

Assessment of Streamflow Regime Alterations in Tang River, China

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Abstract. The biodiversity and integrity of river ecosystems are depending on the natural streamflow regime. Therefore, assessing alteration of hydrologic regimes becomes a fundamental step in river ecosystem protection and restoration. In this paper, the Range of Variability Approach (RVA) was used to analyze the alteration hydrologic regimes from 1959 to 2016 in the Tang River, the upstream of Baiyangdian Lake Basin, China. Several results can be drawn: (i) annual streamflow presented a decreasing trend, and an abrupt change was detected in 1979; (ii) the significant changed indicators of hydrologic variation in upstream of Baiyangdian Lake Basin were the monthly streamflow in March, April, August, November, time of 3-day and 90-day maximum streamflow, date of maximum streamflow occurrence, rise rate and number of reversals; and (iii) monthly water should be restored in flood and delivered in non-flood season, and annual extreme streamflow frequency and duration of high and low streamflow also should be regulated to maintain the streamflow regimes in the Tang River Basin, China. The results will help to provide the suitable ecological streamflow and maintain the integrity of river ecosystem in changing environment.

1 Introduction

The biodiversity and integrity of river ecosystems depend on natural streamflow conditions, and can be characterized by ecologically relevant hydrologic indicators of streamflow data [1]. However, climate changes combined with human activities (e.g., water diversion, dam construction, and urban development) have changed the natural streamflow of rivers around the world. Alteration of hydrologic regimes are considered to be the main cause of degradation of river ecosystems [2]. In this context, to explore the changes of hydrologic regimes and diagnosis alteration of hydrologic indicators have been regarded as one of effective methods to support river management.

Range of Variations method (RVA) was proposed by Richter *et al.* [3] which has been widely used to obtain streamflow characteristics in natural and changed conditions [4-7]. However, there still remained uncertainty in providing suitable streamflow regime for restoring aquatic ecosystem. Consequently, our objectives are: (i) to explore the temporal trend of streamflow in annual scale; (ii) to obtain the Indicators of Hydrologic Alteration (IHA) parameters with significant changes; and (iii) to propose the suitable ecological streamflow for the river restoration. The results should help to provide the suitable ecological streamflow and maintain the integrity of river ecosystem.

2 Study sites and data

Baiyangdian Lake is the largest freshwater lake in northern China [8]. Historically, nine rivers flow into the lake. In recent decades, most rivers influenced by the climate changes and human activities have dried up, which has led to degradation of aquatic ecosystem in the Baiyangdian Lake. In order to maintain the integrity of Baiyangdian Lake, several water transfer projects have been conducted to meet the ecological water requirement since 1980s, which have altered the natural hydrologic processes. Especially, planning outline of the national Xiong'an new district, which is intended to optimize regional spatial patterns and enhance ecosystem services and living environment, provide a new goal for the ecological restoration in the Baiyangdian Lake. This study selected Tang River as a study site in the upper reaches of Baiyangdian Lake to explore the alteration of hydrologic regimes using IHA and RVA (Figure 1). The daily hydrologic data were obtained from Zhongtangmei hydrologic station during 1959 and 2016.

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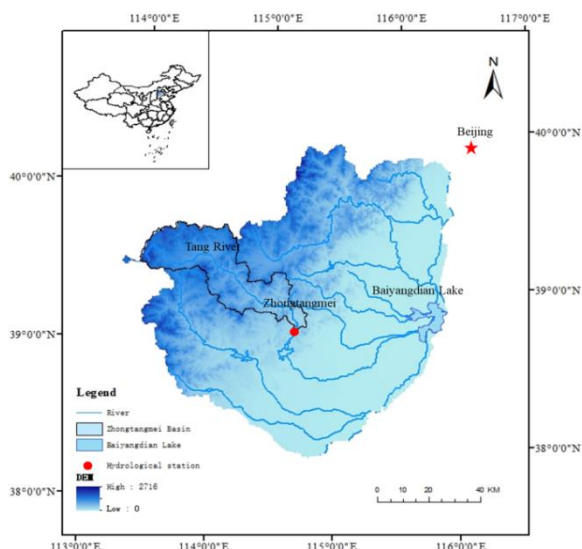


Figure 1. The locations of Tang River Basin and hydrologic station in the Baiyangdian Lake Basin.

3 Methodology

3.1 Temporal trend of streamflow

Mann-Kendall non-parametric test can be used for abrupt changes testing. For time series x_1, x_2, \dots, x_n , build order column [9, 10]:

$$S_k = \sum_{i=1}^k r_i \quad (k = 2, 3, \dots, n), \quad (1)$$

when $x_i > x_j$, $r_i = 1$, when $x_i < x_j$, $r_i = 0$ ($j=1, 2, \dots, i$).

