Water **2014**, *6*, 1419-1434; doi:10.3390/w6051419

OPEN ACCESS

water

ISSN 2073-4441

www.mdpi.com/journal/water

Article

Assessment of Hydrologic Alterations Caused by the Three Gorges Dam in the Middle and Lower Reaches of Yangtze River, China

Liuzhi Jiang [1,2], Xuan Ban [1,3], Xuelei Wang [1,3,]* and Xiaobin Cai [1,3]

1 Institute of Geodesy and Geophysics, Chinese Academy of Sciences, 340 XuDong Rd., Wuhan 430077, Hubei, China; E-Mails: jiangliuzhi.0622@163.com (L.J.); banxuan@whigg.ac.cn (X.B.); xbcai@whigg.ac.cn (X.C.)

2 University of Chinese Academy of Sciences, No.19A Yuquan Road, Beijing 100049, China

3 Hubei Key Laboratory of Environment and Disaster Monitoring and Evaluation, 340 XuDong Rd., Wuhan 430077, Hubei, China

* Author to whom correspondence should be addressed; E-Mail: xueleiwang@whigg.ac.cn; Tel./Fax: +86-027-6888-1389.

Received: 31 March 2014; in revised form: 1 May 2014 / Accepted: 14 May 2014 / Published: 22 May 2014

Abstract: Hydrologic regime plays a major role in structuring biotic diversity within river ecosystems by controlling key habitat conditions within the river channel and floodplain. Daily flow records from seven hydrological stations and the range of variability approach were utilized to investigate the variability and spatial pattern of the hydrologic alterations induced by the construction of the Three Gorges Dam (TGD) in the middle and lower reaches of the Yangtze River, China. Results show that the impoundment of the TGD disturbed the hydrologic regime downstream and directly affected the streamflow variations. The rate of changes and the annual extreme conditions were more affected by the TGD, particularly the low-flow relevant parameters. The alterations in the hydrologic regime were mainly caused by the TGD storing water during early autumn and releasing water during winter and spring. The effects on spatial patterns decreased as the distance from the dam increased, which was mainly attributed to the inflows from large tributaries along the Yangtze River as well as the interaction with the two largest natural lakes (*i.e.*, Dongting Lake and Poyang Lake). These hydrologic alterations not only break the natural balance of eco-flow regimes but also result in undesirable ecological effects, particularly in terms of habitat availability for the fish community.

Keywords: hydrologic alteration; range of variability approach; indicators of hydrologic alteration; Three Gorges Dam; Yangtze River

1. Introduction

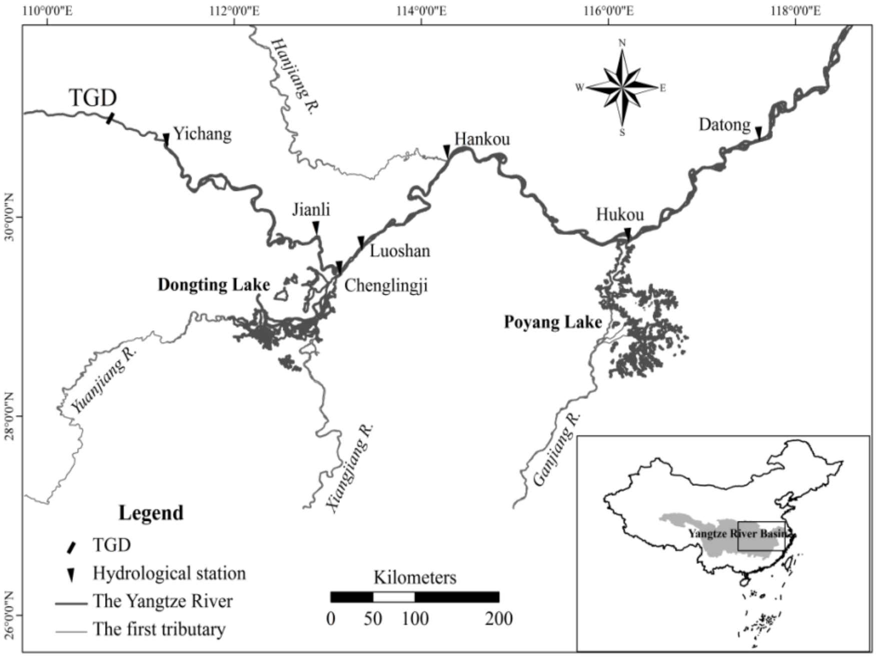
Natural flow regime is extremely important in sustaining river environments and aquatic ecosystems and has been widely adopted as a paradigm for ecological integrity conservation and restoration; it is well recognized by river scientists, stream ecologists, and water resource managers [1–5]. Flow regime (*i.e.*, intra- and inter-annual flow variability) is the primary driving force of the structure and function of riverine ecosystems and the distribution, composition, and diversity of lotic biota [4,6]. Streamflow controls many physical and ecological aspects of river form and processes, including sediment transport and nutrient exchange, which in turn control many habitat factors, such as flow depth, velocity, and habitat volume [1,7]. However, global hydrologic regime has undergone major changes because of intensive human activities, such as dam construction, irrigation, and land use change [8,9]. Building dams for flood control and hydroelectric generation can alter the downstream hydrologic regime by affecting the total runoff quantity, water quality, and duration of extreme runoff, thereby resulting in hydrologic fragmentation both longitudinally and laterally [10]. Hydrologic regime may also affect the distribution and availability of riverine habitat conditions, with potentially adverse consequences on the structure and persistence of aquatic communities [11].

Recognizing the significance of hydrologic alterations (HAs) in structuring biotic diversity within river ecosystems, recent studies have adopted multivariable approaches to quantify these alterations [12,13]. Richter *et al.* [11] developed the indicators of hydrologic alteration (IHA) to assess the degree to which human disturbance affects hydrologic regimes based on either hydrologic data available for a specific ecosystem or model-generated data. Richter *et al.* [2] applied IHA and proposed the range of variability approach (RVA) with the aim of setting streamflow-based river management targets that incorporate the concepts of hydrologic variability and aquatic ecosystem integrity. RVA has been proven to be a practical and effective means of assessing HA and has been applied to many river basins around the world that represent a variety of watershed and hydrologic regime types [14–16]. Galat and Lipkin [17] employed RVA to analyze the natural range of variation of the flow regime of Missouri River before and after main-stem impoundment. Their results showed that river flows are significantly affected by reservoirs. Zolezzi *et al.* [18] integrated the well-established RVA with wavelet transform analysis to assess the adverse consequences of hydrological alteration resulting from reservoir construction on the ecological integrity of Adige River in Italy. Yang *et al.* [19] utilized RVA and a mapping technique to investigate the spatial variability of HA resulting from dam construction in the middle and lower reaches of Yellow River in China.

