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The Impact of Multi-Projects on the Alteration of the Flow Regime in the Middle and Lower Course of the Hanjiang River, China

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Abstract: A large number of water resources development projects have significantly changed the natural flow regime of the middle and lower reaches of the Hanjiang River, especially the Danjiangkou Reservoir, cascade reservoirs, the South-to-North Water Diversion Middle Line Project and their compensation projects, completed in 1973, 2000, and 2014, respectively. The daily streamflow data of three stations in the middle and lower mainstream of the Hanjiang River are divided into four periods corresponding to pre-impact (1954–1973), interim (1974–1999), transition (2000–2013) and post-impact (2014–2018). Eco-flow metrics and indicators of hydrologic alteration (IHA) were used to study the change of natural flow regime. The annual streamflow decreased gradually during the four periods. The construction of the Danjiangkou Reservoir increased streamflow, minimum flow value, and the number of reversals in the dry season along the middle and lower course of the Hanjiang River. Moreover, the dam reduced streamflow, maximum flow value, low pulse duration, and the rise and fall rates in the wet season. Additionally, the streamflow reduced corresponding to the completion of cascade reservoirs and the Middle Route of South-to-North Water Diversion Project. In particular, the streamflow decreased drastically from July to September, affected by the Middle Route of the South-to-North Water Diversion Project. Furthermore, the compensation projects, such as the Yangtze-Hanjiang Water Diversion Project, mitigate the reduction of streamflow from July to September in the downstream. The study provides insights into the ecological and economic benefits associated with water resources development and use in the mainstream of the middle and lower course of the Hanjiang River for the achievement of sustainable development in the region.

Keywords: altertation of streamflow regime; multiple hydraulic engineering infrastructures; South-to-North Water Diversion; Danjiangkou Reservoir; Hanjiang River

1. Introduction

Rivers play a key regulatory function in maintaining the health and sustainability of ecological processes [1] and are essential to human well-being. The shortage of water resources due to uneven distribution poses a growing risk to the societies, economic developments, and ecosystems that rely on them. To relieve water scarcity, the majority of rivers are managed and regulated by dams and diversions constructed around the world, aiming to make full use of water resources, and for preventing flood and drought. However, the construction and operation of some projects have significantly altered the characteristic patterns of the rivers regarding quantity, timing, and variability of flow, temperature, or the transportation of sediments and nutrients [2–11], and have often led to impairment of eco-hydrologic system function and environmental degradation [12–15]. Assessment of the alteration degree of hydrologic characteristics is a fundamental and distinctive requirement for providing economic and social progress and for maintaining and restoring the main river ecological functions.

Valuation of changes in the flow characteristics is a determining factor because it helps decision-makers to manage the available resources more efficiently, especially when there are complex circumstances due to interlinked natural-social processes [16–18]. Numerous metrics have been proposed to evaluate the extent to which human activities have altered the hydrologic characteristics of rivers and quantify the influence of the implementation of hydraulic engineering projects. Among them, the method known as indicators of hydrologic alterations (IHA) has been applied worldwide with proven success [19–25]. The IHA consists of 32 parameters, initially, expanding to 33 parameters in follow-up research [20], which focus on variation in flows, considering the magnitude, duration, timing, frequency, and rate of water condition changes. The range of variability (RVA) approach was proposed by Richter [24], complementing the IHA method, suggesting that the 25th and 75th percentile range of indicators could be regarded as management targets based on natural flow.

Due to population growth and increasing economic activity around the world, the demands of water resources have also increased. Various hydraulic projects, including dams, reservoirs, and diversions, have been constructed along the rivers [12,26,27]. On the other hand, the regulation of the natural flow regime of the rivers is dominated by changing discharge, and connectivity fragmentation. This can strongly affect the structure and functioning of river ecosystems. In the case of China, some studies have evaluated the impacts on hydrologic alterations, emphasizing the influence of dams in some river basins [16–18,28,29]. In the Yangtze River, the largest river in China, more than 50,000 projects have been commissioned on the basin [30]. The Yangtze River represents the river in China most affected by flow regulation through impoundment, with severe social and environmental problems relative to the construction of projects. As for the largest tributary of the Yangtze River, the Hanjiang River, almost all types of projects have been constructed during the past decades. For instance, the Danjiangkou Reservoir (DJK), the Middle Route of South-to-North Water Diversion Project (MSNWDP), and the Yangtze–Hanjiang Water Diversion Project (YHWDP). To date, few attempts have been made to quantify the impacts of flow regulation associated with dam construction or channelization. Wang et al. [31] analyzed the flow regime along the Hanjiang River before and after the construction of the Danjiangkou Reservoir. Chen et al. [32] modeled the water quantity affected by four regulation scenarios given by engineering infrastructures with the long-term time series from 1956 to 1998 hydrologic data. The main gaps of previous studies were that engineering projects were not considered under real-world conditions. On the other hand, the impacts of the most recently implemented projects remain unknown to a great extent.

In this study, the objectives were: (1) the assessment of the changes in the flow regime caused by various hydraulic engineering infrastructures and their characteristics in three stations located along the mainstream of the middle and lower reaches of the Hanjiang River; and (2) the analysis of the impacts and the investigation of the potential causes in the flow changes in the river.

2. Study Area and Data

The Hanjiang River is the largest tributary of the Yangtze River in the subtropical monsoon climate zone of China. It has a length of 1577 km and a drainage area of 159,000 km^2, and flows through two provinces of China (Figure 1). The DJK is the key hydraulic engineering commissioned in 1973 across the river with a normal storage capacity of 17.4 billion m^3, being increased to 29 billion m^3 to serve as a source for the MSNWDP. The MSNWDP, one of the largest and longest water diversion projects in the world, started operation in 2014. The project intends to divert 9.5 billion m^3 of water from DJK to Beijing City annually, spanning four provinces to solve water shortages in these areas. The YHWDP completed in 2014 to compensate water loss by the upstream project, namely in the

MSNWDP. The target of the YHWDP is to divert 3.7 billion m^3 of water from upstream of the Yangtze River to the Hanjiang River.

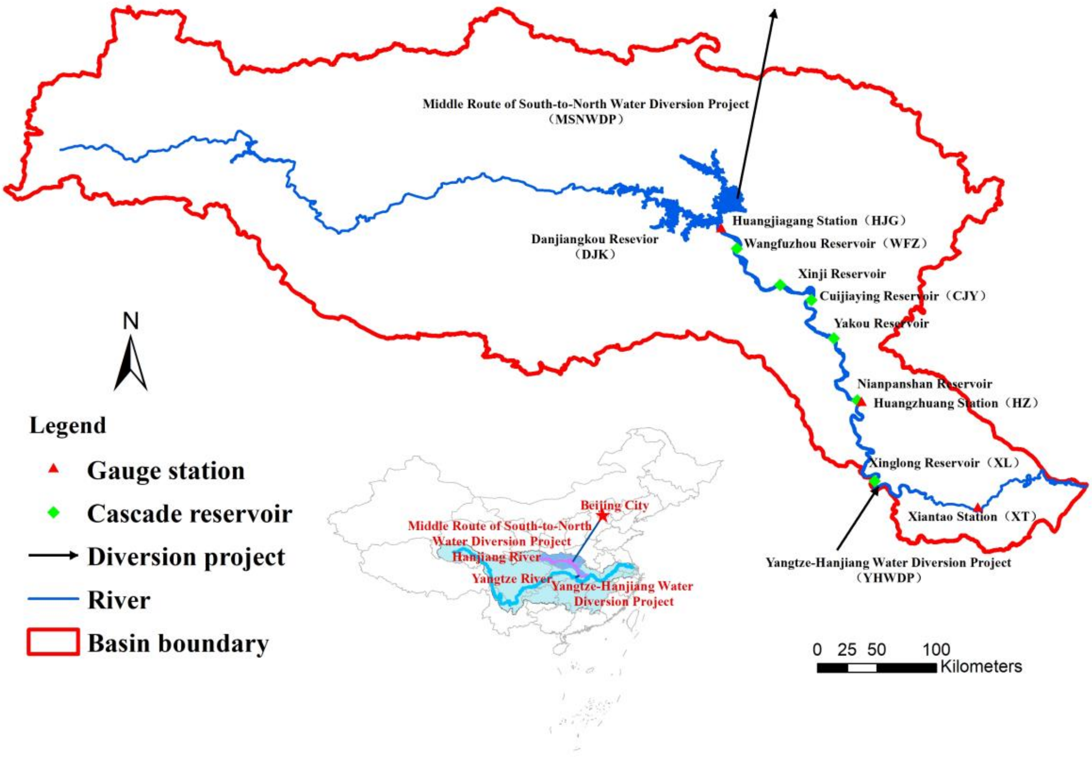


Figure 1. Location of projects and gauge stations in the mainstream of the middle-lower reaches of the Hanjiang river.

There are six cascade reservoirs located in the downstream of the DJK (Figure 1), half of them have been commissioned—Wangfuzhou (WFZ), Cuijiaying (CJY) and Xinglong (XL)—while the three others—Xinji, Yakou, and Nianpanshan—have still not been constructed. The characteristics of the main projects are shown in Table 1.

Table 1. Characteristics of the main projects in the Hanjiang river.