Under the assumption that the time series is randomly independent, the defined statistics are:

$$UF_k = \frac{[S_k - \bar{S}_k]}{\sqrt{Var(S_k)}} \quad (k = 1, 2, \dots, n), \quad (2)$$

where, $UF_1 = 0, Var(S_k), \bar{S}_k$ are cumulative amount accumulation variance and mean of S_k , respectively, can be calculated from the following formula:

$$\bar{S}_k = \frac{n(n-1)}{4}, \quad (3)$$

$$Var(S_k) = \frac{n(n-1)(2n+5)}{72}, \quad (4)$$

where, UF_k is in a standard normal distribution, which is a statistical sequence calculated from the time series x_1, x_2, \dots, x_n , given the significance level 0.05, the critical value is $U(0.05) = \pm 1.96$.

Create an invert time series x_n, \dots, x_2, x_1 named UB_k , repeating the above procedure, $UF_k = -UB_k$ ($k=n, n-1, \dots, 1$), $UB_1=0$. If the two curves UF_k and UB_k intersect, and the intersection is between the critical lines, then the corresponding moment of intersection is the time at which the mutation begins.

3.2 Indicators of Hydrologic Alteration

The RVA method proposed by Richter *et al.*[3] has been widely used to analysing the hydrologic regimes characteristics. In RVA method, IHA are categorized in five groups, as shown in Table 1 [6, 11].

Table 1. Indicators of hydrologic alteration (IHA).

IHA group	Hydrologic indicators
Group 1: Magnitude of monthly water conditions	Mean value for each calendar month 1-day minimum 3-day minimum 7-day minimum 30-day minimum 90-day minimum
Group 2: Magnitude and duration of annual extreme water conditions	1-day maximum 3-day maximum 7-day maximum 30-day maximum 90-day maximum
Group 3: Timing of annual extreme water conditions	Date of minimum Date of maximum Low pulse count
Group 4: Frequency and duration of high and low pulses	Low pulse duration High pulse count High pulse duration Rise rate Fall rate
Group 5: Rate and frequency of water condition changes	Number of reversals Number of zero days Base streamflow index

3.3 Range of Variability Approach

The RVA is based on the IHA, with detailed flow data to determine the state of river streamflow before and after change, in order to analyze the degree of hydrologic change before and after river change.

The definition of hydrologic alteration is as follows [12]:

$$D_i = \frac{N_i - N_e}{N_e} \times 100\% \quad (5)$$

where, D_i is the degree of change of the i^{th} hydrometric indicator, N_i is the number of years in which the annual total streamflow fall within the target range after the variation of the eco-hydrometric indicator, N_e is the expected number of years, $N_e = rN_t$, where r is the proportion of the pre-interference hydrologic indicators falling within the RVA target, in this study, from 25.00% to 75.00% of each hydrologic indicator as the RVA target, then r is 50%, and N_t is the number of years of the interference after streamflow observation. To map hydrologic alteration, Richter divided the ranges of hydrologic alteration (0-100.00%) into three classes of

equal range and assigned each class a distinct pattern: (i) 0-33.33% represents little or no alteration; (ii) 34.00%-66.00% represents moderate alteration; (iii) 67.00%-100% represents a significant alteration.

4 Results and Discussion

4.1 Temporal trends of streamflow

Annual streamflow presented a significant decreasing trend ($P < 0.05$) with an average increase of $-0.0059 \times 10^9 \text{ m}^3 \cdot \text{a}^{-2}$ during 1959 and 2016 (Figure 2a). The results were consistent with Tian *et al.*[13]. According to Mann-Kendall method, the downward abrupt change was detected in 1979 (Figure 2b). The results were consistent with Liu *et al.*[14]. According to timing of abrupt change, annual streamflow can be divided into two periods: natural period (1959-1978) and changed period (1979-2016). The average annual streamflow were $0.37 \times 10^9 \text{ m}^3 \cdot \text{a}^{-1}$ and $0.20 \times 10^9 \text{ m}^3 \cdot \text{a}^{-1}$ in the natural and changed period, respectively.

