Assessing the impact of Danjiangkou Reservoir on the hydrologic alterations in the middle reach of the Hanjiang River using the histogram comparison approach

X Z Chunyu[1,2,3], F Huang[1,2,3,4], L D Guo[3] and Z Q Xia[1,2,3]

[1]State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Hohai University, Nanjing 210098, China
[2]College of Hydrology and Water Resources, Hohai University, Nanjing 210098, China
[3]International Research Center of Hohai University, Nanjing 211100, China

E-mail: hfeng0216@163.com

Abstract. The Histogram Comparison Approach was used to assess the hydrologic alteration of the Hanjiang River using daily streamflow data collected from the Huangzhuang hydrometric station, which monitors the hydrologic processes in the middle reach of the river, for the period 1951-2014. The Danjiangkou Reservoir, which is the water source for the middle route of South-to-North Water Diversion Project in China, was constructed from 1967-1974, with 1951-1966 considered the pre-impact period and 1976-2014 as the post-impact period. 32 indicators were calculated to quantify the alteration of the hydrologic regime of the Hanjiang. The overall degree of alteration was valued at 47% and was classified as "moderate". The alterations of all 32 parameters ranged from 21%-83%; of these, 2, 25, and 5 parameters were classified as "high", "moderate" and "low", respectively. Significant increases were observed from the number of reversals and low-flow relevant parameters, including the monthly flow from December to March, the annual flow minima, and the base flow index. The results of the present research have important scientific significance for maintaining the health of the riverine ecosystem in the middle reach of the Hanjiang River.

1. Introduction

The composition, structure, and function of riverine ecosystem is determined by its a natural hydrologic regime. Therefore, maintaining the change rule of the natural hydrologic regime is the key for river health. However, as numerous scholars have shown [1-5], climate change and anthropogenic activities can alter it.

The Hanjiang River, the longest branch of the Yangtze River, is of extremely high economic and ecological value to China. The Danjiangkou Reservoir is the key hydraulic project in the Hanjiang river basin; as the water source for the middle route of South-to-North Water Diversion Project, it has altered the natural hydrologic regime in the middle and lower reaches of the Hanjiang River. In recent years, the impacts and ecological implications of the Reservoir have attracted much attention from researchers [6-11]. For example, Wang *et al* [11] used the Indicators of Hydrologic Alteration (IHA) and Range of Variability Approach (RVA) to determine the types of hydrologic changes caused by the Danjiangkou Reservoir. Their results showed that the reservoir significantly altered the natural hydrologic regime downstream and affected the spawning time of four major Chinese carp species.

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Bai *et al* [12] also used the RVA to estimate the temporal and spatial variation in the hydrologic regime in the middle reach of the Hanjiang River after the impoundment of the Danjiangkou Reservoir. They found that marked changes in the hydrologic regime had not only influenced carp spawning behavior, but that it had also increased the probability that water bloom would occur.

This study aims at assessing the hydrologic changes in the Hanjiang River further, improving upon previous work mainly in in two aspects. Firstly, it assesses the hydrologic regime alterations using the Histogram Comparison Approach (HCA), a relatively new approach based on the IHA method that can make up for the shortcomings of the RVA and the Histogram Matching Approach (HMA). This method concerns changes over the entire range of the hydrologic regime. It also considers class-by-class and cross-class correspondences, respectively; synthesizes the correspondence by degree of similarity; and deduces the alteration degree. Secondly, all analyses are based on the latest daily flow data from a specific hydrometric station. Therefore, the results of this study could help accurately determine the kinds of hydrologic alterations occurring in the middle reach of the Hanjiang River, which would provide stronger data to support the regulation of the Danjiangkou Reservoir and better protect the riverine ecosystem.

