

Article

# Is It Optimal to Use the Entirety of the Available Flow Records in the Range of Variability Approach?

Yuanyuan Sun, Cailing Liu, Yanwei Zhao \*, Xianqiang Mao, Jun Zhang and Hongrui Liu

State Key Laboratory of Water Environment Simulation, School of Environment, Beijing Normal University, Xijiekouwai Street, Beijing 100875, China; sunyuanyuanbnu@163.com (Y.S.); wenwencailing@163.com (C.L.); maoxq@bnu.edu.cn (X.M.); zj0207@bnu.edu.cn (J.Z.); remain7@163.com (H.L.)

\* Correspondence: awei1974@bnu.edu.cn; Tel.: +86-10-5880-1719

Received: 10 August 2020; Accepted: 20 November 2020; Published: 22 November 2020



**Abstract:** Reducing the degree of flow regime alteration is a basic principle for biodiversity conservation in rivers. The range of variability approach (RVA) is the most widely used method to assess flow regime alteration. Generally, researchers tend to put all of the available pre-impact and post-impact flow records into the RVA. However, no research has tested whether it is optimal to use the entirety of the available flow records from the perspective of calculation accuracy for the degree of flow regime alteration. In this research, a series of numerical simulations is conducted, demonstrating that the greatest accuracy for flow regime alteration degree assessed by the RVA is achieved when the length of both the pre- and post-impact flow time series is set equal to multiples of periodicity length, and that, when attempting to put the whole available flow record into the RVA, calculation accuracy may be reduced. On the basis of these findings, we further propose revising the traditional RVA procedure by assessing the periodicity of the pre- and post-impact flow time series in advance. If the periodicity of the pre- or post-impact flows is detected, the length of the time series should be set equal to its periodicity.

**Keywords:** flow regime; hydrologic alteration; RVA; record length; hydrologic periodicity

## 1. Introduction

The natural flow regime plays a crucial role in preserving the structures and functions of riverine ecosystems [1,2]. It can be defined by five major ecologically relevant characteristics, i.e., magnitude, frequency, duration, timing, and rate of change [3,4]. Alteration of these hydrologic characteristics could have significant ecological consequences [5–7]. Maintaining the natural flow regime is a foundational principle for biodiversity conservation in rivers [1,6], but human activities and climate change have seriously altered the natural flow regimes of rivers worldwide, leading to degradation of riverine ecosystems [8–10]. Assessing the degree of flow regime alteration is a basic step in river protection and restoration.

Many methods have been developed to assess flow regime alteration. Among them, the range of variation approach (RVA) proposed by Richter et al. [11–13] is the most widely used approach and represented a milestone in efforts to assess the degree of hydrologic alteration. It has been cited more than 2400 times in scientific publications by 2020 according to Google Scholar. The RVA is widely used to assess the difference in flow regimes between two time periods [14–16] and to optimise the operation of hydraulic facilities [17–23]. The RVA includes 32 hydrologic indicators, which form a suite of indicators of hydrologic alteration (IHAs). The difference between the proportions of pre- and post-impact values falling within the target range is considered to represent the degree of alteration of the IHAs [12]. If the frequency is the same for the pre- and post-impact time series, flow regime alteration is considered to be negligible. After the establishment of the RVA, many scientists seek to

further improve the method. For example, Shiau and Wu [19] refined the RVA by considering the proportions of the study period in which a hydrologic indicator fell within each of the three ranges (i.e., above the 75th-, between 75th- and 25th-, and below the 25th-percentile for pre-impact daily flows) and by adopting the degree of dissimilarity between the pre- and post-impact histograms as a metric for assessing the intensity of hydrologic alterations. Yang et al. [24] argued that the RVA only considered the frequency of each IHA but did not account for the equally important temporal order of these IHAs. To deal with the problem, they refine the RVA by incorporating the periodogram method and maximum entropy spectral analysis method. Yin et al. [25] pointed out that the RVA underestimated the flow regime alteration degree because it did not consider alteration of the order of hydrologic year types and adopted the Euclidean distance to address the problem. Yu et al. [26] proposed that the 32 IHAs were interrelated in each year and should be treated as a set. They further combined the set pair analyses method with the RVA. Because some IHAs may not be critical to some specific riverine ecosystem, Singh and Jain [27] further proposed to use the principal component analysis to select ecologically relevant hydrologic indicators from IHAs.

Richter et al. [13] suggested a record length of at least 20 years for the pre-impact/post-impact flows as the minimum standard for the RVA, to decrease the effects of inter-annual climatic variation on hydrologic statistics. Consequently, when the RVA is used to assess the degree of flow regime alteration, users tend to put all of the available pre-impact and post-impact flow data into the RVA. This record usage pattern is based on a hypothesis that a longer length of flow time series used in the RVA can improve the accuracy of the RVA. Research has demonstrated that the length of the time series can affect some hydrological indices [28–31]. Undoubtedly, the flow record length will also influence the values of the IHAs used in the RVA and, consequently, influence the value of the RVA. As a result of the limited operation time of many hydrological gauging stations, the pre-impact/post-impact flow records are also limited and may be only two or three decades long. Thus, we question whether a longer flow time series used in the RVA will always improve accuracy. Is it always reasonable to put all of the available pre-impact and post-impact flow records into the RVA, from the perspective of improving the accuracy of flow regime alteration assessment? In addition, if the application of all of the available pre-impact and post-impact flow records is not the best option, then what is the optimal length for flow records used in the RVA?

In this research, we explore the influence of flow record length on the RVA and test the value of using all of the available pre-impact and post-impact flow records in the RVA. A series of numerical simulations is conducted to investigate these questions. We also propose an improvement to the RVA procedure by considering optimal flow record length. The Roanoke River is adopted as a case study to evaluate the performance of the improved RVA.

## 2. Methods

In the method section, the traditional RVA was briefly introduced for comparison with the revised RVA. Then, the method to generate flow time series was developed based on the Thomas-Fiering model. Finally, a series of scenarios of flow record lengths was established based on the randomly generated flow time series to explore the influence of flow record length on the RVA.

### 2.1. RVA

In the RVA, 32 IHAs were used to assess the degree of flow regime alteration. On the basis of pre-impact flows, the values of each of the 32 IHAs were divided into three ranges. The target range was defined as extending from the 25th to the 75th percentiles of the pre-impact indicator values. The difference between the proportions of pre- and post-impact values falling within the target range was considered to represent the degree of alteration of the IHA, which was defined by

$$D_m = \left| \frac{N_{o,m} - N_{e,m}}{N_{e,m}} \right| \times 100\% \quad (1)$$

where  $D_m$  was the alteration degree for the  $m$ th *IHA*;  $N_{o,m}$  was the observed number of post-impact years in which the value of the  $m$ th *IHA* fell within its *RVA* target range; and  $N_{e,m}$  was the expected number of post-impact years in which the *IHA* value fell within the *RVA* target range. The average degree of alteration of these *IHAs* was applied to quantify the overall impact on the river, which can be expressed as follows:

$$D = \frac{1}{32} \sum_{m=1}^{32} D_m \quad (2)$$

where  $D$  was the overall degree of flow regime alteration [11–13].

In the *RVA*, the first step is to input the pre-impact and post-impact flow data. In this step, users tend to include all of the available pre-impact and post-impact flow records. Improving this step is the key aim of this paper.

## 2.2. Method to Generate Random Daily Flow Time Series

To test the validity of using all of the available pre-impact and post-impact flow records in the *RVA*, a series of daily flow time series need to be randomly generated. The following steps were used for random flow generation.

### • Step 1: Generate annual mean flows

The Thomas-Fiering model is widely applied to generate weekly, monthly and annual flow sequences [32–34]. A simplified Thomas-Fiering model, shown in Equation (3), is adopted in this research for annual mean flow generation [35]. The parameters in this model include mean annual flow, the coefficient of variation, and the correlation coefficient of the flows, which are denoted as  $\mu$ ,  $C_v$ , and  $\rho$ .  $Q_t$  is the annual mean flow for year  $t$ ;  $\delta$  is a standard normal random number.

$$Q_{t+1} = \mu + \rho(Q_t - \mu) + \sqrt{1 - \rho^2}(\mu C_v)\delta \quad (3)$$

According to research on global rivers by McMahon et al. [36], the annual coefficient of variation ( $C_v$ ) varies between 0.062 and 2.97, and the correlation coefficient ( $\rho$ ) varies between  $-0.48$  and  $0.90$ . For the generation of each annual mean flow sequence, the parameters  $C_v$  and  $\rho$  were randomly determined within these ranges. The mean annual flow  $\mu$  was set equal to 1 in this research, and the annual mean flow for the first year  $Q_1$  was also randomly chosen within 0 and 1.

### • Step 2: Generate daily flows based on the annual mean flows generated above

In previous research on flow generation, it is generally assumed that flows have a certain distribution type. Normal, log-normal, Gumbel, Weibull, and Pearson type 3 (gamma) are commonly used probability distribution types [37]. The normal and log-normal distributions generally fit the annual flow generation [38]. Gumbel and Weibull distributions are used for extreme values of flows [39,40]. Pearson type 3 (gamma) distribution has the advantage of having only positive values, which is consistent with the characteristics of flows, and is commonly used in daily flow analysis [41]. In China, Pearson type 3 distribution is recommended for water resources planning and management [42]. As a result, Pearson type 3 distribution was also adopted in this research for daily flow generation.

The mean, variance, and skewness coefficient of daily flows are key parameters in Pearson type 3 distribution of daily flows [43]. The mean flow for each year adopts the values of annual mean flow generated above. To date, no studies have given ranges for the skewness coefficient and the coefficient of variation for global daily flows. Here, the skewness coefficient range was set between  $-3$  and  $3$  [42]. The range of variation coefficient simply adopted the range for global annual flows, i.e., from 0.062 to 2.97 [36]. In the process of daily flow generation, the two parameters were randomly chosen within these ranges.

- **Step 3: Generate flow time series with the specific length of periodicity based on the daily flows generated above**

Following steps 1 and 2, one daily flow time series could be randomly generated with a length of  $N$  years. The generated time series was repeated four times to form a new time series (i.e., the length of the new time series is  $4N$  years). The newly formed time series was periodic and the periodicity length was  $N$  years. The flows of the first  $2N$  years and the last  $2N$  years were considered the pre- and post-impact flows, respectively.

### 2.3. Method to Test the Influence of Flow Time Series Length on the RVA

The  $4N$ -year flow time series represented the flow process in nature. However, actual flow data available for humans may not cover the entire process. Because the establishment date of gauging stations varies, the flow time series available for the assessment of flow regime alteration may not start at the beginning of the  $4N$ -year flow time series and may instead start at any year (for example, start at the  $i$ th year). Similarly, due to the gauging time length of flows, the flow time series available for the assessment of flow regime alteration may not end at the end of the  $4N$ -year flow time series and may end at any year of the  $4N$ -year flow time series (for example, end at the  $j$ th year). The flow data from the  $i$ th to  $(2N)$ th year and from the  $(2N + 1)$ th to  $j$ th year were the actual pre- and post-impact flow data available for humans.

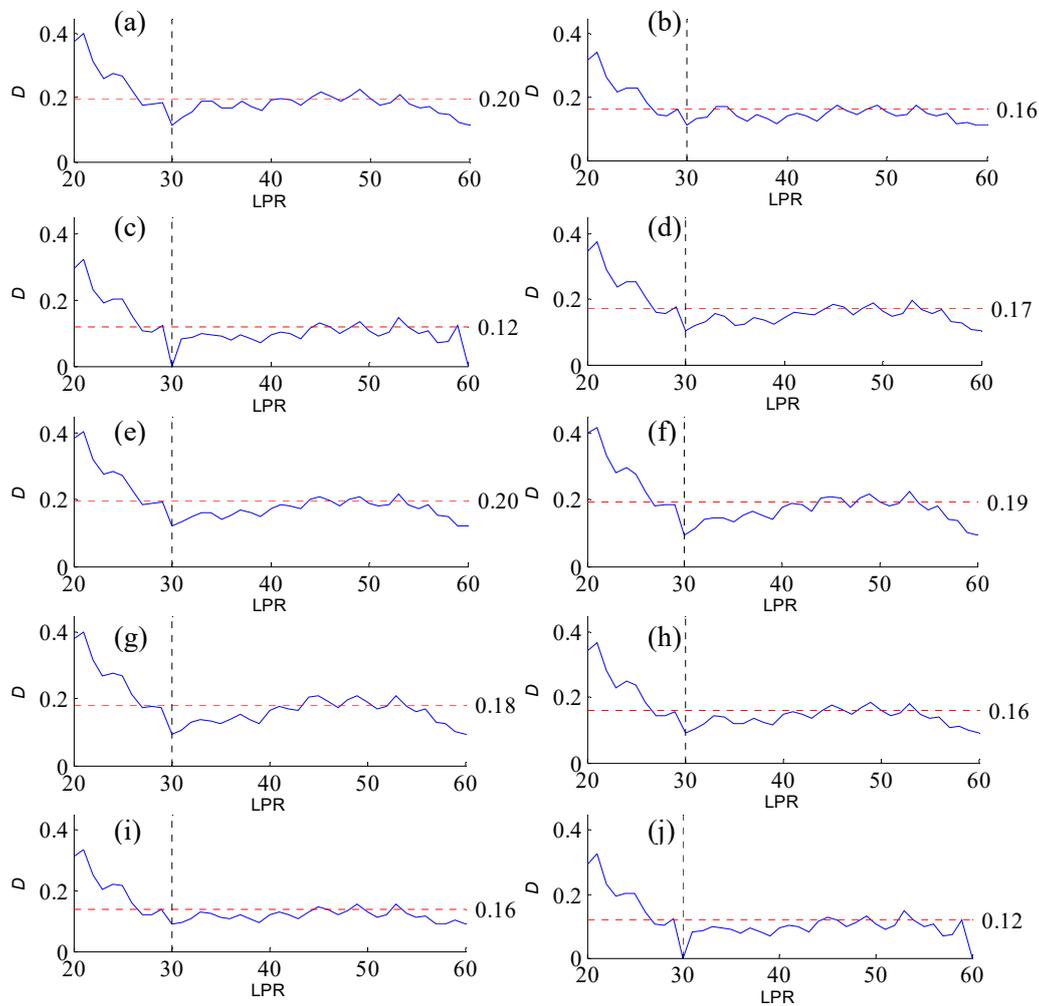
To explore the influence of pre-impact flow time series length, we designed many sub-pre-impact flow time series and sub-post-impact flow time series based on the above  $4N$ -year flow data. The designed sub-pre- and sub-post-impact flow time series represented different scenarios of available data length (i.e., different  $i$  and  $j$  values). The pre-impact flow time series were constructed by choosing flow data from year 20 to  $2N$  with increments of one year, and thus  $2N - 19$  sub-pre-impact flow time series were produced. They all ended at the  $2N$ th year (the point separating the pre- and post-impact flows). In addition, 10 sub-post-impact flow time series were produced based on the  $2N$ -year post-impact flow data. The lengths of 10 sub-post-impact flow time series were set from  $(1-2/7)N$  to  $2N$  years with a step of  $N/7$  years. They all started at the  $(2N + 1)$ th year (the point separating the pre- and post-impact flows). We further calculated the RVA values under all combinations of sub-pre-impact ( $2N - 19$  scenarios) and sub-post-impact flow time series (10 scenarios). Then, we could plot 10 figures. In each figure, the length of the sub-post-impact flow time series was fixed to one of the 10 scenarios, and the sub-pre-impact flow length varied and covered all the  $2N - 19$  scenarios. Each figure showed the influence of pre-impact flow length on the RVA.

