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Hydrologic Alteration Associated with Dam Construction in a Medium-Sized Coastal Watershed of Southeast China

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Abstract: Sustainable water resource management requires dams operations that provide environmental flow to support the downstream riverine ecosystem. However, relatively little is known about the hydrologic impact of small and medium dams in the smaller basin in China. Flow duration curve, indicators of hydrologic alteration andrange of variability approach were coupled in this study to evaluate the pre- and post-impact hydrologic regimes associated with dam construction using 44 years (1967–2010) of hydrologic data in the Jiulong River Watershed (JRW), a medium-sized coastal watershed of Southeast China, which suffered from intensive cascade damming. Results showed that the daily streamflow decreased in higher flow while daily streamflow increased in lower flow in both two reaches of the JRW. The dams in the North River tended to store more water while the dams in the West River tended to release more water. The mean daily streamflow increased during July to January while decreased during February to May after dam construction in both two reaches of the JRW. After dam construction, the monthly streamflow changed more significantly and higher variability of monthly streamflow exhibited in the West River than in the North River. The homeogenizing variability of monthly streamflow was observed in both two reaches of the JRW. The earlier occurrence time of extreme low streamflow event and later occurrence time of extreme high streamflow event exhibited after dams construction. The extreme low and high streamfow both decreased in the North River while both increased in the West River of the JRW. All of the indicators especially for the low pulse count (101.8%) and the low pulse duration (−62.1%) changed significantly in the North River. The high pulse count decreased by 37.1% in the West River and the count of low pulse increased abnormally in the North River. The high pulse duration in the post-impact period increased in the two reaches of JRW. The rise rate decreased by 26.9% and 61.0%,and number of reversals increased by 40.7% and 46.4% in the North River and West River, respectively. Suitable ranges of streamflow regime in terms of magnitude, rate, and frequency were further identified for environmental flow management in the North River and West River. This research advances our understanding of hydrologic impact of small and medium dams in the medium-sized basin in China.

Keywords: damming; hydrologic alteration; eco-hydrology; environmental flow management; coastal watershed

1. Introduction

Rivers play an important role in the development of human society by providing goods and services for human beings, by which the streamflow regime in turn has been altered for thousands of years due to various human activities [1–3]. By constructing large numbers of dams, human can utilize and control rivers by changing natural streamflow variability to suit human needs [4]. As a result, the past decades have witnessed the great alteration of streamflow regime in the watersheds throughout the world for their extensive dam construction [5–8]. Identifying the environmental impacts caused by hydraulic engineering facilities (e.g., dams) has therefore become an essential component in water resources planning and management [9–12].

The construction of large modern dams produced a dramatic change in the magnitude of hydrologic, geomorphologic and ecologic impacts on rivers [12,13]. Water development, mostly related to dams and diversions, contributed to the declines of more threatened and endangered species than any other resources-related activity [14]. Previous studies show that dam regulation generally had stronger effects on hydrologic regime than other disturbances by reducing the hydrologic variability of river systems [5,15,16]. Obviously, hydrologic regime alteration is responsible for the ecological system change in the rivers [1,17,18]. Dam construction has great impacts on hydrology, therefore, it is of scientific importance to evaluate the hydrologic alteration induced by dam construction.

Many attempts have been made to explore the hydrologic consequences associated with dam construction in recent decades [13,16,19–21]. More than 170 hydrologic metrics (e.g., average flow, flood frequency, peak discharge) have been developed to elaborate the different components of streamflow regime and their contribution to ecological consequence in the river ecological system in the past decade [22]. However, studies on streamflow-related disturbances are mainly on high-steamflow and low-streamflow events [1], which just partially characterize streamflow change. The full range of natural streamflow needs to be identified for its necessarity in evaluating ecosystem health of rivers [12,23–26]. The method of indicators of hydrologic alteration (IHA) was developed by Richter et al. [27] because of their close relationship to ecological functioning as well as for their ability to reflect human induced changes to streamflow regimes for a wide range of disturbances [28]. The IHA method was employed widely to assess the hydrologic change of the dam construction in many rivers worldwide such as the Great Plains, Illinois River, Southeastern US, Yellow River, Yangtze River, and Huaihe River [8,13,16,24,26,29]. The results prove that it is possible to identify the hydrologic change by dam construction over a full range. Moreover, flow duration curve (FDC) was developed to evaluate the overall impact of the streamflow regulation [30] and further applied to effectively determine whether human activities including dams construction can modify the pattern of the ecodeficit and ecosuplus of streamflow [31,32].

Implementation of environmental flows is one of the measures taken to restore or to maintain good ecological statusof rivers [33]. Estimates suggest that by 2050 many countries will face water scarcity, placing increasing pressures on face the water-dependent ecosystems of rivers and estuaries [34]. Obviously, maintaining natural streamflow variability has become an essential principle for environment flow management [35,36]. So far, most of the studies only focus on the minimum release rule so as to maximize human benefits such as water supply or hydropower generation [37,38]. However, provision of a single minimum streamflow cannot protect the biodiversity of a river, which requires the full range of natural flows [24,39–41]. Therefore, to satisfy such strategy of environmental flow management, reservoir planners and operators should seek to minimize the degree of natural flow regime alteration along the regulated river [42]. Based on the 33 indicators of IHA, Richter et al. [27] introduced a useful approach referred to as Range of Variability Approach (RVA) to quantitatively evaluate the degree of hydrologic alteration induced by human disturbance. This method has been demonstrated as a practical and effective way to identify the reasonable range of streamflow regime for environmental flow management [24,41,42].

The hydrologic regime is an indispensable dynamic of the ecosystem change in the watershed, which requires reasonable strategies to protect the magnitude, frequency, duration, timing and rate of change in the streamflow [26,43,44]. The impacts of the dams construction on hydrologic regime show regional difference, since the effects of dams on magnitude, frequency and timing of streamflow change with the types, operations, storage capacity of dams [16,27,45,46]. For example, the groundwater levels rise significantly below ground surface after dam construction in the Tarim River [47], while the water level in the river decreased appreciably in time after dams construction in Yangtze River, Yellow River, Huaihe River [24,26,48]. Moreover, it has been reported that the pattern of the monthly streamflow change due to damming is location-dependent [7,13,49,50]. In China, the accelerating development of economy increases the demand for energy and water resource, thus raising the need for the hydraulic engineering facilities, such as dams and reservoirs [51]. So far, most studies have focused on the impacts of large dams in large basins of China including Yangtze River and Yellow River [12,26,48,52,53]. However, relatively little is known about the hydrologic impact of small and medium dams in the smaller basins. More attentions should be paid to the small and medium dams because of their abundance (with more than 800,000 throughout the world) and their vital roles in maintaining local aquatic ecosystem health and water security [54–56].