The Yangtze River (Figure 1), the longest and largest river in China and the third largest river in the world, plays a vital role in ecological environmental conservation and in the economic development of China. In recent decades, more than 45,700 dams with a total capacity of 220.0 billion m^3 have been constructed in the Yangtze River basin [20]. As a large river, the Yangtze River is experiencing drastic hydrological changes [21–23], especially after the construction and operation of the Three Gorges

Dam (TGD). A number of studies have indicated that the operation of the TGD has influenced the river discharge and sediment transport in the Yangtze River basin [24–27]. For example, Dai *et al.* [28] examined the impacts of the TGD and serious drought on river discharge reduction in 2006. Zhang *et al.* [29] investigated the monthly streamflow and sediment load changes in the middle reaches of the Yangtze River after the TGD started operation and found that the TGD showed more significant impacts on monthly sediment load than monthly streamflow. Using scanning *t*-test and the simple two-phase linear regression, Zhang *et al.* [30] analyzed the abrupt changes in sediment load and streamflow at different time scales in the Yangtze River basin. In a recent study, Gao *et al.* [31] adopted the IHA metrics to detect flow regime changes in the middle-lower Yangtze River and evaluated the contribution of the TGD to these changes.

Figure 1. Location of the study region and the hydrological stations.



Obviously, the construction of the TGD has drawn considerable attention on the changes in the downstream river's flow regime. However, most of the studies have focused on trend detection [32] and periodicity analysis [33,34] of annual or seasonal river discharge and sediment load based on monthly or annual datasets. The ecologically relevant indicators (*i.e.*, IHA metrics) were employed in Gao *et al.* [22,31], but were limited to analyze the deviations of the annual mean IHA values between the pre- and post-impact periods. The full range of natural flow regime changes and the degree of hydrological alteration remains unclear, which is crucial for environmental flow assessment and rivers management. Additionally, the spatial patterns of HA along the middle-lower Yangtze River was seldom evaluated. Using the method of RVA and daily discharges at seven hydrological stations (Figure 1) in the period of 1980–2012, the current study is (1) to quantify and characterize the alteration of natural flow regimes in the middle-lower Yangtze River after TGD construction; (2) to examine the spatial differences in the degree of HA in the seven stations along the mainstream; and (3) to investigate the possible reasons behind flow regime changes and discuss the possible ecological implications due to these changes. The results in this study are expected to provide technical support and decision reference for improving the operation of the Three Gorges-Gezhouba cascade reservoirs and sustaining the Yangtze River ecosystem health.

2. Study Region and Data

The Yangtze River originates from the Tibetan Plateau and follows a sinuous west-to-east route before emptying into the East China Sea; it has a length of 6300 km and a drainage area of 1.8 million km^2. The Yangtze River is located in a region with a subtropical monsoon climate, where monsoon activities transport a huge amount of atmospheric moisture from the East and South China Sea to the basin, thereby influencing the spatial and temporal variability of precipitation in the Yangtze River basin. The river discharge changes with precipitation [23]. The TGD, one of the largest dams in the world, is located in the upper reaches of the Yangtze River (Figure 1) and has a length of 2309 m and a height of 185 m [34]. The construction of the TGD began on 14 December 1994, and ended in 2009. The dam has a total storage capacity of 39.3 billion m^3, approximately 4.5% of the Yangtze River's annual discharge. The dispatch modes for the TGD are as follows: (1) pre-discharge dispatch, water release in late May–early June to empty the flood control capacity; (2) flood-control dispatch, flow regulation in July–August; (3) water-storage dispatch, water impounding in mid-September–October for electricity generation and water supply in winter; and (4) water-supplement dispatch, water release in December–April [35]. The Yichang, Hankou and Datong station controls the discharge of the upper, middle and lower reach, respectively. River discharges between the Yichang and Jianli stations are partially diverted into the Dongting Lake via three distributaries, which together with upstream discharge of the Dongting Lake flow into the main channel at the Chenglingji station. The Poyang Lake and the Yangtze River have a common outlet or inlet located at the Hukou station (Figure 1).

Daily streamflow data at seven hydrological stations (Figure 1) were obtained from the Hydrological Bureau of the Yangtze River Water Resources Commission, China. The time series of these data covers the period from January 1980 to December 2012, except for Chenglingji and Datong stations (1987–2012). The timing of the TGD impoundment (in 2003) was used as a changing point to divide the pre-impact (1980–2002) and post-impact (2003–2012) periods. The homogeneity and reliability of the data were verified and firmly controlled prior to their release. The data series utilized in this study are highly consistent and have no missing data. Detailed information on the seven hydrological stations is provided in Table 1; the locations of these stations are shown in Figure 1.

3. Methods

3.1. Range of Variability Approach

RVA employs 33 hydrologic parameters to evaluate HA [2]; these parameters are categorized into five groups based on the magnitude, timing, frequency, duration, and rate of change. Given that zero-flow days were not observed in the seven hydrological stations during the study period, the parameter "number of zero-flow days" was not included in the study. Below are the five groups of hydrologic parameters.

Table 1. Detailed information of the hydrological stations in the middle and lower Yangtze River.

Station name	Location	Drainage area (km^2)	Sequence length	Characteristics	Station name
Yichang	111°17′ E	30°42′ N	1,005,501	1980–2012	Controls the river discharge of the upper Yangtze River, 44 km downstream of the Three Gorges Dam.
Jianli	112°53′ E	29°49′ N	—	1980–2012	Located at the main spawning reaches of the four major Chinese carps.
Chenglingji	113°08′ E	29°25′ N	—	1987–2012	The outlet controlling station of Dongting lake.
Luoshan	113°22′ E	29°40′ N	1,294,911	1980–2012	Controls the confluence of the Yangtze River and Dongting Lake.
Hankou	114°17′ E	30°35′ N	1,488,036	1980–2012	Located where the Hanjiang River flows into the Yangtze River.
Hukou	116°13′ E	29°45′ N	162,225	1980–2012	Located at the interface between the Poyang Lake and the Yangtze River.
Datong	117°37′ E	30°46′ N	1,705,383	1987–2012	Located at the tidal limit of the estuary; is the last controlling station measuring the Yangtze River's discharge to the sea.