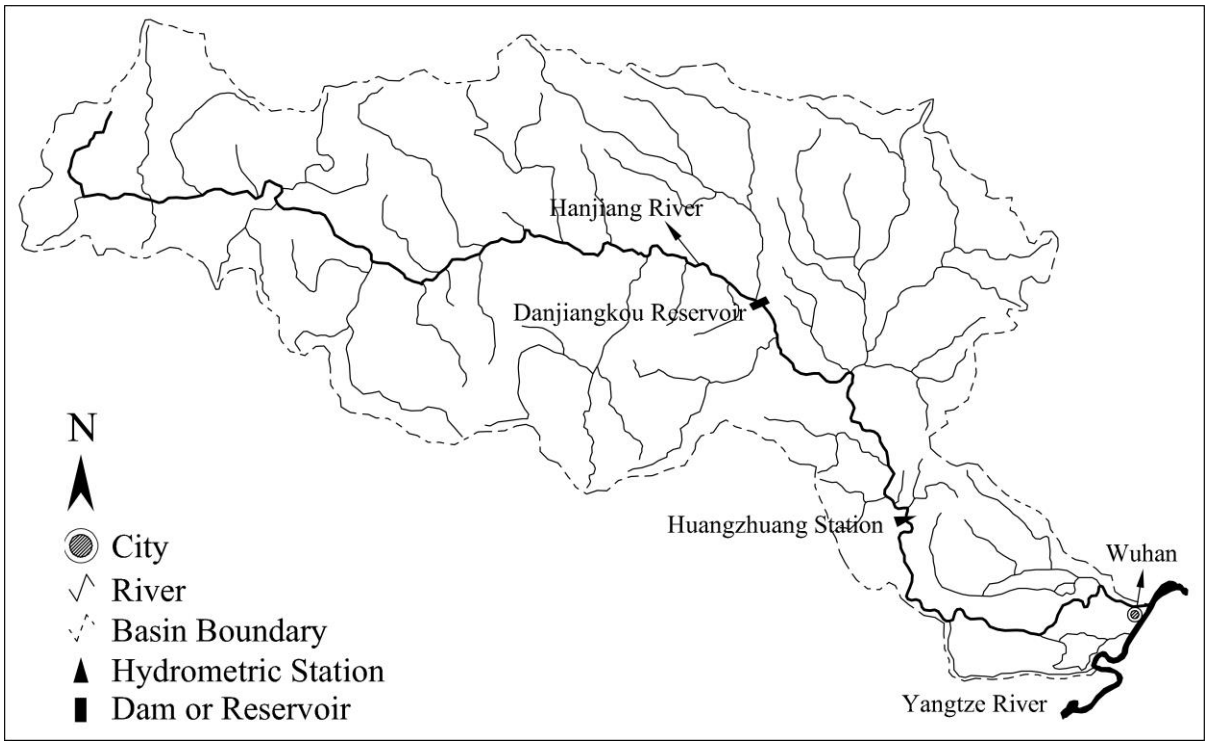


Figure 1. Location of the Hanjiang River and Huangzhuang hydrometric station.

2. Study area and data

The Hanjiang River originates from the Qinling Mountains in southern China (figure 1). It flows through Shanxi and Hubei provinces before draining into the Yangtze River in Wuhan. It is 1,577 km long in total and its basin covers an area of 154,700 km^2. It is in a region with a typical subtropical monsoon climate where the annual average temperature is 15-17℃. This region gets 600-1,300 mm of precipitation annually, on average, and more than 70% of this occurs in the summer. The wet season determines the hydrologic year that ranges from May to April of the next calendar year [11-14]. The total storage capacity of the Danjiangkou Reservoir increased from 17.45 billion m^3 to 29.05 billion m^3 when the height of the dam was increased in 2012 [15]. It became functional in 1967 and the process of impoundment ended in 1974. Its benefits include flood control, power generation, irrigation, navigation, aquaculture, and tourism.