Name	Commission Year	Total Capacity (billion m^3)
MSNDWP	2014	9.50
YHDWP	2014	3.70
Danjiangkou Reservoir	(1973) 2013 *	(22.31) 33.91
Wangfuzhou Reservoir	2000	0.31
Xinji Reservoir	-	0.44
Cuijiaying Reservoir	2010	0.25
Yakou Reservoir	-	0.70
Nianpanshan Reservoir	-	0.90
Xinglong Reservoir	2014	0.49

* Danjiangkou reservoir was commissioned in 1973, and it has been heightened in 2013.

To estimate the impact of these projects on flow regime in the Hanjiang River, daily data were collected from three hydrologic gauge stations along the mainstream, including Huangjiagang (HJG), Huangzhuang (HZ) and Xiantao (XT), obtained from the Yangtze River Conservancy Commission of the Ministry of Water Resources (Figure 1).

3. Methods

3.1. Mann–Kendall Test

The Mann–Kendall test, a rank-based non-parametric method, is widely used to detect the monotonic trends in hydrological time series $(x_1, x_2, x_3, \ldots x_n)$. UF_k and UB_k are two key statistical parameters. The cumulative number is set as r_i when the sample x_i is larger than x_j $(1 \le j \le i)$. The calculation formula of statistic S_k is shown as follows:

$$r_i = \left\{ \begin{array}{cc} 1 & x_i > x_j \\ 0 & else \end{array} \right\} j = 1, 2, \ldots, i \tag{1}$$

$$\mathrm{S}_k = \sum_{i=1}^{k} r_i \ (2 \le k \le n) \tag{2}$$

The mean and variance of the statistic S_k, which is assumed to be independent identically distributed, are shown as follows:

$$\mathrm{E}(\mathrm{S}_k) = k(k-1)/4 \tag{3}$$

$$\mathrm{var}(\mathrm{S}_k) = k(k-1)(2k+5)/72 \tag{4}$$

The UF_k is defined as:

$$\mathrm{UF}_k = (\mathrm{S}_k - \mathrm{E}(\mathrm{S}_k))/\sqrt{\mathrm{var}(\mathrm{S}_k)} \tag{5}$$

where UF_k is calculated by forwarding sequence, and UB_k is obtained by the same process with a reversed time series. When the intersection point of UF_k and UB_k is located within the confidence interval, the point is a potential beginning of abrupt change. In this study, the significance level $\alpha = 0.05$ was used, the statistic $\mathrm{UF}_k > 1.96$ indicates a significant ascending trend, whereas the statistic $\mathrm{UF}_k < -1.96$ implies a significant descending trend [33,34].

3.2. Indicators of Hydrologic Alteration

The IHA method is widely used to characterize the natural flow regime and evaluate the human-induced alterations on river flow. The IHA contains 33 hydrologic parameters, which are classified into five groups (as shown in Table 2): (1) magnitude of monthly water conditions, (2) magnitude and duration of annual extreme water conditions, (3) timing of annual extreme water conditions, (4) frequency and duration of high and low pulses, and (5) rate and frequency of water condition changes [20]. In this study, the IHA method was selected to assess the changes of discharge due to the construction of multi-projects in the Hanjiang River.

HJG is located downstream of the DJK, the boundary of the upstream and midstream of the Hanjiang River, at a distance of 6 km. The streamflow of HJG can be a good representative of the discharge from DJK. Daily data collected at HJG from 1954 to 2018 were used to estimate the alteration caused by the construction of DJK and the operation of MSNWDP, as well as the consistency with other stations. The record was divided into four sub-periods, i.e., the pre-impact period (1954–1973), the interim period (1974–1999), the transition period (2000–2013), and the post-impact period (2014–2018). HZ is located at the boundary between midstream and downstream of the Hanjiang River; the length of the hydrologic record at HZ is identical to HJG. Considering the construction of WFZ and CJY, the record was also divided into four sub-periods, similar to HZ. XT is the last hydrologic gauge station before the Hanjiang River flows into the Yangtze River; the hydrologic data was obtained from 1972 to 2018, since there is no historical series of previous data. Similarly, the data of XT was divided into three sub-periods to estimate the impact of WFZ, CJY, XL, MSNWDP and YHWDP on the Hanjiang River, respectively, in the interim period (1974–1999), the transition period (2000–2013) and the post-impact period (2014–2018).

Table 2. Thirty-three Parameters of the indicators of hydrologic alterations.

Category	**Parameters**	
Group 1: Magnitude of monthly water conditions	Mean flow in January	Mean flow in April
	Mean flow in July	Mean flow in October
	Mean flow in February	Mean flow in May
	Mean flow in August	Mean flow in November
	Mean flow in March	Mean flow in June
	Mean flow in September	Mean flow in December
Group 2: Magnitude and duration of annual extreme water conditions	Annual minima, 1-day mean	Annual maxima, 1-day mean
	Annual minima, 3-day means	Annual maxima, 3-day means
	Annual minima, 7-day means	Annual maxima, 7-day means
	Annual minima, 30-day means	Annual maxima, 30-day means
	Annual minima, 90-day means	Annual maxima, 90-day means
	Number of zero-flow days	Base flow index *
Group 3: timing of annual extreme water conditions	Date of 1-day maximum	Date of 1-day minimum
Group 4: frequency and duration of high and low pulses	Number of low pulses each year	Number of high pulses each year
	Mean duration of low pulses (days)	Mean duration of high pulses (days)
Group 5: rate and frequency of water condition changes	Rise rates: Mean of all positive differences between consecutive daily values	Fall rates: Mean of all negative differences between consecutive daily values
	Number of hydrologic reversals	

* The base flow index is calculated using the ratio of the seven-day minimum flow to the annual mean flow.

3.3. Eco-Flow Metrics

Vogel et al. [35] proposed a non-dimensional eco-flow metric that contains ecodeficit and ecosurplus to reflect the overall loss or gain for the river in any period of interest, such as year, season and month, in order to make up for inadequate of a single measure. The flow duration curve (FDC) is a good metric for illustrating the overall hydrologic state of a river system, such that it has a long history in the field of hydrology, but the traditional definition of the FDC depends on the particular period of the data, leading to some criticism. A new nonparametric framework of FDC has been proposed to improve this defect of FDC, and provided new applications in some projects [36,37]. The eco-flow metric was based on the previous research by simplification of other indicators of hydrologic alteration, to assess hydrologic alteration caused by reservoirs and other forms of river regulation [21]. The ecodeficit and ecosuplus were computed by the flow duration curve (FDC), which was plotted by the ordered daily data, defined the discharges Q_i arranged in descending order, with Q_1 being the largest value, as a function of their exceedance probability $p_i = i/(n+1)$, where n is the daily flow and i is the rank [35]. As shown in Figure 2, the blue line indicates the FDC of the river in a natural period without any regulation, while the orange line indicates the FDC of the river while being regulated. The ecodificit is defined as the area within both below the unregulated FDC and above the regulated FDC. On the contrary, the ecosurplus is defined as the area that is both above the unregulated FDC and below the regulated FDC. In this paper, the median seasonal FDCs of three stations were employed within the pre-impact period to be a reference for the natural flow regime.

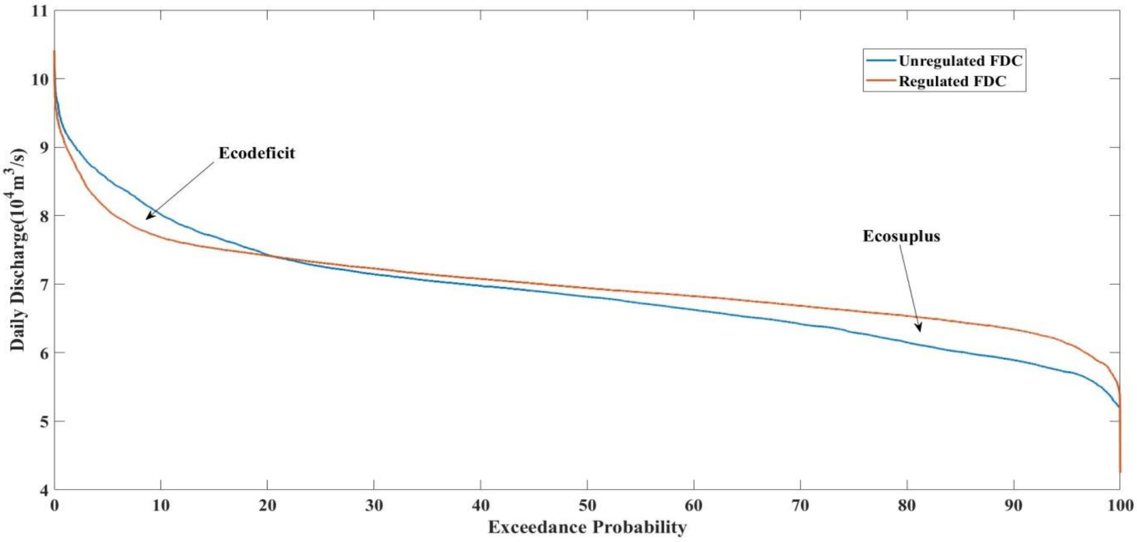


Figure 2. Definition of the ecodeficit and ecosurplus corresponding to the flow duration curves.

4. Results

In this study, the daily series data over a long-term period in three representative stations (HJG, HZ, and XT) are employed to indicate the variation of discharge caused by different projects in the mainstream of the middle-lower reaches of Hanjiang River at different scales, including annual, seasonal and other characteristics of the flow regime.