Group 1. Twelve monthly median flows describe the normal flow condition.

Group 2. Ten parameters describe the magnitude and duration of annual extreme flows, including 1-, 3-, 7-, 30-, and 90-day annual maxima and minima encompassing the daily, weekly, monthly, and seasonal cycles. The base flow index was obtained by dividing the 7-day minimum flow by the annual mean flow.

Group 3. Julian dates for 1-day annual maximum and minimum indicate the timing of annual extreme flows.

Group 4. Four parameters refer to the frequency and duration of the high and low pulses. The high pulses are periods within a year when the daily flows are above the 75th percentile daily flow of the pre-impact period. The low pulses are periods within a year when the daily flows are below the 25th percentile daily flow of the pre-impact period [11].

Group 5. Three parameters (fall rate, rise rate, and number of reversals) indicate the numbers and mean rates of both positive and negative changes in flow in two consecutive days.

In the absence of specific ecological information, the ranges of natural variability are usually based on selected percentile levels or a simple multiple of the parameter standard deviations for the natural or pre-impact hydrologic regime. The management objective is not to have the river attain the target range every year but rather, to attain the range in the same frequency as that in the natural or pre-impact flow regime [14]. Considering its robustness and good estimation of skewed hydrologic data [11], the nonparametric approach was employed in this study to define the median (50th percentile) as the central tendency value and the range between the 25th and 75th percentile as the targeted range of variability for the post-impact period. The degree to which the RVA target range is not attained is a measure of HA. HA, expressed as a percentage, can be calculated as [14]

$$\text{HA}\ (\%) = \frac{\text{Observed} - \text{Expected}}{\text{Expected}} \times 100 \tag{1}$$

where "Observed" is the number of years wherein the observed value of the hydrologic parameter fell within the targeted range and "Expected" is the number of years wherein the value is expected to fall within the targeted range; HA is equal to zero when the observed frequency of the post-impact annual values that fall within the RVA target range equals the expected frequency. A positive deviation value indicates that the annual parameter values fall within the RVA target range more often than expected; negative values indicate that the annual values fall within the RVA target window less often than expected. Richter *et al.* [14] proposed a simple three-class evaluation system for individual IHA, in which the degrees of HA are classified into minimal or no alteration (0%–33% as indicated by L), moderate alteration (34%–67% as indicated by M), and high alteration (68%–100% as indicated by H).

3.2. Indicator Selection for Spatial Assessment

The calculations for RVA were based on hydrologic data collected at a single point (hydrological station) and therefore only measured HA in a temporal (rather than a spatial) dimension at that point. However, such point-based data and evaluations usually reflect hydrologic conditions and processes over a wide and long area of the river. These data also provide information on hydrologic conditions that extend to the upstream and downstream sections of the station location. Once point-based data are analyzed and their spatial applicability determined, they can be employed to assess the spatial extent of hydrologic alteration for river reaches at and between hydrological stations.

Since the percentile values of most IHA indicators contributing to the overall degree of HA in the basin are less than 67%, it is not necessary to determine the overall degree of HA by all IHA indicators [14,19]. Hence, we need to detect the IHA factors with statistically significant contributions to the overall degree of HA. Firstly, the median of absolute degree for each IHA indicator observed in the seven hydrological stations was calculated; then, these medians were ranked and the percentile values were computed; thereafter, the major factors can be singled out according to the medians which exceed the 67th percentile (*i.e.*, HA = 45%), and accepted to examine the spatial pattern of HA in the investigation; finally, the average absolute degrees of alteration for the selected factors were computed for each hydrological station, obtaining the overall degrees of HA.

4. Results

The medians, coefficients of dispersion, ranges, and degrees of HA for all the 32 hydrologic parameters in the seven hydrological stations were calculated with the IHA software version 7.1. The 25th and 75th percentile values were calculated based on the available pre-impact records, which were considered the low and high boundaries of the RVA target range. The results of the RVA analysis are shown in Table 2.

Table 2. Measures of hydrologic alteration (HA) [a] (%) at seven hydrological stations.

