and the yellow zones denote the full operation period of the TGD from 2009 to 2018).

Moreover, the comparison of the maximum 1-day discharge between the five gauging stations from 2009 to 2018 and the comparison of the maximum 1-day discharge during different periods at each station are shown in Figure 7. As shown in Figure 7a, the linear trend line of the Datong gauging station is farther away from the 1:1 line than that of the Yichang gauging station after the full operation of the TGD. The farther away the trend line is from the 1:1 line, the larger the difference between the observed data and the reconstructed data. As shown in Figure 7b–f, the linear trend lines of the five gauging stations after the full operation of the TGD in 2009 are farther away from the 1:1 line than those after the initial operation of the TGD. Although the TGD is thought to be responsible for this difference, the TGD is not the only reason for these differences at the four gauging stations downstream from the Yichang gauging station. The Han River, the Dongting Lake, the Poyang lake, and other reservoirs also have impact on the change in maximum 1-day discharge.

To quantify the TGD's impact on the maximum 1-day discharge of the Yangtze River, the difference between the reconstructed maximum 1-day discharge and the observed maximum 1-day discharge after the full operation of the TGD from 2009 to 2018 at the five gauging stations was calculated (see Table 3). The maximum 1-day discharge at the Yichang gauging station decreased by an average of 8074.7 m^3/s between 2009 and 2018 after the full operation of the TGD. The difference at the Yichang gauging station, 8074.7 m^3/s, was routed to the four gauging stations downstream from the Yichang gauging station using the Muskingum model (see Table 4), and the Yichang gauging station was assumed to be totally controlled by the TGD.

The comparison of the TGD's impact on the maximum 1-day discharge at the five gauging stations is shown in Figure 8. The operation of TGD reduced the maximum 1-day discharge by 50.2%, 40.6%, 34.0%, and 18.3% at the Luoshan, Hankou, Jiujiang, and Datong stations, respectively.

4.2.2. The Maximum 30-Day Runoff during Flood Season

As shown in Figure 9, the reconstructed maximum 30-day runoff is larger than the observed maximum 30-day runoff at these five gauging stations downstream from the TGD. As the distance from gauging station to the TGD becomes longer, the difference is gradually larger.

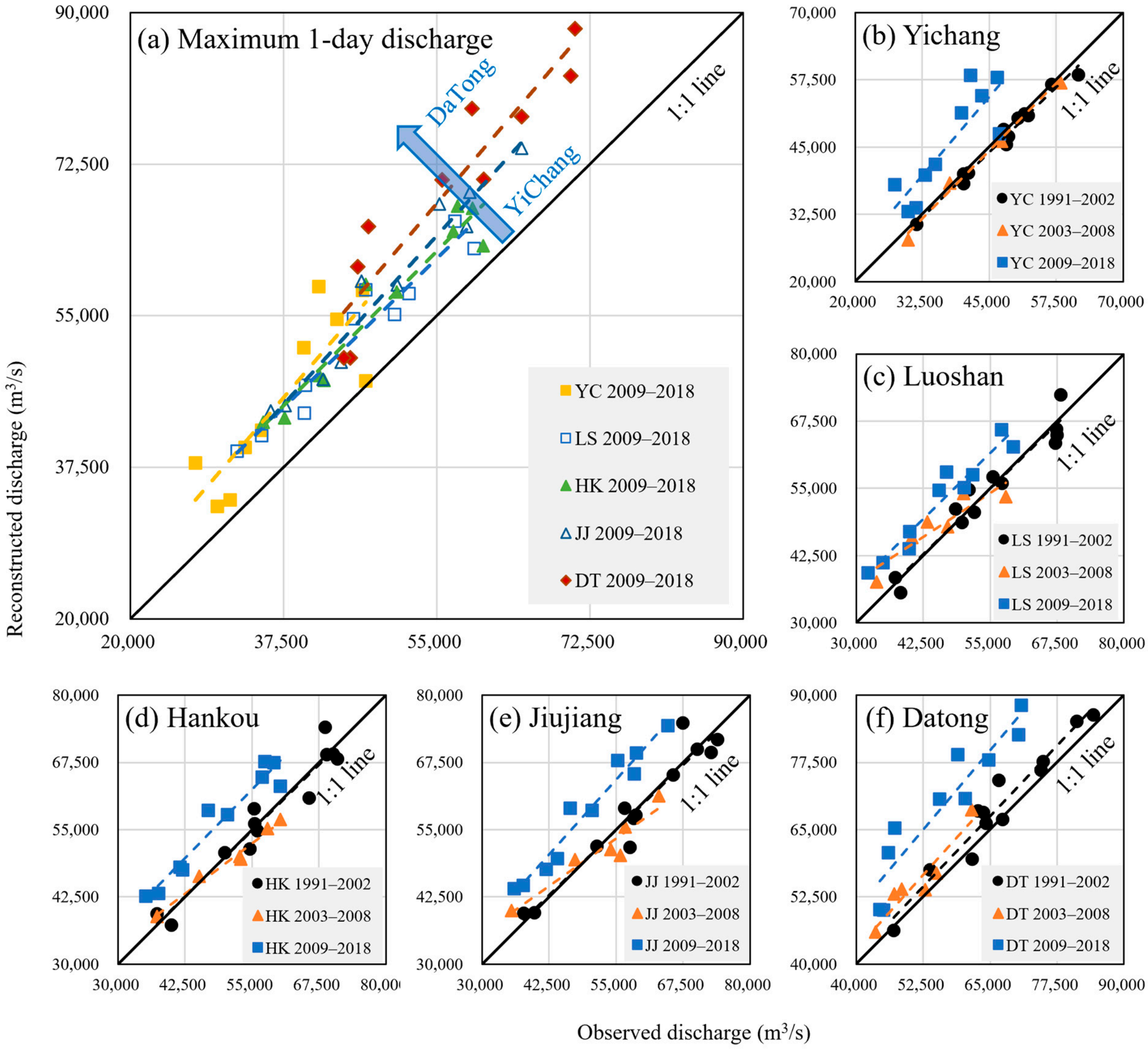

Figure 7. Comparison of the maximum 1-day discharge during flood season between the five gauging stations. If points are above the 1:1 line, the reconstructed discharge is greater than the observed discharge, and the TGD has reduced the maximum 1-day discharge. In contrast, if points are below the 1:1 line, the reconstructed discharge is less than the observed discharge, and the TGD has increased the maximum 1-day discharge.

Table 3. The difference between the reconstructed maximum 1-day discharge and the observed maximum 1-day discharge after the full operation of the TGD from 2009 to 2018. If the difference is greater than 0, the TGD has reduced the maximum 1-day discharge during flood season. Difference = $Q_{Re} - Q_{Ob}$; Q_{Re}: reconstructed maximum 1-day discharge; Q_{Ob}: observed maximum 1-day discharge.

Year	Yichang	Luoshan	Hankou	Jiujiang	Datong
2009	11,517	6946	5408	5652	5006
2010	16,838	11,106	2737	6920	13,292
2011	10,585	7127	7470	8001	14,673
2012	11,453	8785	10,269	12,575	19,931
2013	6766	6153	5589	6935	5741
2014	531	4942	7367	8074	15,058
2015	2324	3852	6479	5557	10,369
2016	6662	5751	7837	9610	17,332
2017	3099	3431	8317	10,458	12,361
2018	10,972	9147	11,681	12,571	18,089
Average	8074.7	6724.0	7315.4	8635.3	13,185.2

Table 4. The difference between the reconstructed maximum 1-day discharge and the observed maximum 1-day discharge at the Yichang gauging station was routed to the four gauging stations downstream from the Yichang gauging station by using the Muskingum model. If the difference is greater than 0, the TGD has reduced the maximum 1-day discharge during flood season.