Similarly, to explore the influence of post-impact flow time series length, we also designed many sub-post-impact flow time series and 10 sub-pre-impact flow time series based on the  $4N$ -year flow data. The sub-post-impact flow time series were constructed by choosing flow data from year 20 to  $2N$  with increments of one year, and thus  $2N - 19$  sub-post-impact flow time series were produced. They all started at the  $(2N + 1)$ th year (the point separating the pre- and post-impact flows). In addition, the lengths of 10 sub-pre-impact flow time series were set from  $(1-2/7)N$  to  $2N$  years with a step of  $N/7$  years. They all ended at the  $2N$ th year (the point separating the pre- and post-impact flows). Ten figures could also be plotted for these data as well. In each figure, the sub-pre-impact flow time series length was fixed to one of the 10 scenarios, and the sub-post-impact flow length varied and covered all the  $2N - 19$  scenarios. Each figure showed the influence of post-impact flow length on the RVA.

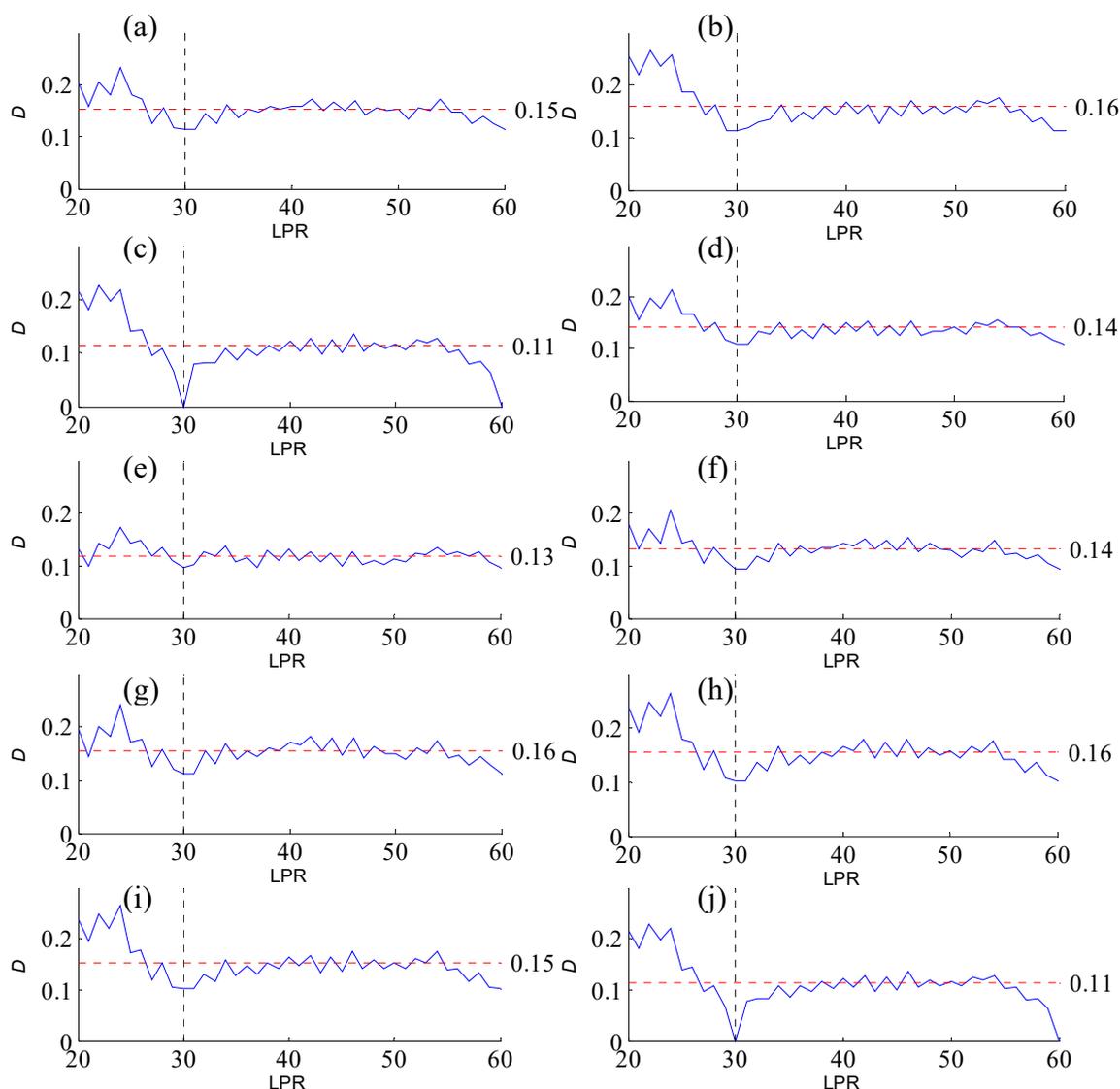
## 3. Results

To reduce the arbitrary nature of  $N$  selection ( $N$  represents the periodicity length in pre-impact and post-impact flows),  $N$  was set between 25 and 40 with an increment of 1 (i.e., 16 scenarios) in this research. Following the methods established above, random daily flows were generated, and the RVA was performed under each length scenario for the pre- and post-impact flow time series.

Figure 1 shows the variation of RVA values with changes in the length of the pre-impact flow time series under a flow periodicity (i.e., N) of 30 years. The RVA variation under the other 15 values of N are shown in the Appendix A for the sake of brevity (the results were similar under all the 16 scenarios of N). The RVA values were clearly influenced by the length of the pre-impact flow time series under all 10 post-impact flow scenarios. Theoretically, the hydrologic alteration degree is expected to be constant at zero because no human or climatic impacts are imposed on the post-impact flows, and the pre-impact and post-impact flow regimes are the same. The anomalous measurements of flow regime alteration degree by the RVA resulted from uncertainty related to the operation date of the gauging stations and the attempt to include all of the available flow records in the RVA. Figure 2 showed the variation of RVA values with changes in length of the post-impact flow time series. These RVA values were also clearly influenced by the length of the post-impact flow time series. Theoretically, the hydrologic alteration degree should also be constant at zero, due to a lack of human or climatic influence, although the RVA does not exhibit this behavior. The anomalous measurements of flow regime alteration degree also related to uncertainty around the operation date of the gauging stations and the attempt to include all of the available flow records in the RVA.



**Figure 1.** Variation of flow regime alteration degree (D) measured by the range of variation approach (RVA) with changes in length of the pre-impact flow time series (LPR) under a periodicity of 30 years. (a–j) correspond to a post-impact flow time series of length = 21, 26, 30, 34, 39, 43, 47, 51, 56, and 60 years, respectively. The abscissa value for the vertical dotted line is 30. The ordinate value for the horizontal dotted line is the mean degree of flow regime alteration in each subfigure.



**Figure 2.** Variation of flow regime alteration degree ( $D$ ) measured by the RVA with the changes in length of post-impact flow time series (LPR) under a periodicity of 30 years. (a–j) correspond to a pre-impact flow time series length = 21, 26, 30, 34, 39, 43, 47, 51, 56, and 60 years, respectively. The abscissa value for the vertical dotted line is 30. The ordinate value for the horizontal dotted line is the mean degree of flow regime alteration in each subfigure.

Figure 1c,j and Figure 2c,j showed that the degree of flow regime alteration was equal to zero when the length of both the pre- and post-impact flow time series was 30 or 60 years, i.e., multiples of periodicity length. The degree of flow regime alteration should be zero. Thus, the optimal flow record length should be multiples of periodicity length for both the pre- and post-impact flow time series.

In addition, the other sub-figures in Figures 1 and 2 showed that the flow regime alteration values measured by the RVA had minimum values when the pre-/post-impact flow time series length was 30 years or 60 years under different post-/pre-impact flow time series lengths, although the alteration degree was not equal to zero. (Figures A1–A32 in Appendix A also showed that minimum RVA values occurred when the pre-/post-impact flow time series length was equal to multiples of periodicity length.) Lesser degrees of flow regime alteration measured by the RVA indicated higher accuracy of the RVA. Thus, if periodicity can be detected in the pre-/post-impact flows, the optimal pre-/post-impact flow record length in the RVA should be multiples of periodicity length.

The horizontal dotted line in each sub-figure showed the mean degree of flow regime alteration. The mean alteration degree under post-impact flow lengths of 30 and 60 years in Figure 1 was equal to 0.12, while the mean alteration degree under other lengths was always no less than 0.16. Similarly, the mean alteration degree under the pre-impact flow lengths of 30 and 60 years was equal to 0.11 in Figure 2, while the mean alteration degree under other lengths was always no less than 0.13. These results further demonstrate that if periodicity could be detected in the pre-/post-impact flows, the optimal pre-/post-impact flow record length in the RVA should be multiples of periodicity length.

## 4. Discussion

### 4.1. Improving the RVA Procedure

Due to the drawbacks in using all of the available flow data in the RVA, it is necessary to determine the periodicity of pre- and post-impact flows to improve the accuracy of RVA. There are four possible situations for pre- and post-impact flows: (1) Both pre- and post-impact flow time series have hydrologic periodicity; (2) neither pre- or post- impact flow time series have hydrologic periodicity; (3) only the pre-impact flow time series has periodicity; and (4) only the post-impact flow time series has periodicity. The following procedure was proposed to improve the RVA.

- (1) Determine the periodicity of pre- and post-impact flow time series.

Many methods, such as the maximum entropy spectrum analysis [44] and wavelet analysis [45], have been developed for periodicity determination. Using these methods, we can determine whether the pre- and post-impact flow time series have periodicity. If periodicity is seen, the length of the periodicity can be further determined. The periodicity length values determined by these methods will not show obvious difference. Any periodicity determination method could be adopted.

- (2) Change the length of pre- and post-impact flow time series.

On the basis of the periodicity results, the length of pre- and post-impact flow time series could be changed for flow regime alteration analysis by the RVA. If both the pre- and post- impact flow time series have hydrologic periodicity (situation 1), the lengths of pre- and post-impact flow time series are set at one periodicity for the RVA. If only the pre-impact/post-impact flow time series displays periodicity (situations 3 and 4), the length of the pre-/post-impact flow record should be changed to one periodicity, whereas all of the available records of the other flow time series are used in the RVA, i.e., the length of the post-impact/post-impact flow time series does not change. If neither the pre- or post-impact flow time series displays periodicity (situation 2), all of the available pre- and post-impact flow time series are used in the RVA.

- (3) Apply the RVA to determine the flow regime alteration degree.

If the time series are long enough to cover several periodicities, one flow records of one periodicity length had better be adopted. When the flow time series have periodicity, the starting point of the flow record under a record length of one periodicity will not obviously influence the results of the RVA. Here, we simply use the latest pre-/post-impact flow records of one periodicity length in the RVA. Using the pre- and post-impact flow time series determined above, the RVA is applied to determine the degree of flow regime alteration. This step of the revised RVA is the same as the traditional RVA.

### 4.2. Comparison of Results from the Traditional and Revised RVA

The Roanoke River in the United States was used as a case study to compare the results from the traditional and revised RVA, because Richter et al. [11–13] used this case study to illustrate the IHA software and the RVA method (the USGS streamflow gauging station 02080500). Dam impacts on the Roanoke River system began with the completion of Philpott Lake on the Smith River (in the upper

watershed) in 1950. In the same year, the Kerr Reservoir was constructed for the purpose of flood control. In 1955, Roanoke Rapids Lake was built downstream of the Kerr Reservoir, which was used for hydropower generation. After that, another reservoir, Lake Gaston, was built between Roanoke Rapids Lake and the Kerr Reservoir. Daily flow data for the Roanoke River have been collected by the U.S. Geological Survey (USGS) since 1913. The pre-impact period was defined as 1912–1949, and the post-impact period covers 1956–2004 [11,13].

The periodicity of the pre- and post-impact flow time series was assessed by the wavelet analysis method, using the continuous Morlet wavelet [46–48]. The confidence level of the significance test was set to 90%. The pre-impact stage had significant periodicity, and the average period was approximately 20 years. The post-impact stage also had significant periodicity, with a period of approximately 18 years. Because both of the stages had periodicity, with the data matched the first periodicity situation. Flow regime alterations were assessed by the revised and traditional RVA. The alteration degrees of the majority of IHAs (28 of 32) were different under the traditional and improved RVA. However, the alteration categories (low alteration, moderate alteration, high alteration) for most IHAs (21 of 32) did not change. Among the 32 IHAs, the values for the 18 indicators under the improved RVA were greater than those under the traditional RVA. In addition, the overall flow regime alteration degree under the improved RVA was 0.64, greater than the value (0.56) measured by the traditional RVA. The results indicate that although the two RVA values belong to the category of moderate change, the alteration degree of the Roanoke River was higher than previously thought.