4.1. Analysis of Annual Discharge

The statistics and trends of the annual discharge within four periods at the HJG, HZ and XT stations are shown in Figure 3. A similar trend of the mean annual discharge was observed at the three stations, decreasing over time with a fluctuation in the post-impact period.

The mean annual discharge at the HJG (Figure 3a) shows a slightly decreasing tendency in the interim period decreasing from 1229 m^3/s to 1057 m^3/s and a remarkable decreasing trend in the post-impact period from 1050 m^3/s to 741 m^3/s. Additionally, no significant change was observed in the transition period compared with the interim period. The reduction of the mean annual discharge during the interim period had less impact on the volume of the water in the river due to the construction of DJK. This was aimed at improving the capacity of controlling the draught and flood for the downstream of Hanjiang River.

The markedly decreasing trend over the post-impact period was mainly caused by the operation of MSNWDP, which diverted water out of the Hanjiang River basin. The mean annual discharge both at HZ (Figure 3b) and XT (Figure 3c) had no conspicuous signs of change during the pre-impact and interim periods, despite the lack of data for XT, differing from HJG and proving that the impact of the construction of DJK on the farther downward stream gradually decreased. In the transition period, the mean annual discharge at HZ decreased from 1486 m^3/s to 1393 m^3/s, while at XT decreased from 1273 m^3/s to 1177 m^3/s. In comparison with HJG, the annual discharge was not strongly affected by WFZ and CJY through their storages and the release of impounded water. The annual discharge at HZ during the post-impact period fell from 1393 m^3/s to 1038 m^3/s, similar to HJG. MSNWDP had a strong impact on the annual discharge in the streamflow. In comparison with HJG and HZ, a lesser discharge at XT, dropped from 1177 m^3/s to 919 m^3/s, was attributable to the joint effect of infrastructures in XL, YHWDP, and MSNWDP. This fact evidences that the compensation projects for MSNWDP, namely, YHWDP and cascade XL, had a compensatory function on the negative effect of discharge due to the MSNWDP.

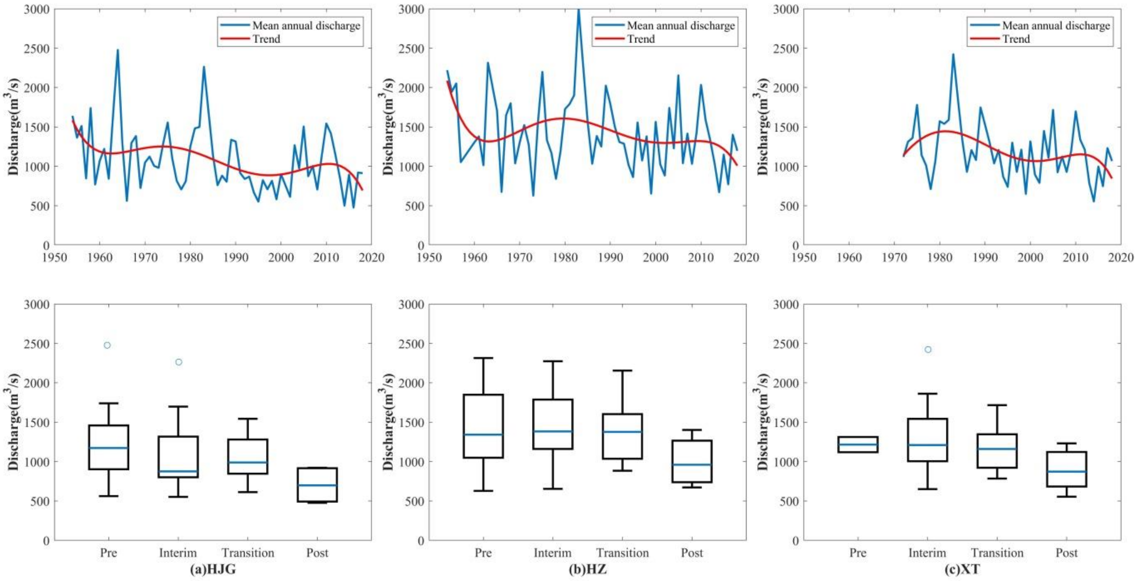


Figure 3. Mean annual discharge at three stations along the middle-lower reaches of the Hanjiang river.

In this study, the Mann–Kendall test was also applied to analyze the trends and abrupt points in the series of long-term data (Figure 4). The UF at HJG (Figure 4a) exhibits a descending trend after the intersection point when approaching the year 1974, with a transient fluctuation until 2018. However, there are no clear trends at HZ and XT that can be identified on the basis of the curves before the year 2010 (Figure 4b,c), while the UF curves imply decreasing trends after that, although the changes are not significant. The changes of the mean annual discharge at the stations are well-identified by the Mann–Kendall test, and they evidence the impact of multiple projects on the streamflow in the Hanjiang River.

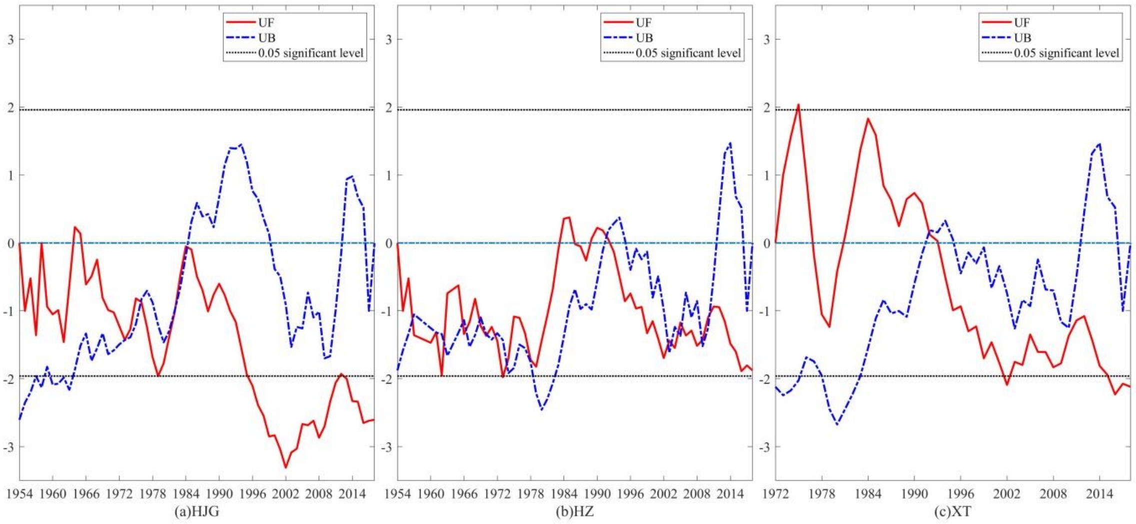
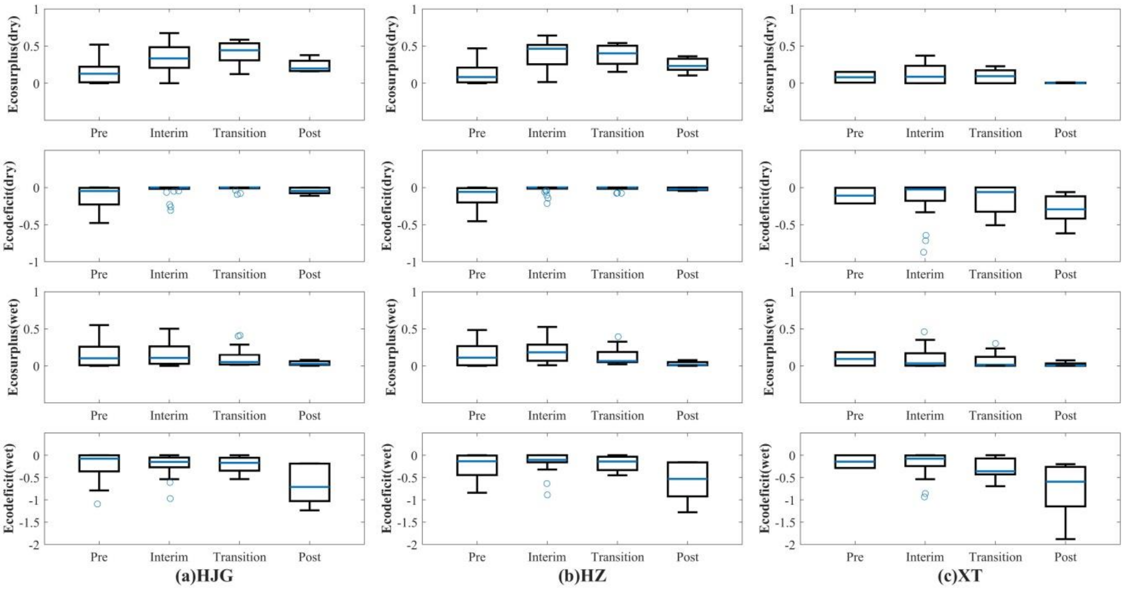


Figure 4. Mann–Kendall test for the annual discharge in three stations along the middle-lower reaches of the Hanjiang river.