Year	Luoshan	Hankou	Jiujiang	Datong
2009	4012	3244	3179	2070
2010	6118	5164	5127	5161
2011	5186	4652	4577	3777
2012	2775	2064	2125	1615
2013	3244	2875	2811	2139
2014	1151	1626	1633	1877
2015	1727	1987	1991	2762
2016	3863	2987	2867	1041
2017	1331	1058	1052	475
2018	4355	4026	3965	3203
Average	3376.0	2968.2	2932.6	2412.0

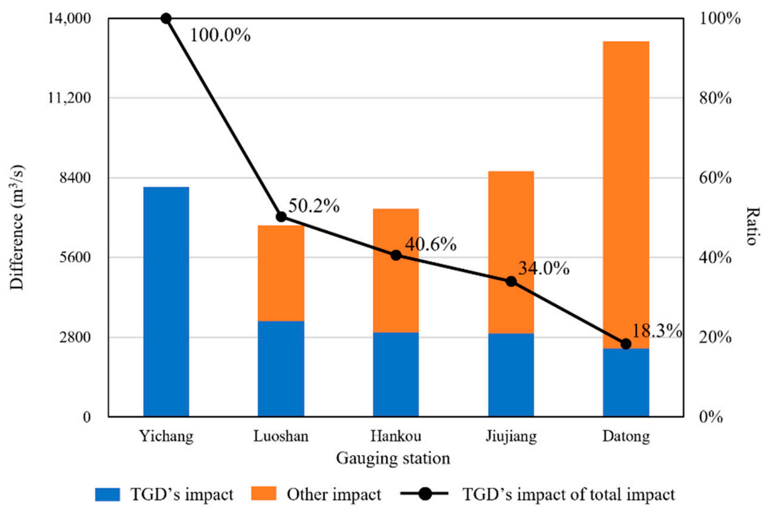

Figure 8. The TGD's impact on five gauging stations after its full operation based on an analysis of the maximum 1-day discharge. These results were calculated from the average of the difference between the observed maximum 1-day discharge and the reconstructed maximum 1-day discharge after the full operation of the TGD (see Tables 3 and 4). The TGD's impact on the Luoshan, Hankou, Jiujiang, and Datong gauging stations was calculated by the Muskingum routing model based on the TGD's impact on the Yichang gauging station, assuming that the Yichang gauging station is completely controlled by the TGD.

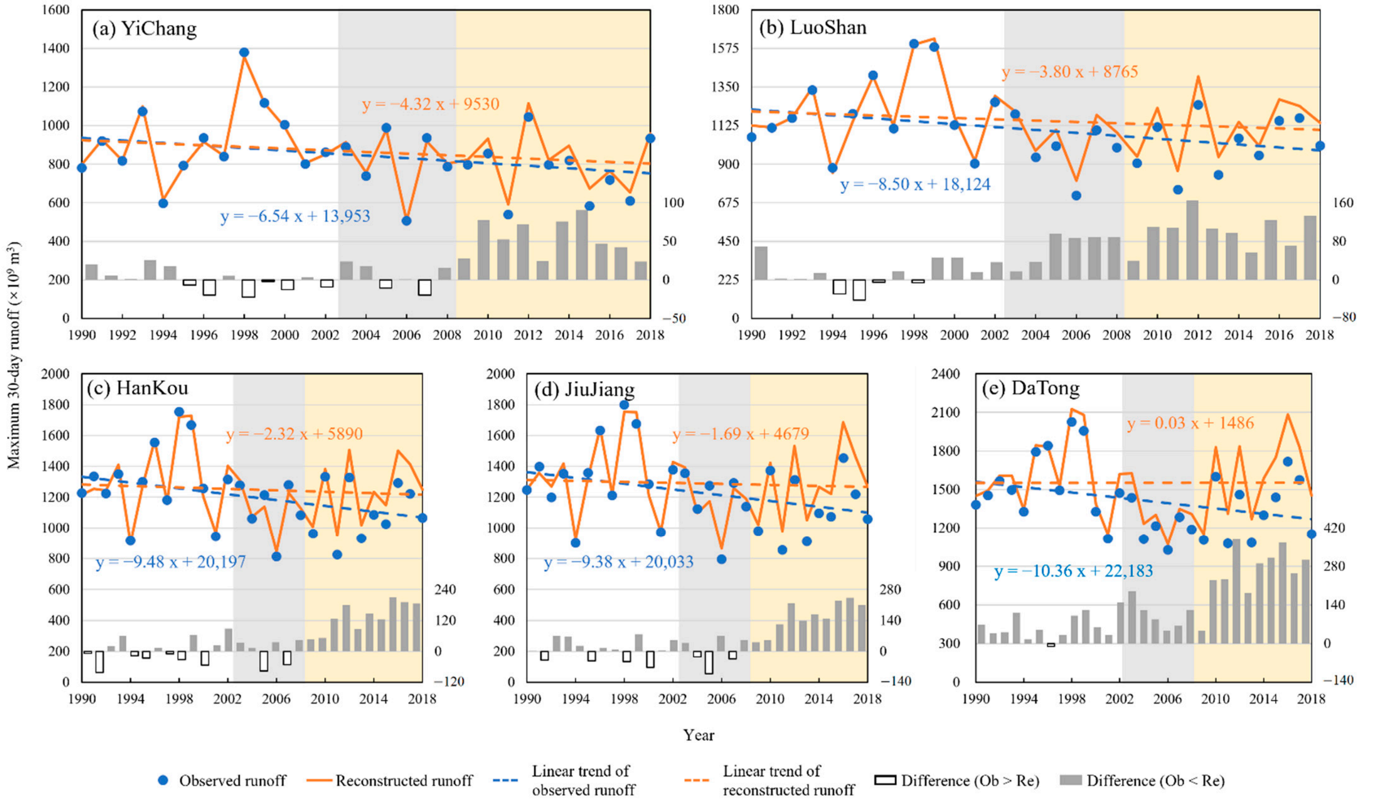

Figure 9. Analysis of the maximum 30-day runoff during flood season in the five gauging stations (the grey zones denote the initial operation period of the TGD from 2003 to 2008, and the yellow zone denotes the full operation period of the TGD from 2009 to 2018).

Moreover, the comparison of the maximum 30-day runoff between the five gauging stations from 2009 to 2018 and the comparison of the maximum 30-day runoff during different periods at each station are shown in Figure 10. As shown in Figure 10a, the linear trend line of these five gauging stations deviate from the 1:1 line. Among them, the linear trend line of the Datong gauging station is farther away from the 1:1 line than that of the other four gauging stations, which means that the difference between the reconstructed maximum 30-day runoff and the observed maximum 30-day runoff at Luoshan is larger than the difference at the other four gauging stations. As shown in Figure 10b–f, the linear trend lines of the Yichang gauging station after the initial operation of the TGD and the full operation of the TGD are both slightly away from the 1:1 line, but the linear trend lines of the other four gauging stations after the full operation of the TGD are farther away from the 1:1 line than those after the initial operation of the TGD.

To quantify the TGD's impact on the maximum 30-day runoff of the Yangtze River, the difference between the reconstructed maximum 30-day runoff and the observed maximum 30-day runoff after the full operation of the TGD from 2009 to 2018 at the five gauging stations was calculated (see Table 5). The maximum 30-day runoff at the Yichang gauging station decreased by an average of 53.27 $\times$ 10^9 m^3 between 2009 and 2018 after the full operation of the TGD. Taking the difference at the Yichang gauging station, 53.27 $\times$ 10^9 m^3, as the standard, the comparison of the TGD's impact on the maximum 30-day runoff at the five gauging stations is shown in Figure 11. The operation of TGD only reduced the maximum 30-day runoff by 52.8%, 39.6%, 33.8%, and 20.5% at the Luoshan, Hankou, Jiujiang, and Datong stations, respectively.