## 5. Conclusions

Assessing the degree of flow regime alteration in rivers is a basic principle for sustainable water resources management. The RVA is the most widely used method to assess flow regime alteration. In this research, we test the suitable length of flow record that should be put into the RVA. The following conclusions are drawn:

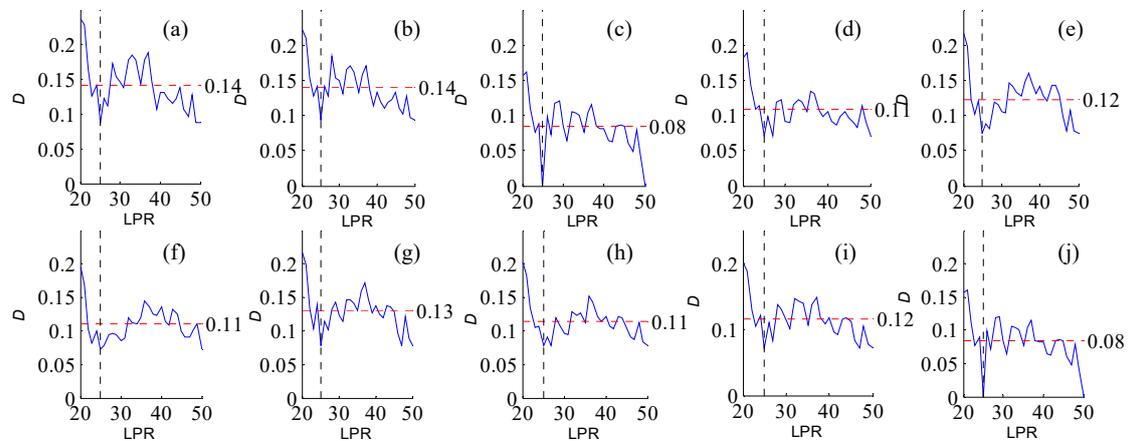
- The greatest accuracy for flow regime alteration degree assessed by the RVA is achieved when the length of both the pre- and post-impact flow time series is set equal to multiples of periodicity length.
- Due to the drawbacks in using all of the available flow data in the traditional RVA, we propose revising the traditional RVA procedure by assessing the periodicity of the pre- and post-impact flow time series in advance. If the periodicity of the pre- or post-impact flows is detected, the length of the time series should be set equal to its periodicity.

**Author Contributions:** Conceptualization, Y.S., C.L. and Y.Z.; methodology, Y.S., C.L., X.M.; data curation, Y.S. and H.L.; writing—original draft preparation, Y.S., X.M., Y.Z. and J.Z.; writing—review and editing, Y.S., C.L., X.M., H.L., Y.Z. and J.Z. All authors have read and agreed to the published version of the manuscript.

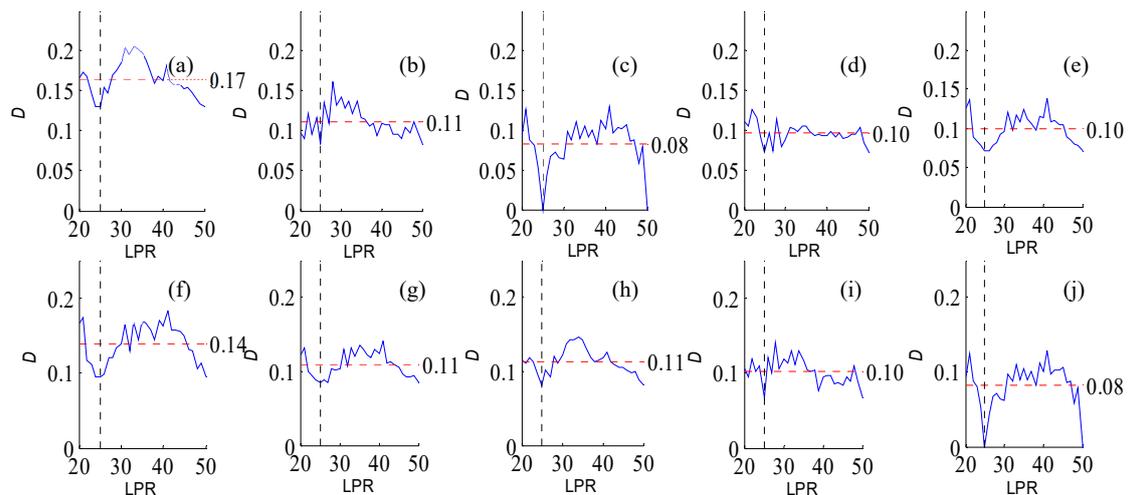
**Funding:** We thank National Key R&D Program of China (2017YFC0404504), the Major Science and Technology Program for Water Pollution Control and Treatment (2018ZX07110001), the Global Energy Internet Group Co., Ltd. (SGTYHT/18-JS-206), and the National Natural Science Foundation of China (52079007) for their financial support.

**Conflicts of Interest:** The authors declare no conflict of interest.

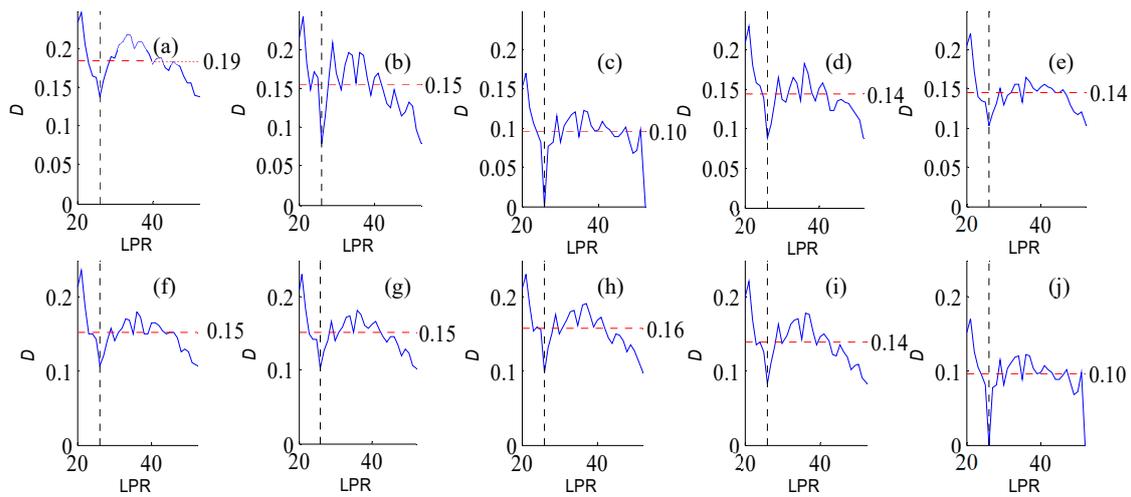
Appendix A



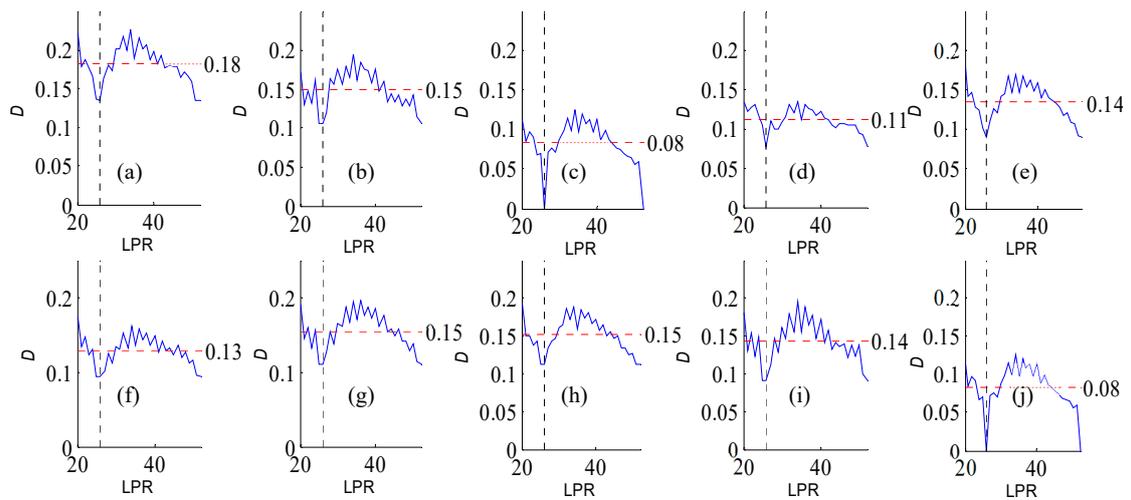
**Figure A1.** Variation of flow regime alteration degree (D) measured by the RVA with change in the length of pre-impact flow time series (LPR) under a periodicity of 25 years. (a–j) correspond to post-impact flow time series length = 18, 21, 25, 29, 32, 36, 39, 43, 46, and 50 years, respectively. The abscissa value for the vertical dotted line is 25. The ordinate value for the horizontal dotted line is the mean degree of flow regime alteration in each subfigure.



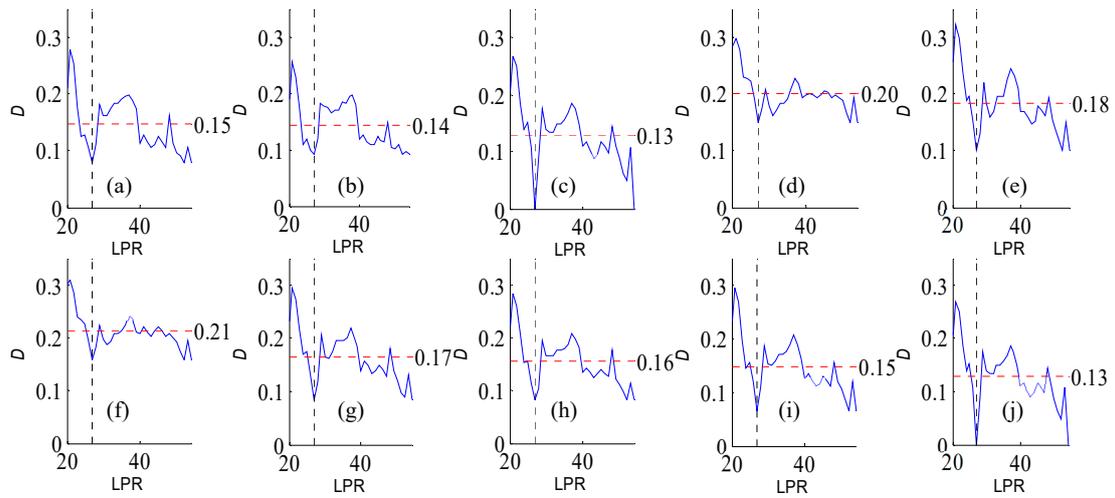
**Figure A2.** Variation of flow regime alteration degree (D) measured by the RVA with change in the length of post-impact flow time series (LPR) under a periodicity of 25 years. Figure (a–j) correspond to pre-impact flow time series length = 18, 21, 25, 29, 32, 36, 39, 43, 46, and 50 years, respectively. The abscissa value for the vertical dotted line is 25. The ordinate value for the horizontal dotted line is the mean degree of flow regime alteration in each subfigure.



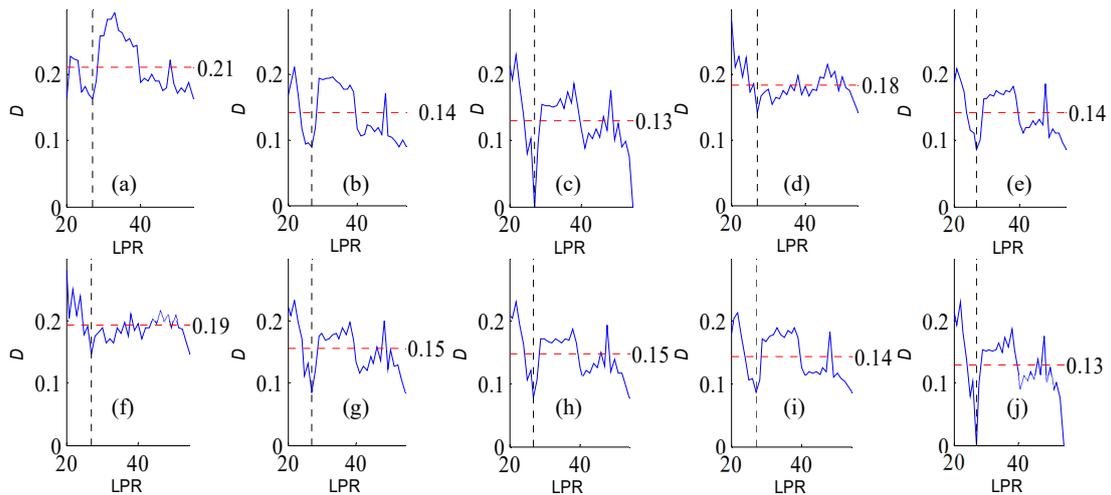
**Figure A3.** Variation of flow regime alteration degree (D) measured by the RVA with change in the length of pre-impact flow time series (LPR) under a periodicity of 26 years. (a–j) correspond to post-impact flow time series length = 19, 22, 26, 30, 33, 37, 41, 45, 48, and 52 years, respectively. The abscissa value for the vertical dotted line is 26. The ordinate value for the horizontal dotted line is the mean degree of flow regime alteration in each subfigure. The ordinate value for the horizontal dotted line is the mean degree of flow regime alteration in each subfigure.