The Jiulong River Watershed (JRW), a medium-sized coastal watershed in Southeast China, suffered from intensive human activities with over 13,500 hydraulic engineering facilities including over 120 small or medium dams along the mainstream and major tributaries. Our previous study partly characterized the hydrologic impact of cascade dam in JRW [57]. However, we need more attempts to fully delineate the hydrologic alteration associated with for watershed management. The objectives of this study are: (1) to evaluate the full range of streamflow regime change induced by dam construction; (2) to identify the suitable range of streamflow regime for environmental flow management in the JRW.

2. Materials and Methods

2.1. Study Area

The Jiulong River Watershed (JRW), covering approximately 14,700 km^2 in the eastern coastal area of China (116°46′55″–118°02′17″ E, 24°23′53″–25°53′38″ N) (Figure 1). Two main tributaries, namely, the North River and West River reaches, meet in Zhangzhou, which produces an annual flow of 12 billion m^3 into the Jiulong River estuary and Xiamen-Kinmen coast. The JRW plays an extremely important role in the region economic and ecological health. Water resources in the JRW have been highly developed and supply great demand to many stakeholders, like water supply, irrigation, hydropower and industry. More than ten million residents from Xiamen, Zhangzhou and Longyan use the Jiulong River as their source of water for residential, industrial and agricultural activities. The construction of large dams along the mainstream and major tributaries of JRW greatly altered the natural streamflow regime of the river over the last several decades.

Our previous study showed that the earliest changes in streamflow regime associated with dam construction in the JRW were detected in 1992 [3,57]. As shown in Figure 2, there is distinct difference in terms of flashiness index (the ratio of absolute day-to-day fluctuations of streamflow relative to total flow in a year) between pre-impact period (namely, 1967–1991) and post-impact period (namely, 1992–2010).

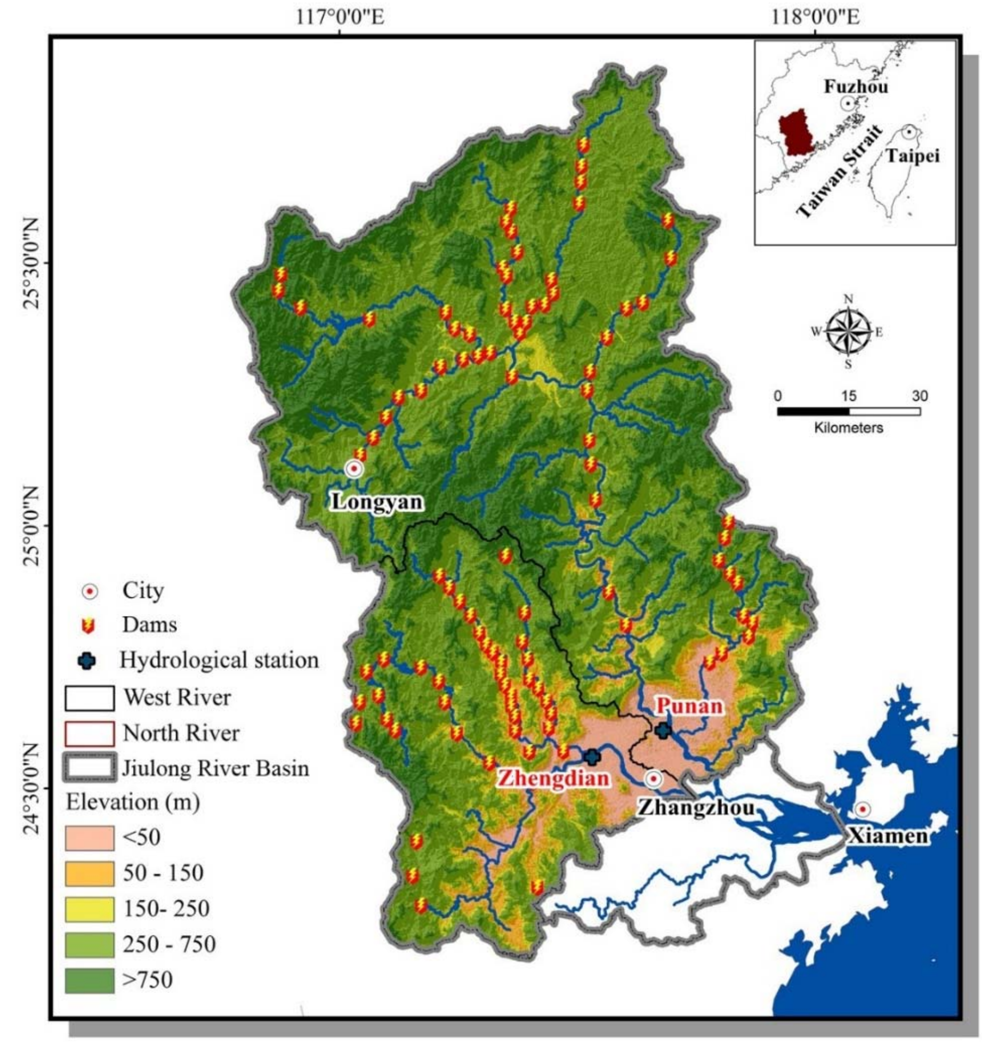

Figure 1. Study area.

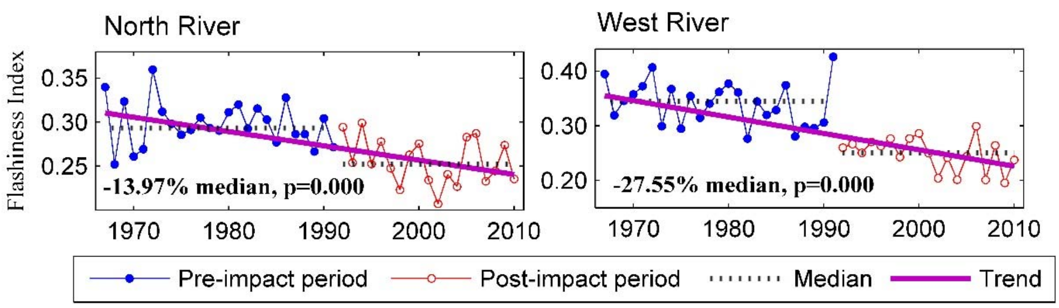

Figure 2. Temporal trend of flashiness index during 1968–2010 (modified from Huang et al., 2013).