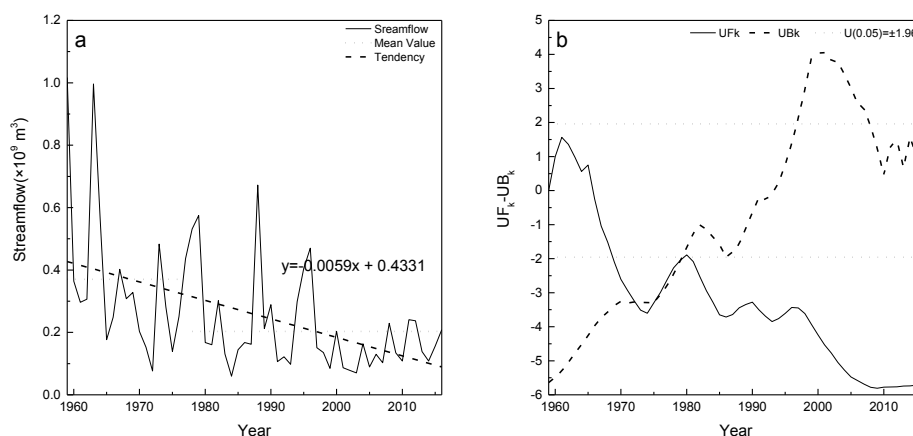


Figure 2. The temporal trend (a) and abrupt change detection using Mann-Kendall method (b).

4.2 Streamflow regime alteration assessment

Assessed by hydrologic degree of variation (D), hydrologic parameters altered between natural and changed periods (Table 2). Generally, the greatest variations at monthly scales presented a significant decrease ($|D| > 66.00\%$) trend in four months: March,

April, August, and November; and D for these four months were -67.00% , -80.00% , -87.00% and -67.00% , respectively. For count and duration of annual extreme streamflow, 3-day and 90-day maximum streamflow presented significant variation. Values of D for the two parameters were both -74.00% .

Table 2 IHA alteration and degree of variation for hydrologic Tang River Basin.

	Natural period: 1959-1978				Changed period: 1979-2016				RVA Boundaries		Hydrologic Alteration (%)
	Means	Variation	Minimum	Maximum	Means	Variation	Minimum	Maximum	Low (25%)	High (75%)	
January	4.97	0.71	2.93	10.20	3.93	0.42	0.00	7.97	4.01	6.82	-1
February	5.16	0.61	2.93	12.70	3.82	0.36	0.00	6.80	4.21	6.45	-21
March	4.97	0.64	2.36	10.80	3.32	0.63	0.00	5.55	4.34	6.49	-67
April	4.19	0.82	0.93	11.20	0.98	2.11	0.00	4.60	3.00	5.36	-80
May	1.71	1.35	0.25	7.62	0.87	1.58	0.00	3.58	1.19	2.81	-8
June	2.16	1.41	0.55	7.89	0.79	1.35	0.17	10.35	1.43	3.06	-61
July	10.56	1.09	0.40	47.90	4.21	1.58	0.37	28.00	7.56	12.92	-54

August	24.05	1.02	2.70	144.00	8.14	1.35	0.71	135	16.49	27.56	-87
September	11.13	1.02	1.61	46.30	7.06	0.73	1.82	30.00	8.79	15.79	-41
October	8.98	0.71	1.21	24.70	5.53	0.60	0.00	14.70	6.31	12.31	-28
November	7.19	0.66	1.61	18.20	3.30	0.85	0.00	6.73	5.50	8.42	-67
December	5.37	0.63	2.12	13.90	4.48	0.37	0.00	8.69	4.54	7.58	-1
1-day minimum	0.60	3.17	0.08	2.90	0.21	2.19	0.00	1.55	0.20	1.12	12
3-day minimum	0.75	2.76	0.10	3.56	0.21	2.23	0.00	1.67	0.23	1.21	-1
7-day minimum	1.09	1.95	0.11	4.71	0.26	1.80	0.00	1.89	0.44	1.59	-8
30-day minimum	1.76	1.26	0.24	6.45	0.47	1.86	0.00	2.47	0.84	2.53	-21
90-day minimum	2.55	1.20	0.81	7.12	1.02	1.28	0.00	3.13	1.94	3.55	-47
1-day maximum	127.50	2.07	8.83	3350	52.40	2.52	5.46	720	97.35	177.10	-34
3-day maximum	93.55	1.55	5.83	2191	40.61	2.17	4.57	516	67.45	123.80	-74
7-day maximum	59.71	1.81	5.34	1099	27.39	2.31	4.06	387.10	50.99	89.35	-54
30-day maximum	34.38	1.57	4.66	294.90	15.58	1.54	3.52	174.90	26.20	68.70	-54
90-day maximum	22.14	1.36	4.18	108.80	9.93	1.15	3.15	73.69	17.79	36.67	-74
Number of zero days	0.00	0.00	0.00	0.00	0.00	0.00	0.00	243.00	0.00	0.00	-8
Base flow index	0.10	2.02	0.01	0.41	0.07	1.87	0.00	0.36	0.04	0.18	18
Date of minimum	177	0.08	122	187	147	0.15	1.00	275	174	179.10	-77
Date of maximum	217.50	0.06	188	241	217.50	0.06	163	253	211	226.10	12
Low pulse count	8.00	0.88	1.00	20	6.00	0.54	1.00	14.00	4.93	11.00	29
Low pulse duration	4.00	1.06	2.00	18	12.00	1.26	2.00	114	3.00	6.04	-47
High pulse count	5.00	0.60	0.00	11	3.00	0.67	0.00	11.00	4.00	7.00	-65
High pulse duration	4.00	0.63	1.00	14.50	4.00	2.19	1.00	54.50	3.00	4.00	-42
Rise rate	0.56	0.57	0.24	1.70	0.26	1.44	0.03	3.67	0.50	0.64	-74
Fall rate	-0.59	-0.53	-1.80	-0.30	-0.36	-0.97	-2.20	-0.07	-0.67	-0.48	-61
Number of reversals	102.00	0.16	76	130	48.00	1.06	20.00	124	94.93	107.10	-67

