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Assessment of Hydrological Changes and Their Influence on the Aquatic Ecology over the last 58 Years in Ganjiang Basin, China

Yinghou Huang [1], Binbin Huang [1], Tianling Qin [2,*], Hanjiang Nie [2,3], Jianwei Wang [2], Xing Li [4] and Zhenqian Shen [5]

1 School of Hydraulic & Ecological Engineering, Nanchang Institute of Technology, Nanchang 330099, China
2 State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research, Beijing 100038, China
3 Department of Hydraulic Engineering, Tsinghua University, Beijing 100084, China
4 Water resources and Hydeopower Planning Design Institute of Ji'an City, Ji'an 343000, China
5 The Pearl River Hydraulic Research Institute, Guangzhou 510611, China
* Correspondence: qintl@iwhr.com; Tel.: +86-010-6878-1316

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Abstract: Runoff is the key driving factor of the Ganjiang River ecosystem. Human activities such as reservoir construction have greatly changed the state of runoff. In order to analyze the influence of Ganjiang Reservoir on the hydrological regime, the following paper is based on the daily precipitation data of 53 rainfall stations in Ganjiang River Basin from 1959 to 2016, and the daily runoff data of three stations in Dongbei, Ji'an, and Waizhou from 1959 to 2016. The Mann–Kendall test (MK) was used to analyze the trend of precipitation and runoff in Ganjiang River Basin. The Sliding t-Test (ST) was used to determine the abrupt change time of runoff in flood season within typical cross-sections of upper, middle, and lower reaches of Ganjiang River Basin, Ji'an, and Waizhou. Indicators of hydrological change (IHA), range of variability approach (RVA), and other methods were used to analyze the changes of 32 hydrological indicators in Ganjiang River Basin. The results showed that (1) The annual and flood season precipitation in Ganjiang River Basin increased from 1992 to 2016, but it did not reach a significant level. The change of annual runoff at Dongbei and Waizhou Stations was the same as that of the annual precipitation in Ganjiang River Basin. The runoff of Dongbei Station in flood season decreased from 1986 to 2016, and the runoff of Waizhou Railway Station in flood season decreased from 2008 to 2016. It showed that precipitation had a great influence on annual runoff, and human activities made the annual runoff distribution process more uniform; (2) The abrupt changes of runoff in flood season at three hydrological stations in Ganjiang River Basin occurred in 1991, and reached a significant level of 0.01; (3) There were five hydrological indicators of Dongbei Station which had reached height change. The change degree of low (l) pulse duration was −92.24%, the change degree of high (h) pulse count was −86.8%, the change degree of flow rise rate was 87.06%, the change degree of fall rate was −92.24%, and the change degree of number of reversals was −100%. Four hydrological indicators of Ji'an Station had reached high change degree, the count and duration of high pulse changes were −73.33% and −73.65%, the change degree of fall rate was −79%, and the change degree of number of reversals was −100%. Waizhou Station did not reach the high change indicator. The hydrological regime of the upper and middle reaches of Ganjiang River has changed greatly, while the hydrological regime of the lower reaches has changed little. The hydrological regime in the upper and middle reaches of Ganjiang River Basin has been highly changed by human activities such as dam construction. The change of hydrological conditions in the upper and middle reaches of Ganjiang River Basin may reduce the area of aquatic organisms' habitat, be harmful to the spawning, migration, and survival of aquatic organisms, reduce the interception of organic matter in floodplains, and increase the drought pressure of plants. The reservoir ecological operation of rivers with numerous reservoirs should be considered, joint reservoir dispatching schemes should be formulated for the study area so as to maximize the comprehensive benefits. This study provides a reference for water resources management and reservoir operation in Ganjiang River Basin. The next step is to use a habitat model to simulate the habitat of Ganjiang River Basin.

Keywords: Ganjiang River Basin; trend analysis; indicators of hydrological change; variability of hydro-meteorological indicators; eco-hydrological

1. Introduction

Runoff is the key driving factor of the river ecosystem; runoff timing changes are caused by climate change and human activities [1,2]. At the same time, the size of the surface drainage facilities and the construction of the reservoir have a significant impact on the runoff [3–5]. Runoff regime change is generally considered to be one of the most serious and persistent threats to river ecological sustainability [6,7]. The impact of hydrological regime changes on ecosystem diversity has received increasing international attention [8–10].

Intensive impact of human activities in catchments contributes to the degradation of their water ecological status, which reflected in reduced abundance and diversity of particular species of aquatic organisms [11]. In order to quantitatively evaluate the impact of human activities such as reservoir construction on the hydrological status of the ecosystem, a large number of evaluation methods have been proposed by relevant scholars, for instance, Pareto-optimal solutions for ecological flow schemes [12,13]. It involves determining the trade-off between human water supply and ecological flow objectives, ranging from vulnerability, elasticity, and reliability to water quality, safety, and cost. However, many studies only focus on a single goal, without an acceptable set of ecological flow objectives. Vogel et al. [12,13] introduced the nondimensional metrics of ecodeficit and ecosurplus, which are based on a flow duration curve (FDC). Importantly the ecodeficit and ecosurplus can be computed over any time period of interest and reflect the overall loss or gain during that period [8–10]. However, only the influence of water amount on ecology was considered, and other factors in the runoff process were not considered. Richter et al. [14] proposed an approach known as "indicators of hydrological change" (IHA). The index is based on available hydrological data or model generation within the ecosystem and takes into account the full range of natural flow changes, including amplitude, frequency, time, duration, and rate of change. The indicator of hydrological change (IHA) is one of the most popular and widely used indicators [15–17]. Olden and Poff [18] reviewed 170 available hydrological indicators (including IHA) and found that IHA can fully represent the flow patterns with ecological knowledge. All of those studies suggest that IHA can be used to assess hydrological changes and to understand the interaction between flow and river ecosystems [19]. Many scholars have studied the impact of human activities and climate change on the hydrological situation of rivers. However, they usually study the impact of a dam on the hydrological situation of the lower reaches, and have not studied rivers with many reservoirs as a whole. The study attempts to provide an idea for the study of the overall hydrological status change in the river basin with numerous reservoirs. Several typical sections of the river basin are selected to calculate the hydrological status changes before and after the impact period based on the abrupt change points of the long-sequence runoff process. The hydrological status changes of the river basin is evaluated as a whole.

There are many reservoirs in the Ganjiang River Basin. As of 2009, 3959 reservoirs have been built in the basin [20]. Current studies on the runoff of Ganjiang River usually focus on the change of flow size [21], but did not evaluate the overall hydrological situation change of the Ganjiang River Basin, while the operation of numerous reservoirs will inevitably affect the hydrological situation of the Ganjiang River. In order to further clarify the different changes of the hydrological situation in the upper, middle, and lower reaches of Ganjiang River and the impact of reservoirs on the hydrological situation change, this research paper analyzes the situation using the following steps: (1) Study the trend of precipitation and runoff change in Ganjiang River Basin from 1959 to 2016, and find the abrupt change point of runoff. (2) Quantify the change degree of hydrological indicators (IHA) of typical sections in the upper, middle, and lower reaches of the Ganjiang River Basin with abrupt runoff as the cut-off point, in order to study the change rule of hydrological index in Ganjiang River Basin as a whole. (3) Analyze the impact of reservoirs on hydrological regime and the river ecosystem, with a view to providing reference for water resources management and reservoir operation in Ganjiang River Basin.