2.2. Data Source

In this study, daily streamflow data during 1967–2010 for two downstream hydrologic stations (Punan and Zhengdian) in two reaches, namely, North River and West River were used to evaluate the effect of dam regulation on downstream streamflow in the JRW. A basic description of the two hydrologic stations is shown in Table 1.

Table 1. The streamflow for two gauging station in the JRW.

Station	Longitude	Latitude	Discharge Area (km^2)	Length (km)	Number of Dams Upstream from Stations	Pre-Impact	Post-Impact
Punan (North River)	117.67° E	24.61° N	9640	274	87	1967–1999	2000–2010
Zhengdian (West River)	117.53° E	24.56° N	3940	172	37	1967–1994	1995–2010

2.3. Method

2.3.1. Flow Duration Curve Analysis (FDC)

FDC is constructed from streamflow data over a time interval of interest and to provide a measure of the percentage of time duration that streamflow equals to or exceeds a given value. An annual FDC reflects the variability of daily streamflow during a typical period in a year. The FDC plots can be calculated by the following formula:

$$\mathrm{Pi} = i/(n+1) \quad (1)$$

where n is the number of the days of streamflow and i is the rank.

2.3.2. Indicators of Hydrologic Alteration (IHA)

IHA was used in this study to assess the hydrologic shifts associated with dam construction in a full range. The IHA computes 32 indices that describe the hydrologic regime in the watershed through the frequency, magnitude, duration, timing and rate of the streamflow (Figure 3). The IHA indicators can be divided into five groups: monthly streamflow indices, extreme flow indices, timing indices, high-flow and low-flow indices, and rising and falling indices.

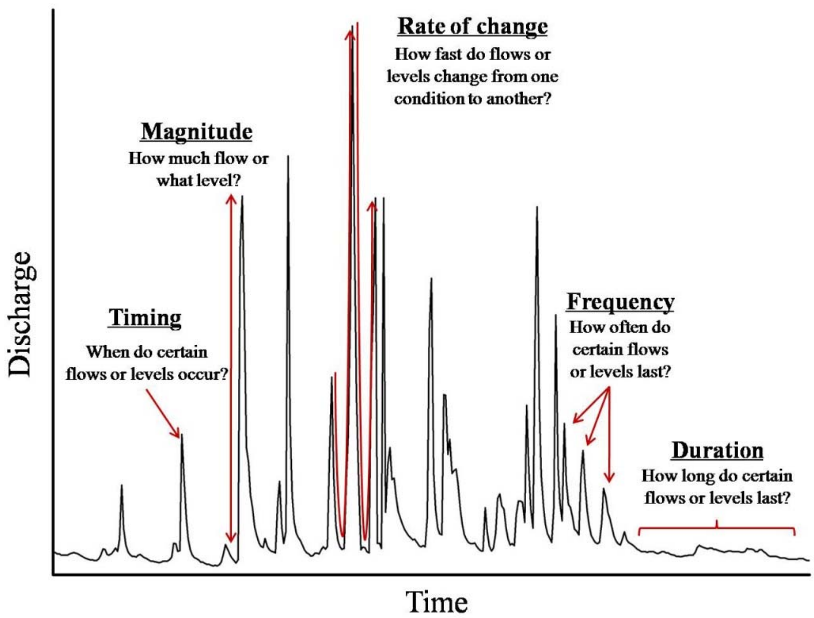

Figure 3. Quantified hydrologic regime using IHA method.

2.3.3. Range of Variability Approach (RVA)

RVA was used in this study to quantitatively evaluate the degree of hydrologic alteration induced by dam construction. In an RVA analysis, the full range of pre-impact data for each parameter is divided into three different categories. The low-level category contains all values less than or equal to the 33th percentile; the middle-level category contains all values falling in the range of the 34th to 67th percentile; and the high-level category contains all values greater than the 67th percentile. A Hydrologic Alteration (HA) factor is calculated for each of the three categories as following formula:

$$\text{HA} = (\text{observed frequency} - \text{expected frequency})/\text{expected frequency} \quad (2)$$

In this study, we divided the absolute ranges of HA factor into three classes: little or no alteration (⩽33%), moderate alteration (33%–67%) and high alteration (⩾67%) according to Richter et al. (1998) [58].

The coefficient of dispersion was a commonly used indicator to evaluate the variability of daily streamflow. It is calculated as the following formula:

$$\text{The coefficient of dispersion} = (\text{75th percentile} - \text{25th percentile})/\text{50th percentile} \quad (3)$$

2.3.4. Method for Measuring Environmental Flow

RVA was used in this study to identify the reasonable range of streamflow regime for environmental flow management. The basic consideration using RVA method for environmental flow identification here is that the preferred environmental flow regime in terms of magnitude, rate, and frequency should maintain streamflow variability as natural as possible in order to sustain the majority of riverine ecological functions. The variability of streamflow magnitude (i.e., daily streamflow) and the three indicators on the rate and frequency of the daily streamflow (i.e., rise rate, fall rate and number of reversals) involved in the IHA indicators can effectively represent the environment change induced by hydropower operations in the river system. In practice, the suitable range of the magnitude, rate and frequency should be identified for environmental flow associated with dams regulation.

The Tennant method (also known as Montana method), by which 20% of the daily average flow was used as the minimum ecological and environmental flow [59,60], was performed in this study to calculate the environmental flow in JRW in order to make comparison with the values from RVA method.

2.3.5. Statistical Analysis

The Kolmogorov–Smirnov (K–S) goodness of fit test was first used to test for normality ofthe distribution of the indicators representing the regime of streamflow. The *t*-test was then used to determine if means for each of the indicators during pre-impact period were statistically different from one another during post-impact period where significance was defined as $p < 0.05$.

3. Result

3.1. Overall Hydrologic Impact Assessment

The effect of regulation by dams on downstream flow regime was assessed using FDC in the North River and West River. As shown in Figure 4, the variability of daily streamflow exhibited anoverall decreasing trend for both two reaches of JRW. In the North River, the daily streamflow slightly decreased in lower percentiles (i.e., higher flows), while daily streamflow slightly increased in the higher percentiles (i.e., lower flows). Comparatively, daily streamflow slightly increased in the higher percentiles (i.e., the lower flows) in the West River. The crossing point of the two curves was calculated to be 136 days and 116 days in the North River and West River, respectively. The dams in the North River stored approximately 0.42 billion m^3 water during a 136-day higher flows period while release only 0.06 billion m^3 water in the subsequent 229 days in lower flow. In the West River, the dams stored only 0.06 billion m^3 water during a 116-day higher flow period while release 0.13 billion m^3 water in the subsequent 249 days in lower flow. This phenomenon indicated that the dams in the North River tend to store more water while the dams in the West River tend to release more water.