IHA factor	Yichang	Jianli	Chenglingji	Luoshan	Hankou	Hukou	Datong	Average [b]
Group 1								
January	−12(L)	−47(M)	20(L)	6(L)	−47(M)	42(M)	33(L)	29
February	***−82(H)***	−65(M)	40(M)	42(M)	6(L)	6(L)	14(L)	36
March	−47(M)	−34(M)	0(L)	59(M)	24(L)	−12(L)	***−73(H)***	36
April	42(M)	06(L)	0(L)	6(L)	24(L)	−47(M)	−20(L)	21
May	6(L)	24(L)	***−80(H)***	−29(L)	−12(L)	−29(L)	−20(L)	29
June	−12(L)	−29(L)	0(L)	−29(L)	−12(L)	−47(M)	−47(M)	25
July	−29(L)	−65(M)	−40(M)	−65(M)	−29(L)	59(M)	***−73(H)***	51
August	−12(L)	−1(L)	20(L)	42(M)	42(M)	−47(M)	7(L)	24
September	6(L)	−12(L)	40(M)	6(L)	15(L)	42(M)	33(L)	22
October	***−67(H)***	−47(M)	***−80(H)***	−29(L)	−47(M)	−12(L)	−40(M)	46
November	−18(L)	−29(L)	−40(M)	−29(L)	−34(M)	−65(M)	−20(L)	34
December	59(M)	38(M)	20(L)	31(L)	42(M)	15(L)	33(L)	34
Group 2								
1-day minimum	***−84(H)***	***−82(H)***	0(L)	−65(M)	−47(M)	−12(L)	−54(M)	49
3-day minimum	***−82(H)***	***−82(H)***	40(M)	−12(L)	−47(M)	42(M)	−47(M)	50
7-day minimum	−65(M)	***−82(H)***	***80(H)***	***−82(H)***	−47(M)	−12(L)	−20(L)	55
30-day minimum	−65(M)	***−82(H)***	40(M)	−47(M)	−47(M)	−12(L)	33(L)	47
90-day minimum	***−82(H)***	−47(M)	***80(H)***	42(M)	−12(L)	−12(L)	7(L)	40
1-day maximum	−29(L)	6(L)	−20(L)	−47(M)	−12(L)	−12 (L)	−47(M)	25
3-day maximum	−29(L)	−29(L)	−20(L)	−47(M)	6(L)	−29(L)	−47(M)	30
7-day maximum	−29(L)	−29(L)	−40(M)	−47(M)	−12(L)	6(L)	−47(M)	30
30-day maximum	−29(L)	−12(L)	0(L)	−29(L)	−12(L)	−12(L)	−47(L)	20
90-day maximum	6(L)	24(L)	−20(L)	−12(L)	6(L)	−47(M)	−47(M)	23
Base flow index	−65(M)	−47(M)	0(L)	***−82(H)***	***−82(H)***	−47(M)	−20(L)	49
Group 3								
Date of minimum	−51(M)	6(L)	60(M)	−65(M)	−47(M)	24(L)	***−77(H)***	47
Date of maximum	−29(L)	15(L)	−40(M)	−47(M)	−12(L)	42(M)	***−73(H)***	37
Group 4								
Low pulse count	***−85(H)***	−54(M)	−52(M)	−14(L)	−14(L)	−46(M)	−42(M)	44
Low pulse duration	−65(M)	−39(M)	−20(L)	−29(L)	−12(L)	−47(M)	60(M)	39
High pulse count	−23(L)	−39(M)	−20(L)	2(L)	22(L)	−27(L)	−9(L)	20
High pulse duration	31(L)	−1(L)	−4(L)	−51(M)	24(L)	−18(L)	7(L)	19
Group 5								
Rise rate	−51(M)	***−85(H)***	***−100(H)***	−51(M)	−57(M)	−18(L)	7(L)	52
Fall rate	−54(M)	***−71(H)***	−60(M)	***−74(H)***	−1(L)	***−82(H)***	14(L)	51
Number of reversals	***−82(H)***	−18(L)	44(M)	24(L)	−51(M)	***−85(H)***	−47(M)	50

Notes: [a] A positive deviation value indicates that the annual parameter values fell within the RVA target window more often than expected (e.g., >50% of post-impact years); negative values indicate that the annual values fell within the RVA target window less often than expected (e.g., <50%); [b] Average values are based on the absolute values of each deviation.

4.1. Characterization of HA

4.1.1. Group 1: Magnitude of Monthly Streamflow

On average, the magnitude of monthly median flow is less than the pre-impact values from June to November, particularly in October and November. However, from December to May, the monthly median flow increased after 2003. Moderate and low degrees of HA were observed for most months, whereas high degrees were observed in October, February, March, and May at Yichang, Chenglingji, and Datong (Table 2). With Yichang station as an example, the monthly median flow for February is 17.3% greater than the pre-impact value (Figure 2a), with a statistically significant increase at the 95% confidence level. This increase was mainly caused by water release of TGD in dry seasons. Figure 2a also shows that the annual median flows for February fell less frequently within the RVA target range after 2003, most of which were well beyond the RVA high boundary and resulted in high HA of −82%. Correspondingly, the monthly median flows for October in the post-impact period declined with fluctuation, most of which were below the RVA low boundary (Figure 2b) with HA of −67%. Water storage by TGD was one major reason for the reduction of river flow. In addition, the median monthly flow for May and October at Chenglingji and for March and July at Datong were highly altered, with HA of −80% and −73%, respectively.

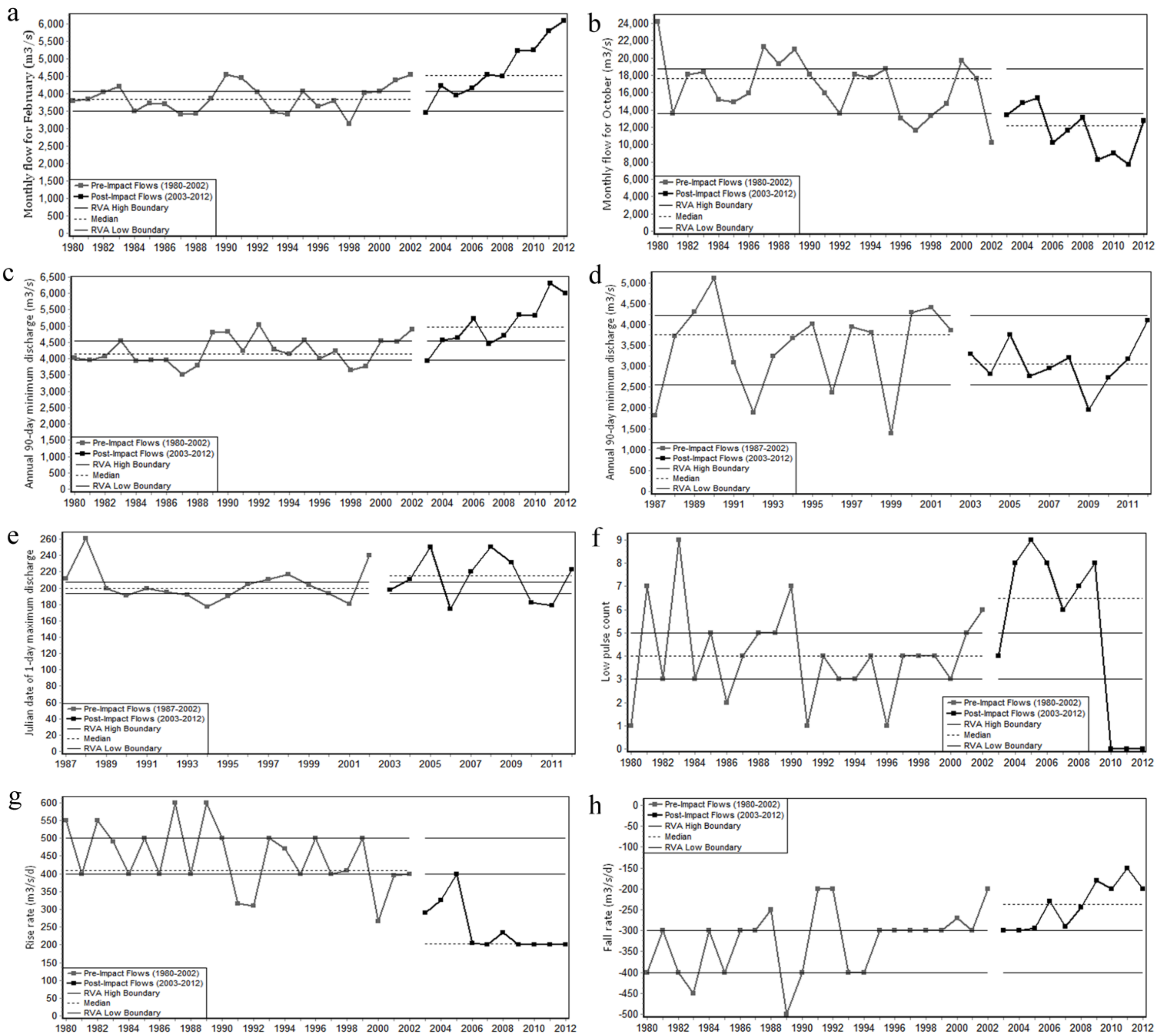
4.1.2. Group 2: Magnitude and Duration of Annual Extreme Conditions