2. Materials and Methods

2.1. Ganjiang River Basin

The study area is Ganjiang River Basin which is the seventh largest tributary of Yangtze River. The Ganjiang River Basin covers an area of about 83,500 km^2 and accounts for 51% of the territory in Jiangxi Province in central China. The location of the basin is 113°46′~116°28′ east longitude and 24°29′~29°50′ north latitude (Figure 1). The average elevation is approximately 112 m above mean sea level. The basin has undulating terrain and is stepped from south to north, with an altitude of 12~2103 m. The average elevation is approximately 112 m above mean sea level. The mean annual air temperature is around 17.8 °C. The highest and lowest temperatures are 39.5 °C and −5.8 °C. The basin is affected by monsoon climates and typhoons, and interacts with complex terrain to bring in large amounts of rainfall. The average annual precipitation in the basin is 1580 mm, and the precipitation is unevenly distributed during the year. The precipitation in the wet season (April–September) accounts for 78.6% of the total annual precipitation. Ganjiang River runoff is recharged by precipitation, and the characteristics of runoff correspond to those of precipitation. Waizhou Hydrological Station has a collection area of 80,948 km^2 and an average annual runoff of 68.6 billion m^3; the wet season (April–September) runoff accounts for 72.3% of annual runoff. The vegetation in the basin is rich, and the natural vegetation is dominated by evergreen broad-leaved forests. Since the 1980s, Jiangxi Province has carried out a comprehensive watershed management project to improve the forest coverage in the watershed from 31.5% to 60%. In 2009, 3959 reservoirs of various types were built in the basin, including 13 large reservoirs, 118 medium reservoirs, and 3828 small reservoirs (Large reservoir: total reservoir capacity is more than 100 million m^3; medium reservoir: total reservoir capacity is more than 10 million m^3; small reservoir: total reservoir capacity is more than 100,000 m^3).

2.2. Data

The precipitation data from 53 Meteorological stations located in the Ganjiang River Basin (Figure 1) were obtained from National Climate Centre of China Meteorological Administration (CMA). The period of record of 53 meteorological stations used in this study is 1959–2016. Runoff data were obtained from Hydrology Bureau of Jiangxi Province, including daily runoff data from Waizhou Station (1959–2016), Dongbei Station (1959–2016), and Ji'an Station (1964–2016). Dongbei Station is a typical section in the upper reaches of Ganjiang River Basin, Ji'an Station is a typical section in the middle reaches, and Waizhou Station is a typical section in the lower reaches (Figure 1). Dongbei Station is the most upstream hydrological station of Ganjiang River, located 15 km downstream of Wan'an Reservoir, which can quantify the hydrological variability caused by Wan'an Reservoir. Ji'an Station is located in the middle reaches of Ganjiang River Basin. The downstream of Ji'an Station is Jishui Fish Spawning Ground [22]. The hydrological status changes of Ji'an Station can provide a basis for discussing the change of Aquatic ecology in Ganjiang River Basin. Waizhou Station is the most downstream hydrological station of Ganjiang River, which can reflect the hydrological status changes of Ganjiang River Basin as a whole.

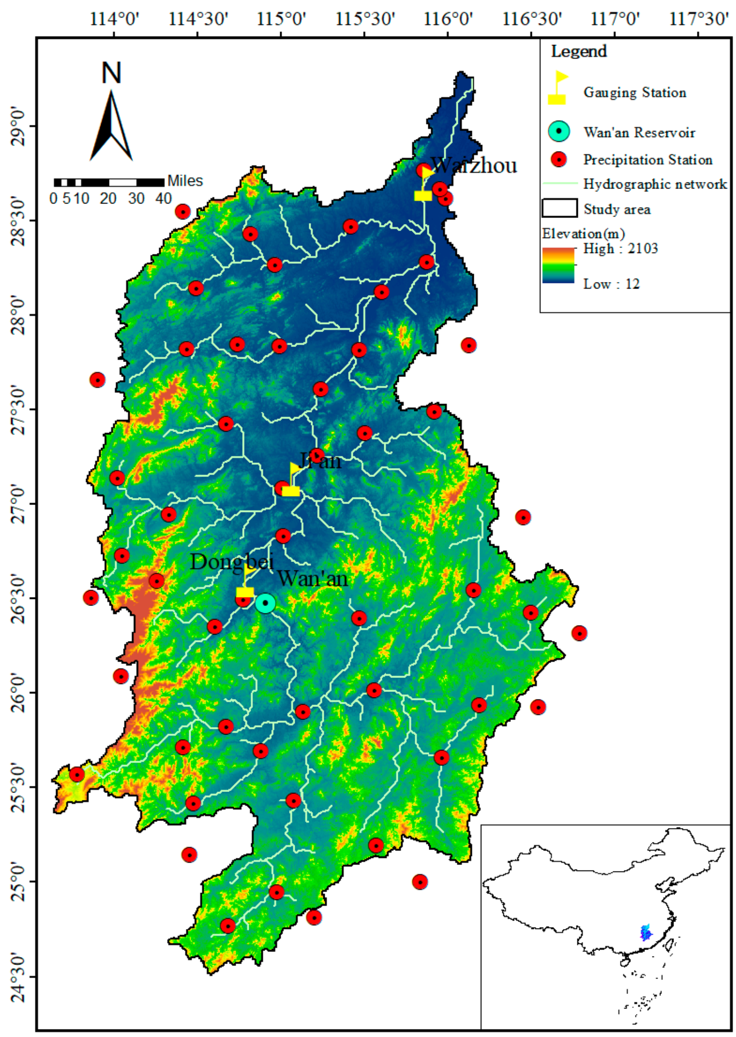

Figure 1. Ganjiang River Basin.

2.3. Method

2.3.1. Trend and Abrupt Change Analysis Method

The Mann–Kendall (MK) trend test [23,24] is recommended by the World Meteorological Organization (WMO) as an effective tool to evaluate the trend of a hydrological and meteorological data series, which is widely used in the trend and significance testing of precipitation and runoff [25–27]. In this paper, the Durbin–Watson test is used to test the hydro-meteorological series of the Ganjiang River Basin, the MK test is used to analyze the trend and significance of rainfall and runoff in the Ganjiang River Basin. In addition, Sliding *t*-Test (ST) is used to test the abrupt point of runoff series. Detailed methods of MK test and Sliding *t*-Test (ST) are described in the literature [28,29].

The Durbin–Watson test [30,31] is frequently used to detect the existence of autocorrelation in the r_i residuals after regression [32]. The equation is

$$d_w = \frac{\sum_{i=2}^{N}(r_i - r_{i-1})^2}{\sum_{1}^{N} r_i^2} \tag{1}$$

Durbin and Watson summarized the upper limit d_u and the lower limit d_l of d_w. If $d_u \leq d_w \leq 4 - d_u$, there is no autocorrelation in the original sequence; d_u and d_l can be obtained by looking up tables.

Mann–Kendall is a nonparametric statistical test method, for time series x with n sample sizes, an order sequence is created:

$$s_k = \sum_{i=1}^{k} r_i \; k = 2, 3, \cdots, n \tag{2}$$

where

$$r_i = \begin{cases} +1 \text{ if } x_i > x_j \\ 0 \text{ otherwise} \end{cases} \quad (j = 2, 3, \cdots, i) \tag{3}$$

Under the assumption of random independence of time series, the statistic UF is defined:

$$\mathrm{UF}_k = \frac{[s_k - \mathrm{E}(s_k)]}{\sqrt{\mathrm{Var}(s_k)}} \; (k = 2, 3, \cdots, n) \tag{4}$$

where $\mathrm{UF}_1 = 0$, $\mathrm{E}(s_k)$, $\mathrm{Var}(s_k)$ are the mean and variance of the cumulative number. If $x_1, x_2, \cdots, x_n$ are independent and continuous, the calculation formula is as follows:

$$\mathrm{E}(s_k) = \frac{n(n+1)}{4} \tag{5}$$

$$\mathrm{Var}(s_k) = \frac{n(n-1)(2n+5)}{72} \tag{6}$$

Repeat the above process according to the time series x inverse order $x_n, x_{n-1}, \cdots, x_1$, and make $\mathrm{UB}_k = -\mathrm{UF}_k$, $k = n, n-1, \cdots, 1$. If the value of UF or UB is greater than 0, the sequence shows an upward trend, and if the value of UF or UB is less than 0, the sequence shows a downward trend. If |UF| or |UB| is larger than U_α, it indicates a significant trend change in the sequence. $\mathrm{U}_{0.05} = 1.96$, $\mathrm{U}_{0.01} = 2.898$, and the significance level of trend analysis selected in this study was 0.05.