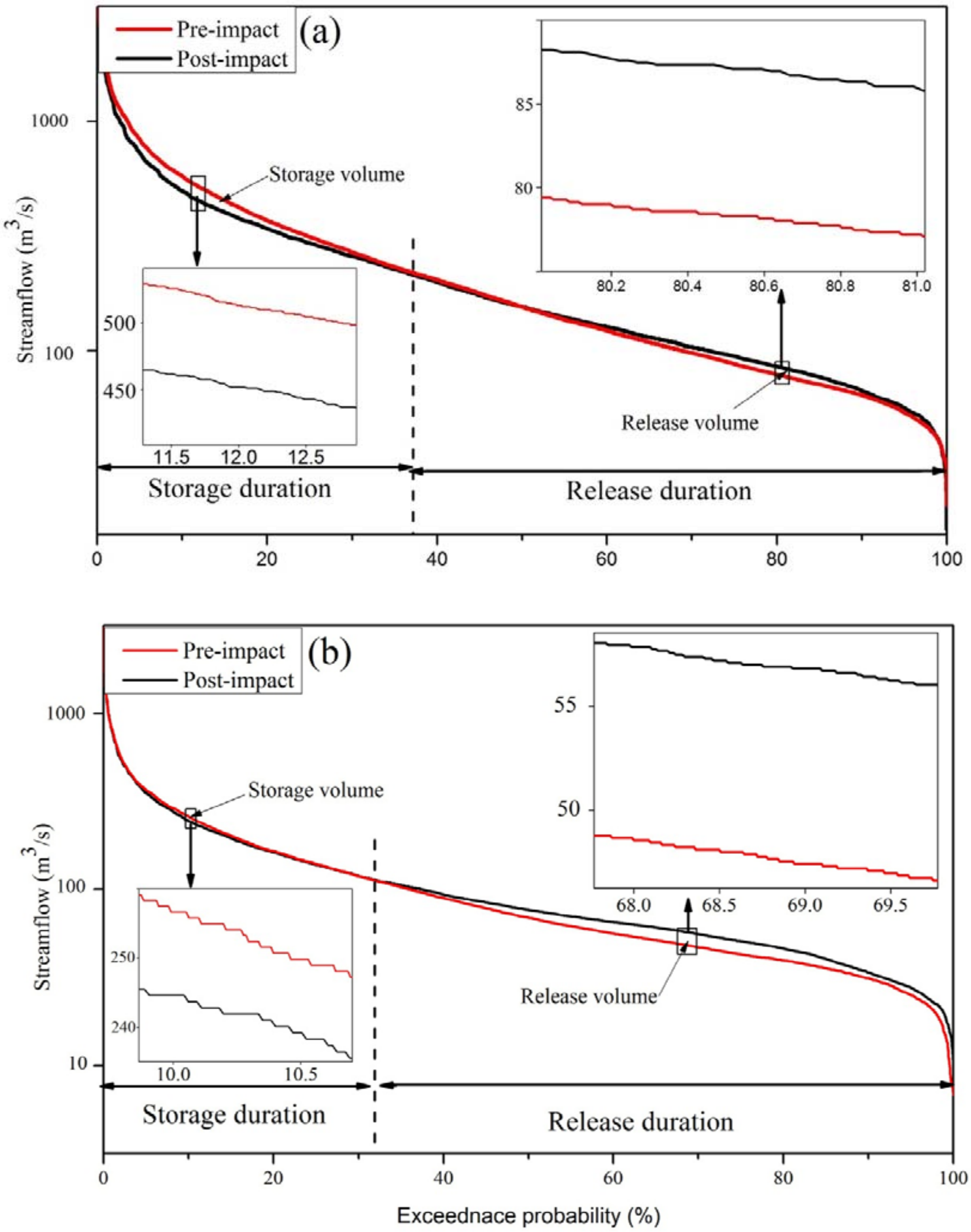

Figure 4. The flow duration curve change in JRW (**a**) North River reach; (**b**) West River reach.

3.2. Hydrologic Regime Changein a Full Range

3.2.1. Magnitude of Monthly Streamflow Regime

Themagnitude of monthly streamflow alteration was identified using IHA in the North River and West River. Similar variability patterns were observed in both two reaches of the JRW, namely, the monthly streamflow during July to January increased while decreased during February to May (Table 2). In addition, the monthly streamflow changed more significantly in the West River than in the North River. The monthly streamflow in January, August and December increased significantly in the West River while the monthly streamflow decreased significantly in May in the North River (Table 2).

Table 2. Monthly streamflow change due to dam construction in the JRW (%).

Two Reaches	Jan.	Feb.	Mar.	April	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
North River	10.5	−12.1	−37.7	−10.1	−33.4 *	6.4	21.6	17.4	10.7	6.2	4.8	10.7
West River	18.7 *	−13.3	−14.1	−19.1	−23.2	−8	30.3	54.2 *	25.3	28	11.1	20.9 *

Note: * $p < 0.05$.

Figure 5 shows the homogenizing variability of monthly streamflow in the JRW. The coefficient of dispersion increased in the period with high variability of streamflow (e.g., March in the North River, Figure 5a) while decreased in the period with low variability of streamflow in the JRW (e.g., Jan in the North River, Figure 5b). Particularly, the variability of monthly streamflow tend to decrease with the coefficient of dispersion more than 0.7 whereas it increased with the coefficient of dispersion less than 0.7 in both two reaches of the JRW. Interestingly, the variability of monthly streamflow in the flood season (e.g., in July and August) in the West River increased after dam construction, which might be related to the increasing frequency of extreme weather events.