4.3 Analysis of hydrologic alteration detected by RVA

(1) Monthly streamflow variation

For monthly streamflow, variations in flood (e.g., April) and non-flood (e.g. August) seasons were presented in Figure 3. For April, average streamflow are $0.14 \times 10^9 \text{ m}^3$ and $0.040 \times 10^9 \text{ m}^3$ in natural and changed periods, respectively. According to RVA boundaries,

streamflow in 40.00% years (8/20) and 10.52% (4/38) years reached to suitable ecological streamflow in the natural and changed periods, respectively. For August, average streamflow are $0.23 \times 10^9 \text{ m}^3$ and $0.13 \times 10^9 \text{ m}^3$ in natural and changed periods, respectively; streamflow in 40.00% years (8/20) and 7.89% (3/38) years reached to suitable ecological streamflow in the natural and changed periods, respectively.

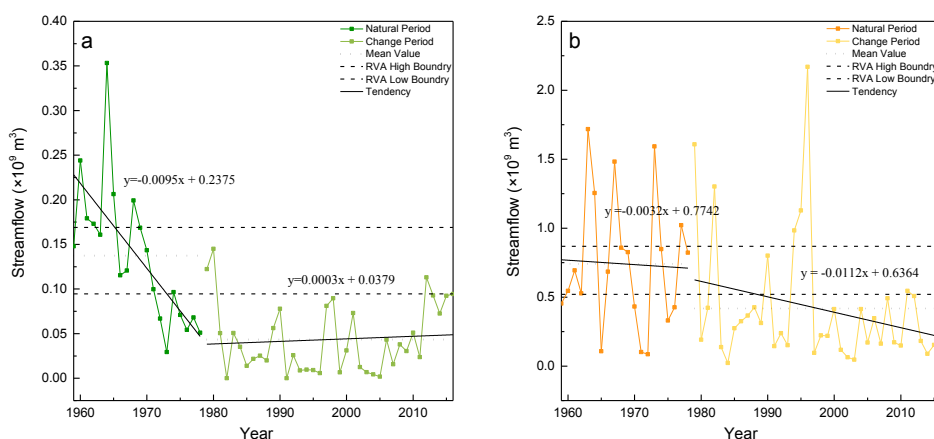


Figure 3. Variation of monthly streamflow during natural and changed period (a. April; b. August).

(2) Annual extreme streamflow occurrence

The Julian date of annual minimum and maximum streamflow was slightly earlier in changed period than that in natural period (Figure 4). A small difference existed in D variation between natural and changed

periods, with D value ranging from -77.00% to 12.00%, respectively. The date for 1-day minimum streamflow and 1-day maximum streamflow were earlier in the changed period than that in natural period.