Sliding t-Test is set to be a reference point in time series "X" with a sample size "n". The two subsequences before and after the reference point were defined to be X_1 and X_2.

$$t = \frac{\overline{X}_1 - \overline{X}_2}{s \cdot \sqrt{\frac{1}{n_1} - \frac{1}{n_2}}} \tag{7}$$

where

$$s = \sqrt{\frac{n_1 s_1^2 + n_2 s_2^2}{n_1 + n_2 - 2}} \tag{8}$$

n_1 and n_2 is the sample size of X_1 and X_2, separately, usually $n_1 = n_2$; $\overline{X}_1$ and $\overline{X}_2$ is the average of X_1 and X_2, separately; s_1^2 and s_2^2 is the variance of X_1 and X_2, separately. If $|t_i| < t_\alpha$ there is no significant difference between the two subsequence. Otherwise, there is an abrupt change at the reference point; $t_{0.05} = 1.96$, $t_{0.01} = 2.898$.

2.3.2. Indicators of Hydrological Alteration (IHA)

Richter et al. (1996) described a method for Assessing Hydrologic Alteration (IHA) [14] that has five groups of 33 indicators, including quantity, time, frequency, duration, and change of rate, which are closely related to the changes of the river ecosystems (Table 1).

Table 1. Summary of indicators of hydrological change (IHA) parameters and ecological implications [14].

Statistics Group	Hydrologic Parameters	Ecosystem Influences
Group 1: Magnitude of monthly water conditions	Mean value for each calendar month	Habitat availability for aquatic organisms Soil moisture availability for plants Availability of water for terrestrial animals
Group 2: Magnitude and duration of annual extreme water conditions	Annual minima 1-day means Annual maxima 1-day means 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	Balance of competitive, ruderal and stress tolerant organisms Creation of sites for plant colonization Structuring of aquatic ecosystems by abiotic vs. biotic factors Structuring of river channel morphology and physical habitat conditions
Group 3 Timing of annual extreme water conditions	Julian date of each annual 1-day maximum Julian date of each annual 1-day minimum	Compatibility with life cycles of organisms Predictability/avoidability of stress for organisms Access to special habitats during reproduction or to avoid predation
Group 4: Frequency and duration of high and low pulses	No. of high pulses each year No. of low pulses each year Mean duration of high pulses within each year Mean duration of low pulses within each year	Frequency and magnitude of soil moisture stress for plans Frequency and duration of anaerobic stress for plans Availability of floodplain habitats for aquatic organisms Nutrient and organic matter exchanges between river and floodplain
Group 5: Rate and frequency of water condition changes	Means of all positive differences between consecutive daily means Means of all negative differences between consecutive daily means No. of rises No. of falls	Drought stress on plans Entrapment of organisms on islands, flood plains Desiccation stress on low mobility stream edge (varial zone) organisms

Richter et al. [32] developed the Range of Variability Approach (RVA) method to assess changes in hydrological conditions. The method uses 32 hydrological parameters to assess flow characteristics before and after the point of change. Ecologically related hydrological parameters can be divided into five groups: size, time, frequency, duration, and parameter change rate. The RVA target range is IHA values that fall in the ranges (usually between 25th percentile value and 75th percentile value) during the post- periods. This is to attain the targeted range at the same frequency as that which occurred in the natural or pre-impact flow state. For example, the RVA target range defined by the 25th and 75th percentile values for specific parameters is expected to be reached in 50% of the years. The extent to which the target range of RVA is not reached is the degree of hydrological change. The degree of the hydrological change, expressed as a percentage, can be calculated as follows [33]:

$$D = \left(\frac{Observed - Espected}{Expected}\right) \times 100 \tag{9}$$

In Equation (9), "Observed" is the number of years in which the observed values of hydrological parameters fall within the target range; "Expected" is the number of years in which the expected values fall within the target range. When the frequency of the observed value falling within the RVA target range after the impact period is equal to the expected frequency, the hydrological variation is equal to zero; positive values indicate that the frequency of annual parameters falling within the RVA target range is higher than expected; negative values indicate that the frequency of annual values falling within the RVA target range is lower than expected. In order to map hydrological changes, Richter et al. (1998) divided the hydrological variation range (0–100%) into three equal categories:

(1) 0–33% (L) represents little or no change; (2) 34–67% (M) represents moderate change; (3) 68–100% (H) represents height change.

3. Results

3.1. Trend and Abrupt Change Analysis of Precipitation and Runoff

The Durbin–Watson test was used to test the autocorrelation of hydro-meteorological data. Based on the absence of autocorrelation in the data series, the trend of annual precipitation and flood season precipitation in Ganjiang River Basin and annual runoff and flood season runoff in three typical sections were analyzed by the Mann–Kendall test. Sliding t-Test was used to determine the abrupt change points of three typical cross-section flow series.

The d_w calculated by the Durbin–Watson test satisfies $d_u \leq d_w \leq 4 - d_u$ (Table 2), when the significance level is 0.05, the precipitation-runoff data series rejects autocorrelation. The Mann–Kendall test can be used to analyze the trend of precipitation and runoff in typical sections of Ganjiang River Basin.

Table 2. Autocorrelation test results of precipitation and typical section data series in Ganjiang River Basin.

Data Sequence	d_w (Annual)	d_w (Wet Season)	d_u	4-d_u	Results
Precipitation	2.150	2.094	1.614	2.386	Reject autocorrelation
Dongbei Staion	2.120	2.325	1.614	2.386	Reject autocorrelation
Ji'an Staion	2.129	2.379	1.599	2.401	Reject autocorrelation
Waizhou Staion	2.134	2.344	1.614	2.386	Reject autocorrelation

The annual and flood season precipitation in Ganjiang River Basin increased from 1992 to 2016, but it did not reach a significant level (Figure 2). The annual average runoff of Dongbei Station and Waizhou Station increased from 1990 to 2016. Runoff in Dongbei flood season showed a decreasing trend from 1986 to 2016, and runoff in Waizhou Station showed a decreasing trend from 2008 to 2016. The annual and flood season runoff of Ji'an Station has been increasing from 1972 to 2016 (Figure 3). None of the above trends reached a significant level. The annual runoff of Dongbei and Waizhou increased with the increase in precipitation, while the runoff in flood season showed a decreasing trend with the increase in precipitation in flood season, this indicates that precipitation has a greater impact on annual runoff, and the distribution of runoff in the year may be greatly affected by human activities. The annual and flood season runoff of Ji'an Station shows an increasing trend, which indicates that different locations in Ganjiang River Basin are affected by human activities differently. In this paper, the abrupt point of flood season discharge series is regarded as the limit, and the abrupt change time is considered as before the pre-impact and after the post-impact. The IHA index changes of Dongbei, Ji'an, and Waizhou Stations representing the upper, middle, and lower reaches of Ganjiang River Basin are analyzed in order to reflect the influence of human hyperactivity on the hydrological situation in different locations of Ganjiang River Basin. Since the UF curve has more intersections with the UB curve in the MK analysis, the abrupt points of the discharge series of three hydrological stations in flood season are determined by Sliding t-Test.