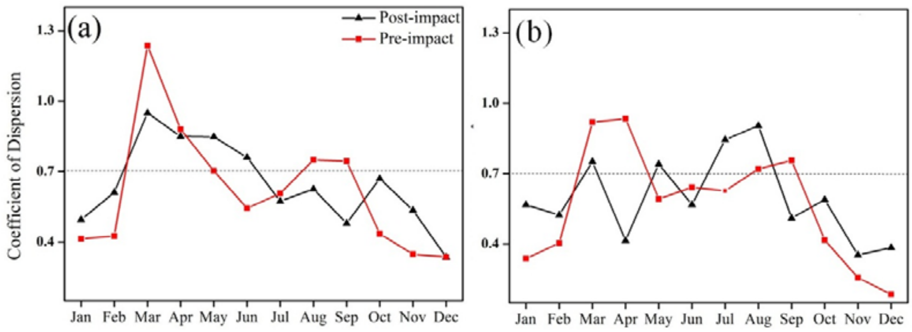

Figure 5. The variability of monthly streamflow in the JRW (**a**) North River reach; (**b**) West River reach.

Variability patterns of streamflow magnitude were delineated using RVA method and are presented in Figure 6. The similar variability patterns of monthly streamflow exhibited in the North River and West River, namely, the frequency of the monthly streamflow with high-level category increased during August to January (Figure 6) in both two reaches of JRW. Obviously, after dam construction, the monthly streamflow changed more intensively in the West River than in the North River. Particularly, the frequency of the monthly streamflow with high-level category all increased during August to January in the West River.

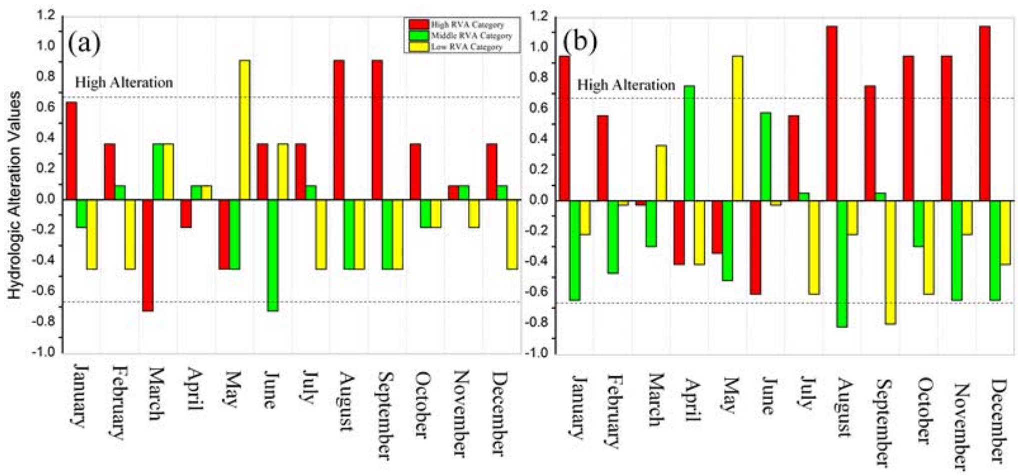

Figure 6. Hydrologic alteration of monthly streamflow in the JRW based on RVA method. (**a**): North River reach; (**b**) West River reach.

3.2.2. Magnitude, Duration and Timing of Extreme Streamflow Regime

The occurrence time of the annual extreme streamflow in the North River was approximately one month earlier than that in the West River (Table 3). The minimum and maximum streamflow occurred in early February and early July in the North River, while the minimum and maximum streamflow were in late February and early August in the West River. The Julian dates of minimum streamflow in the post-impact period for both two reaches of JRW were earlier than those in the pre-impact period, while the Julian date of maximum streamflow showed the opposite results (Table 3). In particular, the extreme low streamflow event occurred 14 days earlier than before in the West River and the extreme high streamfow event occurred 18 day later than before in the North River.

Table 3. The median of Julian date of the extreme streamflow.

Two Reaches	Pre-Impact Min Q	Post-Impact Min Q	Pre-Impact Max Q	Post-Impact Max Q
NorthRiver	34.0	33.0	171.0	189.0
West River	64.5	50.5	211.5	215.0

The baseflow index (BFI) increased by 18.8% and 17.7% in the West River and North River reaches, respectively. Given that BFI is the ratio of the 7-day minimum streamflow to the annual streamflow, the BFI increased more than the 7-day minimum streamflow, which might indicate a potential discharge decreasing trend in both two reaches of JRW (Table 4). Most of indicators of extreme streamflow decreased in the post-impact period in the North River. In contrast, most of the indicators of the extreme streamflow increased in the West River.

Table 4. The change of magnitude and duration of annual extreme streamflow condition in the JRW (%).

Two Reaches	1-Day Min	3-Day Min	7-Day Min	30-Day Min	90-Day Min	1-Day Max	3-Day Max	7-Day Max	30-Day Max	90-Day Max	BFI
North River	−20.3	−5.9	7.2	10.4	−0.4	−9.6	−7.4	−6.6	−7.5	−8.2	18.8 *
West River	8	11.7	13.7	12.7	7.1	6	−2.1	−0.2	8	9.8	17.7

Note: * $p < 0.05$.

Most of the indicators change little (HA ⩽ 33%) or moderately (HA = 33%–67%) in the JRW (Figure 7). The frequency of 30-day minimum streamflow which falled into high-level RVA category (HA ⩾ 67%) increased intensively in the North River and West River, indicating the increased frequency of minimum monthly streamflow with high-level category in both two reaches of JRW. The frequency of 30-day maximum streamflow which falled into high RVA category (HA ⩾ 67%) increased intensively in the West River, suggesting the increased frequency of maximum monthly streamflow with high-level category in the West River.

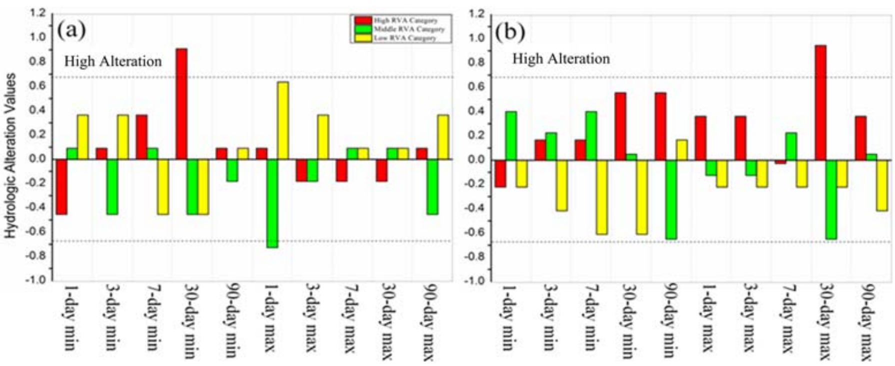

Figure 7. Hydrologic alteration of annual extreme streamflow in the JRW based on RVA method. (**a**) North River reach; (**b**) West River reach.