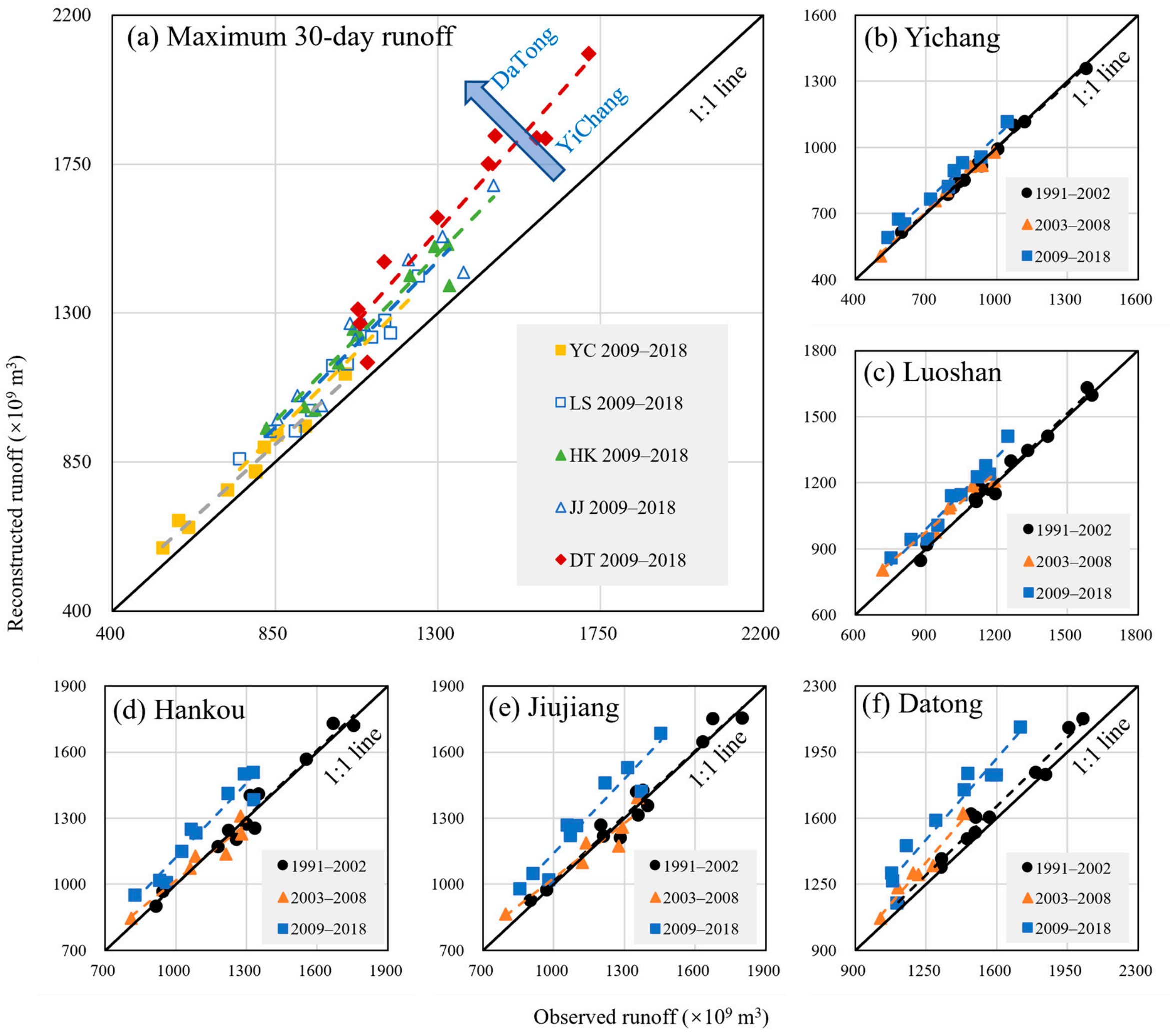

Figure 10. Comparison of the maximum 30-day runoff during flood season between the five gauging stations. If points are above the 1:1 line, the reconstructed runoff is greater than the observed runoff, and the TGD has reduced the maximum 30-day runoff. In contrast, if points are below the 1:1 line, the reconstructed runoff is less than the observed runoff, and the TGD has increased the maximum 30-day runoff.

Table 5. The difference between the observed maximum 30-day runoff and the reconstructed maximum 30-day runoff after the full operation of the TGD from 2009 to 2018. If the difference is greater than 0, the TGD has reduced the maximum 30-day runoff during flood season. Difference = $R_{Re} - R_{Ob}$; R_{Re}: reconstructed maximum 30-day runoff; R_{Ob}: observed maximum 30-day runoff.

Year	Yichang	Luoshan	Hankou	Jiujiang	Datong
2009	27.6	39.3	46.5	41.8	47.0
2010	77.1	110.0	51.8	51.1	229.2
2011	52.3	108.5	125.6	122.1	231.9
2012	72.2	165.0	178.8	217.7	377.6
2013	24.2	105.6	86.2	137.9	183.5
2014	75.5	97.1	147.6	169.2	290.1
2015	90.5	56.3	124.6	149.6	311.5
2016	46.9	124.6	209.7	230.8	366.0
2017	42.7	70.6	191.0	242.2	255.6
2018	23.6	132.5	185.1	211.4	302.5
Average	53.27	100.97	134.68	157.38	259.50

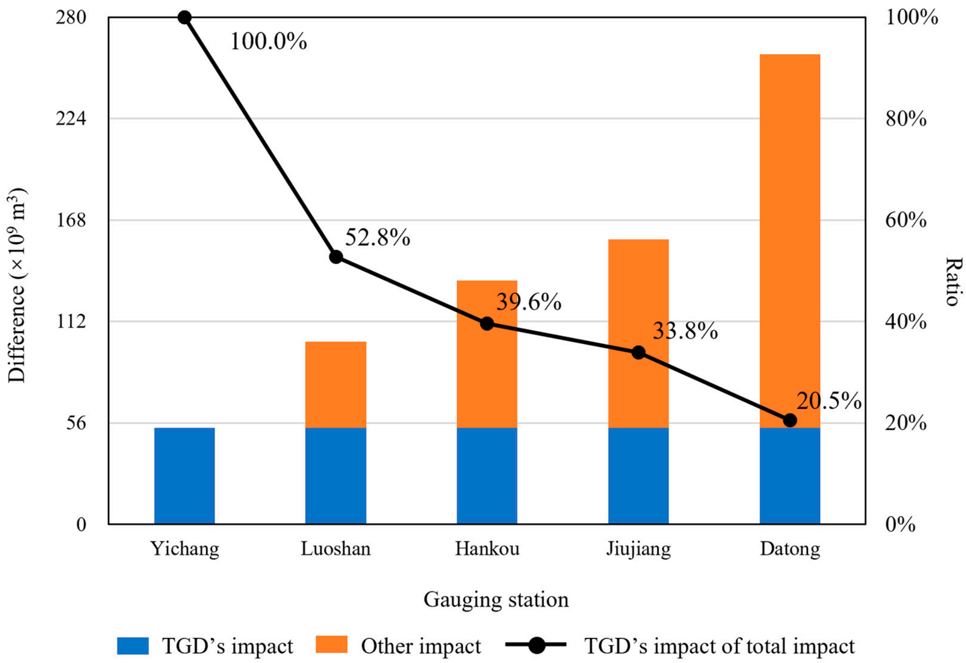

Figure 11. The TGD's impact on five gauging stations based on an analysis of the maximum 30-day runoff. These results were calculated from the average of the difference between the observed maximum 30-day runoff and the reconstructed maximum 30-day runoff after the full operation of the TGD (see Table 5). The TGD's impact on the Luoshan, Hankou, Jiujiang, and Datong gauging stations is equal to the TGD's impact on the Yichang gauging station, assuming that the Yichang gauging station is completely controlled by the TGD.

4.2.3. The Flood Season Runoff

As shown in Figure 12, the reconstructed flood season runoff at the Yichang gauging station was larger than the observed flood season runoff, which means that the TGD decreased the flood season runoff at the Yichang gauging station. In addition, the reconstructed flood season runoff at the other four gauging stations was also larger than the observed flood season runoff after the full operation of the TGD. As the differences at the other four gauging stations are greater than that at the Yichang gauging station, other impacts are believed to have decreased the flood season runoff at the four gauging stations much more than the TGD. In addition, the ratios of the flood season runoff to the annual runoff at the five gauging stations both show a downward trend.