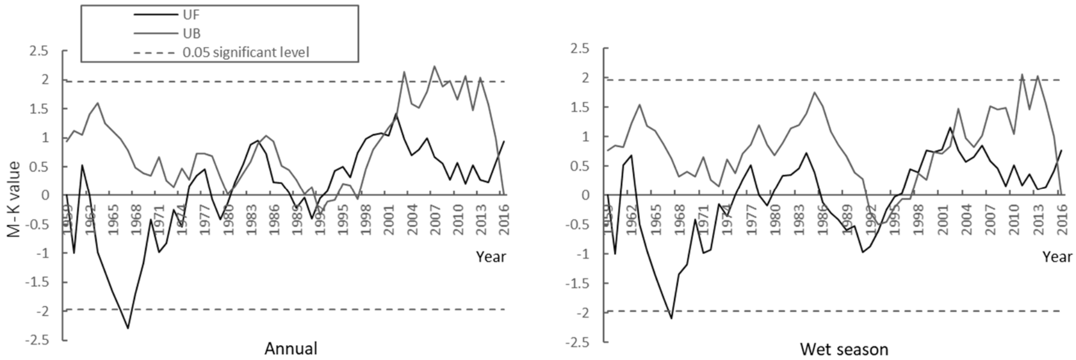

Figure 2. Mann–Kendall test for the annual and wet season precipitation of the Ganjiang River Basin, Wet season: April–September.

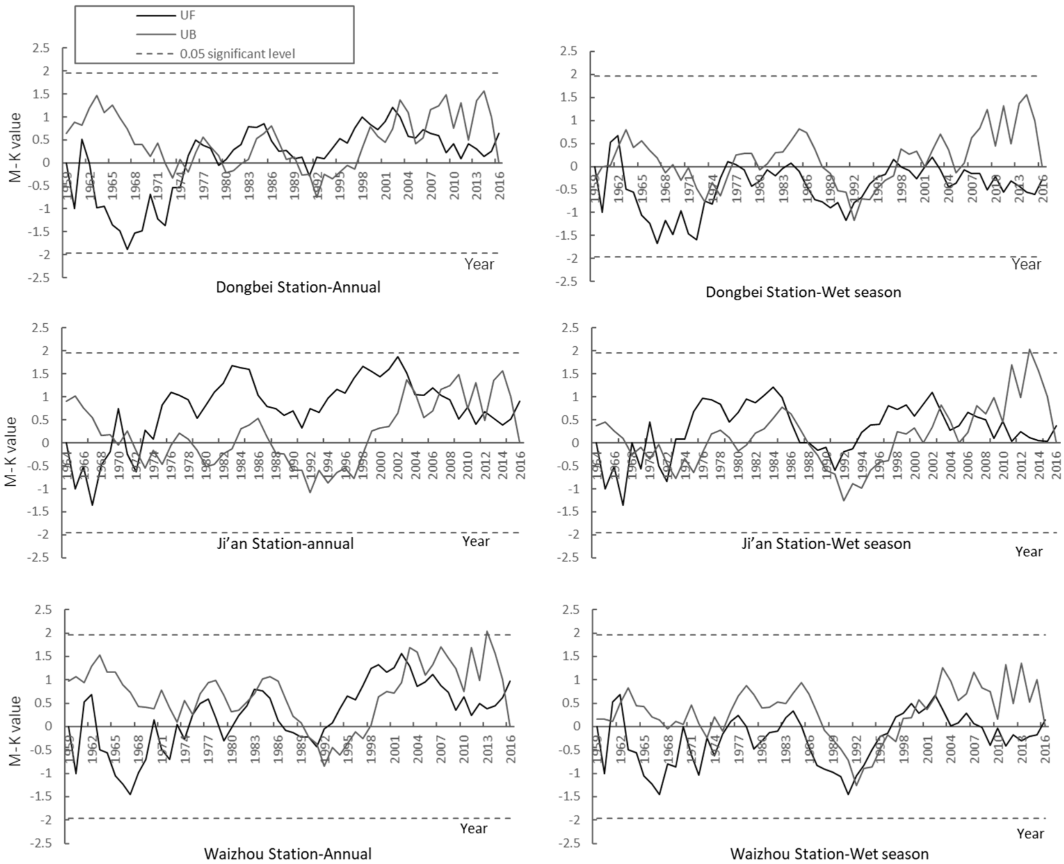

Figure 3. Mann–Kendall test for the annual and wet season streamflow in the three gauging stations of the Ganjiang River, Wet season: April–September.

Sliding *t*-Test results of runoff series with different subsequence lengths ($n = 6, 7, 8$) in flood season showed that the maximum value of T-statistics appeared in 1991 (Figure 4), and reached 0.01 significant level (Table 3).

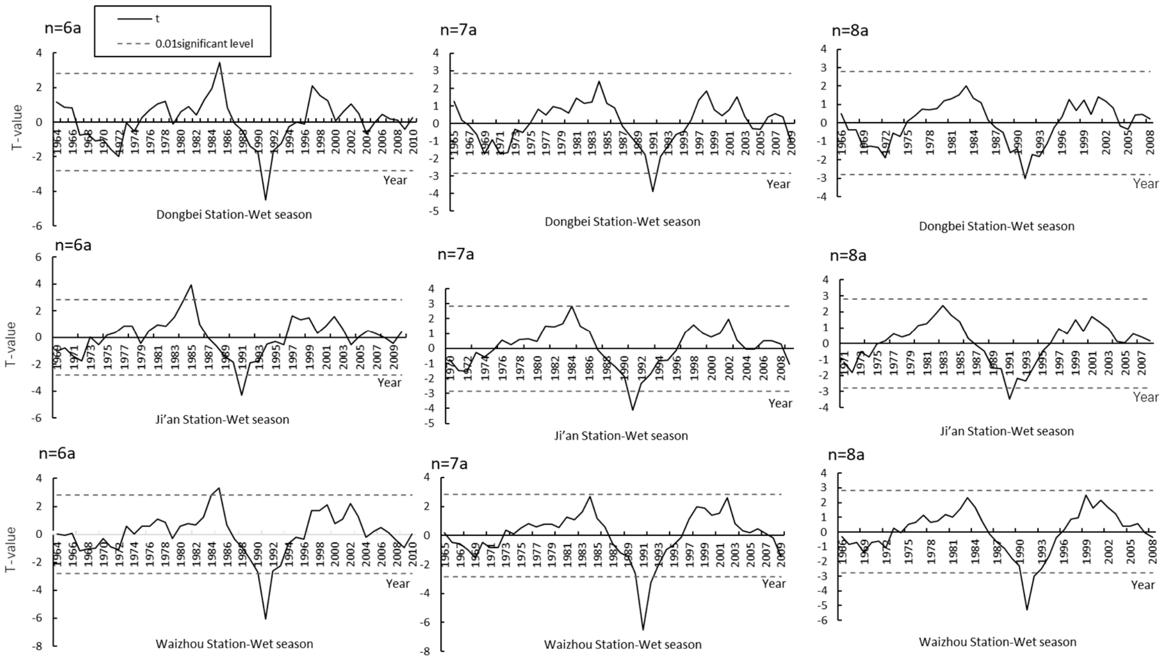

Figure 4. Sliding *t*-Test for the wet season streamflow in the three gauging stations of the Ganjiang River.

Table 3. Analysis of the abrupt change of season streamflow in the three Gauging Stations.

Station	Time Series	Results	Significance
Dongbei	n = 6a	1985, 1991	*
	n = 7a	1991	*
	n = 8a	1991	*
Ji'an	n = 6a	1985, 1991	*
	n = 7a	1991	*
	n = 8a	1991	*
Waizhou	n = 6a	1985, 1991	*
	n = 7a	1991	*
	n = 8a	1991	*

* Significant at the 0.01 level.