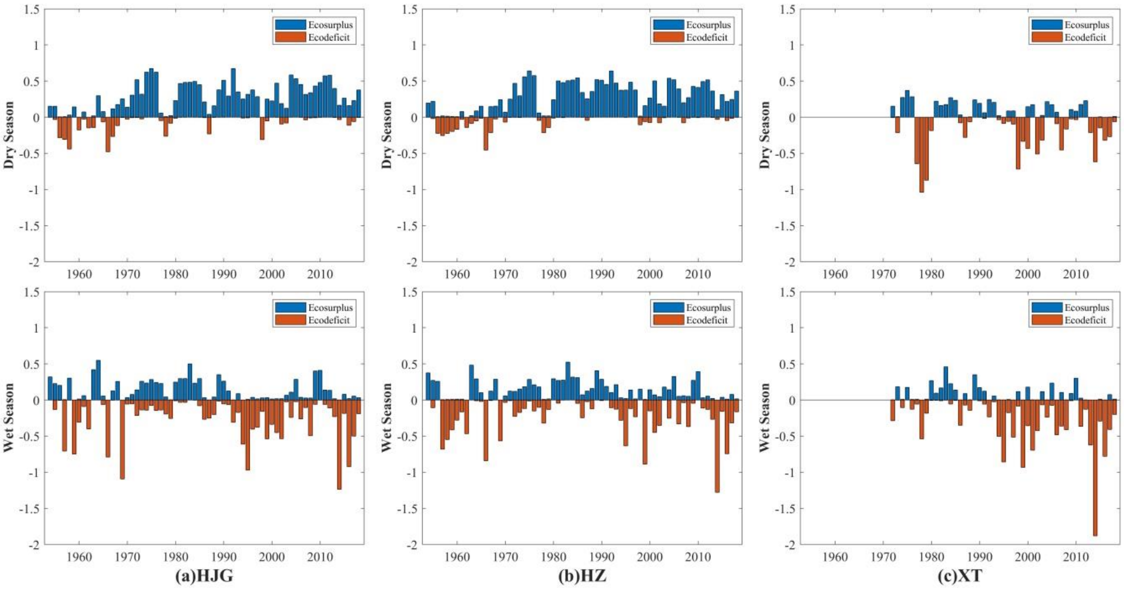
4.2. Analysis of Seasonal Discharge

The streamflow was regulated by hydraulic infrastructures that store and release water during the wet and dry seasons, respectively, in order to provide multiple functions such as hydropower generation, water supply, and irrigation of crops. In the Hanjiang River basin, the wet season is from May to October and the dry season from November to April. Seasonal ecosurplus and ecodeficit values of streamflow in the stations are shown in Figures 5–7. The ecosurplus values show a similar trend both at HJG, HZ, and XT (Figure 5), while the amplitude of the variation at XT is smaller than HZ and HJG. During the dry seasons, the ecodeficit values were nearly zero after the construction of DJK at HJG and HZ. Nevertheless, the trend of ecodeficit value was descending at XT, and in a completely different respect to HJG and HZ. In the wet seasons, extremely low ecodeficit values emerged from the operation of the MSNWDP in the year 2014 for all of the stations, especially at XT (Figure 6).



(a)HJG (b)HZ (c)XT

Figure 5. Boxplots of the seasonal ecosurplus and ecodeficit during four periods in the stations.



(a)HJG (b)HZ (c)XT

Figure 6. Changes of seasonal ecosurplus and ecodeficit in the stations.

In the dry seasons, the mean ecosurplus value was 0.14 at HJG during pre-impact period, and increased to 0.34 during the interim period due to the construction of DJK (Figure 7). However, with the construction of the MSNWDP, the value decreased to 0.24, but within a normal range during the post-impact period, implying that there was a less negative impact associated with the project on runoff during the dry seasons. The mean value of ecodeficit was −0.13 during the pre-impact period, but it reached −0.04 and stayed stable in the subsequent two periods, evidencing the positive effect due to the dam on the streamflow during the dry seasons. In the post-impact period of dry seasons, the range of ecodeficit values underwent a minor increase due to the operation of the MSNWDP with less negative impact, as well as the ecosurplus values at HJG. In the wet seasons, the mean values of ecosurplus at HJG were 0.15 both during the pre-impact and interim periods, whereas the mean value was 0.04 in the post-impact period. The ecodeficit values were −0.24 and −0.21 during the pre-impact and interim periods, respectively, and this sharply changed to −0.61 during the post-impact period. Therefore, the construction of DJK had no impact on the ecosurplus and ecodeficit at HJG during the wet seasons.

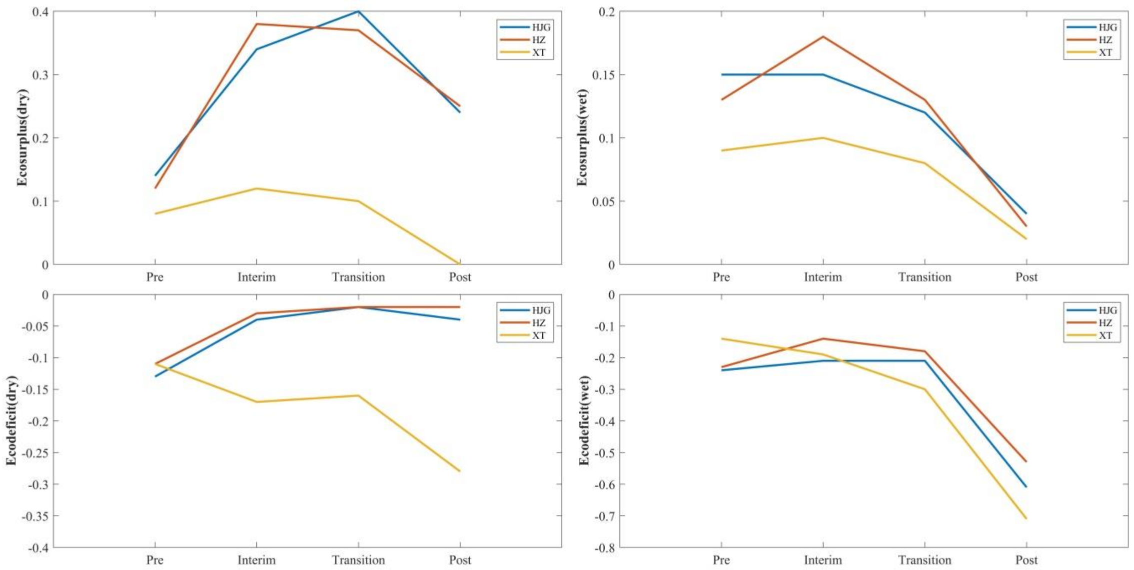


Figure 7. Mean values of seasonal ecosurplus and ecodeficit in the stations.

On the contrary, there was a negative impact on the streamflow in the post-impact period due to the operation of the MSNWDP. The range and mean eco-flow metric values were similar at HZ and HJG. In the dry seasons, the mean values of ecosurplus were 0.12, 0.38, 0.37, and 0.25 during the four periods, respectively. The mean ecodeficit value was −0.11 during the pre-impact period, −0.03 within the interim period, and remained stable at −0.02 in the other two periods. In the wet seasons, the mean values of ecosurplus were 0.13, 0.18, 0.13, and 0.03 in the four periods, respectively. The mean ecodeficit values were −0.23, −0.14, −0.18, and −0.53 for the different periods. Such records imply that the completion of DJK provided benefits to the discharge at HZ. However, in the transition and post-impact periods, the mean ecosurplus values decreased mainly owing to the constructions of WFZ and CJY, and to the operation of MSNWDP. The discharge into the river was negatively affected by the MSNWDP because of the lack of the total capacity of WFZ and CJY compared with MSNWDP.

During the dry seasons, the mean ecosurplus values were 0.08, 0.12, 0.1, and 0 at XT for the four periods. The general trend of the values was similar to the observed at HJG and HZ. Nevertheless, the magnitude of increase at XT was rather smaller than those found at HJG and HZ from the pre-impact to interim periods, indicating that DJK has less positive function on the ecosurplus values at XT since they are far away from the mean. The mean ecodeficit values were −0.11, −0.17, −0.16, and −0.28 in the different periods. For the first two periods, the values dropped from −0.11 to −0.17, indicating that the construction of DJK deteriorated the eco-hydrologic conditions at XT instead of favoring as in the cases of HJG and HZ. In the transition period, the change of ecodeficit at XT was the same as HZ, affected by WFZ and CJY, although the mean ecodeficit value, in the last period, decreased sharply from −0.16 to −0.28 with the operation of MSNWDP. The reservoirs XL and YHWDP should theoretically improve the eco-hydrological conditions at XT, but MSNWDP adversely affected them, making the positive function of XL and YHWDP, inoperative. In the wet season, the mean ecosurplus had a similar tendency as HJG and HZ with low values. The mean ecodeficit values gradually decreased from −0.14

to −0.71 over the four periods. The completion of DJK improved the ecosurplus values at a certain level while the ecodeficit values worsened at XT.

Overall, the results of the eco-flow metrics for the middle and lower course of the Hanjiang River can be mainly attributed to the operations of DJK and MSNWDP, and the fact that streamflow is definitely reduced due to the MSNWDP, which supply water from DJK to Beijing City all the time. In the middle course of the Hanjiang River, the functions of the DJK, including flood control, hydropower generation, and navigation, decrease the discharge during the wet seasons while it is increased during the dry seasons, leading to changes in the seasonal flow based on the ecosurplus and ecodeficit values at HJG and HZ, from the pre-impact to interim periods. Conversely, the streamflow at HZ is reduced by the constructions of WFZ and CJY during the wet and dry seasons.