The comparison of the maximum 30-day runoff between the five gauging stations from 2009 to 2018 and the comparison of the maximum 30-day runoff during different periods at each station are shown in Figure 13. As shown in Figure 13a, the linear trend line of the Yichang gauging station is above the 1:1 line, and the linear lines of the other four gauging stations are also above the 1:1 line. Among them, the linear trend line of the Datong gauging station is farther away from the 1:1 line than that of the other four gauging stations, which means that the difference between the reconstructed flood season runoff and the observed flood season runoff at Luoshan is larger than the difference at the other four gauging stations. As shown in Figure 13b–f, the linear trend line of the Yichang gauging station is slightly away from the 1:1 line after the full operation of the TGD. The linear trend lines of the other four gauging stations after the full operation of the TGD are farther away from the 1:1 line than those after the initial operation of the TGD. It is clear that other impacts decreased the flood season runoff at the four gauging stations downstream from the Yichang gauging station much more than the TGD.

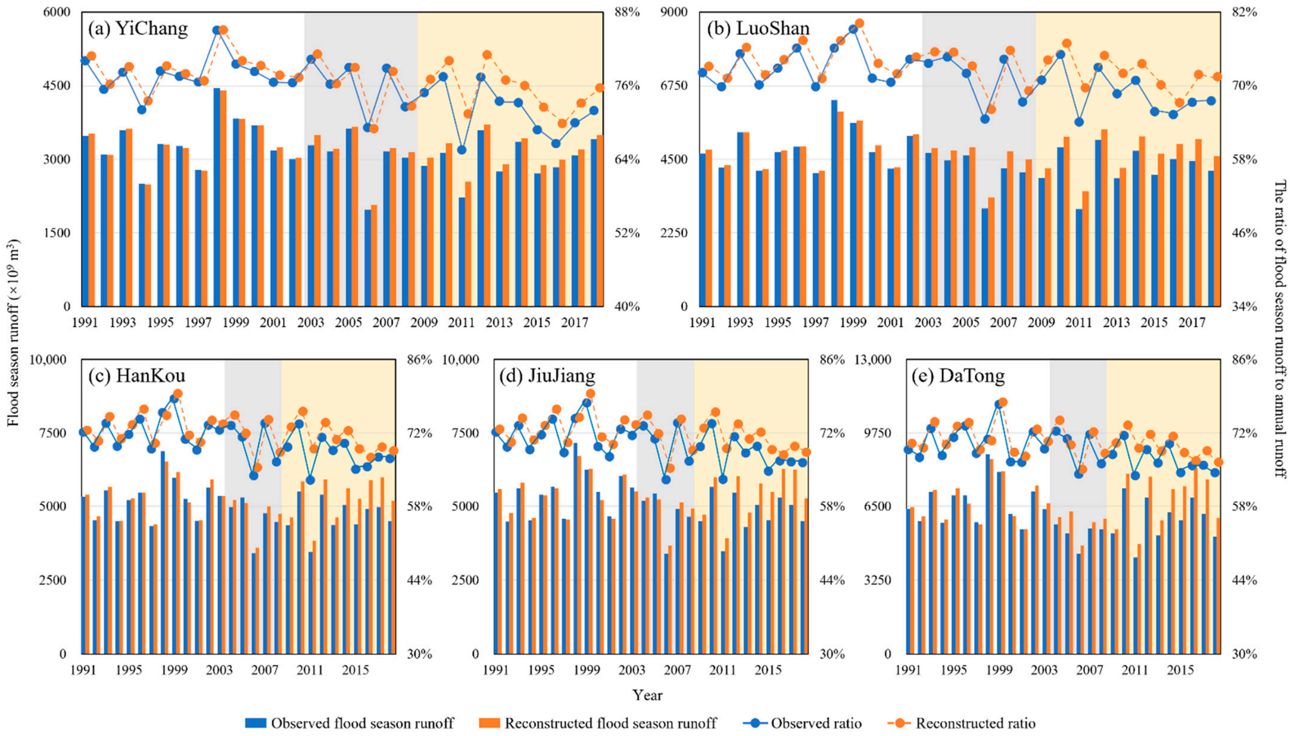

Figure 12. Analysis of the flood season runoff in the five gauging stations (the grey zones denote the initial operation period of the TGD from 2003 to 2008, and the yellow zones denote the full operation period of the TGD from 2009 to 2018).

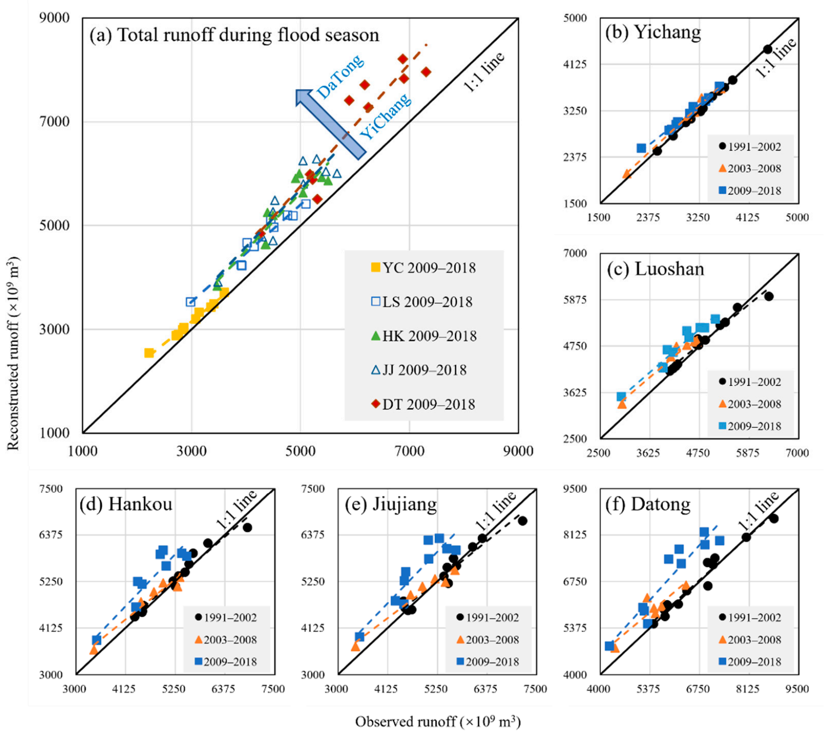

Figure 13. Comparison of the flood season runoff during flood season between the five gauging stations. If points are above the 1:1 line, the reconstructed runoff is greater than the observed runoff, and the TGD has reduced the flood season runoff. In contrast, if points are below the 1:1 line, the reconstructed runoff is less than the observed runoff, and the TGD has increased the flood season runoff.

To quantify the TGD's impact on the flood season runoff of the Yangtze River, the difference between the reconstructed flood season runoff and the observed flood season runoff after the full operation of the TGD at the five gauging stations was calculated (see Table 6). The flood season runoff at the Yichang gauging station decreased by an average of 153.24×10^9 m^3 between 2009 and 2018 after the full operation of the TGD. Taking the difference at the Yichang gauging station, 153.24×10^9 m^3, as the standard, the comparison of the TGD's impact on the flood season runoff at the five gauging stations is shown in Figure 14. The operation of the TGD changed the flood season runoff by 34.4%, 25.7%, 22.9%, and 16.6% at the Luoshan, Hankou, Jiujiang, and Datong stations, respectively.

Table 6. The difference between the observed flood season runoff and the reconstructed flood season runoff after the full operation of the TGD from 2009 to 2018. If the difference is less than 0, the TGD has increased the flood season runoff. Difference = $R_{Re} - R_{Ob}$; R_{Re}: reconstructed flood season runoff; R_{Ob}: observed flood season runoff.