In summary, the abrupt changes of runoff in flood season at three hydrological stations in Ganjiang River Basin occurred in 1991. In the paper, the stations were divided into two time periods, Dongbei and Waizhou Stations from 1959 to 1991 as the pre-impact period, and 1992 to 2016 as the post-impact period; Ji'an Station from 1964 to 1991 was taken as the pre-impact period and from 1992 to 2016 as the post-impact period. The construction of Wan'an Reservoir was completed in 1990, and the Dongbei Station is located 15 km downstream of Wan'an Reservoir (Figure 1), which can quantify the hydrological variability caused by Wan'an Reservoir.

3.2. IHA Changes in Typical Sections of the Upper, Middle and Lower Reaches of the Ganjiang River Basin

3.2.1. Upstream Typical Section

The IHA hydrological index of Dongbei Hydrological Station changed greatly (Table 4). Among the first parameter group, January, March reservoir ecological operation May, July and October–December were low level changes. The change in February was −37.88%, in June it was 47.53%, in August it was −61.18%, and in September it was 47.53%. Among the second parameter group, the change in 7-day minimum was −45.65%, the 90-day minimum was 39.76%, the 30-day maximum was 63.06%, and the 90-day maximum was 39.76%. The other seven parameters were all low-level changes. Among the third parameter group, the change in date of minimum was 55.29%, and the change in date of maximum was −23.58%. Among the fourth parameter group, the low pulse count changed to −58.32%, the low pulse duration and the high pulse count changed to −92.24% and −86.8% respectively, and the high pulse duration changed to a low degree. Among the fifth parameter group, the rise rate was 87.06%, the fall rate was −92.24%, and the number of reversals was −100% (Figure 5).

Table 4. Dongbei Station IHA calculation results; L represents little or no change, M represents moderate change, H represents height change.

5 Groups	Pre-Impact Period: 1959–1991	Post-Impact Period: 1975–2006	RVA Targets	Hydrologic Alteration	Degree	
	Medians	Medians	Low	High	D (%)	
Parameter Group #1						
January	302	345	227	449.5	0.9412	L
February	399.5	442.5	308.5	572.3	−37.88	M
March	642	694	420.5	1100	32	L
April	1210	1225	917.8	1885	−6.824	L
May	1580	1540	1050	2155	−22.35	L
June	1700	1995	1158	2788	47.53	M
July	686	1060	487	1050	−22.35	L
August	599	921	457.5	784	−61.18	M
September	532.5	699	348.8	893.8	47.53	M
October	414	437	316.5	577	16.47	L
November	357	381	264.3	540.3	16.47	L
December	283	365	215.5	370.5	0.9412	L
Parameter Group #2						
1-day minimum	176	195	136	217	−6.824	L
3-day minimum	177.3	214	137.7	219.5	−14.59	L
7-day minimum	179	235.9	145.9	225.5	−45.65	M
30-day minimum	201.5	299.7	175.9	289.5	−22.35	L
90-day minimum	366	417.5	277.5	509.2	39.76	M
1-day maximum	6340	7360	5290	10150	16.47	L
3-day maximum	5333	6767	4402	8648	16.47	L
7-day maximum	4291	4939	3370	6574	32	L
30-day maximum	2963	3058	2024	4363	63.06	M
90-day maximum	2130	2249	1570	2881	39.76	M
Base flow index	0.1892	0.202	0.158	0.2367	8.706	L
Parameter Group #3						
Date of minimum	11	338	30	354.5	55.29	M
Date of maximum	145	166	102.5	170	−23.58	L
Parameter Group #4						
Low pulse count	5	13	3.5	8	−58.32	M
Low pulse duration	8.75	2	4.625	14	−92.24	H
High pulse count	9	14	7	11	−86.8	H
High pulse duration	5	3.5	3.5	7	−23.58	L
Parameter Group #5						
Rise rate	60	101	44.75	109.5	87.06	H
Fall rate	−41	−102	−55.75	−30.25	−92.24	H
Number of reversals	87	172	80	100.5	−100	H

The median of low pulse duration at Dongbei Station during the post-impact period was reduced to 2 days (Table 4) and 84.4% compared with 8.7 days before the pre-impact period, and the duration of the post-impact was more stable each year (Figure 5c). The median of high pulse count increased by 55.6% from 9 to 14 times pre-impact period. The post-impact period changed more than the number of pulses each year pre-impact period, and it was almost not located in the target interval (Figure 5d). The median of rise rate from 60 cms/d pre-impact period to 101 cms/d, an increase of 85% compared with pre-impact period; the annual frequency variation was stable, but the number in the target range was less (Figure 5b). The median of fall rate increased from −41 cms/d pre-impact period to −102 cms/d, an increase of 100%; the post-impact period was basically not in the target range (Figure 5f). The median number of reversals increased from 87 to 172 pre-impact period, an increase of 98%. The post-impact period had no target range (Figure 5a).

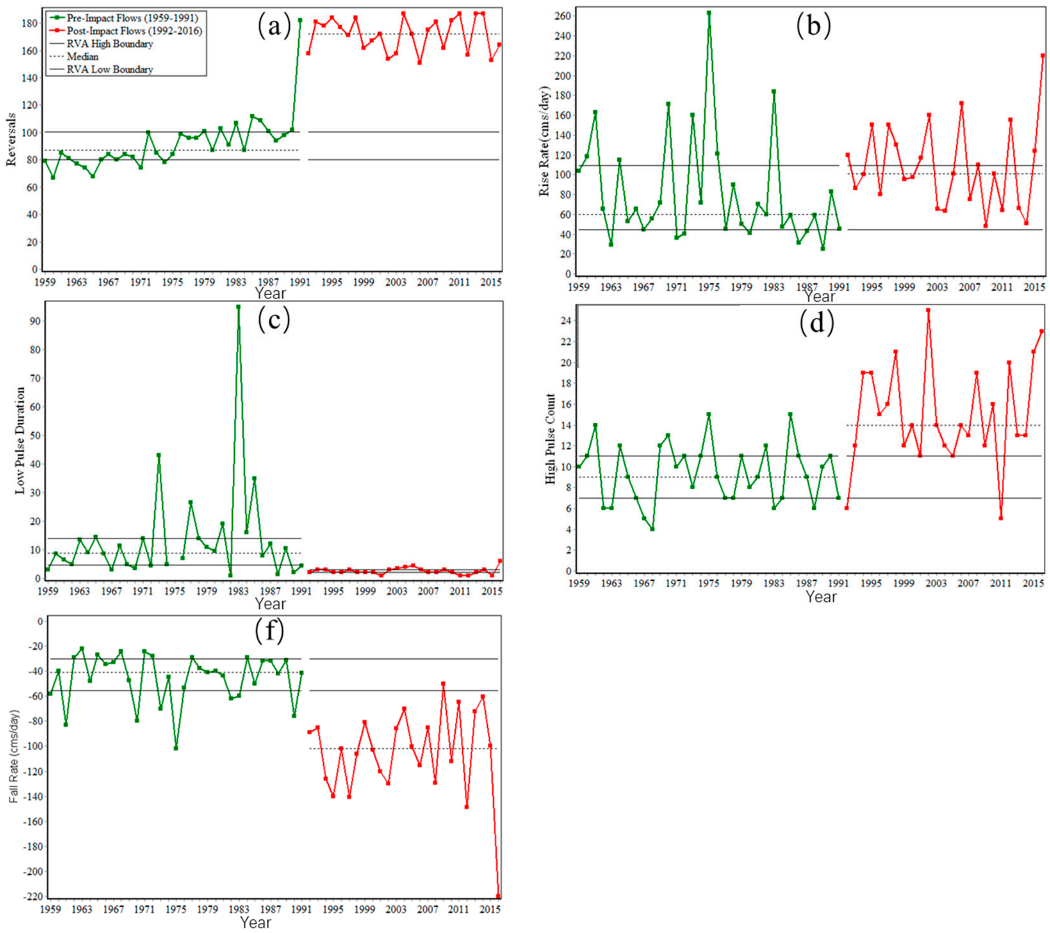

Figure 5. Dongbei Station high change degree IHA situation; (**a**) Reversals, (**b**) Rise Rate, (**c**) Low Pulse Duration, (**d**) High Pulse Count, (**f**) Fall Rate.