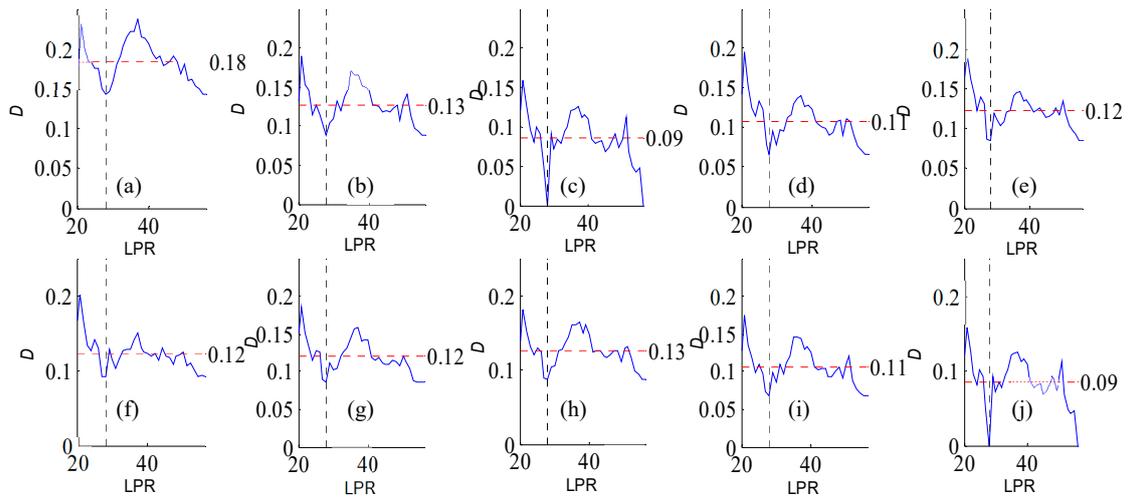
**Figure A4.** Variation of flow regime alteration degree (D) measured by the RVA with change in the length of post-impact flow time series (LPR) under a periodicity of 26 years. (a–j) correspond to pre-impact flow time series length = 19, 22, 26, 30, 33, 37, 41, 45, 48, 52 years, respectively. The abscissa value for the vertical dotted line is 26. The ordinate value for the horizontal dotted line is the mean degree of flow regime alteration in each subfigure.



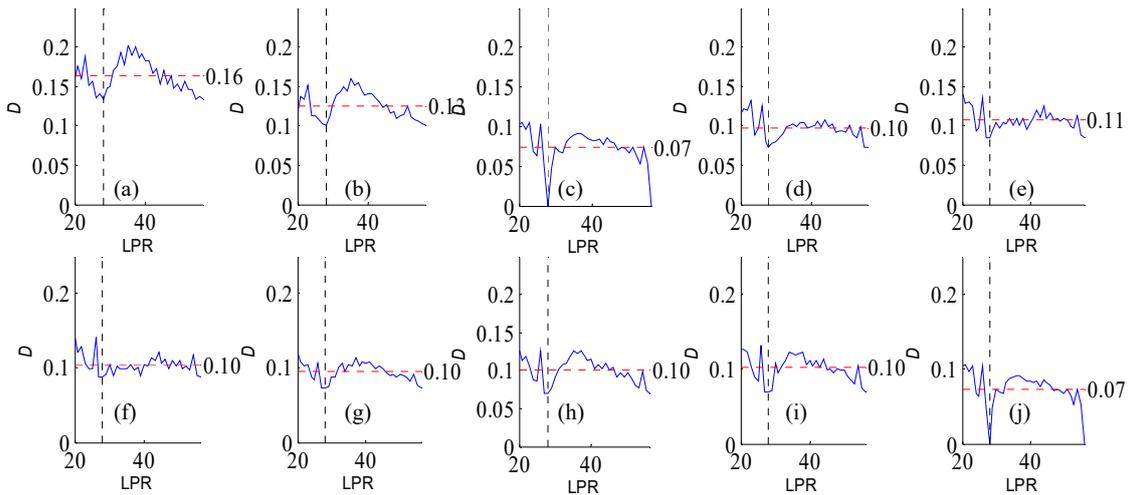
**Figure A5.** Variation of flow regime alteration degree ( $D$ ) measured by the RVA with change in the length of pre-impact flow time series (LPR) under a periodicity of 27 years. (a–j) correspond to pre-impact flow time series length = 19, 23, 27, 31, 35, 39, 42, 46, 50, and 54 years, respectively. The abscissa value for the vertical dotted line is 27. The ordinate value for the horizontal dotted line is the mean degree of flow regime alteration in each subfigure.



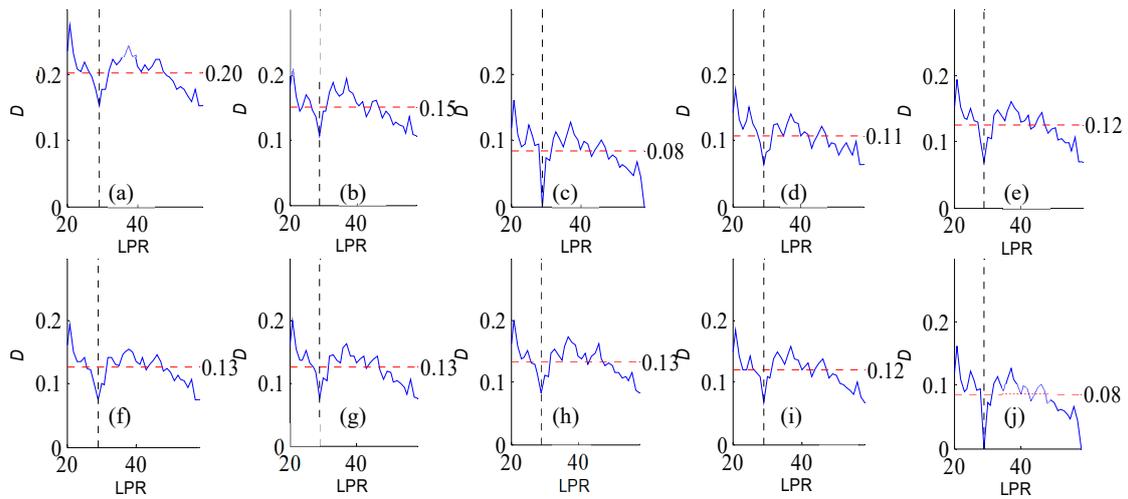
**Figure A6.** Variation of flow regime alteration degree ( $D$ ) measured by the RVA with change in the length of post-impact flow time series (LPR) under a periodicity of 27 years. (a–j) correspond to pre-impact flow time series length = 19, 23, 27, 31, 35, 39, 42, 46, 50, and 54 years, respectively. The abscissa value for the vertical dotted line is 27. The ordinate value for the horizontal dotted line is the mean degree of flow regime alteration in each subfigure.



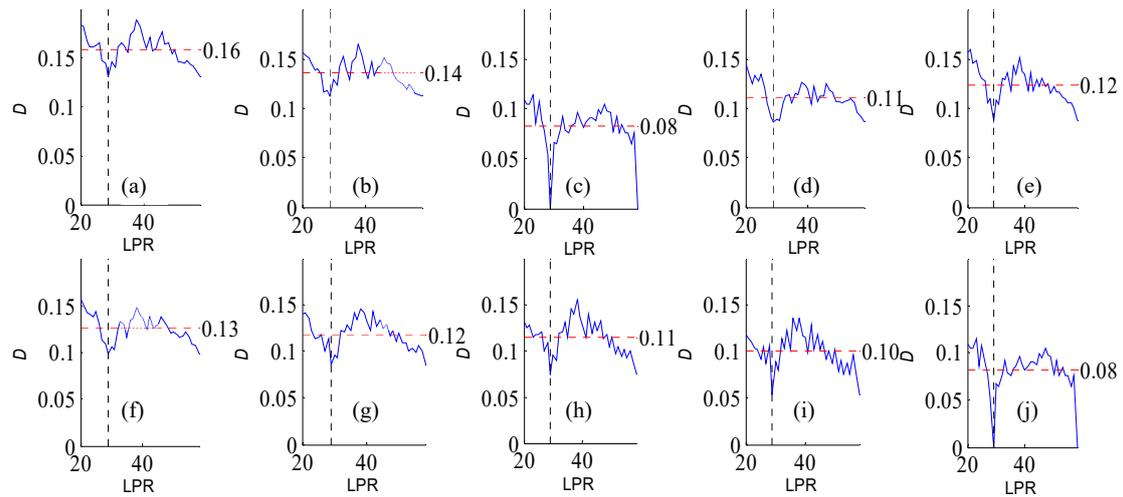
**Figure A7.** Variation of flow regime alteration degree (D) measured by the RVA with change in the length of pre-impact flow time series (LPR) under a periodicity of 28 years. (a–j) correspond to pre-impact flow time series length = 20, 24, 28, 32, 36, 40, 44, 48, 52, and 56 years, respectively. The abscissa value for the vertical dotted line is 28. The ordinate value for the horizontal dotted line is the mean degree of flow regime alteration in each subfigure.



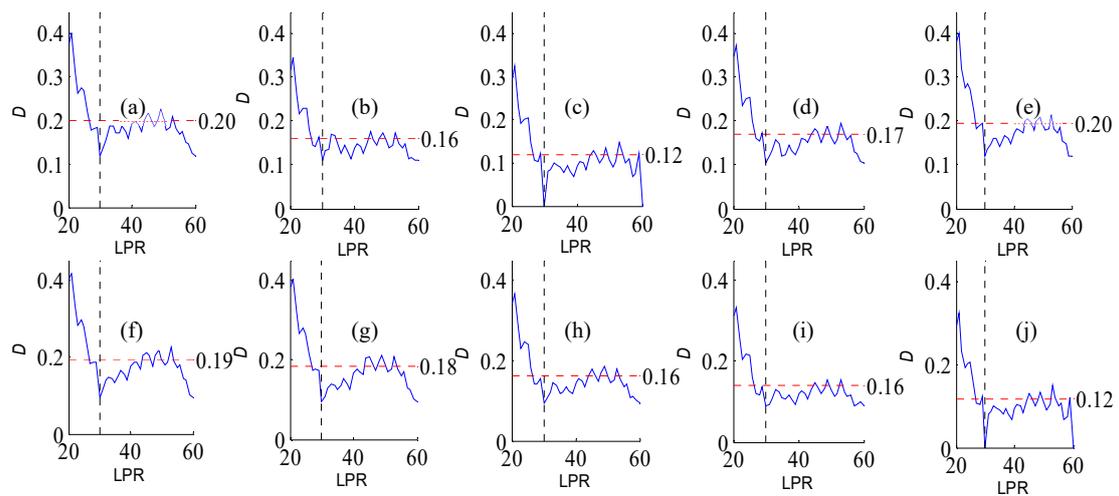
**Figure A8.** Variation of flow regime alteration degree (D) measured by the RVA with change in the length of post-impact flow time series (LPR) under a periodicity of 28 years. (a–j) correspond to pre-impact flow time series length = 20, 24, 28, 32, 36, 40, 44, 48, 52, and 56 years, respectively. The abscissa value for the vertical dotted line is 28. The ordinate value for the horizontal dotted line is the mean degree of flow regime alteration in each subfigure.



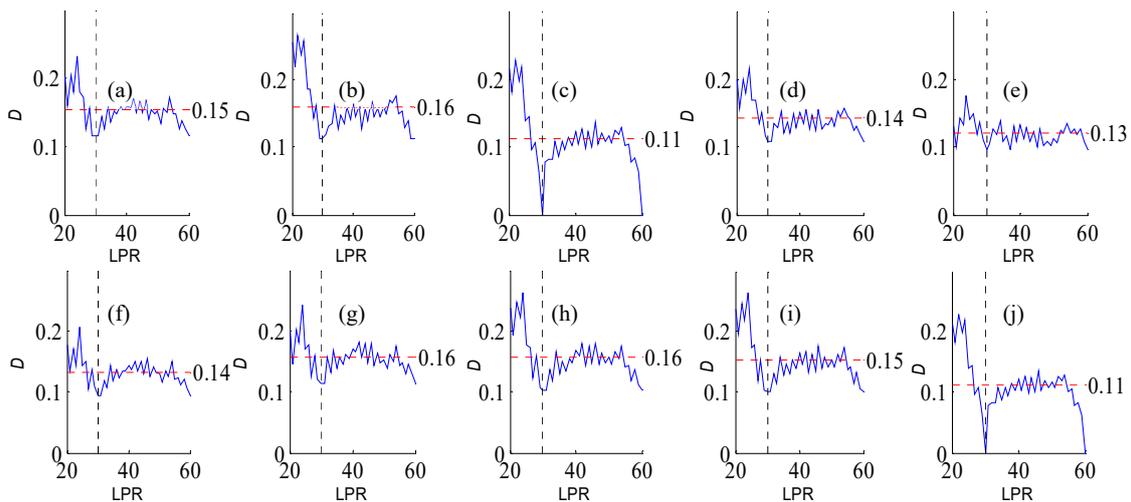
**Figure A9.** Variation of flow regime alteration degree (D) measured by the RVA with change in the length of pre-impact flow time series (LPR) under a periodicity of 29 years. (a–j) correspond to pre-impact flow time series length = 21, 25, 29, 33, 37, 41, 46, 50, 54, and 58 years, respectively. The abscissa value for the vertical dotted line is 29. The ordinate value for the horizontal dotted line is the mean degree of flow regime alteration in each subfigure.