3.2.3. Frequency and Duration of High and Low Pulses

The frequency and duration of high and low pulses are quantified by the count and duration of the low pulse and high pulse, respectively. Except for the low pulse count, the other three indicators in Table 5 displayed the same trend after dams construction in the JRW. The frequency and duration of high and low pulses changed significantly in the last 44 years especially during the post-impact period in both two reaches of JRW. All of the indicators, especially for the low pulse count (101.8%) and the low pulse duration (−62.1%), changed significantly in the North River. The high pulse count decreased by 37.1%in the West River (Table 5). Most of the indicators increased significantly in low or middle level categories whereas decreased intensively in high-level category in the North river and West River, implying that the dams might effectively attenuate the high flow pulse event in both two reaches of JRW (Figure 8).

Table 5. The change of the frequency and duration of high and low pulses in the JRW (%).

Two Reaches	Low Pulse Count	Low Pulse Duration	High Pulse Count	High Pulse Duration
North River	101.8 **	−62.1 **	−21.4 *	19.2 *
West River	−15.5	−29.0	−37.1 **	6.7

Notes: ** $p < 0.005$; * $p < 0.05$.

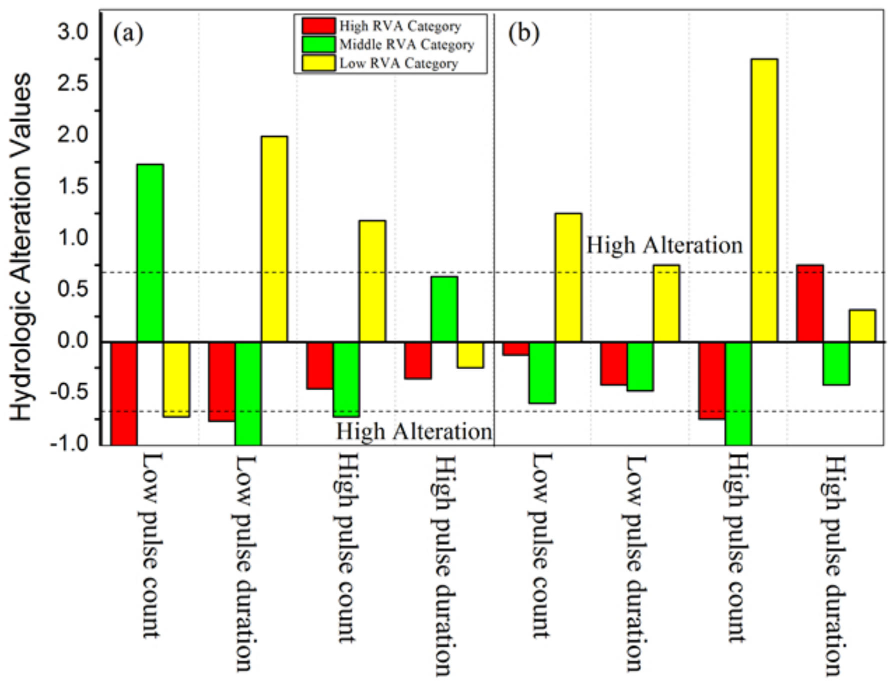

Figure 8. Hydrologic alteration frequency and duration of high and low pulses in the JRW based on RVA method. (**a**) North River reach; (**b**) West River reach.

3.2.4. Rate and Frequency of Streamflow Regime Change

The rate and frequency of the daily streamflow regime were quantified by the rise rate, fall rate and number of reversals (Table 6, Figure 9). The rate and frequency of streamflow regime changed intensively in both two reaches of JRW. The three indicators on the rate and frequency of the daily streamflow (i.e., rise rate, fall rate and number of reversals) revealed the similar trend in the post-impact period based on the observed data in the two reaches of JRW. The rise rate decreased by 26.9% and 61.0% in the North River and West River, respectively. The number of reversals increased by 40.7% and 46.4% in the North River and West River, respectively. The fall rate increased by 28.3% in the North River while increased by 0.8% in the West River (Table 6).

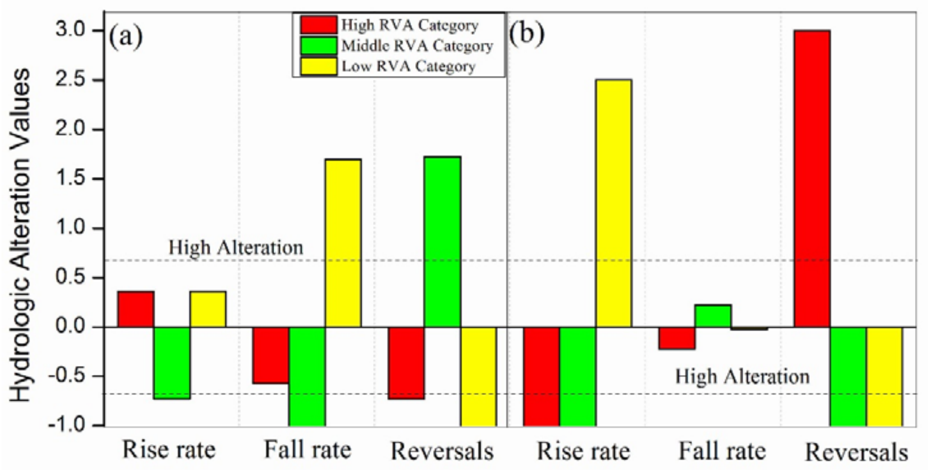

Figure 9. Hydrologic alteration of rate and frequency of the daily streamflow in the JRW based on RVA method. (**a**) North River reach; (**b**) West River reach.

Table 6. The change of the rate and frequency of the daily streamflow in the JRW (%).

Two Reaches	Rise Rate	Fall Rate	Number of Reversals
North River	−26.9 *	28.3 *	40.7 **
West River	−61.0 **	0.8	46.4 **

Notes: ** $p < 0.005$; * $p < 0.05$.