Significant differences were observed in the annual minima flows between the two periods; the post-impact values were all greater than the pre-impact values. By contrast, the annual maxima flows decreased slightly in the post-impact period. The majority of extreme minima flows experienced high or moderate alterations, particularly at Yichang and Jianli, whereas most of the extreme maxima flows presented low alterations (Table 2). For example, the annual 1-, 3-, and 90-day minima flows at Yichang are obviously greater than those during the pre-impact period and fell less frequently within the RVA target range (Figure 2c), with high alterations of −84%, −82%, and −82%, respectively. As shown in Figure 2c, the annual 90-day minimum flows at Yichang station changed periodically before 2003 but increased continuously in the post-impact period. In contrast with other stations, the annual 7-day and 90-day minima flows at Chenglingji fell within the RVA target range more often than expected after 2003 (Figure 2d), both with high alteration of 80%. Additionally, the fluctuation range of the 90-day minima flow in the post-impact period was less than that in the pre-impact period. This finding mainly resulted from the strengthened forcing of Dongting Lake on the river, which made the flow variations flatter and had buffering effect on the river flow variations. The base flow index was clearly altered in Luoshan and Hankou, and the post-impact values increased by 24% and 27%, respectively, both of which exhibited HA of −82% (Table 2).

4.1.3. Group 3: Timing of Annual Extreme Water Conditions

In general, the Julian dates of 1-day annual minimum at most stations (*i.e.*, Yichang, Jianli, Luoshan, and Hankou) were earlier than that of the pre-impact period, whereas the Julian dates of 1-day annual maximum were later than that of the pre-impact period. All of them had HAs below 67%, which is categorized as moderate and low degrees (Table 2). However, the two parameters were highly altered at Datong station, where the Julian date of 1-day annual maximum was 15.5 days later than that of the pre-impact period; the annual median values fell less frequently within the RVA target range in the post-impact period (Figure 2e) with high HA of −73%. Although the Julian date of 1-day annual minimum was only delayed for 2 days, the HA reached −77%, which was classified as a high degree.

Figure 2. Examples of changes in the hydrological regime at seven hydrological stations. (**a**) Monthly flow for February at Yichang; (**b**) Monthly flow for October at Yichang; (**c**) Annual 90-day minimum discharge at Yichang; (**d**) Annual 90-day minimum discharge at Chenglingji; (**e**) Julian date of annual 1-day maximum discharge at Datong; (**f**) Low pulse count at Yichang; (**g**) Rise rate at Jianli; (**h**) Fall rate at Jianli.



4.1.4. Group 4: Frequency and Duration of High and Low Pulses

The frequency and duration of the low pulse changed more than that of the high pulse (Table 2). Except for the low pulse count at Yichang, the other parameters in this group were slightly altered in all the stations with moderate or low HA. With Yichang station as an example, the median values of the duration of low and high pulses decreased in the post-impact period but with opposite HA of −65% and 31%, respectively. No apparent change was observed in the high pulse count with low HA of −23%. The median low pulse count increased by 62.5%, far beyond the RVA high boundary in the post-impact period. Almost all of the annual low pulse counts fell outside the RVA target range, with HA as high as −85% (Figure 2f).

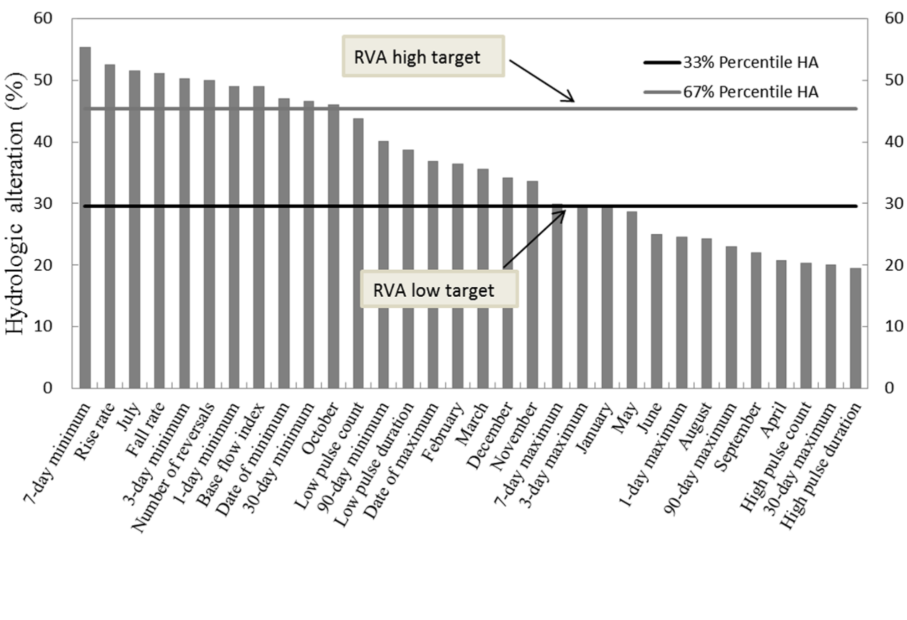
4.1.5. Group 5: Rate and Frequency of Water Condition Changes