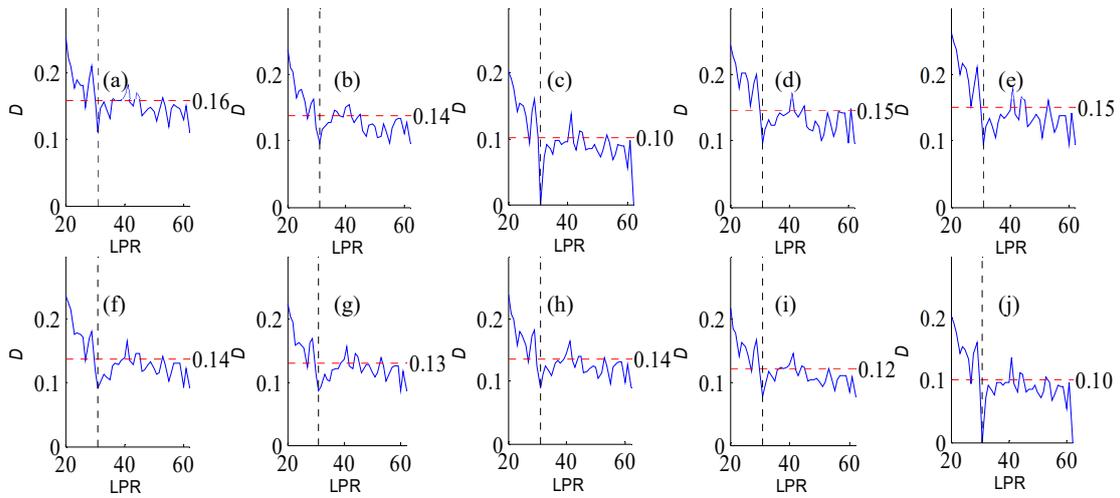
**Figure A10.** Variation of flow regime alteration degree (D) measured by the RVA with change in the length of post-impact flow time series (LPR) under a periodicity of 29 years. (a–j) correspond to pre-impact flow time series length = 21, 25, 29, 33, 37, 41, 46, 50, 54, and 58 years, respectively. The abscissa value for the vertical dotted line is 29. The ordinate value for the horizontal dotted line is the mean degree of flow regime alteration in each subfigure.



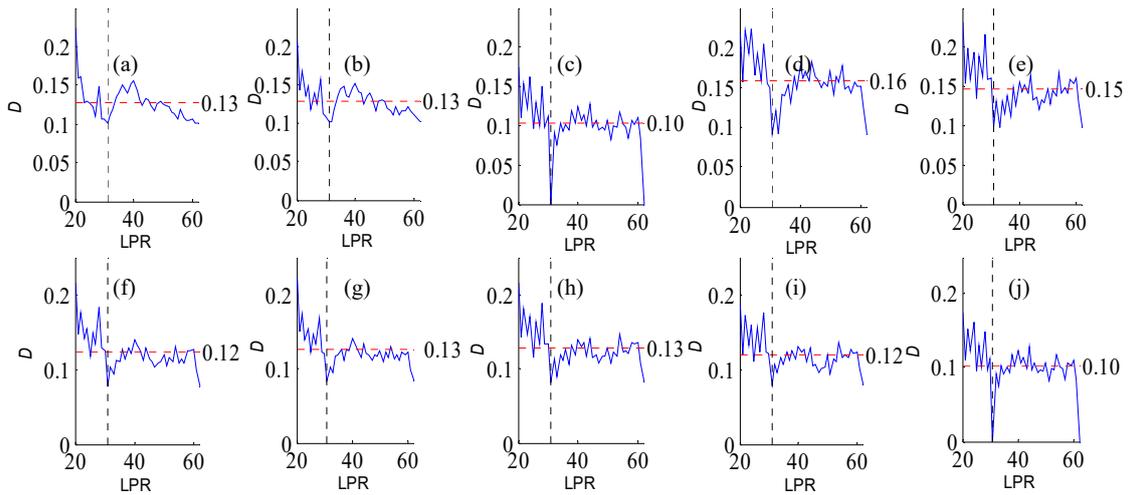
**Figure A11.** Variation of flow regime alteration degree (D) measured by the RVA with change in the length of pre-impact flow time series (LPR) under a periodicity of 30 years. (a–j) correspond to pre-impact flow time series length = 21, 26, 30, 34, 39, 43, 47, 51, 56, and 60 years, respectively. The abscissa value for the vertical dotted line is 30. The ordinate value for the horizontal dotted line is the mean degree of flow regime alteration in each subfigure.



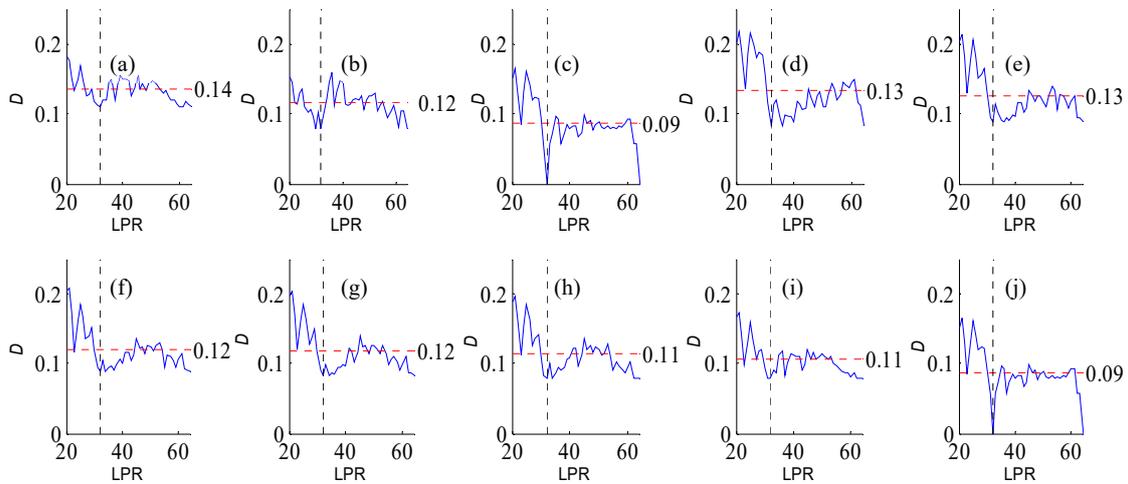
**Figure A12.** Variation of flow regime alteration degree (D) measured by the RVA with change in the length of post-impact flow time series (LPR) under a periodicity of 30 years. (a–j) correspond to pre-impact flow time series length = 21, 26, 30, 34, 39, 43, 47, 51, 56, and 60 years, respectively. The abscissa value for the vertical dotted line is 30. The ordinate value for the horizontal dotted line is the mean degree of flow regime alteration in each subfigure.



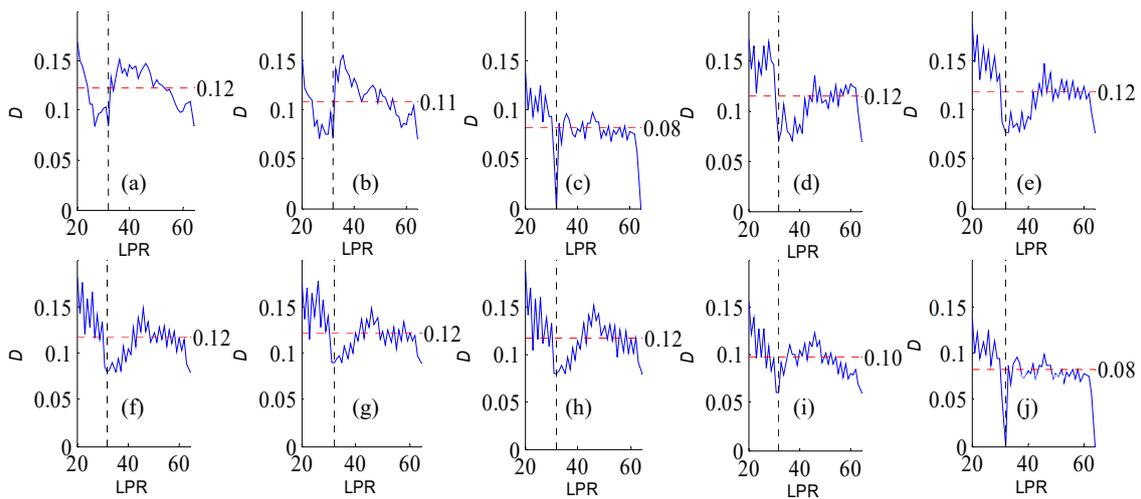
**Figure A13.** Variation of flow regime alteration degree (D) measured by the RVA with change in the length of pre-impact flow time series (LPR) under a periodicity of 31 years. (a–j) correspond to pre-impact flow time series length = 22, 27, 31, 35, 40, 44, 49, 53, 58, and 62 years, respectively. The abscissa value for the vertical dotted line is 31. The ordinate value for the horizontal dotted line is the mean degree of flow regime alteration in each subfigure.



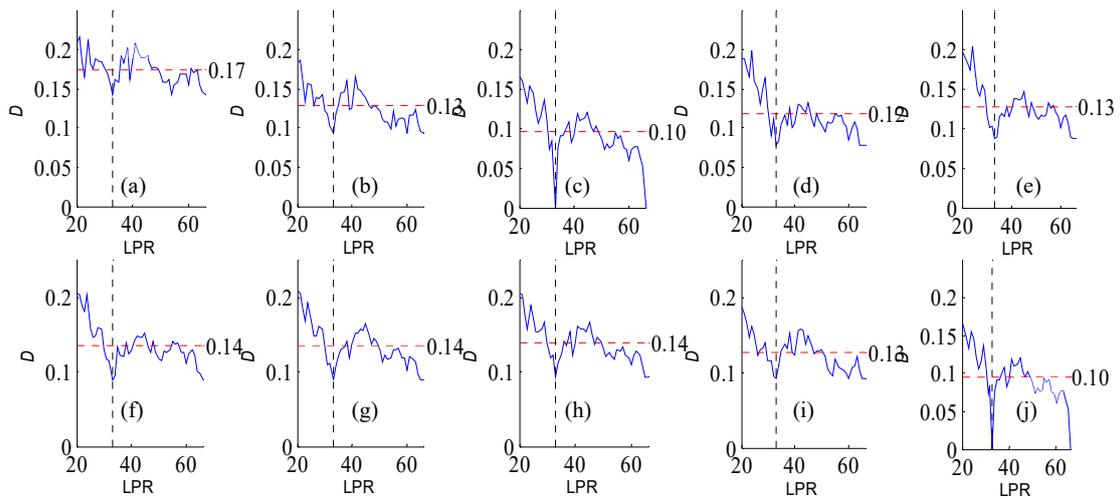
**Figure A14.** Variation of flow regime alteration degree (D) measured by the RVA with change in the length of post-impact flow time series (LPR) under a periodicity of 31 years. (a–j) correspond to pre-impact flow time series length = 22, 27, 31, 35, 40, 44, 49, 53, 58, and 62 years, respectively. The abscissa value for the vertical dotted line is 31. The ordinate value for the horizontal dotted line is the mean degree of flow regime alteration in each subfigure.



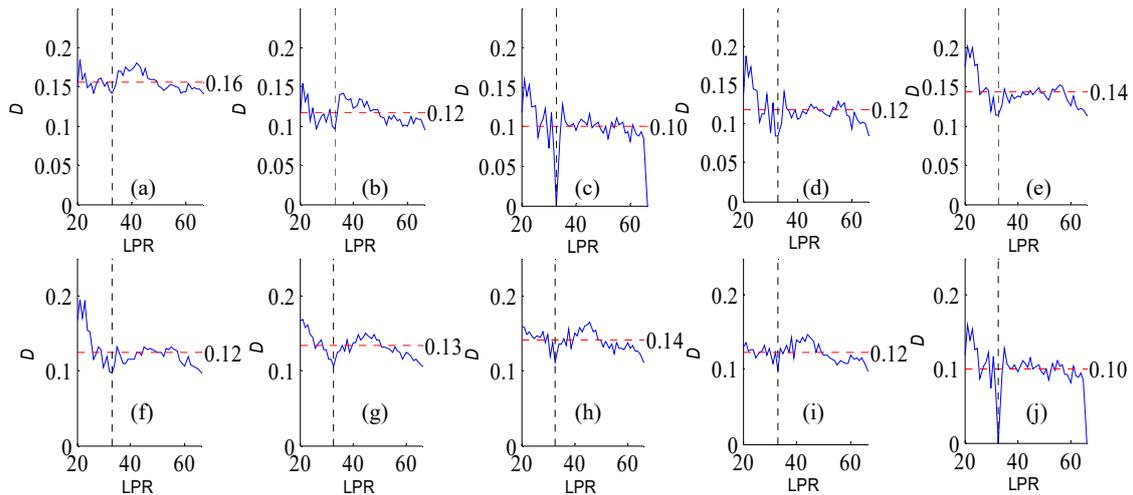
**Figure A15.** Variation of flow regime alteration degree (D) measured by the RVA with change in the length of pre-impact flow time series (LPR) under a periodicity of 32 years. (a–j) correspond to pre-impact flow time series length = 23, 27, 32, 37, 41, 46, 50, 55, 59, and 64 years, respectively. The abscissa value for the vertical dotted line is 32. The ordinate value for the horizontal dotted line is the mean degree of flow regime alteration in each subfigure.