The Huangzhuang hydrometric station was selected as the source of data used to assess the hydrologic alterations. It is located 223 km downstream of the Danjiangkou Reservoir and controls a 142,000 km^2 catchment area that accounts for approximately 92% of the total area of the Hanjiang river basin. Daily streamflow data from Huangzhuang station for 1951-2014 was collected from the Changjiang Water Resources Commission, China. This impact assessment considered 1951-1966 as the pre-impact period and 1976–2014 as the post-impact period. The construction period (1967-1974) was not considered.

3. Methodologies

3.1. Indicators of Hydrologic Alteration (IHA)

The IHA method was developed by Richter *et al* [16] as a way to characterize intra- and inter-annual variations in a hydrologic regime using a series of biologically relevant attributes. Therefore, 33 parameters that represent these hydrologic attributes were calculated to quantify the changes in a hydrologic regime between the pre- and post-impact periods. These parameters can be divided into five groups: magnitude, timing, frequency, duration, and rate of change. The parameter "number of zero-flow days" was not used in this study because no zero-flow events occurred throughout the study period.

3.2. Histogram Comparison Approach (HCA)

The RVA was established by Richter *et al* [17] as a way to assess the alteration of the hydrologic regime and set streamflow-based river ecosystem management targets based on the IHA. Although it has been applied widely in assessments of hydrologic alteration [18-22], this method still has two potential limitations. One is that it only considers the frequency of the hydrologic parameters within the target range, ignoring the variations, and the other is that the frequency and variations of the parameters that fall both above and below the range of targets are completely ignored. Therefore, they could result in an incorrect assessment of the alterations. Shiau and Wu [23] thus presented the innovative HMA algorithm to eliminate the limitations of the RVA; however, Huang *et al* [24] found that it, too, had a few restrictions that could lead to unreasonable results. Thus, they proposed the HCA method, based on the HMA, to overcome the restrictions of the first two methods and arrive at the right assessment of hydrologic alterations. The restrictions of both the HMA, and further details on its procedures, can be found in the relevant cited literature.

After assessing the alterations using the HCA method, the degree of alteration of each parameter was categorized into three specific classes according to the patterns established by Richter *et al* [25]. These were: 1) little or no alteration (labeled "L") and ranging from 0–33%; 2) moderate alteration (labeled "M") and ranging from 34–67%; and 3) high alteration (labeled "H"), ranging from 68–100%.

4. Results and discussion

The frequency histograms of each hydrologic parameter, comparing the pre- and post-impact period, are given in figure 2. Figure 3 ranks all 32 degrees of hydrologic alteration calculated using the HCA method. The results of the calculations are summarized below.

The overall average of degree of alteration for all the hydrologic indicators is 47% or "moderate alteration". It indicates that the natural hydrologic regime of the Hanjiang River has been affected considerably by the Danjiangkou Reservoir. The degree of alteration ranged from 21–66% each month, and for most of this time it was categorized as "moderate". Only September, November, and April, with 21%, 26%, and 21% degrees of alteration respectively, were classified as having "little or no" alteration. Figure 2 also shows that the December–March period showed the same variation characteristics since the post-impact histograms are more distributed to the right side compared to the pre-impact histograms. That may indicate an increase in dry season streamflow. All median deviations of the annual extreme flows are categorized as "moderate" except the 90-day maximum and base flow index, for which the degrees of alteration were 32% ("little or no" alteration) and 68% ("high"