Year	Yichang	Luoshan	Hankou	Jiujiang	Datong
2009	175.82	297.79	275.62	212.26	195.26
2010	190.00	326.24	352.60	331.87	650.10
2011	320.69	542.67	369.60	427.08	582.98
2012	112.83	309.75	539.03	576.43	936.16
2013	144.10	327.03	259.32	485.05	661.94
2014	70.51	439.70	586.80	746.10	1031.43
2015	163.41	647.71	853.71	956.58	1517.10
2016	153.77	452.01	996.62	994.65	1326.63
2017	119.85	665.01	1027.91	1201.99	1524.93
2018	81.39	445.33	694.77	766.91	810.93
Average	153.24	445.32	595.60	669.89	923.75

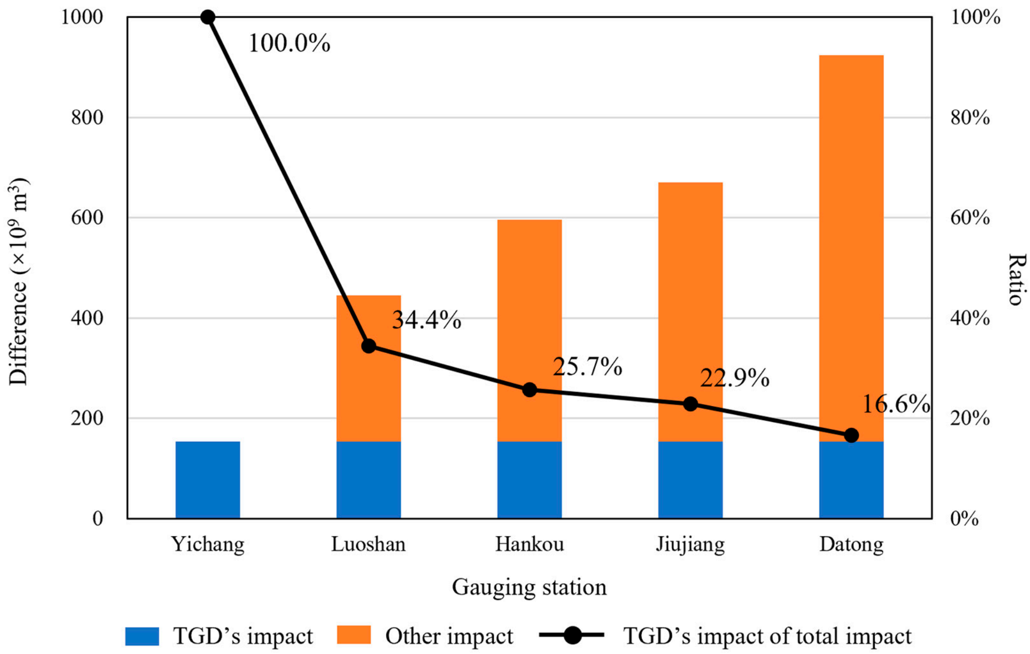

Figure 14. The TGD's impact on five gauging stations based on an analysis of the flood season runoff. These results were calculated from the average of the difference between the observed flood season runoff and the reconstructed flood season runoff after the full operation of the TGD (see Table 6). The TGD's impact on the Luoshan, Hankou, Jiujiang, and Datong gauging stations is equal to the TGD's impact on the Yichang gauging station, assuming that the Yichang gauging station is completely controlled by the TGD.

4.2.4. The C_v and C_s of the Daily Discharge during Flood Season

The coefficient of variation (C_v) shows the extent of the variability of the hydrology data in a sample in relation to the mean of the population [39], and the coefficient of skewness (C_s) is a measure of the asymmetry in the distribution of hydrology data [40].

$$C_v = \sqrt{\frac{\sum_{i=1}^{n} (K_i - 1)^2}{n}} \quad (6)$$

$$C_s = \frac{\sum_{i=1}^{n} (K_i - 1)^3}{nC_v^3} \quad (7)$$

where $K_i = \frac{x_i}{\overline{x}}$; x_i $(i = 1, 2, \ldots, n)$ is the daily discharge; $\overline{x}$ is the mean of the daily discharge; n is the length of the daily discharge.

As shown in Figure 15, at the Yichang gauging station, the C_v of the reconstructed daily discharge is larger than the C_v of the observed daily discharge after the full operation of the TGD. However, at the other four gauging stations downstream from the Yichang gauging station, the C_v of the reconstructed daily discharge is close to the C_v of the observed daily discharge without any obvious deviation after the full operation of the TGD. Additionally, at all five gauging stations, the C_s of the reconstructed daily discharge is larger than the C_s of the observed daily discharge after the full operation of the TGD.

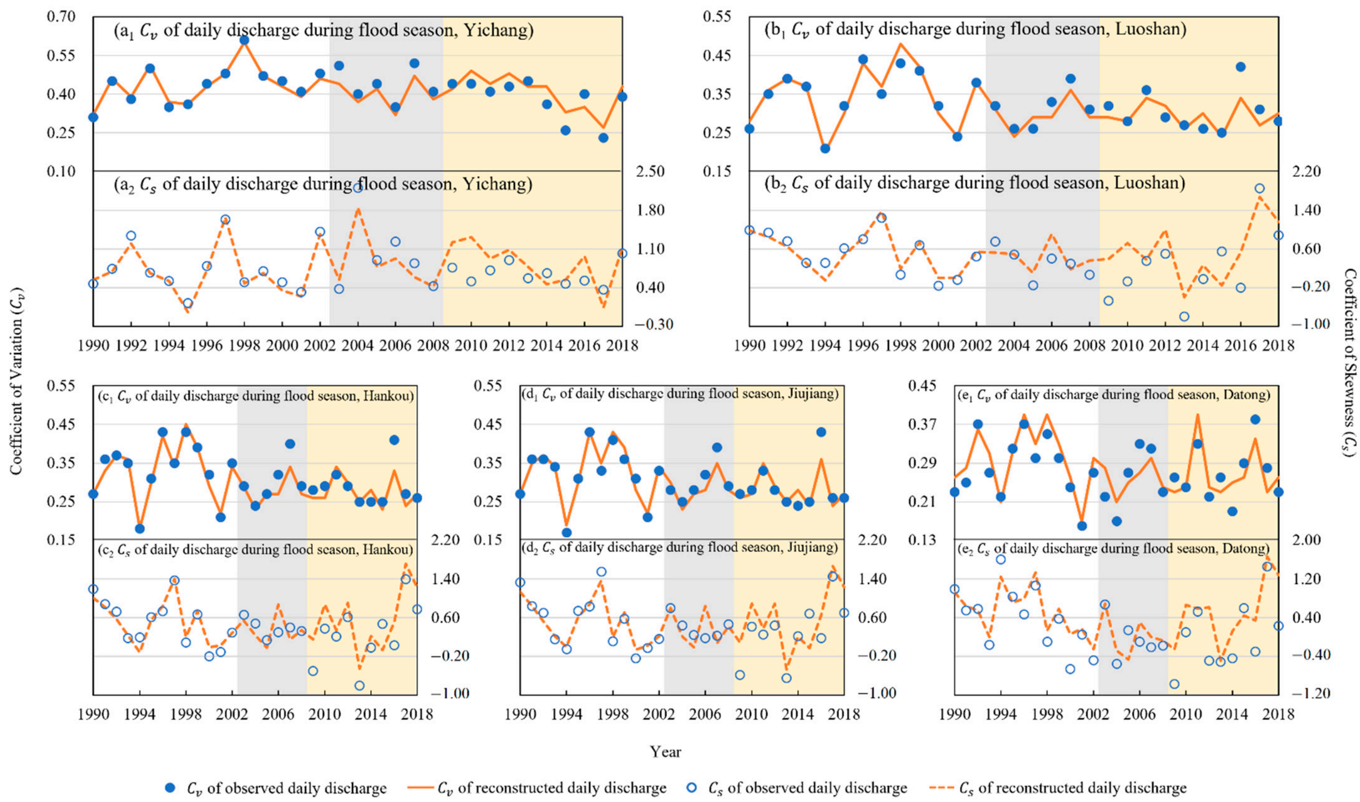

Figure 15. Analysis of C_v and C_s of daily discharge during flood season in the five gauging stations (the grey zones denote the initial operation period of the TGD from 2003 to 2008, and the yellow zones denote the full operation period of the TGD from 2009 to 2018).