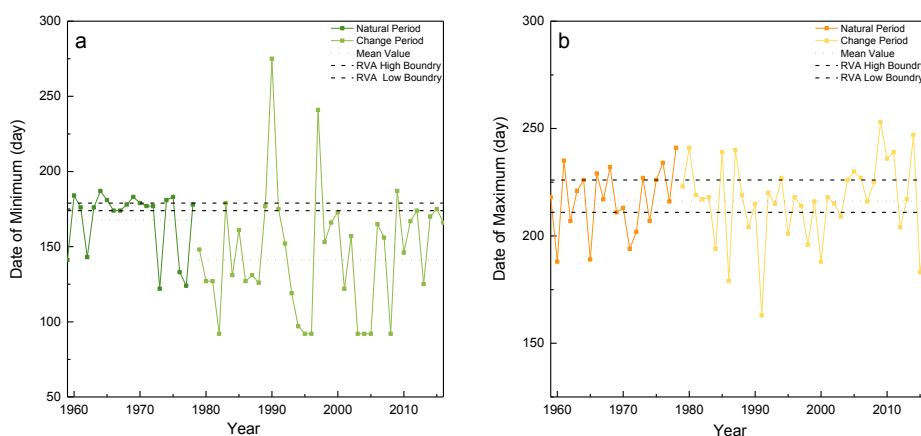


Figure 4. The onset date for maximum and minimum streamflow in Tang River Basin during natural and changed periods (a. date of minimum, b. date of maximum).

(3) Frequency and duration of high and low streamflow

The counts of high and low pulses were reduced by 25.00% and 40.00%, respectively. The D for the count of high and low pulses presented moderate changes ($33.00\% < |D| < 66.00\%$) compared with the natural periods. The high pulse duration D was -42.00%, while the low pulse duration increased ($|D| = 47.00\% < 66.00\%$), increased from 4 days in natural period to 12 days in changed

period. The average count of high pulses (showed in Figure 5) decreased from 5 times in the natural period to 3 times in the changed period. While the count of low pulses in the natural and changed periods were 8 times and 6 times, respectively. The decrease of high and low pulse counts will lead to the disappearance of some low-flow channels, and the nutrients carried by rivers are not easily absorbed by aquatic organisms and surrounding vegetation.

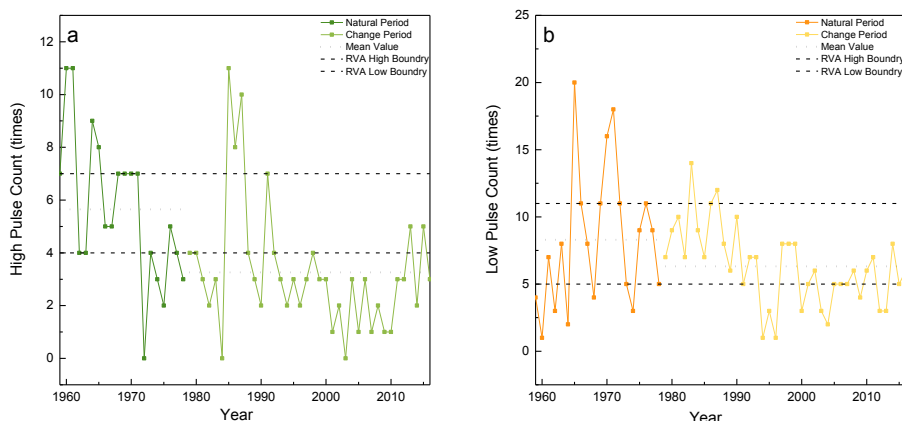


Figure 5. Changes of frequency of high and low pulses for hydrologic data series during natural and changed periods (a. high pulse count, b. low pulse count).

5 Conclusion

Alteration of hydrologic regimes has dramatically influenced integrity of aquatic ecosystem. In present study, alterations of hydrologic processes were analyzed. Several conclusions can be drawn:

(i) The annual streamflow presented a decreasing trend of $0.0059 \times 10^9 \text{ m}^3 \cdot \text{a}^{-2}$ during 1959-2016, and a decreasing abrupt change was detected in 1979, which was used to split hydrologic series into natural and changed periods.

(ii) According to IHA and RVA, the significant alteration of hydrologic indicators were the average streamflow in March, April, August and November, the maximum streamflow time of 3-day and 90-day series, date of maximum streamflow occurrence, rise rate, and number of reversals.

And (iii) according to RVA monthly streamflow results, significant alteration of hydrologic indicator showed monthly streamflow in non-flood season should be from $0.054 \times 10^9 \text{ m}^3$ to $0.28 \times 10^9 \text{ m}^3$, while monthly streamflow in flood season should be ranged from $0.068 \times 10^9 \text{ m}^3$ to $0.76 \times 10^9 \text{ m}^3$. Furthermore, annual extreme streamflow, and frequency and duration of high and low streamflow also should be regulated to maintain the streamflow regimes in the Tang River Basin, China.

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