However, for the downstream of the Hanjiang River, the change caused by DJK in the streamflow differs from that found in the middle course. The main cause is the fact that water consumption has grown considerably with the urbanization of the area since the 1970s. Figure 8 shows the land-use map of the study area in 1990, 2005, and 2015, in which six first-level land-use types of the datasets were used, including cropland, forest, grass, water, urban, and unexploited land. The urban agglomeration in the downstream Hanjiang River is the core district of the middle and lower Hanjiang River, accounting for over half of the urban areas. These maps, for each year, represent the average state of land-use for three periods, including interim, transition, and post-impact. The urban areas of the lower Hanjiang River, in which XT is located covered 852 km^2 in the year 1990, slightly increased to 889 km^2 in 2005, and climbed to 1014 km^2 in 2015. Although the urban areas in the downstream of Hanjiang River possess insufficient data before the 1970s, it is known that this area in the early times of China's foundation was much more backward than after the period of Reform and Opening-up (1970s). In other words, the urban areas of this region expanded rapidly after the 1970s. Therefore, the construction of DJK had a less positive impact on the streamflow at XT in terms of ecosurplus value, while also not avoiding the decrease in the ecodeficit value from the pre-impact to the interim period.

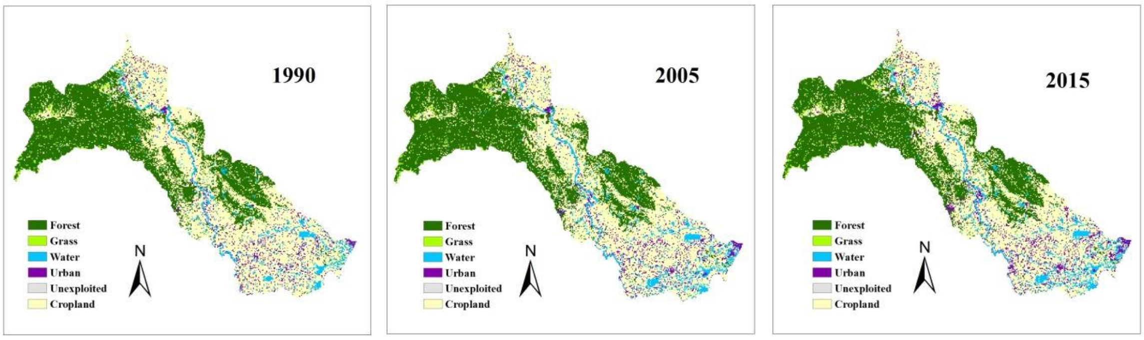


Figure 8. Land use map of the study area in 1990, 2005 and 2015. The dataset was obtained from the National Science & Technology Infrastructure of China, National Earth System Science Data Sharing Infrastructure (http://www.geodata.cn).

5. Discussion

5.1. Impact of DJK on the Streamflow

The changes in IHA indicators during the interim period (1974–1999) and pre-impact period (1954–1973) are shown in Table 3. The operation of DJK had a dramatic impact on the middle and lower Hanjiang River. At HJG and HZ, few alterations were observed for the 33 indicators studied, with changes less than 10% (only two indicators and six indicators, respectively) and with changes greater than 40% (13 indicators and 10 indicators, respectively).

Table 3. Changes of IHA metrics in the interim period.

	Huangjiagang			**Huangzhuang**		
	Pre-Impact Period (1954–1973)	**Interim period (1974–1999)**		**Pre-Impact Period (1954–1973)**	**Interim Period (1974–1999)**	
	Mean Value	**Mean Value**	**Relative Change (%)**	**Mean Value**	**Mean Value**	**Relative Change (%)**
Group 1: Mean Flow						
January	–	693.10	**87.12**	488.00	918.10	**88.14**
February	352.60	635.20	**80.15**	459.90	881.30	**91.63**
March	533.10	655.30	**22.92**	618.50	901.90	**45.82**
April	1055.00	773.50	**−26.68**	1122.00	1008.00	**−10.16**
May	1525.00	873.80	**−42.70**	1769.00	1226.00	**−30.70**
June	1121.00	1046.00	−6.69	1390.00	1491.00	7.27
July	2449.00	1622.00	**−33.77**	3055.00	2410.00	**−21.11**
August	1864.00	1673.00	**−10.25**	2717.00	2630.00	−3.20
September	2281.00	1768.00	**−22.49**	2396.00	2299.00	−4.05
October	1737.00	1299.00	**−25.22**	1884.00	1813.00	−3.77
November	854.90	764.70	**−10.55**	1026.00	1078.00	5.07
December	547.10	688.70	**25.88**	688.50	913.90	**32.74**
Group 2: Annual Extreme						
1-day minimum	197.60	311.10	**57.44**	295.50	565.00	**91.20**
3-day minimum	215.80	377.70	**75.02**	302.60	578.00	**91.01**
7-day minimum	231.60	411.40	**77.63**	321.40	598.50	**86.22**
30-day minimum	274.00	476.50	**73.91**	364.70	671.70	**84.18**
90-day minimum	393.80	555.40	**41.04**	500.30	759.90	**51.89**
1-day maximum	12030.00	6667.00	**−44.58**	12260.00	9146.00	**−25.40**
3-day maximum	10240.00	6003.00	**−41.38**	11170.00	7941.00	**−28.91**
7-day maximum	7537.00	4896.00	**−35.04**	8647.00	6384.00	**−26.17**
30-day maximum	4160.00	2857.00	**−31.32**	4801.00	3834.00	**−20.14**
90-day maximum	2579.00	1914.00	**−25.79**	3080.00	2724.00	**−11.56**
Group 3: Timing of Extreme						
Number of zero days	0.00	0.00	–	0.00	0.00	–
Base flow index	0.21	0.42	**101.10**	0.24	0.43	**78.93**
Date of minimum	112.80	134.15	**18.93**	106.88	141.04	**31.96**
Date of maximum	223.50	206.70	−7.52	209.71	223.65	6.65
Group 4: Frequency and Duration						
Low pulse count	4.55	7.23	**58.92**	3.77	1.15	**−69.35**
Low pulse duration	22.04	4.27	**−80.61**	33.10	15.28	**−53.84**
High pulse count	5.80	1.96	**−66.17**	4.94	3.23	**−34.61**
High pulse duration	5.47	6.19	**13.28**	6.84	5.26	**−23.18**
Group 5: Rate						
Rise rate	447.30	157.50	**−64.79**	431.60	194.70	**−54.89**
Fall rate	230.60	160.30	**−30.49**	217.00	163.70	**−24.56**
Number of reversals	95.35	183.20	**92.13**	72.41	124.50	**71.94**

Note: The number in bold indicates relative change larger than 10%.

It can be shown from Table 3 and Figure 9 that the construction of DJK changed the distribution of runoff within a year in the middle and lower Hanjiang River. The monthly variation of the average streamflow at HJG is higher than that at HZ, with a steady trend, indicating that the confluence is stable in the interval area. The variation of streamflow between HJG and HZ stabilizes at about 15% except in January and December (Figure 9). This is the driest period in the middle and lower Hanjiang River, with a little confluence in the interval from HJG to HZ during December and January, when the runoff at HZ is almost dependent on the discharge of DJK. The relative change between HJG and HZ stayed within a narrow range, and the minimum of the change reaches 1.02% in January, indicating that the streamflow of the mainstream of the Hanjiang River comes mainly from the discharge from DJK during January.

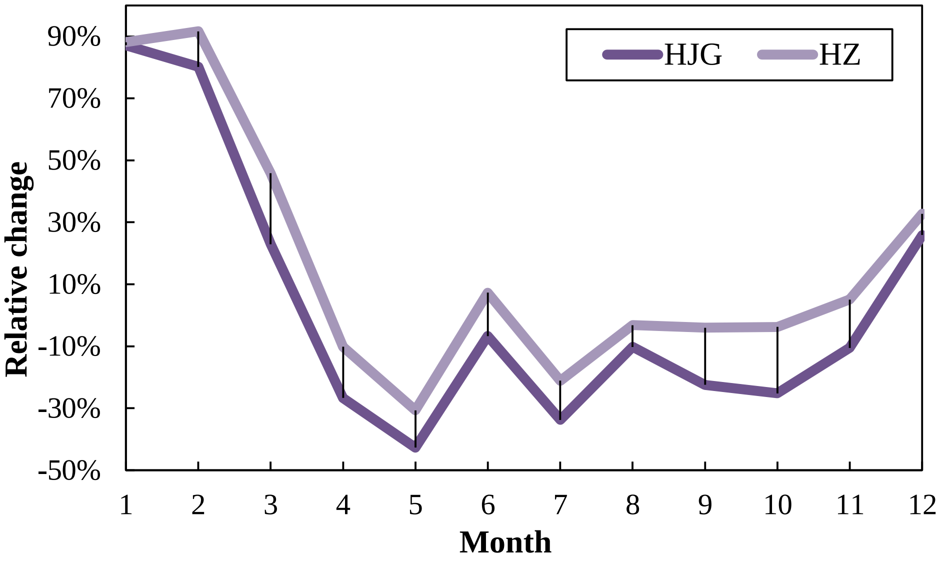


Figure 9. The relative change of monthly average flow at HJG and HZ between the interim and pre-impact periods.