The comparison of the C_v and C_s between the five gauging stations from 2009 to 2018 and the comparison of the C_v during different periods at each station are shown in Figure 16. As shown in Figure 16a, the linear trend line of the Yichang gauging station is above the 1:1 line, but the linear lines of the other four gauging stations are close to the 1:1 line. That means that, at the Yichang gauging station, the C_v of the reconstructed daily discharge is larger than the C_v of the observed daily discharge, but at the other four gauging stations, there is no clear trend between the C_v of the reconstructed daily discharge and that of the observed daily discharge. For the C_s, the linear lines of all five gauging stations are near the 1:1 line and close to each other, which means that the differences between the C_s of the reconstructed daily discharge and the C_s of the observed daily discharge at all five gauging stations are similar. Moreover, as shown in Figure 16b–f, the linear trend line of the Yichang gauging station is above the 1:1 line after the full operation of the TGD, but the linear trend lines of the other four gauging stations are near the 1:1 line after the full operation of the TGD. The C_v of the daily discharge at the Yichang gauging station is clearly decreased by the TGD, but other impacts increased the C_v of the daily discharge at the other four gauging stations downstream from the TGD and offset the TGD's impact. The TGD had a larger impact on the C_v than the C_s of daily discharge during flood season.

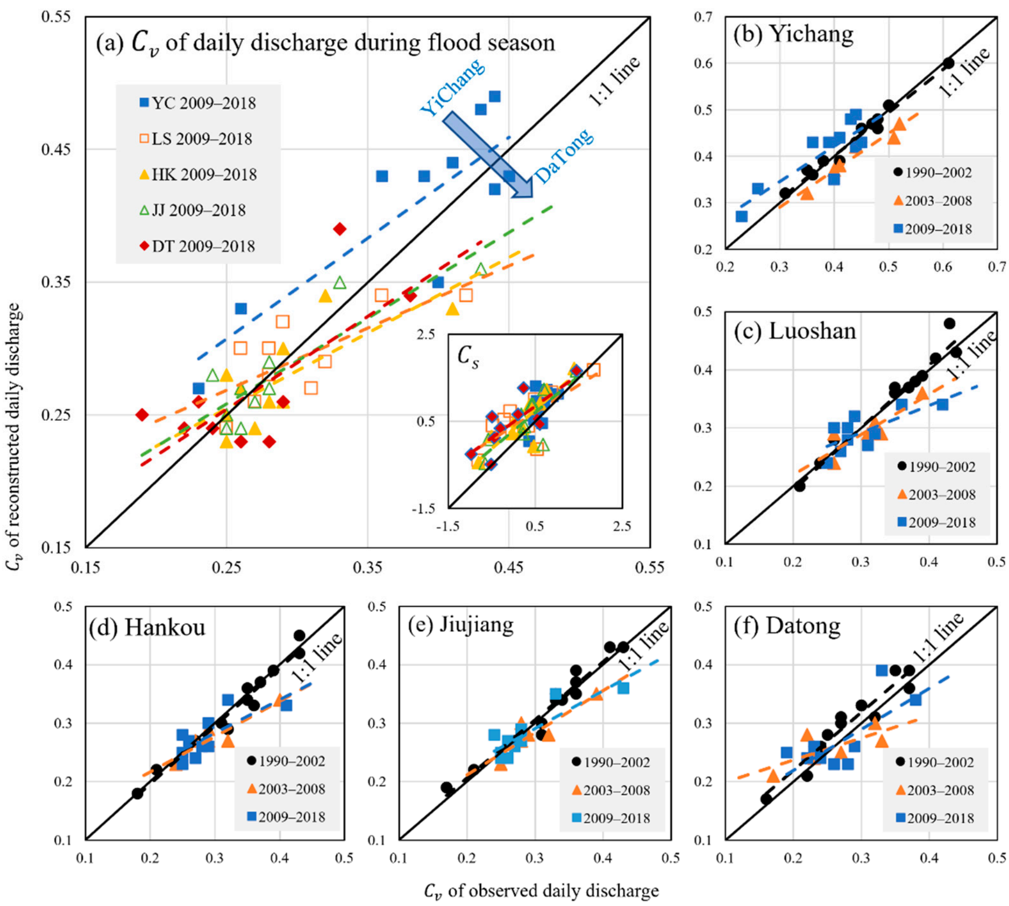

Figure 16. Comparison of the C_v and C_s of daily discharge during flood season between the five gauging stations. If points are above the 1:1 line, the C_v of reconstructed daily discharge is greater than the C_v of the observed daily discharge, and the TGD has reduced the C_v. In contrast, if points are below the 1:1 line, the C_v of the reconstructed daily discharge is less than the C_v of the observed daily discharge, and the TGD has increased the C_v.

5. Discussion

(1) The decreasing effect of the TGD on the lower Yangtze River may be related not only to the regulation and storage of many lakes and reservoirs (See Figure 1), such as the Danjiangkou Reservoir, Poyang Lake, and Dongting Lake (see Figure 1) [28,30], but also to human activity, such as water intake and other water diversion projects [22,24]. The average annual runoff at the Yichang and Datong gauging station is 4100×10^9 m^3 and 8500×10^9 m^3, respectively. The storage capacity of the TGD is 393×10^9 m^3. Moreover, the storage capacity of Dongting Lake, Poyang Lake, and Danjiangkou Reservoir is 220×10^9 m^3,

276×10^9 m^3, and 291×10^9 m^3. The lakes and reservoirs that are downstream of the TGD play a greater role in controlling floods in the lower part of Yangtze Basin. Moreover, there are also more than 16,000 reservoirs in the lower part of Yangtze Basin that can collect water at times of very high rainfall in flood season. Thus, in addition to the TGD, other impacts changed the flooding much more than the TGD in the lower basin.

(2) The decrease in flood season runoff at the Yichang gauging station after the full operation of the TGD was due to a scheduling scheme of the TGD. As the TGD releases water from February to May (sometimes to June) in order to have the capacity to restrict floods and reduce peak flow in July to October [41], the reconstructed runoff is less than the observed runoff in May and June (see Figure 17). Moreover, the reconstructed runoff is larger than the observed runoff in July to October since the TGD stores water to reduce floods in the summer and autumn. In general, water release of the TGD in May and June is less than water storage of the TGD in July to October.

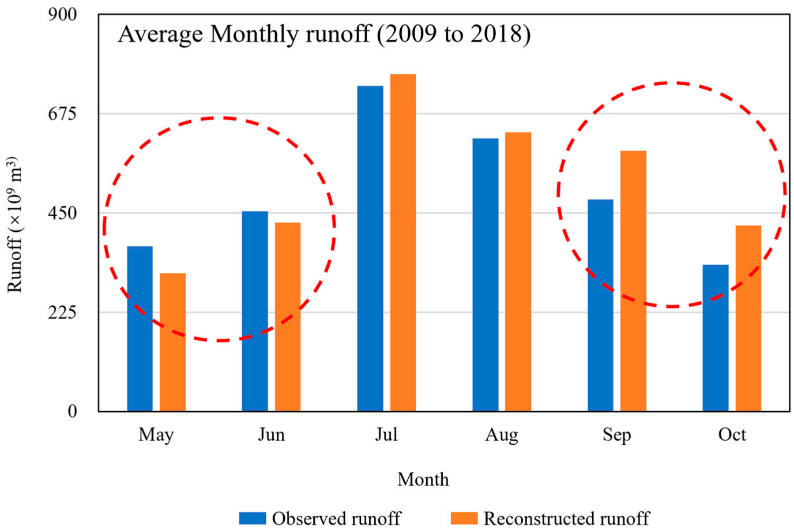

Figure 17. Average monthly runoff during flood season after the full operation of the TGD.