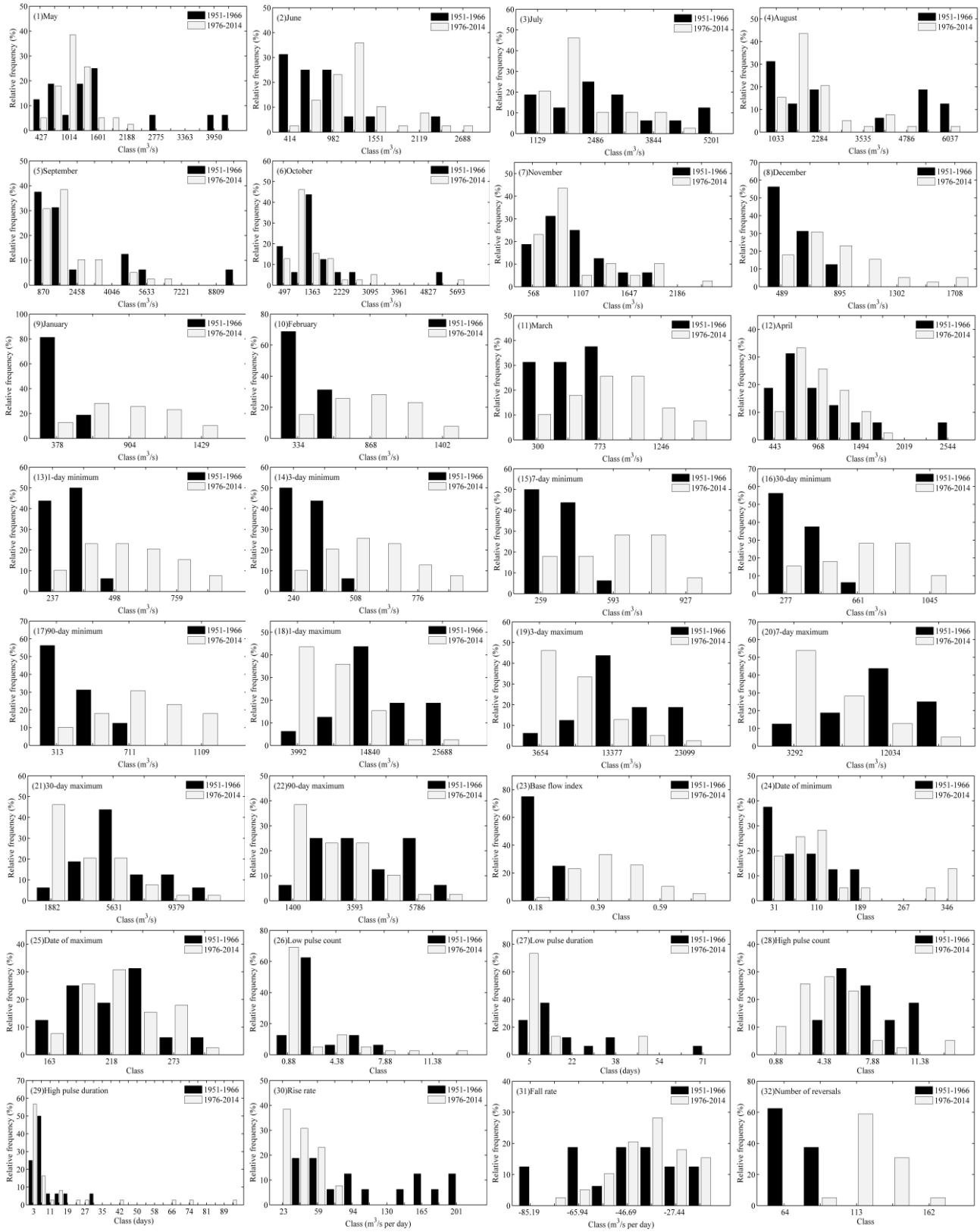


Figure 2. Histograms comparisons of the hydrologic regime at the Huangzhuang station.