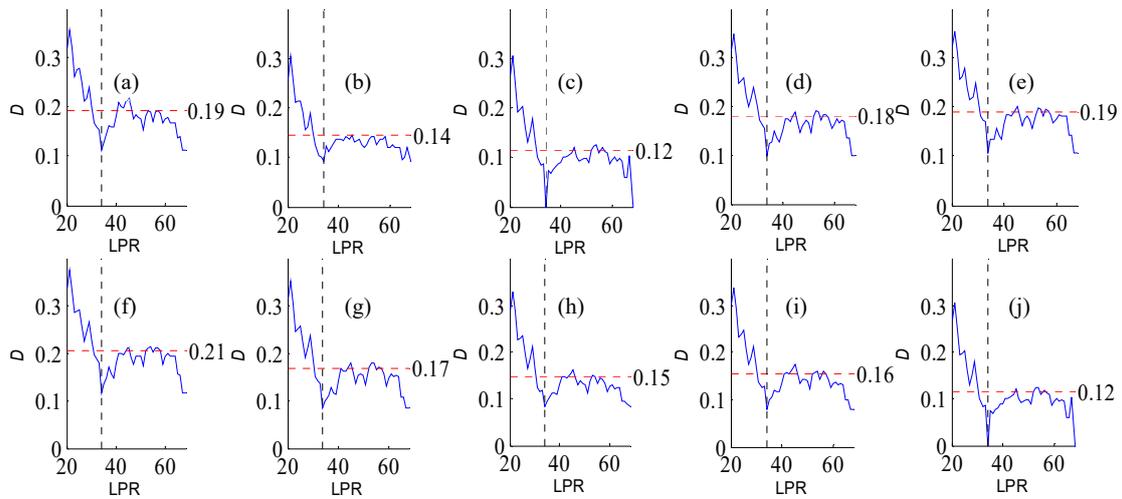
**Figure A16.** Variation of flow regime alteration degree (D) measured by the RVA with change in the length of post-impact flow time series (LPR) under a periodicity of 32 years. (a–j) correspond to pre-impact flow time series length = 23, 27, 32, 37, 41, 46, 50, 55, 59, and 64 years, respectively. The abscissa value for the vertical dotted line is 32. The ordinate value for the horizontal dotted line is the mean degree of flow regime alteration in each subfigure.



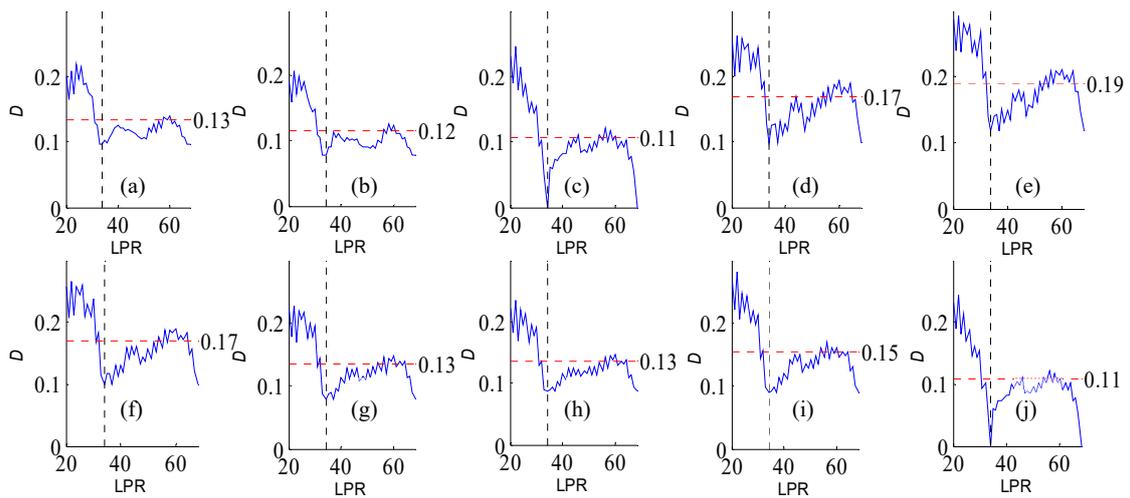
**Figure A17.** Variation of flow regime alteration degree (D) measured by the RVA with change in the length of pre-impact flow time series (LPR) under a periodicity of 33 years. (a–j) correspond to pre-impact flow time series length = 24, 28, 33, 38, 42, 47, 52, 57, 61, and 66 years, respectively. The abscissa value for the vertical dotted line is 33. The ordinate value for the horizontal dotted line is the mean degree of flow regime alteration in each subfigure.



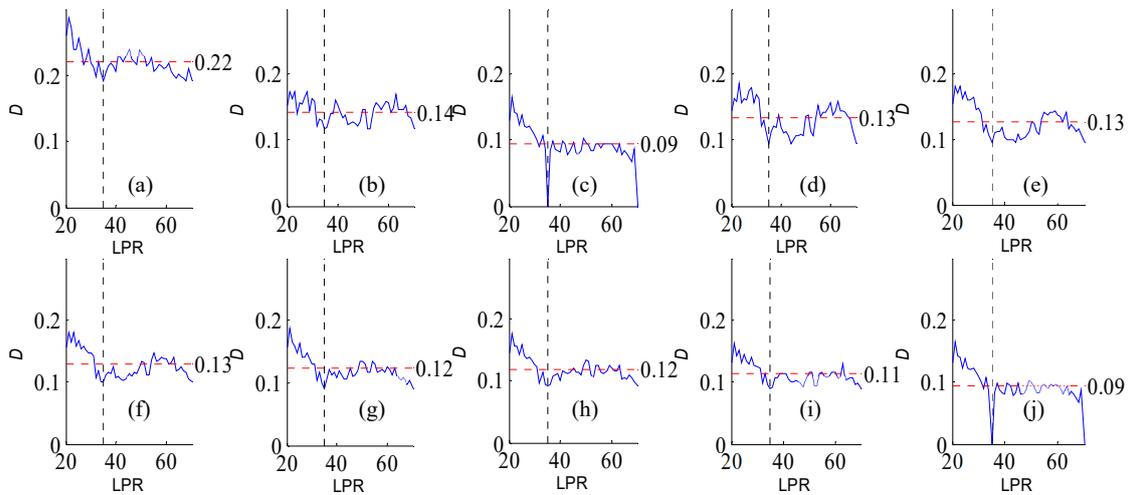
**Figure A18.** Variation of flow regime alteration degree (D) measured by the RVA with change in the length of post-impact flow time series (LPR) under a periodicity of 33 years. (a–j) correspond to pre-impact flow time series length = 24, 28, 33, 38, 42, 47, 52, 57, 61, and 66 years, respectively. The abscissa value for the vertical dotted line is 33. The ordinate value for the horizontal dotted line is the mean degree of flow regime alteration in each subfigure.



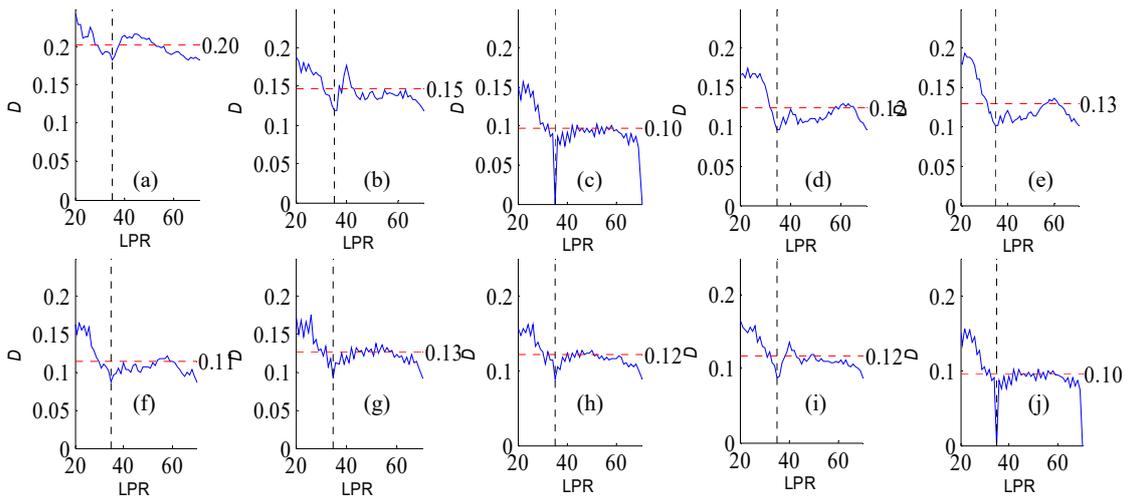
**Figure A19.** Variation of flow regime alteration degree (D) measured by the RVA with change in the length of pre-impact flow time series (LPR) under a periodicity of 34 years. (a–j) correspond to pre-impact flow time series length = 24, 29, 34, 39, 44, 49, 53, 58, 63, and 68 years, respectively. The abscissa value for the vertical dotted line is 34. The ordinate value for the horizontal dotted line is the mean degree of flow regime alteration in each subfigure.



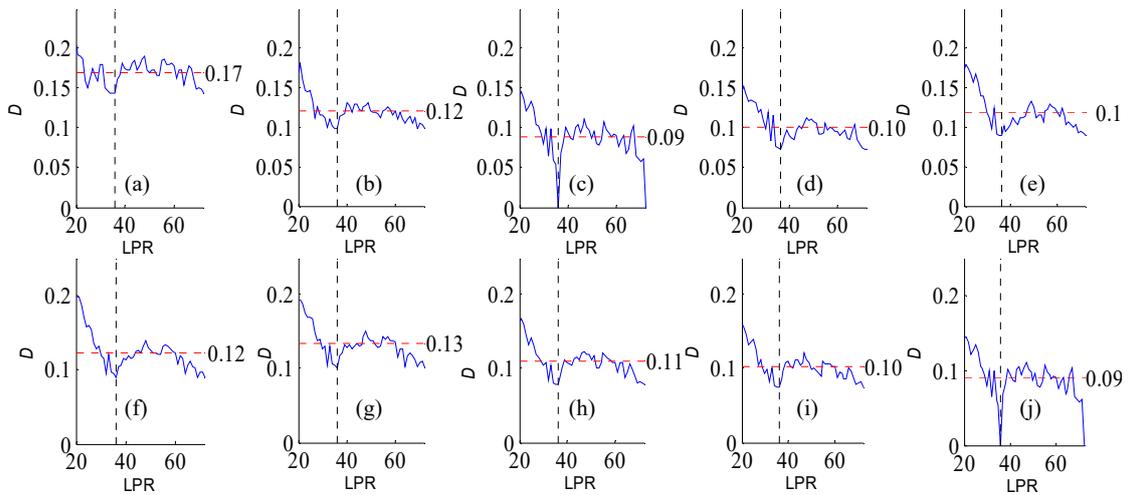
**Figure A20.** Variation of flow regime alteration degree (D) measured by the RVA with change in the length of post-impact flow time series (LPR) under a periodicity of 34 years. (a–j) correspond to pre-impact flow time series length = 24, 29, 34, 39, 44, 49, 53, 58, 63, and 68 years, respectively. The abscissa value for the vertical dotted line is 34. The ordinate value for the horizontal dotted line is the mean degree of flow regime alteration in each subfigure.



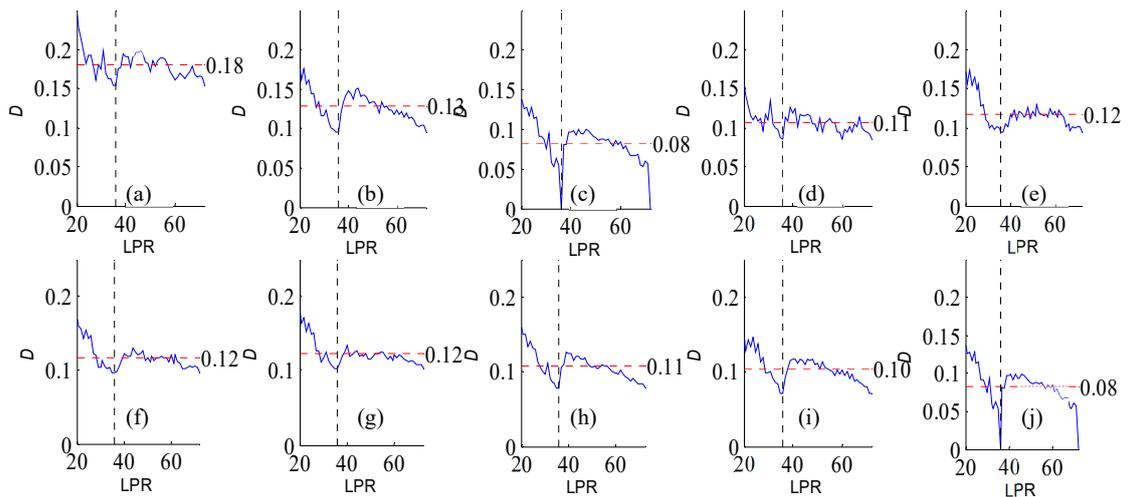
**Figure A21.** Variation of flow regime alteration degree (D) measured by the RVA with change in the length of pre-impact flow time series (LPR) under a periodicity of 35 years. (a–j) correspond to pre-impact flow time series length = 25, 30, 35, 40, 45, 50, 55, 60, 65, and 70 years, respectively. The abscissa value for the vertical dotted line is 35. The ordinate value for the horizontal dotted line is the mean degree of flow regime alteration in each subfigure.



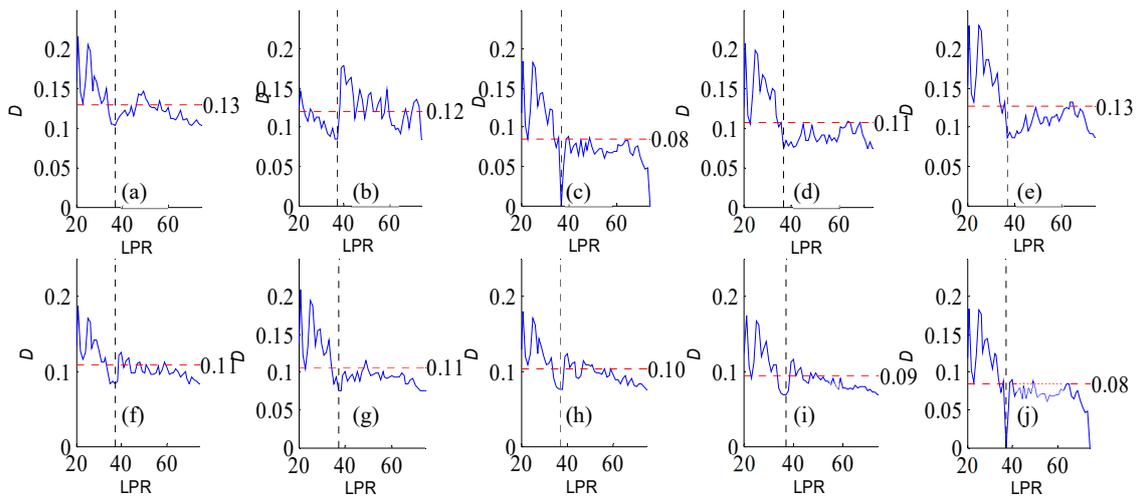
**Figure A22.** Variation of flow regime alteration degree (D) measured by the RVA with change in the length of post-impact flow time series (LPR) under a periodicity of 35 years. (a–j) correspond to pre-impact flow time series length = 25, 30, 35, 40, 45, 50, 55, 60, 65, and 70 years, respectively. The abscissa value for the vertical dotted line is 35. The ordinate value for the horizontal dotted line is the mean degree of flow regime alteration in each subfigure.