The HAs of the parameters in this group were generally high, most of them were categorized as high or moderate, particularly for the rise rate at Chenglingji where no values fell within the RVA target range and HA reached −100% (Table 2). For example, the median of the rise rate at Jianli decreased from 410 m^3/d to 202.5 m^3/d and fell below the RVA target range after 2003; HA reached −85% (Figure 2g). On the contrary, the fall rate increased by 21% and fell within the RVA target range less often than expected, with high alteration of −71% (Figure 2h). Similarly, the number of reversals also increased to some extent, with high alteration of −82% and −85% at Yichang and Hukou, respectively.

4.2. Spatial Patterns of HA

The spatial distribution of hydrological alterations varies considerably for each of the 32 IHAs (Table 2). With the indicator selection method mentioned previously, the 33rd and 67th percentile values were computed with the medians of the 32 IHAs for the seven stations. Then, indicators with medians higher than the 67th percentile value (*i.e.*, HA ≥ 45%), namely, 7-day minimum, rise rate, July, fall rate, 3-day minimum, number of reversals, 1-day minimum, base flow index, date of minimum, 30-day minimum, and October (Figure 3), were singled out for spatial assessment of HA in the middle and lower Yangtze River. These indicators focused on the rate of change and extreme low flow conditions, and were supposed to be strongly affected by construction and operation of TGD located upstream.

Figure 3. Ranked median absolute degrees and percentile value of 32 indicators of hydrologic alteration for seven hydrological stations in the middle and lower Yangtze River.



For each hydrological station, the overall degrees of HA were determined according to these 11 selected indicators. As shown in Table 3, the overall degree of HA for the seven stations ranged from 37% to 63%, all belonging to moderate alteration. The results indicated that the hydrologic regime along the middle-lower Yangtze River was moderately affected by the impoundment of TGD. The results also showed that the overall degree of HA decreased with the decrease in the distance from the dam. In particular, the degree of HA in the Yichang reach (the nearest to TGD) was approximately two times as large as that in the Datong reach (the farthest). Besides, the degrees of HA at Chenglingji and Hukou reaches were lower than the corresponding stations in the downstream (*i.e.*, Luoshan and Datong reaches). This may be related to the special setting of the surface water system in the middle-lower Yangtze River, where the river interacts directly with the two largest freshwater lakes (*i.e.*, Dongting and Poyang Lakes), both of which play buffering roles at varying degrees for the Yangtze River flow[27,36].

Table 3. Overall degrees of hydrologic alteration (%) at the seven hydrological stations.

No.	IHA factor	Yichang	Jianli	Chenglingji	Luoshan	Hankou	Hukou	Datong
1	7-day minimum	−65	−82	80	−82	−47	−12	−20
2	Rise rate	−51	−85	−100	−51	−57	−18	7
3	July	−29	−65	−40	−65	−29	59	−73
4	Fall rate	−54	−71	−60	−74	−1	−82	14
5	3-day minimum	−82	−82	40	−12	−47	42	−47
6	Number of reversals	−82	−18	−44	24	−51	−85	−47
7	1-day minimum	−84	−82	0	−65	−47	−12	−54
8	Base flow index	−65	−47	0	−82	−82	−47	−20
9	Date of minimum	−51	6	60	−65	−47	24	−77
10	30-day minimum	−65	−82	40	−47	−47	−12	33
11	October	−67	−47	−80	−29	−47	−12	−40
Overall degree of hydrologic alteration [a]		63	61	49	54	46	37	39

Note: [a]. Overall degrees of HA are based on the average absolute values of each item.

5. Discussion

It was known in the above section that the natural flow regime in the middle-lower Yangtze River was significantly changed after the operation of the TGD. The two major changes were an increase in low flow and a decrease in high flow, indicating that the river flow became more smoothness in the post-impact period. The alterations in flow regime were closely related to the operation rules of the TGD, which typically stores water in autumn (mainly in October and November) and releases water to the downstream section from December to May. The results also show that the low-flow relevant parameters were more affected by the construction of the TGD than the high-flow relevant indicators, because low flows often occurred in dry seasons and the TGD mainly released water to facilitate irrigation during these seasons. This trend may have caused the values of related IHA to deviate easily from the RVA targets and the attainment of high HA. In addition, the flood regulation of the TGD at full capacity decreased the duration of annual high and low pulses and increased the rate of changes, implying that the amplitude of streamflow variation decreased and the change frequency increased in the post-impact period. In terms of spatial patterns, the impacts of the TGD on downstream flow regime decreased as distance from the dam increased, which was largely attributed to the increased confluent inflows in many tributaries along the river. These inflows exhibit respective variations and interference to dilute the effects of the TGD. For example, the increased discharge (mainly inflowing from Hanjiang and Ganjiang Rivers) from Yichang to Datong reaches 15,000 m^3/s, and is more than three times the base flow or approximately 50% of the peak flow at Yichang [36]; thus, the effect of the TGD in the lower reaches is reduced.

With its large water storage capacity, the operation of the TGD can reduce the frequency of major flooding downstream from once every ten years to once every 100 years. However, dam-induced HAs not only break the natural balance of eco-flow regimes but may also result in undesirable ecological effects. Ban *et al.* [37] reported that the impoundment of the TGD reduced the average discharge of the Gezhou Dam by approximately 40% and may have an impact on its availability or suitability as a habitat for the Chinese sturgeon (*Acipenser sinensis*). Given that the Chinese sturgeon spawns in October and November [38], the obvious decrease in monthly flow in October at Yichang (Figure 2b) may affect their spawning habitat and propagation. Extreme flow changes may reduce bed-load transport and result in instability of the channel form and may be necessary precursors or triggers for the reproduction of certain species [11]. The timing of extreme flows reflects whether the water condition is synchronized with the life cycle requirements of fish (e.g., spawning season). The increase in low pulse count (Figure 2f) may impose a fundamental constraint on the aquatic communities in the river and strongly affect the diversity and number of organisms that live in the river [39]. Other studies have shown that the duration of consecutive flow increase in the spawning season is a necessary condition for the spawning of four major Chinese carps (*Aristichthys nobilis*, *Hypophthalmichthys molitrix*, *Mylopharyngodon piceus*, and *Ctenopharyngodon idellus*) [40].