The monthly average runoff at HJG and HZ increased significantly from December to March (Table 3). During January and February, the average streamflow at HJG and HZ increased by 87.12% and 91.63%, respectively. At the beginning of the wet season, the DJK began to store water, resulting in a decrease in the average downstream flow, the streamflow reduction at HJG, and HZ achieved the highest value in May, up to 42.70% and 30.70%, respectively. Therefore, DJK had a much greater impact on the downstream runoff during the dry season than the wet season.

As shown in Table 3, the variation of the minimum flow value at HJG and HZ increased significantly during the interim period compared to the pre-impact period. The 7-day minimum flow value at HJG changed substantially, decreasing up to 77.63%, and the 1-day minimum flow value at HZ increased up to 91.20%. On the contrary, the reduction of the maximum flow value at HJG and HZ was much lower than in the case of the minimum flow values. For example, the 7-day maximum flow value at HJG decreased by 35.04%, and the 1-day maximum flow value at HZ decreased by 25.40%, while other indicators had similar patterns.

The date corresponding to the minimum value at HJG was postponed from the 113th day to the 134th day, and from the 107th day to the 141th day in the case of HZ. The date for the maximum value at the two stations did not change significantly. The duration of the flow pulse mainly affects the flooding time of the floodplain and the spawning of floating fish. The duration of the high flow pulse at HJG and HZ is stable for 5–7 days. There is no clear change before and after the construction of DJK, while the low pulse duration changed significantly, from 22 days to 4 days, and from 33 days to 15 days at HJG and HZ, respectively. The rise and fall rates at HJG decreased by 64.79% and 30.49%, respectively, during the interim period, and the number of reversals increased by 92.13%. A similar pattern also appears at HZ, although with a lower variety than in the case of HJG.

The operation of DJK has greatly changed the natural flow regime in the middle and lower Hanjiang River. The annual distribution of runoff tends to be slight, the streamflow decreases during the wet season and increases during the dry season, which in turn, improves the capability of flood prevention and drought resistance. Furthermore, the project is of great benefit to other aspects, for example, for hydropower, the station of DJK has a total capacity of 900,000 KW, solving the power consumption of industry and agriculture in cities such as Wuhan City and Xiangyang City, Hubei Province. For navigation, the downstream river channel is navigable for 300-ton ships throughout the year, and the section from Xiangyang City to Wuhan City changed from seasonal navigation to year-round navigation, which greatly enhances the capacity of navigation. For water demand of agriculture, the area of arable land irrigated by water diversion through DJK exceeds 2400 km^2, and the economic benefits outweigh 500 million yuan. At the same time, the changes in extreme values of runoff, for instance, the decrease in the maximum flow value, the delay in the date of maximum and the reduction in the rising rate, have a high impact on the reproduction of floating fish in the middle and lower Hanjiang River. In fact, the spawning volume of four major Chinese carps decreased from 900 to 93 million between the 1970s and the 2000s. In view of the above, the benefits and disadvantages given by the construction of DJK for the middle and lower Hanjiang River, the accent should be put on the need for comprehensive management favoring the coordination between water demand and sustainability of river ecosystems.

5.2. Impact of WFZ and CJY on the Streamflow

In the transition period (2000–2013), two cascade reservoirs were built in the mainstream of Hanjiang River, WFZ and CJY (Figure 1). The total storage capacity is shown in Table 1. Both reservoirs are located upstream of HZ, and therefore, the changes in the IHA indicators corresponding to HZ and XT reflect the influence of the cascade reservoirs on the hydrological conditions of the middle and lower Hanjiang River during the transition period. As shown in Table 4, the impact of the construction of cascade reservoirs on streamflow is slight, with 13 and 10 indicators changing by more than 10% at HZ and XT, respectively.

In the transition period, the average discharge of HZ increased by 9.79% in September, while decreasing in other months. The average monthly streamflow decreased in May, June and October with a higher range, reaching values of 15.33%, 19.72%, and 15.83%, respectively. The major cause of the decline in streamflow for almost all of the year is the increase in water consumption primarily affected by the rapid development of urbanization, irrigation, and hydropower generation. The changing anomalies of discharge in May, June, September, and October are mainly influenced by the scheduling of cascade reservoirs. The runoff of downstream decreased by more than 10% during May and June, because the cascade reservoirs start to impound at the beginning of the wet season, increasing the efficiency of power generation. Due to the limited storage capacity of the cascade reservoirs, the runoff increased in September. At the end of the wet season, in October, the discharge is decreased to ensure the benefits of hydropower. Additionally, the runoff at XT had a similar change to HZ. In May, June, and October, runoff decreased by 10.83%, 18.78%, and 17.86%, respectively, and increased by 7.96% in September. In other months, the streamflow decreased to a great extent. Generally, the streamflow changes significantly at HZ and XT during May, June, September and October, associated with the degree of efficiency of hydropower generation during the transition period.

The maximum and minimum flow values at HZ and XT decreased within a similar range. The 1-day and 3-day maximum flow values at HZ were reduced by 17.08% and 11.22%, respectively, while they were decreased by 14.75% and 11.49%, respectively, at XT. The 90-day minimum flow value decreased by 10.63%. The date corresponding to the minimum value moved from 141th day to 193th day at HZ, and the date of maximum did not change significantly as well as the date of maximum and minimum at XT. Moreover, the low pulse duration at HZ was further reduced from 15 to 11 days. The variety of low pulse count, high pulse count and high pulse duration was slight compared to the pre-impact period and interim period. There was no low pulse at XT during the interim period and transition period, while the changes in high pulse count and high pulse duration were almost the same as those at HZ. The rise and fall rates at HZ decreased by 23.78% and 26.70%, respectively, during the transition period, and the number of reversals increased by 22.49%, which is a smaller change compared to the interim period.

At XT, both the rise and fall rates decreased by 27.67% and 27.95%, respectively, and there were no significant changes in the number of reversals.

Table 4. Changes of IHA metrics in the transition period.

	Huangzhuang			**Xiantao**		
	Interim Period (1974–1999)	**Transition Period (2000–2013)**		**Interim Period (1974–1999)**	**Transition Period (2000–2013)**	
	Mean Value	**Mean Value**	**Relative Change (%)**	**Mean Value**	**Mean Value**	**Relative Change (%)**
Group 1: Mean Flow						
January	918.10	866.80	−5.59	872.30	814.40	−6.64
February	881.30	838.20	−4.89	832.90	796.10	−4.42
March	901.90	878.10	−2.64	843.90	837.50	−0.76
April	1008.00	917.40	−8.99	850.30	820.80	−3.47
May	1226.00	1038.00	**−15.33**	1028.00	916.70	**−10.83**
June	1491.00	1197.00	**−19.72**	1246.00	1012.00	**−18.78**
July	2410.00	2282.00	−5.31	1974.00	1781.00	−9.78
August	2630.00	2584.00	−1.75	2112.00	1954.00	−7.48
September	2299.00	2524.00	9.79	1885.00	2035.00	7.96
October	1813.00	1526.00	**−15.83**	1568.00	1288.00	**−17.86**
November	1078.00	1016.00	−5.75	999.10	928.60	−7.06
December	913.90	887.80	−2.86	864.80	814.60	−5.80
Group 2: Annual Extreme						
1-day minimum	565.00	519.50	−8.05	495.10	475.10	−4.04
3-day minimum	578.00	542.20	−6.19	531.40	487.90	−8.19
7-day minimum	598.50	563.10	−5.91	556.10	508.90	−8.49
30-day minimum	671.70	627.00	−6.65	621.00	568.20	−8.50
90-day minimum	759.90	701.30	−7.71	701.70	627.10	**−10.63**
1-day maximum	9146.00	7584.00	**−17.08**	5985.00	5102.00	**−14.75**
3-day maximum	7941.00	7050.00	**−11.22**	5554.00	4916.00	**−11.49**
7-day maximum	6384.00	5958.00	−6.67	4773.00	4332.00	−9.24
30-day maximum	3834.00	3795.00	−1.02	3059.00	2925.00	−4.38
90-day maximum	2724.00	2683.00	−1.51	2206.00	2138.00	−3.08
Group 3: Timing of Extreme						
Number of zero days	0.00	0.00	–	0.00	0.00	–
Base flow index	0.43	0.43	−0.65	0.46	0.45	−2.78
Date of minimum	141.04	193.21	**36.99**	139.38	144.50	3.67
Date of maximum	223.65	213.93	−4.35	232.35	215.43	−7.28
Group 4: Frequency and Duration						
Low pulse count	1.15	3.00	**159.97**	0.00	0.00	–
Low pulse duration	15.28	10.72	**−29.84**	–	–	–
High pulse count	3.23	2.29	**−29.25**	3.35	2.36	**−29.56**
High pulse duration	5.26	8.23	**56.46**	7.44	10.48	**40.92**
Group 5: Rate						
Rise rate	194.70	148.40	**−23.78**	124.10	89.76	**−27.67**
Fall rate	163.70	120.00	**−26.70**	96.89	69.81	**−27.95**
Number of reversals	124.50	152.50	**22.49**	97.42	101.90	4.60

Note: The number in bold means relative change is larger than 10%.