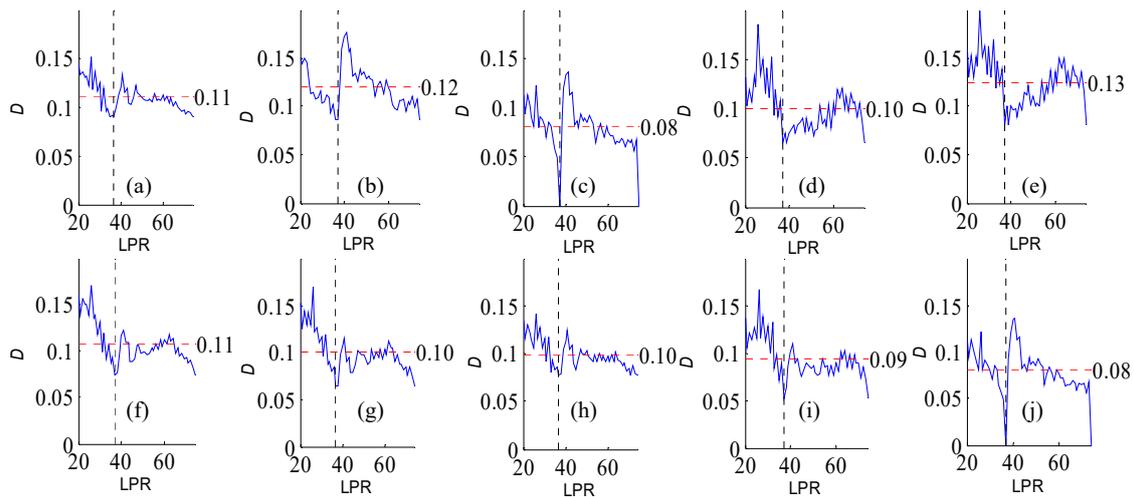
**Figure A23.** Variation of flow regime alteration degree (D) measured by the RVA with change in the length of pre-impact flow time series (LPR) under the periodicity of 36 years. (a–j) correspond to pre-impact flow time series length = 26, 31, 36, 41, 46, 51, 57, 62, 67, and 72 years, respectively. The abscissa value for the vertical dotted line is 36. The ordinate value for the horizontal dotted line is the mean degree of flow regime alteration in each subfigure.



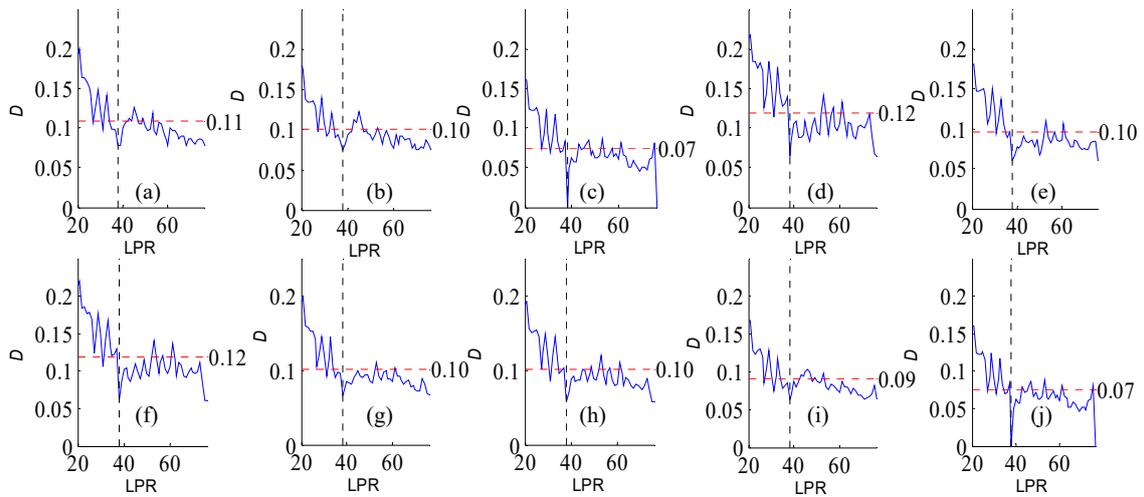
**Figure A24.** Variation of flow regime alteration degree (D) measured by the RVA with change in the length of post-impact flow time series (LPR) under a periodicity of 36 years. (a–j) correspond to pre-impact flow time series length = 26, 31, 36, 41, 46, 51, 57, 62, 67, and 72 years, respectively. The abscissa value for the vertical dotted line is 37. The ordinate value for the horizontal dotted line is the mean degree of flow regime alteration in each subfigure.



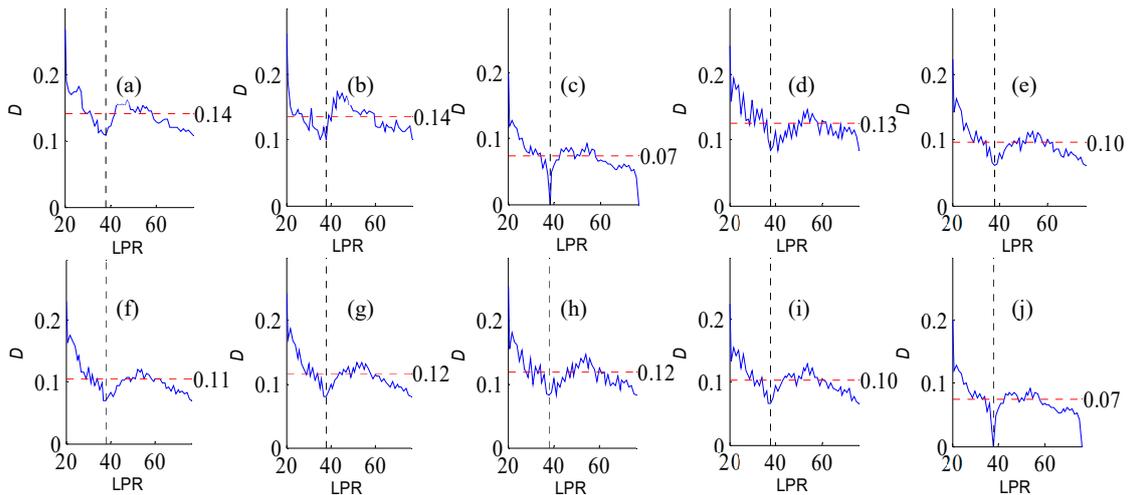
**Figure A25.** Variation of flow regime alteration degree (D) measured by the RVA with change in the length of pre-impact flow time series (LPR) under a periodicity of 37 years. (a–j) correspond to pre-impact flow time series length = 26, 32, 37, 42, 48, 53, 58, 63, 69, and 74 years, respectively. The abscissa value for the vertical dotted line is 37. The ordinate value for the horizontal dotted line is the mean degree of flow regime alteration in each subfigure.



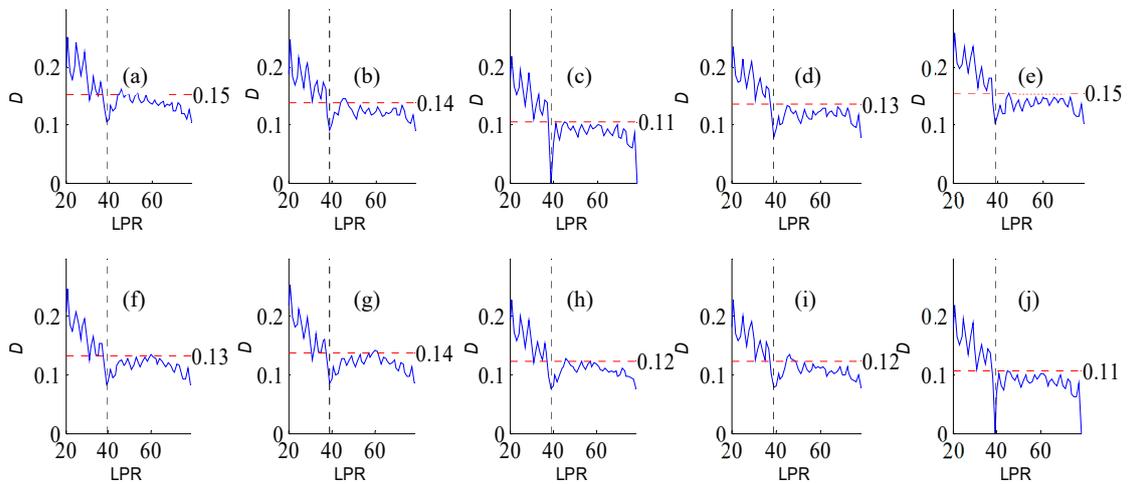
**Figure A26.** Variation of flow regime alteration degree (D) measured by the RVA with change in the length of post-impact flow time series (LPR) under a periodicity of 37 years. (a–j) correspond to pre-impact flow time series length = 26, 32, 37, 42, 48, 53, 58, 63, 69, and 74 years, respectively. The abscissa value for the vertical dotted line is 37. The ordinate value for the horizontal dotted line is the mean degree of flow regime alteration in each subfigure.



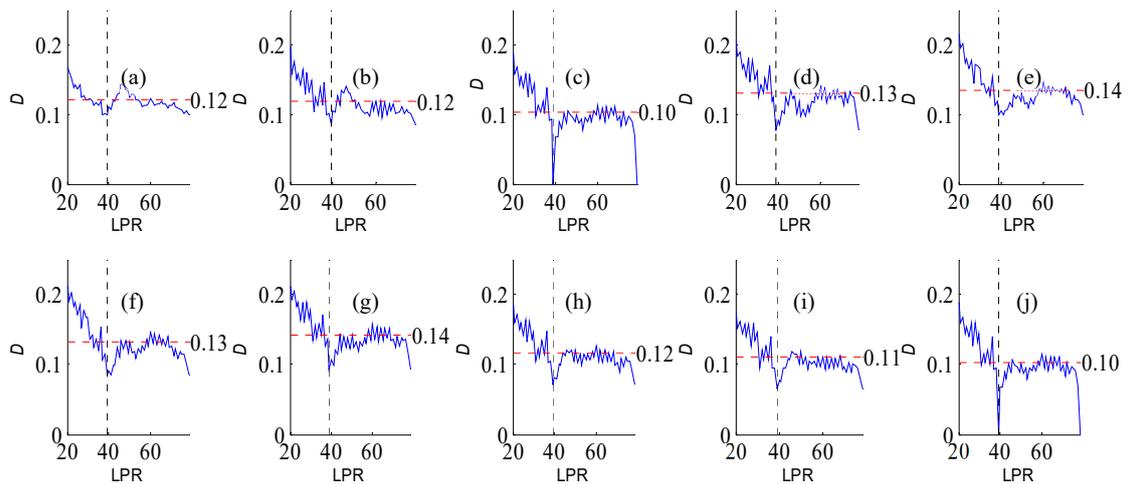
**Figure A27.** Variation of flow regime alteration degree (D) measured by the RVA with change in the length of pre-impact flow time series (LPR) under a periodicity of 38 years. (a–j) correspond to pre-impact flow time series length = 27, 33, 38, 43, 49, 54, 60, 65, 71, and 76 years, respectively. The abscissa value for the vertical dotted line is 38. The ordinate value for the horizontal dotted line is the mean degree of flow regime alteration in each subfigure.



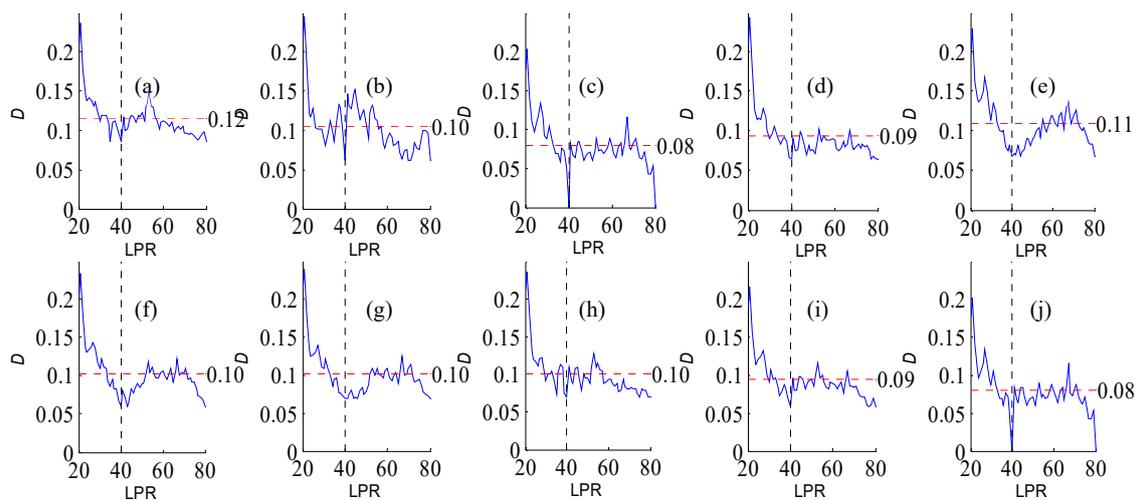
**Figure A28.** Variation of flow regime alteration degree (D) measured by the RVA with change in the length of post-impact flow time series (LPR) under a periodicity of 38 years. (a–j) correspond to pre-impact flow time series length = 27, 33, 38, 43, 49, 54, 60, 65, 71, and 76 years, respectively. The abscissa value for the vertical dotted line is 39. The ordinate value for the horizontal dotted line is the mean degree of flow regime alteration in each subfigure.