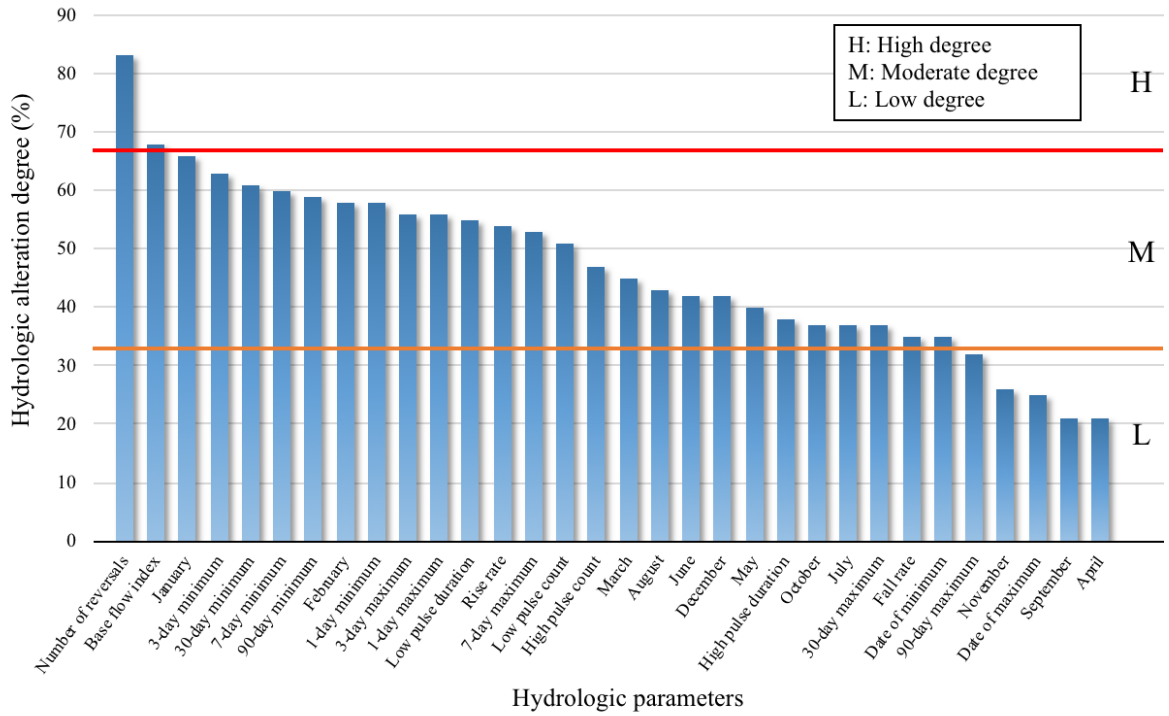
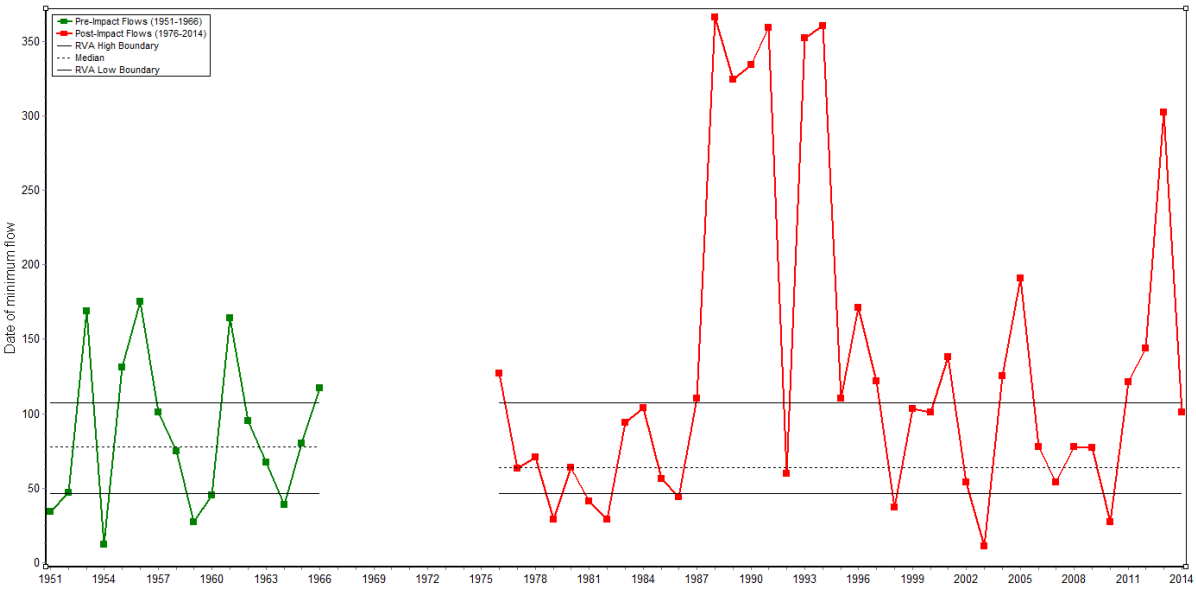