(3) As shown in Figure 18, we used the flood season at the Yichang gauging station in 2018 as an example. After the full operation of the TGD, it is clear that the TGD decreased the peak flow and increased the low flow during flood season. However, the TGD just changed the shape of the daily discharge data a little during this time. These may be the reasons why the TGD had a larger impact on the coefficient of variation (C_v) of daily discharge than the coefficient of skewness (C_s) of daily discharge in this season.

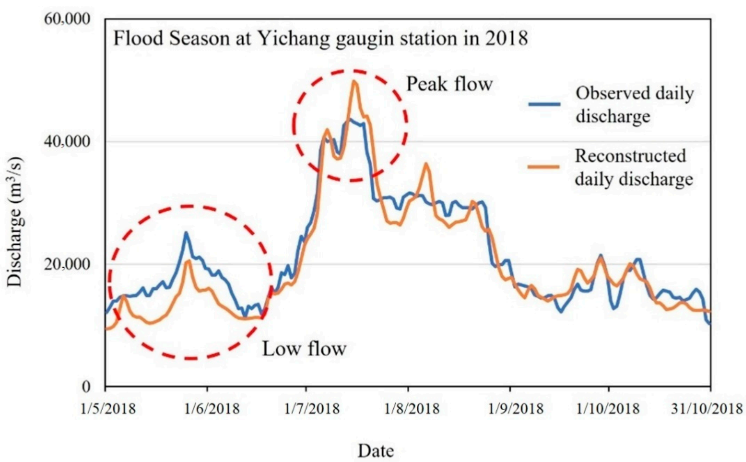

Figure 18. Daily discharge at the Yichang gauging station during flood season in 2008.

(4) Although the hydrological model can well simulate the Yangtze River daily discharge, there are still errors, including the inaccuracy of peak flow. Furthermore, this paper only analyzes the scope of the TGD's impact downstream from the Yangtze River from the perspective of discharge. However, after the full operation of the TGD in 2009, the water level, sediment concentration, and sediment transport also changed [15,19,24,26]. The tributaries and lakes in the downstream regions of the Yangtze River also changed [28,30]. The TGD's impact should be assessed from those perspectives in the future.

6. Conclusions

In the present study, we quantified the TGD's impact on the discharge during flood season after its full operation in 2009. The main findings can be summarized as follows:

(1) The TGD had an impact on the maximum 1-day discharge and maximum 30-day runoff during flood season but had less impact on the flood season runoff of the Yangtze River after its full operation in 2009. In terms of time, the maximum 1-day discharge at the Yichang gauging station decreased by an average of 8074.7 m^3/s between 2009 and 2018, and the maximum 30-day runoff at the Yichang gauging station decreased by an average of 53.27×10^9 m^3 between 2009 and 2018 after the full operation of the TGD. However, the flood season runoff at the Yichang gauging station only decreased by an average of 153.24×10^9 m^3, which is only 5.1% of the flood season runoff, between 2009 and 2018 after the full operation of the TGD.

(2) With an increase in the relative distance of the gauging station from the TGD, the TGD's impact on the discharge of the Yangtze River gradually diminished. In terms of space, the TGD had little impact on the Datong gauging station. As for the maximum 1-day discharge, the TGD was responsible for 50.2%, 40.6%, 34.0%, and 18.3% of the change at the Luoshan, Hankou, Jiujiang, and Datong gauging stations, respectively. As for the maximum 30-day runoff, the TGD was responsible for 52.8%, 39.6%, 33.8%, and 20.5% of the change at the Luoshan, Hankou, Jiujiang, and Datong gauging stations, respectively. However, as for the flood season runoff, the TGD was only responsible for 34.4%, 25.7%, 22.9%, and 16.6% of the change at the Luoshan, Hankou, Jiujiang, and Datong gauging stations, respectively.

(3) The TGD had an impact on the coefficient of variation (C_v) of the daily discharge, but it had less impact on the coefficient of skewness (C_s) of the daily discharge during flood season after its full operation in 2009. The distribution of the daily discharge was stretched by the TGD at the Yichang gauging station, but the distribution of the daily discharge at the other four gauging stations downstream from the Yichang gauging station, including the Luoshan, Hankou, Jiujiang, and Datong gauging stations, was not affected by the TGD significantly. The TGD had less impact on the C_s of the daily discharge at all five gauging stations because the TGD just changes by a little the shape of the daily discharge data and the asymmetry in the distribution during flood season.

(4) The year 2009, not 2003, should be taken as the dividing line for analyzing the TGD's impact before and after its operation. The TGD was initially put into operation by filling the reservoir to the water level of 135 m in June 2003, but the water level reached 175 m in September 2009 [27], which is the TGD's maximum water level. Additionally, the analysis of the maximum 1-day discharge, the maximum 30-day runoff, flood season runoff, and C_v of the daily discharge all show that the TGD had a larger impact on the discharge during its full operation period from 2009 to 2018 than during the initial operation period from 2003 to 2008, which proves that 2009 should be taken as the dividing line for a more accurate understanding of the impact of the TGD on the downstream hydrological regime.

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L.Z.; project administration, W.D. and Y.Z. (Yanjun Zhang); funding acquisition, Y.Z. (Yanjun Zhang) and L.Z. All authors have read and agreed to the published version of the manuscript.

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References

1. Kundzewicz, Z.; Su, B.; Wang, Y.; Xia, J.; Huang, J.; Jiang, T. Flood risk and its reduction in China. *Adv. Water Resour.* **2019**, *130*, 37–45. [CrossRef]
2. Plate, E.J. Flood risk and flood management. *J. Hydrol.* **2002**, *267*, 2–11. [CrossRef]
3. Grill, G.; Lehner, B.; Lumsdon, A.E.; MacDonald, G.K.; Zarfl, C.; Reidy Liermann, C. An index-based framework for assessing patterns and trends in river fragmentation and flow regulation by global dams at multiple scales. *Environ. Res. Lett.* **2015**, *10*, 015001. [CrossRef]
4. Hu, B.; Yang, Z.; Wang, H.; Sun, X.; Bi, N.; Li, G. Sedimentation in the three gorges dam and the future trend of Changjiang (Yangtze River) sediment flux to the sea. *Hydrol. Earth Syst. Sci.* **2009**, *13*, 2253–2264. [CrossRef]
5. International Commision on Large Dams World Register of Dams: General Synthesis 2021. Available online: https://www.icold-cigb.org/GB/world_register/general_synthesis.asp (accessed on 20 December 2021).
6. Sawyer, A.H.; Cardenas, M.B.; Bomar, A.; Mackey, M. Impact of dam operations on hyporheic exchange in the riparian zone of a regulated river. *Hydrol. Process.* **2009**, *23*, 2129–2137. [CrossRef]
7. Zahar, Y.; Ghorbel, A.; Albergel, J. Impacts of large dams on downstream flow conditions of rivers: Aggradation and reduction of the Medjerda channel capacity downstream of the Sidi Salem dam (Tunisia). *J. Hydrol.* **2008**, *351*, 318–330. [CrossRef]
8. Zeilhofer, P.; de Moura, R.M. Hydrological changes in the northern Pantanal caused by the Manso dam: Impact analysis and suggestions for mitigation. *Ecol. Eng.* **2009**, *35*, 105–117. [CrossRef]
9. Zhang, Q.; Liu, C.; Xu, C.; Xu, Y.; Jiang, T. Observed trends of annual maximum water level and streamflow during past 130 years in the Yangtze River basin, China. *J. Hydrol.* **2006**, *324*, 255–265. [CrossRef]
10. Chen, J.; Finlayson, B.L.; Wei, T.; Sun, Q.; Webber, M.; Li, M.; Chen, Z. Changes in monthly flows in the Yangtze River, China—With special reference to the Three Gorges Dam. *J. Hydrol.* **2016**, *536*, 293–301. [CrossRef]
11. Mei, X.; Dai, Z.; van Gelder, P.H.A.J.M.; Gao, J. Linking Three Gorges Dam and downstream hydrological regimes along the Yangtze River, China: Impacts of TGD on Yangtze River system. *Earth Space Sci.* **2015**, *2*, 94–106. [CrossRef]
12. Chen, J.; Wu, X.; Finlayson, B.L.; Webber, M.; Wei, T.; Li, M.; Chen, Z. Variability and trend in the hydrology of the Yangtze River, China: Annual precipitation and runoff. *J. Hydrol.* **2014**, *513*, 403–412. [CrossRef]
13. Dai, Z.; Du, J.; Li, J.; Li, W.; Chen, J. Runoff characteristics of the Changjiang River during 2006: Effect of extreme drought and the impounding of the Three Gorges Dam: Changjiang River runoff. *Geophys. Res. Lett.* **2008**, 35. [CrossRef]
14. Su, Z.; Ho, M.; Hao, Z.; Lall, U.; Sun, X.; Chen, X.; Yan, L. The impact of the Three Gorges Dam on summer streamflow in the Yangtze River basin. *Hydrol. Process.* **2020**, *34*, 705–717. [CrossRef]
15. Guo, L.; Su, N.; Zhu, C.; He, Q. How have the river discharges and sediment loads changed in the Changjiang River basin downstream of the Three Gorges Dam? *J. Hydrol.* **2018**, *560*, 259–274. [CrossRef]
16. Su, Z.; Sun, X.; Devineni, N.; Lall, U.; Hao, Z.; Chen, X. The effects of pre-season high flows, climate, and the Three Gorges Dam on low flow at the Three Gorges Region, China. *Hydrol. Process.* **2020**, *34*, 2088–2100. [CrossRef]
17. Tian, J.; Chang, J.; Zhang, Z.; Wang, Y.; Wu, Y.; Jiang, T. Influence of Three Gorges Dam on downstream low flow. *Water* **2019**, *11*, 65. [CrossRef]
18. Yuan, W.; Yin, D.; Finlayson, B.; Chen, Z. Assessing the potential for change in the middle Yangtze River channel following impoundment of the Three Gorges Dam. *Geomorphology* **2012**, *147–148*, 27–34. [CrossRef]
19. Zhang, Q.; Singh, V.P.; Chen, X. Influence of Three Gorges Dam on streamflow and sediment load of the middle Yangtze River, China. *Stoch. Environ. Res. Risk Assess.* **2012**, *26*, 569–579. [CrossRef]
20. Guo, S.; Xiong, L.; Zha, X.; Zeng, L.; Cheng, L. Impacts of the Three Gorges Dam on the streamflow fluctuations in the downstream region. *J. Hydrol.* **2021**, *598*, 126480. [CrossRef]