3.2.2. Middle Typical Section

The IHA hydrological index of Ji'an Hydrological Station changed greatly (Table 5). Among the first parameter group, the change in February was −52%, in March, June, September and November it was 36%, in July and August it was −44%. The change in other months were low level. Among the second parameter group, the change in 1-day minimum was −36%, the 3-day minimum was −44%, the 90-day minimum was 36%, and the 30-day maximum was 36%. The other seven parameters were all low-level changes. Among the third parameter group, the change in date of minimum was 52%, and the change in date of maximum was 4%. Among the fourth parameter group, the count and duration of low pulse changes were −44% and −32.8%, and the count and duration of high pulse changes were −73.33% and −73.65%. Among the fifth parameter group, the fall rate was −92.24%, and the number of reversals was −100%, and the rise rate changed to a low degree.

The median of high pulse count at Ji'an Station increased by 47% from 8.5 to 12 times pre-impact period (Table 5). The change range of post-impact period was larger and more unstable than that of the pre-impact period (Figure 6d). The median of high pulse duration during the post-impact period was reduced to 4 days and 27% compared with 5.5 days before the pre-impact period, and the change of the post-impact period was larger than that of the pre-impact period (Figure 6c). The median of fall rate increased from −53 cms/d pre-impact period to −107 cms/d, an increase of 100%; it was more stable post-impact period than during pre-impact period (Figure 6b). The median number of reversals increased from 90.5 to 146 pre-impact period, an increase of 61% (Figure 6a).

Table 5. Ji'an Station IHA calculation results; L represents little or no change, M represents moderate change, H represents height change.

5 Groups	Pre-Impact Period: 1964–1991	Post-Impact Period: 1992–2016	RVA Targets		Hydrologic Alteration	Degree
	Medians	Medians	Low	High	D (%)	
Parameter Group #1						
January	439	474	294.3	622.5	20	L
February	573.3	675	513	765.8	−52	M
March	962	1030	568.5	1473	36	M
April	1930	1880	1620	3206	4	L
May	2470	2340	1705	3095	12	L
June	2323	3100	1710	3395	36	M
July	1006	1490	724.3	1403	−44	M
August	825	1260	618.5	1023	−44	M
September	646.8	965	486.4	1061	36	M
October	572	601	445	880.3	28	L
November	498.3	496.5	345.9	806	36	M
December	383.5	480	281.5	538	12	L
Parameter Group #2						
1-day minimum	234.5	304	201.5	300.3	−36	M
3-day minimum	240.5	310	203.8	307	−44	M
7-day minimum	246.1	339.6	206.7	326.7	−20	L
30-day minimum	273	380.1	242	391.4	12	L
90-day minimum	452.2	597.9	364.7	760.9	36	M
1-day maximum	8495	9900	6803	11830	12	L
3-day maximum	7657	9417	5916	10830	12	L
7-day maximum	6336	7074	4647	8775	28	L
30-day maximum	4077	4255	2884	5566	36	M
90-day maximum	2911	3108	2144	3831	28	L
Base flow index	0.1838	0.1987	0.1522	0.2274	20	L
Parameter Group #3						
Date of minimum	362.5	366	21.75	355.8	52	M
Date of maximum	142	166	101.3	174	4	L
Parameter Group #4						
Low pulse count	5	8	2.25	7	−44	M
Low pulse duration	10.5	3.5	5	17.5	−32.8	M
High pulse count	8.5	12	6	10	−73.33	H
High pulse duration	5.5	4	5	7	−73.65	H
Parameter Group #5						
Rise rate	78.75	93.5	60.5	141.5	20	L
Fall rate	−53	−107	−66.38	−40	−79	H
Number of reversals	90.5	146	81.5	94	−100	H

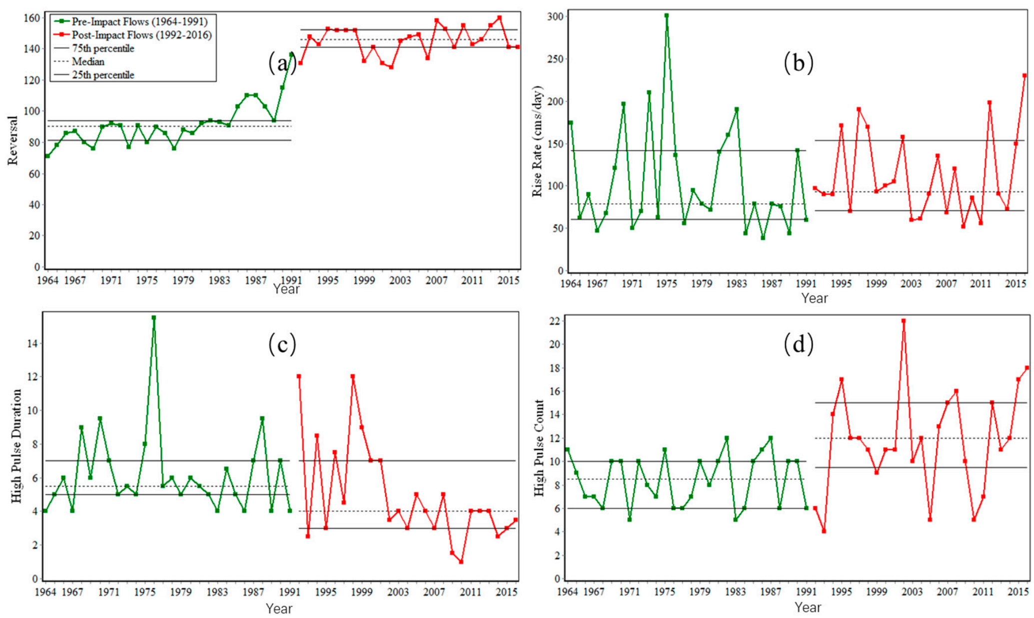

Figure 6. Ji'an Station high change degree IHA situation; (**a**) Reversals, (**b**) Rise Rate, (**c**) High Pulse Duration, (**d**) High Pulse Count.

3.2.3. Downstream Typical Section

The IHA hydrological index of Waizhou Hydrological Station changed little (Table 6). Among the first parameter group, the change in January was 47.53%, in February it was −45.65%, in March it was 39.76%, and in July it was −53.41%. The change in other months were low level. Among the second parameter group, the change in 90-day minimum, 1-day maximum, 3-day maximum, and 7-day maximum were 47.53%. The other parameters were all low-level changes. Among the third parameter group, two parameters were all low level changes. Among the fourth parameter group, the high pulse count changed to −34%, the change in other months were low level. Among the fifth parameter group, the fall rate was −47.2%, the number of reversals was −41.33%, and the rise rate changed to a low degree.

Table 6. Waizhou Station IHA calculation results; L represents little or no change, M represents moderate change, H represents height change.