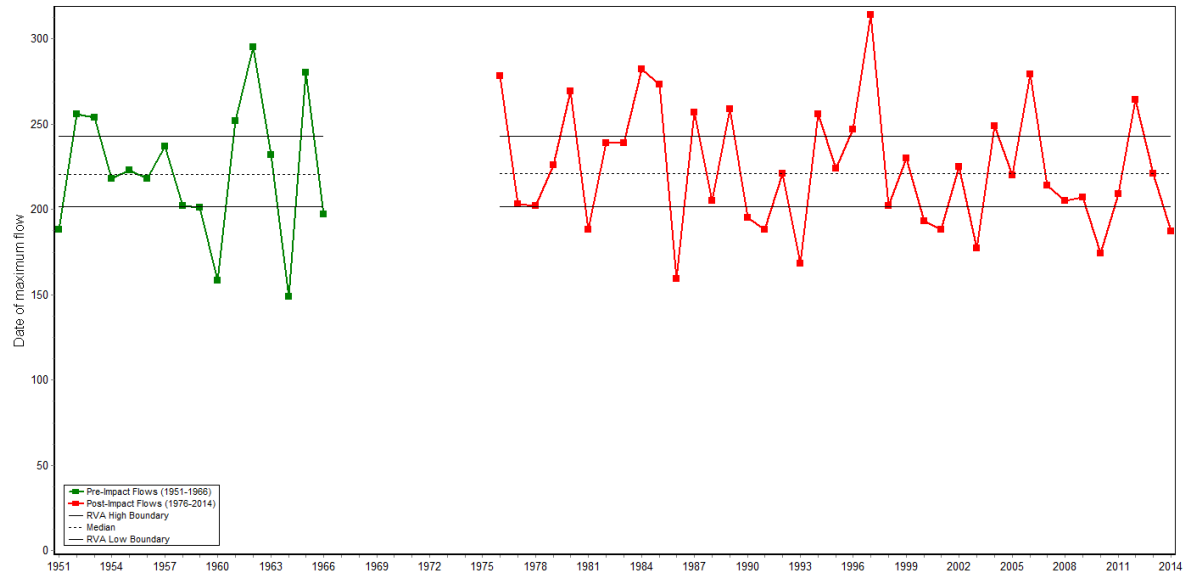
Figure 3. Ranked hydrologic alterations of 32 parameters at the Huangzhuang station in the Hanjiang River.

alteration). The annual flow minima and base flow index illustrated similar changes, which also mean an increased streamflow in the dry season. The median Julian dates of the annual 1-day minimum is significantly different between the two periods. Almost all the annual 1-day minimum flows appeared in first half of the year during the pre-impact period. However, they also appeared sometime in the last two months of the calendar year with a "moderate" alteration (35%) in the post-impact period. However, the alteration of the annual 1-day maximum is only 25% according to the Julian dates. The degrees of hydrologic alteration for low/high pulse counts and durations are all "moderately" altered, recording as 51%, 47%, 55%, and 38%, respectively. The histograms of these four indicators showed similar change patterns; the post-impact histograms shifted to the left of the pre-impact histograms, indicating decreases in high and low pulse events. The rise and fall rates both had "moderate" alteration and their absolute values decreased significantly after 1976. The highest degree of alteration was that of the number of reversals, with a value of 83%. There was a huge increase in this indicator since the post-impact period that could be related to the regulation of the reservoir.