In addition to the operation of TGD, both climate change and other intensive human activities in the basin (such as dam construction in the upper reaches or some tributaries, inter-basin water transfers, and water withdrawals) could also affect the hydrological regimes in the middle-lower Yangtze River [41,42]. Many studies demonstrated that the streamflow variations were partly correlated with the spatial and temporal distribution of precipitation [31,34]. Less precipitation in the upper Yangtze River basin may cause streamflow decreasing in the downstream reach. Besides, climate changes usually influence the hydrological regimes at longer time scales than that of human activities [30]. Although some attempts have been made to remove the possible impacts of climate change on hydrological processes [31,36], it is still difficult to exactly differentiate individual roles of climatic change and dam construction in hydrological alterations. Thus, many uncertainties may be introduced into the assessment of hydrological changes, which should be further quantified and addressed in ongoing research.

6. Conclusions

The construction and operation of the TGD, aiming to control flood and generate electricity, have inevitably caused significantly hydrological alterations, which severely change the balance of natural flow regime and consequently result in undesirable ecological effects. Based on a newly updated hydrological dataset, changes in the hydrological regime and its spatial pattern in the middle-lower

Yangtze River after the operation of TGD were assessed with the widely used RVA method. The major findings are as follows:

(1) The main changes included significant decline of high flows and increase of low flows, which was mainly attributed to the TGD storing water in early autumn and releasing water during winter and spring. The rate of change and extreme flow conditions were more affected by the TGD, while the monthly flow and high/low pulses were less altered;
(2) In spatial patterns, the overall degree of HA along the middle-lower Yangtze River ranged from 37% to 63% and generally decreased with the distance from the dam increased, which was largely attributed to the increased confluent inflows from large tributaries along the Yangtze River. The lake-river interaction has mitigated the impacts of the TGD on the river flow at Chenglingji and Hukou station in certain degree;
(3) Both of the magnitude and degree of HA due to the operation of the TGD were revealed in this study, which can greatly help improve understanding of the influences of the TGD on the hydrological processes in Yangtze River. Besides, there is a serious challenge for the TGD to balance the conflicts between the protection of riverine ecosystems and human needs. To reduce the hydrological alteration and minimize the negative ecological impacts, it is essential to optimize the existing operation rules or develop new reservoir management schemes without significantly affecting the main purposes of the TGD.

Acknowledgments

This work was funded by the (1) National Nature Science Foundation of China (Grant No. 41171426, 40871251, 51109195); (2) National Natural Science Foundation of Hubei, China (Grant No. 2011CDA075); (3) National key basic research and development program 973 plan (project No. 2012CB417001). Cordial thanks should be extended to the Nature Conservancy, USA, for the Indicators of Hydrologic Alteration (IHA) software used in RVA computation and the Yangtze River Water Resources Commission for providing hydrologic data. Thanks should be extended to two anonymous reviewers for their crucial comments which greatly improved the quality of this paper.

Author Contributions

This research was carried out in collaboration between all authors. Liuzhi Jiang conducted data analysis and contributed to the writing of the paper. Xuan Ban designed the research methods and commented on the application of RVA. Xuelei Wang suggested the whole framework of this work and directed this research. Xiaobin Cai focused on the discussion of results in this paper. All authors contributed to the review of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Poff, N.L.; Allan, J.D.; Bain, M.B.; Karr, J.R.; Prestegaard, K.L.; Richter, B.D.; Sparks, R.E.; Stromberg, J.C. The natural flow regime. *Bioscience* **1997**, *47*, 769–784.
2. Richter, B.D.; Braun, D.P.; Mendelson, M.A.; Master, L.L. Threats to imperiled freshwater fauna. *Conserv. Biol.* **1997**, *11*, 1081–1093.
3. Whiting, P.J. Streamflow necessary for environmental maintenance. *Annu. Rev. Earth Planet. Sci.* **2002**, *30*, 181–206.
4. Arthington, A.H.; Bunn, S.E.; Poff, N.L.; Naiman, R.J. The challenge of providing environmental flow rules to sustain river ecosystems. *Ecol. Appl.* **2006**, *16*, 1311–1318.
5. Petts, G.E.; Nestler, J.; Kennedy, R. Advancing science for water resources management. *Hydrobiologia* **2006**, *565*, 277–288.
6. Naiman, R.J.; Latterell, J.J.; Pettit, N.E.; Olden, J.D. Flow variability and the biophysical vitality of river systems. *C. R. Geosci.* **2008**, *340*, 629–643.
7. Shiau, J.T.; Wu, F.C. A dynamic corridor-searching algorithm to seek time-varying instream flow releases for optimal weir operation: Comparing three indices of overall hydrologic alteration. *River Res. Appl.* **2007**, *23*, 35–53.
8. Maingi, J.K.; Marsh, S.E. Quantifying hydrologic impacts following dam construction along the Tana River, Kenya. *J. Arid. Environ.* **2002**, *50*, 53–79.
9. Shiau, J.T.; Wu, F.C. Assessment of hydrologic alterations caused by Chi-Chi diversion weir in Chou-Shui Creek, Taiwan: Opportunities for restoring natural flow conditions. *River Res. Appl.* **2004**, *20*, 401–412.
10. Lajoie, F.; Assani, A.A.; Roy, A.G.; Mesfioui, M. Impacts of dams on monthly flow characteristics. The influence of watershed size and seasons. *J. Hydrol.* **2007**, *334*, 423–439.
11. Richter, B.D.; Baumgartner, J.V.; Powell, J.; Braun, D.P. A method for assessing hydrologic alteration within ecosystems. *Conserv. Biol.* **1996**, *10*, 1163–1174.
12. Extence, C.; Balbi, D.; Chadd, R. River flow indexing using british benthic macroinvertebrates: A framework for setting hydroecological objectives. *Regul. Rivers Res. Manag.* **1999**, *15*, 545–574.
13. Clausen, B.; Biggs, B. Flow variables for ecological studies in temperate streams: Groupings based on covariance. *J. Hydrol.* **2000**, *237*, 184–197.
14. Richter, B.D.; Baumgartner, J.V.; Braun, D.P.; Powell, J. A spatial assessment of hydrologic alteration within a river network. *Regul. Rivers Res. Manag.* **1998**, *14*, 329–340.
15. Koel, T.M.; Sparks, R.E. Historical patterns of river stage and fish communities as criteria for operations of dams on the Illinois river. *River Res. Appl.* **2002**, *18*, 3–19.
16. Shiau, J.T.; Wu, F.C. Feasible diversion and instream flow release using range of variability approach. *J. Water Resour. Plan. Manag. ASCE* **2004**, *130*, 395–404.
17. Galat, D.L.; Lipkin, R. Restoring ecological integrity of great rivers: Historical hydrographs aid in defining reference conditions for the Missouri River. *Hydrobiologia* **2000**, *422*, 29–48.
18. Zolezzi, G.; Bellin, A.; Bruno, M.C.; Maiolini, B.; Siviglia, A. Assessing hydrological alterations at multiple temporal scales: A dige River, Italy. *Water Resour. Res.* **2009**, *45*, doi:10.1029/2008WR007266.
19. Yang, T.; Zhang, Q.; Chen, Y.Q.D.; Tao, X.; Xu, C.Y.; Chen, X. A spatial assessment of