5 Groups	Pre-Impact Period: 1964–1991	Post-Impact Period: 1992–2016	RVA Targets		Hydrologic Alteration	Degree
	Medians	Medians	Low	High	(%)	
Parameter Group #1						
January	679	668	411.5	922	47.53	M
February	985	936	595.8	1263	−45.65	M
March	1700	1920	935.5	2450	39.76	M
April	3265	2915	2350	4428	−6.824	L
May	3610	3830	2625	5180	16.47	L
June	3615	4220	2620	5085	16.47	L
July	1520	2570	1100	2320	−53.41	M
August	1130	1770	864	1545	−22.35	L
September	1014	1390	677	1563	24.24	L
October	846	869	586	1210	16.47	L
November	668.5	818.5	532.5	1123	0.9412	L
December	596	741	405.5	875	16.47	L
Parameter Group #2						
1-day minimum	350	463	287.5	444	−22.35	L
3-day minimum	351	476	294.3	448.8	−22.35	L
7-day minimum	360	484.7	299.1	477.4	−14.59	L
30-day minimum	432	591.5	338.5	583.9	−14.59	L
90-day minimum	687.7	837.7	513.4	1096	47.53	M
1-day maximum	11,900	11,300	7875	14,600	47.53	M
3-day maximum	10,970	10,700	7450	13,950	47.53	M
7-day maximum	9319	9111	6375	12,250	47.53	M
30-day maximum	5685	6258	4841	8273	24.24	L
90-day maximum	4359	4751	3407	5484	24.24	L
Base flow index	0.1857	0.2082	0.156	0.2229	−30.12	L
Parameter Group #3						
Date of minimum	10	9	22	317.5	−22.35	L
Date of maximum	160	171	131	175.5	−4.667	L
Parameter Group #4						
Low pulse count	4	4	3	7	32	L
Low pulse duration	9	6.75	6	15.13	−19.33	L
High pulse count	6	8	5	8	−34	M
High pulse duration	7	7.5	5.5	11.75	−2.737	L
Parameter Group #5						
Rise rate	108	100	64.75	142.8	0.9412	L
Fall rate	−70	−100	−90	−50	−47.2	M
Number of reversals	78	85	71.5	84	−41.33	M

3.2.4. Comparison of Changes in IHA in Upper, Middle and Lower Reaches

Comparison of IHA changes in three hydrological stations (Figure 7). Fourteen parameters of Dongbei Station changed more than moderately. The change of 14 IHA parameters was the greatest of the three stations; among them, the low pulse duration, the high pulse count, the rise rate, the fall rate, and the number of reversals were five parameters of height change. Seventeen parameters of Ji'an Station changed more than moderately. The change of eight IHA parameters was the greatest of the three stations; among them, the count and duration of high pulse, the fall rate, and the number of reversals were four parameters of height change. Eight parameters of Waizhou Station have changed more than moderately. The change of eight IHA parameters was the greatest in three stations; there was no parameter of height change. It indicates that the hydrological index in the upper and middle reaches of Ganjiang River Basin has changed greatly, while the hydrological variation in the lower reaches was relatively small.

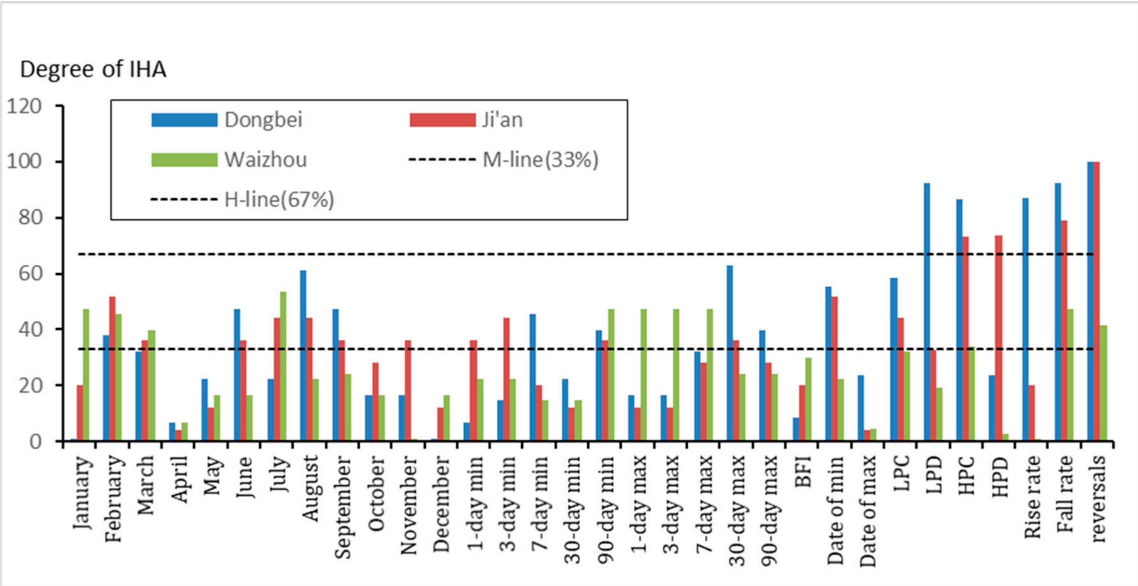

Figure 7. Comparison IHA change in Upper, Middle, and Lower Reaches of Ganjiang River Basin; BFI, representative Base flow index; LPC, representative Low pulse count; LPD, representative Low pulse duration; HPC, representative High pulse count; HPD, representative High pulse duration.

4. Discussion

4.1. Impact of Climate Change and Human Activities on Runoff Change of Ganjiang River

The annual runoff of Ganjiang River shows an increasing trend, which is mainly affected by climate change with percentage of rainfall as the main factor [34]. In addition, precipitation in Ganjiang River Basin continues an increasing trend during flood season, however runoff in flood season is a decreasing trend, which demonstrates that human activities are playing a greater role in regulating runoff annually. Liu et al.'s quantifications of climate and human activities on the runoff in the Ganjiang River Basin indicate that precipitation is the main cause of interannual variation in runoff; Reservoir construction significantly affects the seasonal distribution of runoff, resulting in a significant reduction in runoff during the wet season and a significant increase in runoff during the dry season [34]. Because of the increase of evapotranspiration, the decrease of runoff caused by the increase of forest cover during the rainy season is an especially strong indicator [34,35]. The vegetation coverage in Ganjiang River Basin was below 40% until 1990. Since 1991, the vegetation coverage has gradually increased (Figure 8), which is consistent with the sudden change of runoff in flood season. Some studies have shown that the dam balances the natural flow state over a large area, reducing the maximum flow, while the minimum flow tends to increase [2,36,37]. Similarly, a large number of reservoirs were built in the Ganjiang River Basin in the 1980's and 1990's, especially the Wan'an Reservoir built in 1990, and fill period was 24 August 1990 (Table 7), that may be the reason for the abrupt change of Ganjiang flood season flow in 1991. Precipitation makes runoff more concentrated, increases vegetation cover, and dams stabilize runoff [34,38].

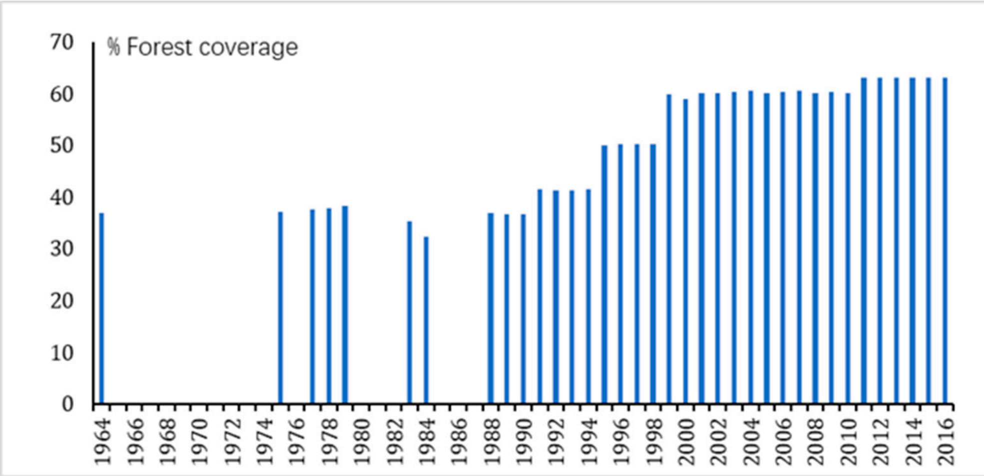

Figure 8. Forest coverage in Ganjiang River Basin represented over many years. The data from Jiangxi Province Lin Zhi [39,40]; Among them, data were lacking in 1965–1973, 1976, 1980–1982 and 1985–1987.