Two cascade reservoirs were built during the transition period in the middle and lower Hanjiang River, both of them located in the area between DJK and HZ. Except for September, the average flow decreased to varying degrees, including the maximum and minimum flow value, indicating that the construction of cascade reservoirs has a continuous negative effect on the streamflow of the mainstream of Hanjiang River. The river′s aquatic habitat was fragmented by the reservoirs, destroying fish spawning and migration channels, at the same time, the hydrological conditions, such as the maximum flow value, date of the maximum value and the rise rate were also affected. This was similar during the interim period, resulting in a high decrease of the spawning of four major Chinese carps from 93 to 3 million between the 2000s and the 2010s. The cascade reservoirs further improved human development efficiency and management capabilities in the middle and lower Hanjiang River, such as flood control and drought resisting and hydropower generation. The construction of two cascade reservoirs has further improved the navigation capacity of the river. WFZ can increase navigable ships from 300 to 500 tons, and CJY can increase navigable ships to 1000 tons. In addition, the annual power generation capacity of the two cascade reservoirs reached 950 million KWh, providing sufficient power for urban development in the basin. Although the negative impact of the cascade reservoirs on the ecological environment of the river is less than that of the DJK, it cannot be ignored, and joint dispatch with the DJK is needed to minimize the negative impacts.

5.3. Impact of Water Diversion Projects and XL on the Streamflow

During the post-impact period (2014–2018), the DJK was heightened, and the total storage capacity increased by 11.6 billion cubic meters, and at the same time, the MSNDWP was operative. According to the statistics of the Ministry of Water Resources of the People's Republic of China, the total water transfer volume exceeded 20 billion cubic meters by 2018. The compensation projects XL and YHDWP for the MSNDWP started to operate in 2014. The main function of XL is to raise the water level in the reservoir area to ensure the water diversion and navigation conditions in the midstream. The YHDWP replenishes the downstream water volume, thus alleviating the negative impact caused by the MSNDWP, located between the HZ and XT (Figure 1). Table 5 and Figure 10 illustrate the changes in various indicators for the three stations during the post-impact period. At these three stations, the indicators decreased to 26, 23, and 23, respectively, indicating that the MSNDWP had further changed the hydrological regime in the middle and lower Hanjiang River.

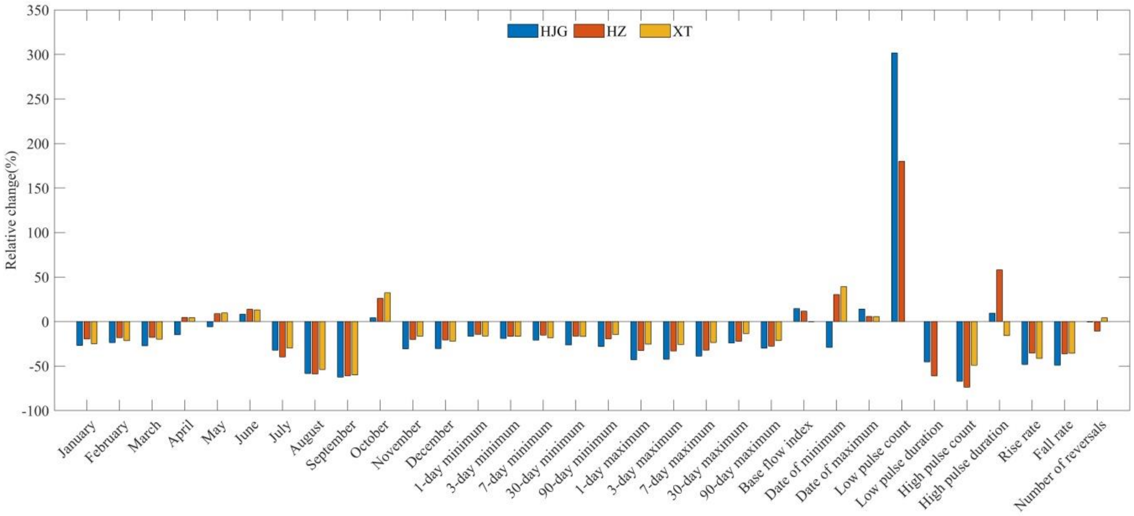


Figure 10. The relative change of 33 IHA indicators at HJG, HZ and XT between the transition and post-impact periods.

As shown in Figure 11, the results evidence the changing process of monthly average discharge of three stations during the post-impact period, the changing laws of which are highly similar. In the dry season, the flow at the downstream station is mainly affected by the discharge from DJK into the small catchment in the midstream of Hanjiang River. Therefore, the average flow reduction of three stations is almost stable at about 20% due to the effect of water transfer. The streamflow mainly occurs during the wet season from July to September and corresponds to the storage period of DJK in the Hanjiang River basin. The discharge at each station decreased to a great extent. The decreased magnitude of runoff at HZ is higher than others, and the average streamflow decreased by 1322 m^3/s in the period, while the runoff at HJG and XT decreased by 859 m^3/s and 934 m^3/s, respectively.

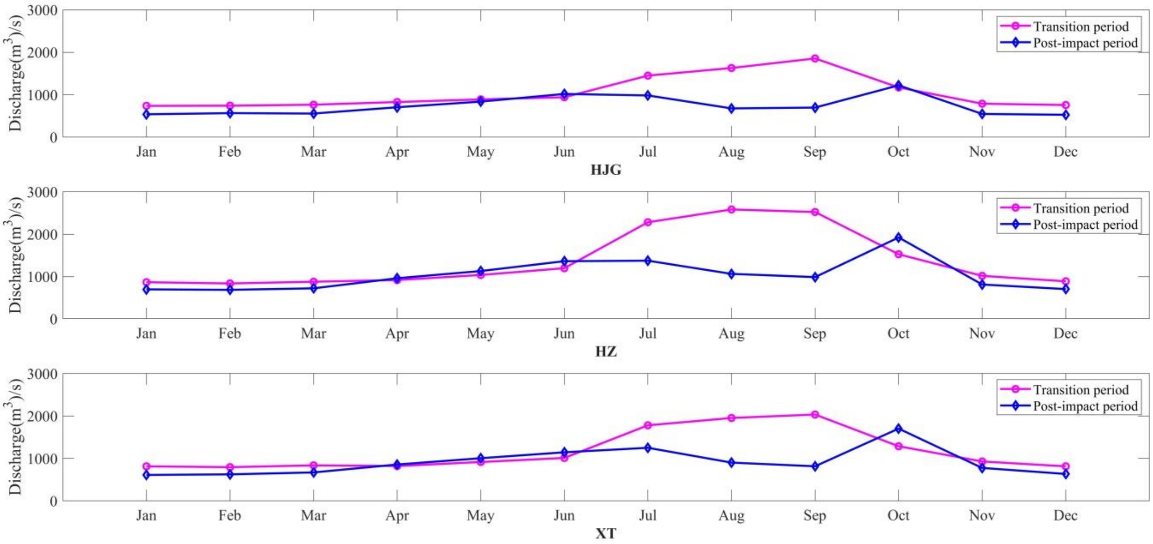


Figure 11. Average monthly flow at HJG, HZ and XT between the transition and post-impact periods.

As shown in Table 4, the average streamflow of HZ and XT did not change significantly from July to September during the interim and transition periods, indicating that the compensation projects of the MSNDWP play a key function in improving the downstream hydrological conditions. The YHDWP started to transfer water when the downstream flow was below a certain level. Figure 12 shows the changes in the number of days below the standard level at XT over different months during the post-impact and the transition periods. The number of days below 530 m^3/s from November to March was reduced from 88 to 51 days, decreased by 42%, the number of days below 600 m^3/s from April to October was reduced from 99 to 32 days, decreasing by 68%, and the number of days below 800 m^3/s from May to September decreased from 157 to 78 days, decreasing by 68%. The results further illustrate that the YHDWP has a significant improvement effect on the downstream hydrological conditions.

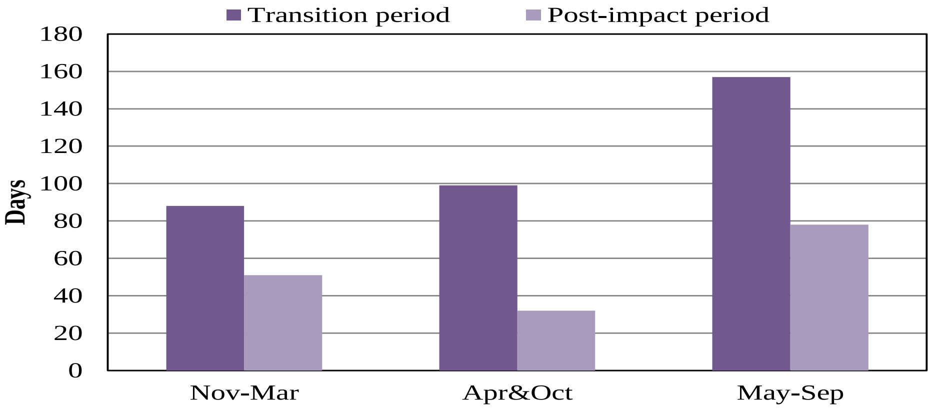


Figure 12. The number of days of low-standard streamflow in different months between the transition and post-impact periods. The standard streamflow from November to March is 530 m^3/s. The standard streamflow in April and October is 600 m^3/s. The standard streamflow from May to September is 800 m^3/s.

In the post-impact period, both maximum and minimum flow values of three stations decreased to some extent. The 1-day, 3-day, 7-day, 30-day and 90-day mimimum flow values decreased from 15% to 30%, and the maximum flow values decreased approximately by 20 to 40%. In general, the reduction degree of the maximum flow value is greater than the minimum flow value, indicating that the MSNDWP has a more significant peak-shaving effect on the middle and lower Hanjiang River.