3.3. The Possible Suitable Range of Streamflow Regime

The suitable ranges of the daily streamflow are meaningful to be developed for environmental flow management in the JRW. Using Tennant method, the minimum environmental flow were 51.3 $m^3/s \cdot d$ and 24.5 $m^3/s \cdot d$ in the North River and West River. On the other hand, the suitable ranges of the daily streamflow were identified for each month using the RVA method (Figure 10). As shown in Figure 10, the monthly streamflow in August was higher than the natural streamflow boundary (i.e., RVA boundary), and the monthly streamflow in May was lower than the natural streamflow boundary in the North River. The similar result was found in the West River where the monthly streamflow in August, September, November, and December were higher than the natural streamflow boundary.

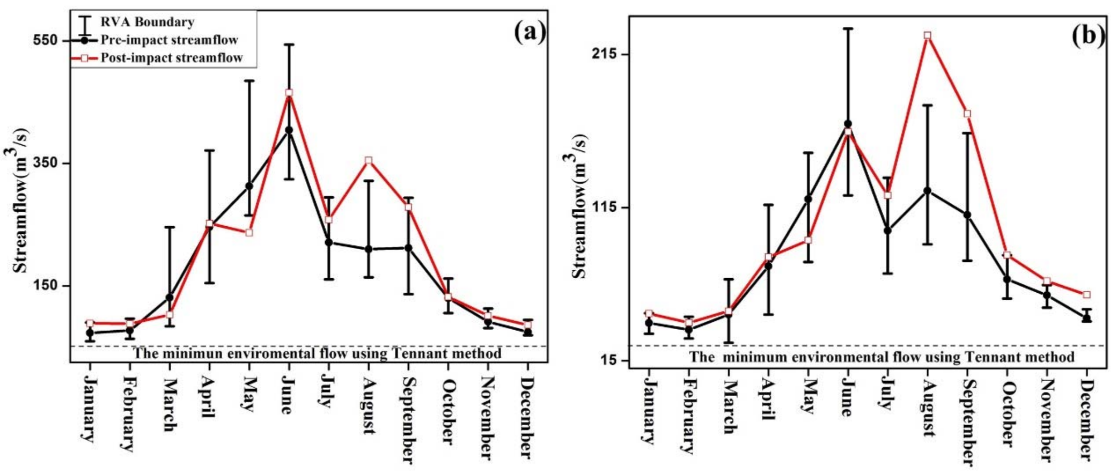

Figure 10. The suitable ranges of the monthly streamflow in the JRW. (**a**) North River reach; (**b**) West River reach.

The rate and frequency of streamflow changed largely due to dams construction in the JRW (Figure 9). From the perspective of the practical regulation, the suitable ranges for rise rate, fall rate and number of reversal in the JRW were identified based on the RVA method and the results are presented in Table 7. The fall rate in the North River and the rise rate in the West River were higher than the RVA boundary. Moreover, the number of reversal was higher than the RVA boundary in both reaches of the JRW.

Table 7. The suitable ranges of the rate and frequency in the JRW.

Hydrologic Parameters	North River			West River		
	RVA Range	Pre-Impact	Post-Impact	RVA Range	Pre-Impact	Post-Impact
Rise rate	16.0~33.5	24.0	17.6	10.1~19.8	15.2	5.9
Fall rate	−17.5~−12.2	−15.0	−19.2	−8.4~−5.5	−7.1	−7.2
Number of Reversals	103.0~137.0	119.9	168.7	98.3~108.8	106.7	156.2

Note: Lower and upper targets of RVA range are the 25th and 75th percentile value of the pre-impact hydrologic parameters including rise rate, fall rate, and number of reversals.

4. Discussion

4.1. Overall Impact of Streamflow Regulation on Flow Regimes

The overall streamflow regime change can be delineated through FDCs, which has been widely examined [30–32]. Our results revealed that the annual variability of daily streamflow decreased in the post-impact period in the North River and West River of JRW. The daily streamflow decreased in higher flow resulting from water storage regulated by dams while daily streamflow increased in lower flow resulting from water release regulated by dams in both two reaches of the JRW. The similar results also were found in the Han River and Yangtze River [8,31]. The dams tend to store more streamflow in the North River. For one thing, there are more dams and more length of river in the North River, which might slow down the downstream streamflow. For another, the downstream reservoirs or dams in the North River are designed to supply local residents with water for drinking, agricultural and industrial uses, which would make the downstream streamflow regulated.

4.2. Magnitude of Monthly Streamflow Regime

The effect of the dams on the monthly streamflow has been widely reported in the literature [13,16,29,61]. In this study, the mean daily streamflow increased during July to January while decreased during February to May after dam construction in the two reaches of JRW. This is similar with the previous findings in Huaihe River, Yangtze River and Langcang River [8,12,24]. Compared to the North River, the daily streamflow displayed a higher variability of monthly streamflow in the West River. This may be attributable to the smaller areas of watershed and less dams in the West River (Table 1). The effects of dam construction on water storage and release are greater for smallwatersheds than for large watersheds [62]. Generally, the impact of damconstruction in the JRW on monthly streamflow regime alteration is relatively complicated when combined with magnitude and inter-annual variability of monthly streamflow.

4.3. Magnitude, Duration and Timing of Extreme Streamflow Regime

Generally, baseflow is the most sensitive indicator to the streamflow regime change associated with dam construction [1,63–66]. The baseflow index (BFI) tends to increase after dam construction [3,8]. The increased BFI is the combined results of the increase in the 7-day minimum streamflow and the decrease in the annual streamflow due to dam construction [8]. Our study revealed that BFI value increased by 18.8 and 17.7%, respectively, in the post-impact period in the North River and West River. This suggests the general hydrologic regime alteration in the JRW due to dam construction. Our study also shows the potential discharge decreasing after construction in the JRW. The reduced discharged may be attributed to the result of increased evaporation or infiltration and loss to groundwater [13]. Our prior study shows that the 10-year average streamflowduring 2001–2010 in the North River and West Riverreaches decreased by 9.2% and 6.7%, respectively, compared to the average annual streamflow during 1967–2000, and the most important driving force for streamflow regime change in the JRW is related to population growth and economic development [3]. The potential discharge decrease after dam construction in the JRW might be related to annual streamflow decrease in recent years and the increasing water demanding in the watershed. Climatic variability in term of precipitation changes had limited effects on this situation, since that there is slightly increasing tendency of the annual precipitation in the West River while the precipitation in the North Riverseemed not to have changed in the past 50 years, as observed in our prior study [3].