Table 7. Reservoir Construction Tables of Ganjiang River Basin in the 1980s–1990s; the data is from River and Lake Dadian of Jiangxi Province [41].

Name of Reservoir	Completion Time	Dead Storage (10^6 m^3)	Total Storage (10^6 m^3)
Sanshiba	1980	6.55	26.53
Youluokou	1981	31.9	110
Wanbao	1981	2.1	28.78
Nanhe	1983	25.7	52.5
Laoyingpan	1983	22	101.6
Fanbuqiao	1983	3	21.2
Wan'an	1990	319	2214
Huangyun	1990	6.7	47.9
Longyuankou	1990	8.55	45.15

4.2. The Influence of Reservoir on Hydrological Regime and River Ecology

Dams on rivers have serious ecological consequences, such as loss of habitat and fragmentation, unsynchronized life cycles, loss of connectivity in river flood plains, invasion of alien species, and diffusion barriers to river biofauna, leading to loss of biodiversity and ecosystem services [42,43]. Reservoirs increase annual runoff distribution, reduce peak flow, and change the time of maximum flow. Increase or decrease in flow will lead to a significant increase in invertebrate drift [7,44]. At the same time, the impact of the reservoir on river ecology is not only the area covered by the reservoir, but also downstream of the entire river system [45,46].

Reservoir construction and afforestation may change the hydrological status of Ganjiang Basin. Human activities such as reservoir construction and afforestation may change the hydrological status in the Ganjiang River Basin.The reservoirs built in the Ganjiang River Basin in the 1980's and 1990's are basically located in the upper and middle reaches of the Ganjiang River Basin. The largest reservoir, Wan'an, is located in the upper reaches of Dongbei Station, 16 km apart (Figure 1). The influence of Wan'an reservoir on hydrological regime can be reflected by Dongbei Station. The construction and operation of large reservoirs have great influence on river ecology [47]. The influence of the upstream reservoir decreases as the downstream distance decreases [38]. Dam operation directly changes the flow state [1], thereby changing the river ecosystem [48]. The low pulse duration, high pulse count, flow rate both rising and falling, and reversals number of the Dongbei Station changed the height. The changes of the count and duration of flow pulses are unfavorable to the conditions of spawning, migration, and survival of aquatic organisms in the region [49]. Reduced high pulses count and duration lead to fewer spawning areas in available habitats, and dams also hinder the migration of aquatic organisms such as fish [48]. Increasing the flow rate will reduce the organic matter interception in floodplains, and the speed of flow decrease will increase the drought pressure of plants. Flow fluctuations have led to a decline in natural diversity and abundance of many native fish and invertebrates [50]. Comparative studies took place on the ecology of Ganjiang River Basin before and after the completion of Wan'an Reservoir [22,51,52]. It was found that the biodiversity of ecosystem in Ganjiang River Basin decreased significantly, the fish spawning grounds suffered serious damage especially. Tian et al.'s 1982–1983 sampling in Ganjiang River Basin [22] found the following: 118 species, 8 phyla, and 63 genera of phytoplankton in Ganjiang River Basin; 125 Species of Zooplankton; 20 species of benthic organisms; 118 species of fish belonging to 74 genera, 22 families, and 11 orders. After the water storage in Wan'an Reservoir, Jiao et al.'s 2009–2010 sampling in Ganjiang River Basin [51] found 47 species, 8 phyla, and 30 genera of phytoplankton in Ganjiang River Basin; 25 Species of Zooplankton; 9 species of benthic organisms; 71 species of fish belonging to 58 genera, 16 families, and 11 orders. The impact of the construction of water conservancy projects on aquatic organisms is mainly reflected in the fish resources. Huang compared the spawning grounds of five fishes in Ganjiang River before and after the construction of Wan'an Reservoir, and found that two of them had disappeared [52].

Improper water conservancy project management will have a greater impact on the hydrological regime of the river [53]. Existing and future dam rules should include objectives to better simulate key aspects of natural changes in river ecosystems [42,43]. The operation of reservoirs in the Ganjiang River Basin should consider the variation range of hydrologic indicators to reflect the ecological objectives, and according to the actual situation, work out the operation plan to balance the production benefits such as power generation and maintain the ecological health of the river. Ganjiang River Basin has developed an installed capacity of 1577 million kw. Cohen et al. [54] have demonstrated that it is possible to achieve energy production and ecological sustainability. Ji'an Station is far away from Wan'an Reservoir, and the IHA still has a high change, which indicates that the reservoir group has a wider impact on the hydrological regime. The current reservoir operation mode in Ganjiang River Basin mainly focuses on the comprehensive utilization benefits such as flood control, power generation, and shipping, and the reservoir operation generally does not consider the ecological function. The best choice for downstream flow management of reservoirs is to simulate natural conditions as much as possible [55]. The main challenge facing reservoir management is to determine acceptable levels of change without compromising ecological health and ecosystem services. In the joint operation of reservoirs, the objective is to maximize the generation capacity of reservoirs, minimize the regional water shortage, and minimize the deviation between flow and natural flow after the operation of each control section. For rivers with many reservoirs similar to Ganjiang River, considering the ecological operation of reservoirs, joint reservoir dispatching schemes should be formulated for the study area so as to maximize the comprehensive benefits [2,36,37].

5. Conclusions

The study presented here analyzed precipitation, runoff trend, and abrupt change of runoff in Ganjiang River Basin, and calculated the variation degree of hydrological regime of three stations in upper, middle, and lower reaches, respectively. The conclusions are as follows:

(1) The annual and flood season precipitation in Ganjiang River Basin increased from 1992 to 2016, but it did not reach a significant level, the change of annual runoff at Dongbei and Waizhou Stations was the same as that of the annual precipitation in Ganjiang River Basin. The runoff at Dongbei Station in flood season decreased from 1986 to 2016, and the runoff at Waizhou Station in flood season decreased from 2008 to 2016. The annual runoff increases with the annual precipitation, but decreases with the increase of precipitation in wet season. It shows that precipitation has a great influence on annual runoff, and human activities made the annual runoff distribution process more uniform.

(2) The abrupt changes of runoff in flood season at three hydrological stations in Ganjiang River Basin occurred in 1991, and reached 0.01 significant level.

(3) There were five hydrological indicators of Dongbei Station which reached height change. Four hydrological indicators of Ji'an Station have reached a high change degree. Waizhou Station did not reach the high change indicator. The hydrological regime of the upper and middle reaches of Ganjiang River has changed greatly, while the hydrological regime of the lower reaches has changed little.

The hydrological regime in the upper and middle reaches of Ganjiang River Basin has been highly changed by human activities such as dam construction. The change of hydrological conditions in the upper and middle reaches of Ganjiang River Basin may reduce the area of aquatic organisms' habitat, be harmful to spawning, migration, and survival of aquatic organisms, reduce the interception of organic matter in floodplains, and increase the drought pressure of plants. Rivers with numerous reservoirs are considering reservoir ecological operations, joint reservoir dispatching schemes should be formulated for the study area so as to maximize the comprehensive benefits. The study provides a reference for water resources management and reservoir operation in Ganjiang River Basin. The next step is to use habitat model to simulate the habitat of Ganjiang River Basin.

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