Table 5. Changes of IHA metrics in the post-impact period.

	Huangjiagang			**Huangzhuang**			**Xiantao**		
	Transition Period (2000–2013)	**Post-Impact Period (2014–2018)**		**Transition Period (2000–2013)**	**Post-Impact Period (2014–2018)**		**Transition Period (2000–2013)**	**Post-Impact Period (2014–2018)**	
	Mean Value	**Mean Value**	**Relative Change (%)**	**Mean Value**	**Mean Value**	**Relative Change (%)**	**Mean Value**	**Mean Value**	**Relative Change (%)**
Group 1: Mean Flow									
January	737.20	539.40	**−26.83**	866.80	697.30	**−19.55**	814.40	611.80	**−24.88**
February	741.80	566.30	**−23.66**	838.20	686.60	**−18.09**	796.10	625.40	**−21.44**
March	764.40	556.30	**−27.22**	878.10	722.00	**−17.78**	837.50	671.30	**−19.84**
April	827.20	704.70	**−14.81**	917.40	959.90	4.63	820.80	857.20	4.43
May	890.00	838.20	−5.82	1038.00	1130.00	8.86	916.70	1006.00	9.74
June	940.90	1018.00	8.19	1197.00	1362.00	**13.78**	1012.00	1145.00	**13.14**
July	1450.00	983.20	**−32.19**	2282.00	1375.00	**−39.75**	1781.00	1251.00	**−29.76**
August	1630.00	678.00	**−58.40**	2584.00	1063.00	**−58.86**	1954.00	902.30	**−53.82**
September	1854.00	697.10	**−62.40**	2524.00	987.00	**−60.90**	2035.00	815.80	**−59.91**
October	1171.00	1221.00	4.27	1526.00	1923.00	**26.02**	1288.00	1704.00	**32.30**
November	788.80	547.50	**−30.59**	1016.00	812.20	**−20.06**	928.60	776.40	**−16.39**
December	756.80	527.30	**−30.33**	887.80	704.00	**−20.70**	814.60	635.40	**−22.00**
Group 2: Annual Extreme									
1-day minimum	425.10	355.10	**−16.47**	519.50	444.90	**−14.36**	475.10	397.70	**−16.29**
3-day minimum	453.00	367.20	**−18.94**	542.20	452.50	**−16.54**	487.90	407.00	**−16.58**
7-day minimum	478.40	378.60	**−20.86**	563.10	477.50	**−15.20**	508.90	416.60	**−18.14**
30-day minimum	540.40	398.40	**−26.28**	627.00	524.50	**−16.35**	568.20	473.10	**−16.74**
90-day minimum	609.00	438.40	**−28.01**	701.30	565.20	**−19.41**	627.10	535.90	**−14.54**
1-day maximum	4998.00	2857.00	**−42.84**	7584.00	5116.00	**−32.54**	5102.00	3808.00	**−25.36**
3-day maximum	4770.00	2748.00	**−42.39**	7050.00	4722.00	**−33.02**	4916.00	3647.00	**−25.81**
7-day maximum	4285.00	2622.00	**−38.81**	5958.00	4043.00	**−32.14**	4332.00	3312.00	**−23.55**
30-day maximum	2632.00	1999.00	**−24.05**	3795.00	2956.00	**−22.11**	2925.00	2532.00	**−13.44**
90-day maximum	1872.00	1312.00	**−29.91**	2683.00	1943.00	**−27.58**	2138.00	1682.00	**−21.33**

Table 5. *Cont.*

	Huangjiagang			**Huangzhuang**			**Xiantao**		
	Transition Period (2000–2013)	**Post-Impact Period (2014–2018)**		**Transition Period (2000–2013)**	**Post-Impact Period (2014–2018)**		**Transition Period (2000–2013)**	**Post-Impact Period (2014–2018)**	
	Mean Value	**Mean Value**	**Relative Change (%)**	**Mean Value**	**Mean Value**	**Relative Change (%)**	**Mean Value**	**Mean Value**	**Relative Change (%)**
Group 3: Timing of Extreme									
Number of zero days	0.00	0.00	–	0.00	0.00	–	0.00	0.00	–
Base flow index	0.47	0.54	**14.56**	0.43	0.48	**11.71**	0.45	0.45	−0.31
Date of minimum	200.36	142.20	**−29.03**	193.21	251.80	**30.32**	144.50	201.20	**39.24**
Date of maximum	210.50	240.00	**14.01**	213.93	226.20	5.74	215.43	227.60	5.65
Group 4: Frequency and Duration									
Low pulse count	1.64	6.60	**301.70**	3.00	8.40	**180.00**	0.00	0.20	–
Low pulse duration	9.45	5.17	**−45.30**	10.72	4.18	**−61.05**	–	3.00	–
High pulse count	1.21	0.40	**−67.05**	2.29	0.60	**−73.75**	2.36	1.20	**−49.09**
High pulse duration	9.14	10.00	9.42	8.23	13.00	**58.05**	10.48	8.83	**−15.72**
Group 5: Rate									
Rise rate	96.35	49.95	**−48.16**	148.40	95.93	**−35.36**	89.76	52.62	**−41.38**
Fall rate	97.57	49.70	**−49.06**	120.00	76.63	**−36.14**	69.81	44.96	**−35.60**
Number of reversals	194.60	193.60	−0.51	152.50	136.20	**−10.69**	101.90	106.20	4.22

Note: The number in bold indicate relative change greater than 10%.

The scheduling rules of DJK were changed on account of the operation of the MSNDWP. The date of minimum flow value at HJG was extended by 58 days, while the date of minimum flow value at HZ and XT was delayed by 59 and 56 days, respectively. The date of maximum flow value of three stations was stable at about 230th day. The low pulse count at HJG and HZ increased by 5 and 5.4, and the low pulse duration decreased by 4.3 days and 6.5 days, respectively. Low flow pulse appeared for the first time at XT in the post-impact period, whereas the values were far less than those at HJG and HZ, indicating that compensation projects, especially YHDWP, played a positive role in downstream of Hanjiang River. The high pulse count further decreased in three stations, which almost disappeared in the middle and lower Hanjiang River. The rise and fall rates of the stations decreased from 35% to 50%, and the number of reversals had inapparent change.

The operation of the MSNWDP benefited more than 60 million people in Henan Province, Hebei Province, Tianjin Province, and Beijing City of China, solving water scarcity and the living conditions of a large number of cities along the route, more than 30 billion m^3 of water has been transferred for five northern provinces and cities by the end of 2019. The MSNWDP have an important role in restoring the groundwater level of the North China Plain, the water diverted from DJK to Beijing City reduced cumulative groundwater depletion by almost 3.6 km^3, accounting for 40% of groundwater recovery in recent years [38]. On the other hand, the water transfer project brought certain problems to the middle and lower Hanjiang River, as well. For example, a reduction water level caused by the significant reduction of runoff, making water catchment along the river difficult. However, many compensation projects, such as the YHDWP, have alleviated the damage to hydrological conditions, navigation, and ecological environment in downstream Hanjiang River.

6. Conclusions

The long-series daily streamflow data obtained from three stations were used to analyze the changes and trends of IHA indicators and eco-flow indicators, in order to study the impact of the implementation of multi-projects on the hydrological conditions of the middle and lower Hanjiang River. The operation of the DJK resulted in a decrease in the annual streamflow in the upstream HJG, while the annual average streamflow was not changed significantly in the middle and downstream stations, although the fluctuations were concentrated within a range. The construction of cascade reservoirs reduced annual streamflow significantly at HZ and XT. The completion of the MSNDWP led to a decrease in the annual average streamflow at three stations that was greater than the impact caused by the finalization of the Danjiangkou Reservoir.

The eco-flow indicators show that the construction of DJK has a positive effect on the ecological status of downstream, while cascade reservoirs have no direct impact, and the operation of the MSNDWP could damage the river ecology. The analysis of the IHA index shows a significant increase in the monthly discharge, and prominently due to the DJK in the downstream stations during the dry season, while it decreased during the wet season. Additionally, the minimum flow value, and the number of reversals increased; the maximum flow value, the low pulse duration, and the rates of rise and fall significantly decreased. Various indicators decreased slightly in downstream stations affected by the cascade reservoir. Moreover, the reduction of the runoff caused by the MSNDWP was higher from July to September during the wet season, than during the dry season. Compensation projects such as YHDWP alleviate the reduction of the discharge downstream from July to September. The maximum and minimum flow values, low pulse duration, and the rates of rise and fall were all reduced; the high pulse almost disappeared.

This study analyzed the impact of various water resources development and use projects on the natural flow regime of the middle and lower Hanjiang River during the past 60 years. On the one hand, the changes in the hydrological conditions negatively affected the river ecosystem, especially in the number of floating fish communities. On the other hand, water resources were better exploited and used through the construction of engineering infrastructures, which involve very significant functions such as hydropower generation, irrigation, navigation, flood control, or for combating drought. This research contributes to achieving a better understanding of the benefits of a joint operation between DJK and cascade reservoirs, which may entail better management of water resources finding a balance between economic and environmental sustainability.

The MSNDWP has operated over a short period, and as the volume of water transfer increases gradually, the impact on the middle and lower Hanjiang River still needs further attention. The benchmarking framework of this study can serve as a point of reference for the evaluation of possible impacts and countermeasures when new infrastructures are built in the future such as Xinji Reservoir, Yakou Reservoir, and Nianpanshan Reservoir.

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