The results of using the RVA method were quite different to those found when the HCA method was used to calculate the degrees of alterations of some indicators, especially the Julian date of minimum and maximum flow. The alterations in those two indicators, as calculated using the HCA (35% and 25%), were larger than those calculated using the RVA (0% and 5%). Figure 4 (a) presents the change in the date of minimum flow and indicates that more values were distributed above the maximum range of the RVA in the post-impact period than in the pre-impact period. Furthermore, the variations among the degrees of alteration in the former are quite different from those in the latter. However, these differences could not be detected due to the restrictions of the RVA method. Thus, it output a false assessment of "0%" degrees of alteration. The variations in the date of maximum flow within the RVA boundaries, which could also lead to an incorrect result, were also ignored (figure 4 (b)). However, the HCA method is based on comparing the histograms of two periods and includes both the frequency and streamflow variation information; therefore, it can truly present the correct degree of alteration.



(a)



(b)

Figure 4. Hydrologic alterations of the date of minimum (a) and maximum (b) flow before and after the construction of Danjiangkou Reservoir in the Hanjiang River.

Alterations in the hydrologic regime are mainly associated with climate change and anthropogenic activities such as the creation of dams and water diversions. A previous study has shown that the water discharge in the area north of the Yangtze River, which includes the Hanjiang River basin, has decreased about 15% in recent decades [26]. Anthropogenic activities, not climate change, are the dominant process in the basin. Xin *et al* [27] stated that the Danjiangkou Reservoir controls a 95,200 km^2 catchment area. Therefore, the sub-catchment constitutes 33% of the total catchment area covered by the hydrometric station, meaning that it could also affect the degree of hydrologic alteration. Therefore, when combined with the results of the previous assessments, we may infer that the natural hydrologic regime of the Hanjiang River was not only altered by the operation and regulation of

Danjiangkou Reservoir- especially in terms of increased streamflow in the dry season, obvious reductions in the frequency and durations of high/low pulses and rise/fall rates, and a huge rise in flow reversals—but also by the changes in the hydrologic regime of the sub-catchment. These alterations may seriously affect the spawning of four major carp species and the distribution of aquatic vegetation in the Hanjiang River riparian zone [11,28]. However, the HCA method can only assess the degree of hydrologic alteration and cannot accurately distinguish the individual effects of climate change and anthropogenic activities. Furthermore, due to data limitations, we could not quantify the impact of the sub-catchment on the results of this study. Therefore, we may consider addressing these issues in further work.

5. Conclusion

The impacts of Danjiangkou Reservoir on the hydrologic regime of the Hanjiang River were assessed, based on long-term daily flow discharge data from the Huangzhuang station, using the HCA method. The overall degree of hydrologic alteration of the Hanjiang River was classified as "moderate", at 47%, and the degrees of alteration of all parameters ranged from 21%-83%. 2, 25, and 5 hydrologic parameters were altered to high, moderate, and low degrees, respectively. Indicators of base flow index and flow reversal counts showed high degrees of alteration, indicating that these parameters increased dramatically after the construction of the dam. There were considerable increases in the flow reversals and low-flow events including the median discharge from December-March, the annual flow minima, and the base flow index. Moreover, there were significant decreases in the high pulse count and rise/fall rates. The increased flow in the dry season after 1976 did help protect the riverine ecosystem, but it is still necessary to optimize the regulation of Danjiangkou Reservoir further to minimize any adverse ecological effects. In further research, we will focus on analyzing and identifying the specific reasons for the alterations.

Acknowledgments

This research is supported financially by the Fundamental Research Funds for the Central Universities, No. 2017B10714, the National Natural Science Foundation Projects of China, No. 41401011 and No. 41401010, and the Program for Changjiang Scholars and Innovative Research Team in University, No. IRT-17R35.

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