21. Nakayama, T.; Shankman, D. Impact of the Three-Gorges Dam and water transfer project on Changjiang floods. *Glob. Planet. Change* **2013**, *100*, 38–50. [CrossRef]
22. Mei, X.; Dai, Z.; Darby, S.E.; Gao, S.; Wang, J.; Jiang, W. Modulation of extreme flood levels by impoundment significantly offset by floodplain loss downstream of the Three Gorges Dam. *Geophys. Res. Lett.* **2018**, *45*, 3147–3155. [CrossRef]
23. Wang, J.; Sheng, Y.; Gleason, C.J.; Wada, Y. Downstream Yangtze River levels impacted by Three Gorges Dam. *Environ. Res. Lett.* **2013**, *8*, 044012. [CrossRef]
24. Yang, Y.; Zhang, M.; Zhu, L.; Liu, W.; Han, J.; Yang, Y. Influence of large reservoir operation on water-levels and flows in reaches below dam: Case study of the Three Gorges Reservoir. *Sci. Rep.* **2017**, *7*, 15640. [CrossRef] [PubMed]
25. Sun, Z.; Huang, Q.; Opp, C.; Hennig, T.; Marold, U. Impacts and implications of major changes caused by the Three Gorges Dam in the middle reaches of the Yangtze River, China. *Water Resour. Manag.* **2012**, *26*, 3367–3378. [CrossRef]
26. Yang, S.L.; Xu, K.H.; Milliman, J.D.; Yang, H.F.; Wu, C.S. Decline of Yangtze River water and sediment discharge: Impact from natural and anthropogenic changes. *Sci. Rep.* **2015**, *5*, 12581. [CrossRef] [PubMed]
27. Jiang, C.; Zhang, Q.; Luo, M. Assessing the effects of the Three Gorges Dam and upstream inflow change on the downstream flow regime during different operation periods of the dam. *Hydrol. Process.* **2019**, *33*, 2885–2897. [CrossRef]
28. Guo, H.; Hu, Q.; Zhang, Q.; Feng, S. Effects of the Three Gorges Dam on Yangtze River flow and river interaction with Poyang Lake, China: 2003–2008. *J. Hydrol.* **2012**, *416–417*, 19–27. [CrossRef]
29. Jiang, L.; Ban, X.; Wang, X.; Cai, X. Assessment of hydrologic alterations caused by the Three Gorges Dam in the middle and lower reaches of Yangtze River, China. *Water* **2014**, *6*, 1419–1434. [CrossRef]
30. Zhang, Q.; Li, L.; Wang, Y.-G.; Werner, A.D.; Xin, P.; Jiang, T.; Barry, D.A. Has the Three-Gorges Dam made the Poyang Lake wetlands wetter and drier? *Geophys. Res. Lett.* **2012**, *39*, 2012GL053431. [CrossRef]
31. Wang, H.; Sun, F.; Liu, W. Characteristics of streamflow in the main stream of Changjiang River and the impact of the Three Gorges Dam. *Catena* **2020**, *189*, 104498. [CrossRef]
32. Ren-jun, Z. The Xinanjiang model applied in China. *J. Hydrol.* **1992**, *135*, 371–381. [CrossRef]
33. Ahirwar, A.; Jain, M.K.; Perumal, M. Performance of the Xinanjiang model. In *Hydrologic Modeling*; Singh, V.P., Yadav, S., Yadava, R.N., Eds.; Water Science and Technology Library; Springer: Singapore, 2018; Volume 81, pp. 715–731. ISBN 978-981-10-5800-4.
34. Li, H.; Zhang, Y.; Chiew, F.H.S.; Xu, S. Predicting runoff in ungauged catchments by using Xinanjiang model with MODIS leaf area index. *J. Hydrol.* **2009**, *370*, 155–162. [CrossRef]
35. Zang, S.; Li, Z.; Zhang, K.; Yao, C.; Liu, Z.; Wang, J.; Huang, Y.; Wang, S. Improving the flood prediction capability of the Xin'anjiang model by formulating a new physics-based routing framework and a key routing parameter estimation method. *J. Hydrol.* **2021**, *603*, 126867. [CrossRef]
36. Das, A. Parameter estimation for Muskingum models. *J. Irrig. Drain. Eng.* **2004**, *130*, 140–147. [CrossRef]
37. Mirjalili, S. Genetic algorithm. In *Evolutionary Algorithms and Neural Networks*; Studies in Computational Intelligence; Springer International Publishing: Cham, Switzerland, 2019; Volume 780, pp. 43–55. ISBN 978-3-319-93024-4.
38. The Definition of Flood Season. Available online: http://www.cma.gov.cn/kppd/kppdrt/201404/t20140409_242890.html (accessed on 14 February 2022).
39. Brown, C.E. Coefficient of variation. In *Applied Multivariate Statistics in Geohydrology and Related Sciences*; Springer: Berlin/Heidelberg, Germany, 1998; pp. 155–157. ISBN 978-3-642-80330-7.
40. Yan, Z.; Tian, B. Ratio method to the mean estimation using coefficient of skewness of auxiliary variable. In *Information Computing and Applications*; Zhu, R., Zhang, Y., Liu, B., Liu, C., Eds.; Communications in Computer and Information Science; Springer: Berlin/Heidelberg, Germany, 2010; Volume 106, pp. 103–110. ISBN 978-3-642-16338-8.
41. Lai, X.; Jiang, J.; Yang, G.; Lu, X.X. Should the Three Gorges Dam be blamed for the extremely low water levels in the middle-lower Yangtze River?: TGD and low water level. *Hydrol. Process.* **2014**, *28*, 150–160. [CrossRef]