The occurrence time of annual extreme condition can effectively reflect the seasonal variation of the hydrologic conditions [29]. The variation of the extreme events changed with geographic areas and climate patterns. Our study indicates the earlier occurrence time of extreme low streamflow event and later occurrence time of extreme high streamflow event after dams construction in the JRW, which is consistent with these asonal variation of the hydrologic conditions in other watersheds in South China [8,24,67]. This means the mode of dams regulation on streamflow regime in the JRW was similar to those in South China.

Previous studies in other watersheds show that minimum streamflow increased and maximum streamflow decreased after dam construction [5,46,68]. However, our study suggests the extreme low and high streamfow both decreased in the North River while both increased in the West River of the JRW. This is the results caused by the seasonal variation of streamflow regime changed in the JRW. The variability of the streamflow increased in February while decreased in July in the North River (Figure 4a), thus the minimum streamflow and maximum streamflow decreased in such two months in the North River. The situation was different in the West River, the variability of the streamflow decreased in March while increased in August (Figure 4b), therefore, the minimum streamflow and maximum streamflow increased in such two months respectively.

4.4. Pulse, Rate and Frequency Change

In response to theoperation of dams and reservoirs, the number of low pulse and high pulse will decrease [13,45,69]. Our study showed the count of low pulse in the North River increased abnormally (Table 5). This might be related to the increasing water demanding in the North River in recent years. As the water source for approximate 10 million resident in Xiamen, Zhangzhou and Longyan, large number of irrigation facilities was established, thereby inducing the low pulse count increased in the North River [3]. Similar observations were obtained in Huaihe River Basin and Tarim River Basinof China [24,47].

Due to the limited capacity of reservoirs, the duration of high pulse will change [29,70]. Our study also showed the increasing high pulse duration in the post-impact period in the JRW. This might be the result of the water storage and release regulated by the dams in JRW. The count of the high extreme high pulse decreased when water storage was operated by dams. This means the dams can store and attenuate all high flow pulse event. However, the dams tend to release the water when the water level exceeds the limited capacity of reservoir in the flood season.

The rate and frequency of streamflow can provide a measure of the rate and frequency of intra-annual environmental change and the decreased rise rate of hydrographs and increased in reversals after dams construction was widely observed [45,46]. Our study revealed that the rise rate decreased by 26.9% and 61.0% and number of reversals increased by 40.7% and 46.4% in the North River and West River, respectively. This is a byproduct of hydropower generation, wherein water is stored in the reservoir until sufficient head is attained to generate power efficiently, at which time the flow is rapidly released through the dam tubbiness [4]. Furthermore,the decreased rise rate and increased fall rate in the JRW also suggested the rate changing from high flow to low flow slowed down and the rate change from low flow to high flow speeded up, implying that the streamflow peak might be delayed (Table 3) and the variability of streamflow changed (Figure 4). Similar results were also found in Huaihe River, Yellow River, Taiwan and Great Plains [13,24,67,70].

4.5. Feasible Streamflow Regime in JRW

Streamflow regime is a primary determinant of structure and function of an aquatic and water quality in streams [3,24,26]. The magnitude of streamflow will influence the available habitat for organisms and the water quality in downstream. Too low streamflow will induce degrading water quality while too high streamflow will increase water level causing lost habitats. In order to protect native biodiversity and evolutionary potential of aquatic, riparian and wetland systems, the natural flow paradigm emphasizes the need to maintain or restore the range natural intra-annual and inter-annual variation of hydrologic regimes [24,39–41]. Our study revealed that the minimum flow requirement using Tennant method were close to the lower target identified using RVA method (Figure 10). Obviously, Tennant method only considers the lowest streamflow (i.e., the lowest streamflow in dry season) in the river but rarely considered the effective habitat quality at varying flow. Our study quantified reasonable range of the streamflow regime using RVA method in order to maintain the natural streamflow regime in the JRW.

Dams may not homogenize all river systems, but may move them outside the bounds of normal river function [16]. Our results suggest a suitable streamflow framework to generalize seasonal patterns inhydrologic alterations due to dam regulation. One the one hand, the suitable ranges in the flood season (e.g., in August) for both reaches of the JRW should be guaranteed by the reasonable regulation from downstream dams. On the other hand, more attention should be paid to the streamflow release or storage in the average season (e.g., May) and dry season (e.g., December) in the North River and West River, respectively.

Our study shows that the three indicators on the rate and frequency of the daily streamflow (i.e., rise rate, fall rate and number of reversals) were informative to delineate the critical role of dam construction on streamflow change. In this study, the fall rate in the North River and the rise rate in the West River were higher than the RVA boundary, which suggests that the dams in the JRW should release more water to get the natural targets of the rise rate and fall rate, so as to maintain the natural streamflow regime in the JRW. Moreover, the mean number of the reversal increased significantly and was higher than the RVA boundary, we therefore suggest that the dams in the JRW should decrease the frequency of store-release streamflow.

5. Conclusions

Flow duration curve analysis, indicators of hydrologic alteration, and range of variability approach were coupled in this study to evaluate the streamflow regime change induced by dam constructionin a full range in Jiulong River Watershed (JRW). The dailystreamflow decreased in higherflow resulting fromwater storage regulated by dams whiledaily streamflow increased in lower flow resulting fromwater release regulated by dams in both two reaches of the JRW. The dams in the North River tend to store more water while the dams in the West River tend to release more water. The mean dailystreamflow increased during July to January while decreased during February to May after dam construction in the two reaches of JRW. After dam construction, the monthly streamflow changed more significantly and higher variability of monthly streamflow was observed in the West River than in the North River. The homeogenizing variability of monthly streamflow exhibited in both two reaches of JRW. The earlier occurrence time of extreme low streamflow event and later occurrence time of extreme high streamflow event after dams construction. The extreme low and high streamfow both decreased in the North River while both increased in the West River of the JRW. All of the indicators especially for the low pulse count (101.8%) and the low pulse duration (−62.1%) changed significantly in the North River. The high pulse count decreased by 37.1% in the West River and the count of low pulse increased abnormally in the North River. The high pulse duration in the post-impact period increased in both two reaches of the JRW. The rise rate decreased by 26.9% and 61.0%,and number of reversals increased by 40.7% and 46.4% in the North River and West River, respectively. The fall rate increased by 28.3% in the North River.

Reasonable range of streamflow regime in terms of magnitude, rate, and frequency was identified using RVA method to sustain environmental flow management. More attention should be paid to the streamflow release or storage regulated by dams in May, August and December in the JRW. The dams in the JRW should release more water and decrease the frequency of store-releases treamflow. This research advances our understanding of hydrologic impact of small and medium dams in the medium-sized basin in China.

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