hydrologic alteration caused by dam construction in the middle and lower Yellow River, China. *Hydrol. Processes* **2008**, *22*, 3829–3843.

20. Yang, G.S.; Ma, C.D.; Chang, S.Y. *Yangtze Conservation and Development Report*; Yangtze Press: Wuhan, China, 2009.
21. Zhang, Q.; Liu, C.; Xu, C.-Y.; 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.
22. Gao, B.; Yang, D.W.; Zhao, T.T.G.; Yang, H.B. Changes in the eco-flow metrics of the upper Yangtze River from 1961 to 2008. *J. Hydrol.* **2012**, *448*, 30–38.
23. Xu, J.; Yang, D.; Yi, Y.; Lei, Z.; Chen, J.; Yang, W. Spatial and temporal variation of runoff in the Yangtze River basin during the past 40 years. *Quat. Int.* **2008**, *186*, 32–42.
24. Yang, Z.-S.; Wang, H.-J.; Saito, Y.; Milliman, J.; Xu, K.; Qiao, S.; Shi, G. Dam impacts on the Changjiang (Yangtze) River sediment discharge to the sea: The past 55 years and after the Three Gorges Dam. *Water Resour. Res.* **2006**, *42*, doi:10.1029/2005WR003970.
25. Li, Q.; Yu, M.; Lu, G.; Cai, T.; Bai, X.; Xia, Z. Impacts of the gezhouba and three gorges reservoirs on the sediment regime in the Yangtze River, China. *J. Hydrol.* **2011**, *403*, 224–233.
26. Li, S.; Xiong, L.; Dong, L.; Zhang, J. Effects of the three gorges reservoir on the hydrological droughts at the downstream yichang station during 2003–2011. *Hydrol. Processes* **2013**, *27*, 3981–3993.
27. 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.
28. 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. *Geophys. Res. Lett.* **2008**, *35*, doi:10.1029/2008GL033456.
29. 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.
30. Zhang, Q.; Singh, V.P.; Xu, C.Y.; Chen, X. Abrupt behaviours of streamflow and sediment load variations of the Yangtze River basin, China. *Hydrol. Processes* **2013**, *27*, 444–452.
31. Gao, B.; Yang, D.; Yang, H. Impact of the Three Gorges Dam on flow regime in the middle and lower Yangtze River. *Quat. Int.* **2013**, *304*, 43–50.
32. Zhang, Q.; Xu, C.-Y.; Singh, V.P.; Yang, T. Multiscale variability of sediment load and streamflow of the lower Yangtze River basin: Possible causes and implications. *J. Hydrol.* **2009**, *368*, 96–104.
33. Zhang, Q.; Chen, G.; Su, B.; Disse, M.; Jiang, T.; Xu, C.-Y. Periodicity of sediment load and runoff in the Yangtze River basin and possible impacts of climatic changes and human activities. *Hydrol. Sci. J.* **2008**, *53*, 457–465.
34. Alberts, H.C.; Alberts, R.M.; Bloom, M.F.; LaFlamme, A.D.; Teerikangas, S. The three gorges dam project from a systems viewpoint. *Syst. Res. Behav. Sci.* **2004**, *21*, 585–602.
35. Ou, C.; Li, J.; Zhang, Z.; Li, X.; Yu, G.; Liao, X. Effects of the dispatch modes of the three gorges reservoir on the water regimes in the Dongting Lake area in typical years. *J. Geogr. Sci.* **2012**, *22*, 594–608.

36. 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*, 19–27.
37. Ban, X.; Du, Y.; Liu, H.; Ling, F. Applying instream flow incremental method for the spawning habitat protection of chinese sturgeon (acipenser sinensis). *River Res. Appl.* **2011**, *27*, 87–98.
38. Chang, J.B.; Cao, W.X. History and prospect of conservation on the Chinese sturgeon in the Yangtze River. *Acta Hydrobiol. Sin.* **1999**, *23*, 713–720. (In Chinese)
39. Chen, H. Assessment of hydrological alterations from 1961 to 2000 in the Yarlung Zangbo River, Tibet. *Ecohydrol. Hydrobiol.* **2012**, *12*, 93–103.
40. Chen, Y.; Liao, W.; Peng, Q.; Chen, D.; Gao, Y. A summary of hydrology and hydrodynamics conditions of four Chinese carp's spawning. *J. Hydroecol.* **2009**, *2*, 130–133.
41. Su, B.; Jiang, T.; Jin, W. Recent trends in observed temperature and precipitation extremes in the Yangtze River basin, China. *Theor. Appl. Climatol.* **2006**, *83*, 139–151.
42. Jiang, T.; Su, B.; Hartmann, H. Temporal and spatial trends of precipitation and river flow in the Yangtze River basin, 1961–2000. *Geomorphology* **2007**, *85*, 143–154.