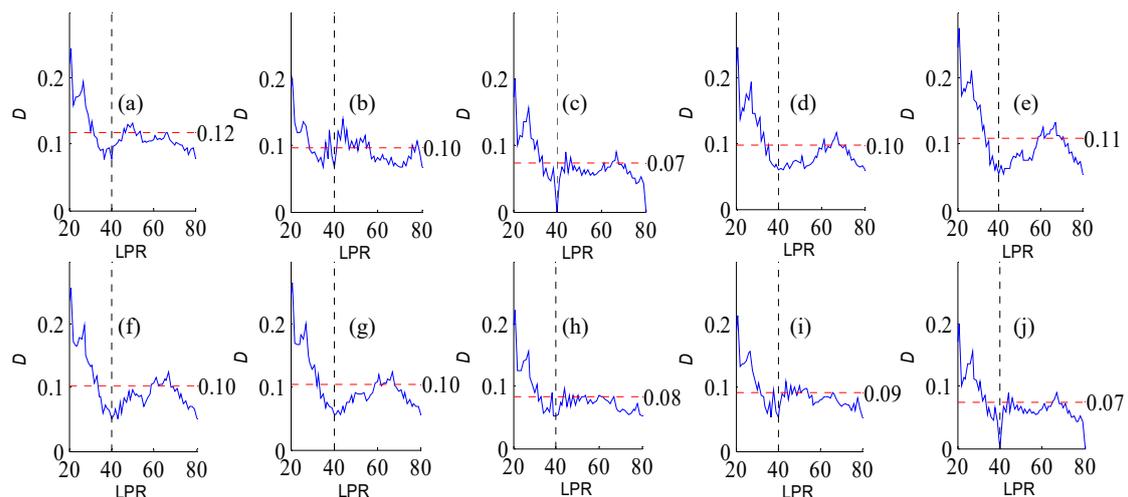
**Figure A29.** Variation of flow regime alteration degree (D) measured by the RVA with change in the length of pre-impact flow time series (LPR) under a periodicity of 39 years. (a–j) correspond to pre-impact flow time series length = 28, 33, 39, 45, 50, 56, 61, 67, 72, and 78 years, respectively. The abscissa value for the vertical dotted line is 39. The ordinate value for the horizontal dotted line is the mean degree of flow regime alteration in each subfigure.



**Figure A30.** Variation of flow regime alteration degree (D) measured by the RVA with change in the length of post-impact flow time series (LPR) under a periodicity of 39 years. (a–j) correspond to pre-impact flow time series length = 28, 33, 39, 45, 50, 56, 61, 67, 72, and 78 years, respectively. The abscissa value for the vertical dotted line is 39. The ordinate value for the horizontal dotted line is the mean degree of flow regime alteration in each subfigure.



**Figure A31.** Variation of flow regime alteration degree (D) measured by the RVA with change in the length of pre-impact flow time series (LPR) under a periodicity of 40 years. (a–j) correspond to pre-impact flow time series length = 29, 34, 40, 46, 51, 57, 63, 69, 74, and 80 years, respectively. The abscissa value for the vertical dotted line is 40. The ordinate value for the horizontal dotted line is the mean degree of flow regime alteration in each subfigure.



**Figure A32.** Variation of flow regime alteration degree (D) measured by the RVA with change in the length of post-impact flow time series (LPR) under a periodicity of 40 years. (a–j) correspond to pre-impact flow time series length = 29, 34, 40, 46, 51, 57, 63, 69, 74, and 80 years, respectively. The abscissa value for the vertical dotted line is 40. The ordinate value for the horizontal dotted line is the mean degree of flow regime alteration in each subfigure.

## References

1. Poff, N. A hydrogeography of unregulated streams in the United States and an examination of scale-dependence in some hydrological descriptors. *Freshw. Biol.* **1996**, *36*, 71–79. [[CrossRef](#)]
2. Arthington, Á.H.; Naiman, R.J.; McClain, M.E.; Nilsson, C. Preserving the biodiversity and ecological services of rivers: New challenges and research opportunities. *Freshw. Biol.* **2010**, *55*, 1–16. [[CrossRef](#)]
3. Puckridge, J.T.; Sheldon, F.; Walker, K.F.; Boulton, A.J. Flow variability and the ecology of large rivers. *Mar. Freshw. Res.* **1998**, *49*, 55–72. [[CrossRef](#)]
4. Lytle, D.A.; Poff, N.L. Adaptation to natural flow regimes. *Trends Ecol. Evol.* **2004**, *19*, 94–100. [[CrossRef](#)] [[PubMed](#)]
5. Bunn, S.E.; Arthington, A.H. Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. *Environ. Manag.* **2002**, *30*, 492–507. [[CrossRef](#)] [[PubMed](#)]

6. Poff, N.L.; Zimmerman, J.K. Ecological responses to altered flow regimes: A literature review to inform the science and management of environmental flows. *Freshw. Biol.* **2010**, *55*, 194–205. [[CrossRef](#)]
7. Renöfält, B.M.; Jansson, R.; Nilsson, C. Effects of hydropower generation and opportunities for environmental flow management in Swedish riverine ecosystems. *Freshw. Biol.* **2010**, *55*, 49–67. [[CrossRef](#)]
8. Palmer, M.A.; Lettenmaier, D.P.; Poff, N.L.; Postel, S.L.; Richter, B.; Warner, R. Climate change and river ecosystems: Protection and adaptation options. *Environ. Manag.* **2009**, *44*, 1053–1068. [[CrossRef](#)]
9. Döll, P.; Zhang, J. Impact of climate change on freshwater ecosystems: A global-scale analysis of ecologically relevant river flow alterations. *Hydrol. Earth Syst. Sci. Discuss.* **2010**, *7*, 1305–1342. [[CrossRef](#)]
10. Merritt, D.M.; Scott, M.L.; Poff, N.L.; Auble, G.T.; Lytle, D.A. Theory, methods and tools for determining environmental flows for riparian vegetation: Riparian vegetation-flow response guilds. *Freshw. Biol.* **2010**, *55*, 206–225. [[CrossRef](#)]
11. Richter, B.D.; Baumgartner, J.V.; Braun, D.P.; Powell, J. A spatial assessment of hydrologic alteration within a river network. *Regul. Rivers Res. Manag. Int. J. Devoted River Res. Manag.* **1998**, *14*, 329–340. [[CrossRef](#)]
12. Richter, B.D.; Baumgartner, J.V.; Powell, J.; Braun, D.P. A method for assessing hydrologic alteration within ecosystems. *Conserv. Biol.* **1996**, *10*, 1163–1174. [[CrossRef](#)]
13. Richter, B.; Baumgartner, J.; Wigington, R.; Braun, D. How much water does a river need? *Freshw. Biol.* **1997**, *37*, 231–249. [[CrossRef](#)]
14. Galat, D.L.; Lipkin, R. Restoring ecological integrity of great rivers: Historical hydrographs aid in defining reference conditions for the Missouri River. In *Assessing the Ecological Integrity of Running Waters*; Developments in Hydrobiology, Jungwirth, M., Muhar, S., Schmutz, S., Eds.; Springer: Dordrecht, The Netherlands, 2000; Volume 149. [[CrossRef](#)]
15. Irwin, E.R.; Freeman, M.C. Proposal for adaptive management to conserve biotic integrity in a regulated segment of the Tallapoosa River, Alabama, USA. *Conserv. Biol.* **2002**, *16*, 1212–1222. [[CrossRef](#)]
16. Mathews, R.; Richter, B.D. Application of the Indicators of hydrologic alteration software in environmental flow setting 1. *J. Am. Water Resour. Assoc.* **2007**, *43*, 1400–1413. [[CrossRef](#)]
17. Shiau, J.T.; Wu, F.C. Compromise programming methodology for determining instream flow under multiobjective water allocation criteria 1. *J. Am. Water Resour. Assoc.* **2006**, *42*, 1179–1191. [[CrossRef](#)]
18. Shiau, J.T.; Wu, F.C. Pareto-optimal solutions for environmental flow schemes incorporating the intra-annual and interannual variability of the natural flow regime. *Water Resour. Res.* **2007**, *43*, W06433. [[CrossRef](#)]
19. Shiau, J.T.; Wu, F.C. A histogram matching approach for assessment of flow regime alteration: Application to environmental flow optimization. *River Res. Appl.* **2008**, *24*, 914–928. [[CrossRef](#)]
20. Yin, X.A.; Yang, Z.F. Development of a coupled reservoir operation and water diversion model: Balancing human and environmental flow requirements. *Ecol. Model.* **2011**, *222*, 224–231. [[CrossRef](#)]
21. Yin, X.A.; Yang, Z.F.; Petts, G.E. Reservoir operating rules to sustain environmental flows in regulated rivers. *Water Resour. Res.* **2011**, *47*, W08509. [[CrossRef](#)]
22. Yin, X.A.; Yang, Z.F.; Petts, G.E. Optimizing environmental flows below dams. *River Res. Appl.* **2012**, *28*, 703–716. [[CrossRef](#)]
23. Yin, X.A.; Yang, Z.F.; Yang, W.; Zhao, Y.W.; Chen, H. Optimized reservoir operation to balance human and riverine ecosystem needs: Model development, and a case study for the Tanghe reservoir, Tang river basin, China. *Hydrol. Process. Int. J.* **2010**, *24*, 461–471. [[CrossRef](#)]
24. Yang, P.; Yin, X.A.; Yang, Z.F.; Tang, J. A revised range of variability approach considering the periodicity of hydrological indicators. *Hydrol. Process.* **2014**, *28*, 6222–6235. [[CrossRef](#)]
25. Yin, X.A.; Yang, Z.F.; Petts, G.E. A new method to assess the flow regime alterations in riverine ecosystems. *River Res. Appl.* **2015**, *31*, 497–504. [[CrossRef](#)]
26. Yu, C.X.; Yin, X.A.; Yang, Z.F. A revised range of variability approach for the comprehensive assessment of the alteration of flow regime. *Ecol. Eng.* **2016**, *96*, 200–207. [[CrossRef](#)]
27. Singh, R.K.; Jain, M.K. Reappraisal of hydrologic alterations in the Roanoke River basin using extended data and improved RVA method. *Int. J. Environ. Sci. Technol.* **2020**, 1–24. [[CrossRef](#)]
28. Olukayode Oladipo, E. A comparative performance analysis of three meteorological drought indices. *J. Climatol.* **1985**, *5*, 655–664. [[CrossRef](#)]
29. Tank, A.M.G.K.; Können, G.P. Trends in indices of daily temperature and precipitation extremes in Europe, 1946–1999. *J. Clim.* **2003**, *16*, 3665–3680. [[CrossRef](#)]

30. Kennard, M.J.; Pusey, B.J.; Olden, J.D.; Mackay, S.J.; Stein, J.L.; Marsh, N. Classification of natural flow regimes in Australia to support environmental flow management. *Freshw. Biol.* **2010**, *55*, 171–193. [[CrossRef](#)]
31. Kennard, M.J.; Mackay, S.J.; Pusey, B.J.; Olden, J.D.; Marsh, N. Quantifying uncertainty in estimation of hydrologic metrics for ecohydrological studies. *River Res. Appl.* **2010**, *26*, 137–156. [[CrossRef](#)]
32. Stedinger, J.R.; Taylor, M.R. Synthetic streamflow generation: 2. Effect of parameter uncertainty. *Water Resour. Res.* **1982**, *18*, 919–924. [[CrossRef](#)]
33. Ahmad, S.; Khan, I.H.; Parida, B.P. Performance of stochastic approaches for forecasting river water quality. *Water Res.* **2001**, *35*, 4261–4266. [[CrossRef](#)]
34. Zhao, T.T.G.; Cai, X.M.; Yang, D.W. Effect of streamflow forecast uncertainty on real-time reservoir operation. *Adv. Water Resour.* **2011**, *34*, 495–504. [[CrossRef](#)]
35. Loucks, D.P.; Stedinger, J.R.; Haith, D.A. *Water Resource Systems Planning and Analysis*; Prentice-Hall: Upper Saddle River, NJ, USA, 1981.
36. McMahon, T.A.; Vogel, R.M.; Peel, M.C.; Pegram, G.G. Global streamflows—Part 1: Characteristics of annual streamflows. *J. Hydrol.* **2007**, *347*, 243–259. [[CrossRef](#)]
37. Aksoy, H. Use of gamma distribution in hydrological analysis. *Turk. J. Eng. Environ. Sci.* **2000**, *24*, 419–428.
38. Khosravi, G.; Majidi, A.; Nohegar, A. Determination of suitable probability distribution for annual mean and peak discharges estimation (case study: Minab river-barantin gage, iran). *Int. J. Probab. Stat.* **2012**, *1*, 160–163. [[CrossRef](#)]
39. Gumbel, E.J. *Statistics of Extremes*; Columbia University Press: New York, NY, USA, 1954.
40. Nadarajah, S. Exact distribution of the peak streamflow. *Water Resour. Res.* **2007**, *43*, W02501. [[CrossRef](#)]
41. Buckett, J.; Oliver, F.R. Fitting the Pearson type 3 distribution in practice. *Water Resour. Res.* **1977**, *13*, 851–852. [[CrossRef](#)]
42. Xu, W.C. *Water Resource Evaluation and Management*; Science Press: Beijing, China, 2011.
43. Ewemoje, T.A.; Ewemoje, O.S. Best distribution and plotting positions of daily maximum flood estimation at Ona River in Ogun–Oshun river basin, Nigeria. *Agric. Eng. Int. CIGR J.* **2011**, *13*, 1–13.
44. Sang, Y.F.; Wang, D.; Wu, J.C.; Zhu, Q.P.; Wang, L. A New Method of Periods’ Identification in Hydrologic Series Based on EEMD. In Proceedings of the 2009 International Conference on Artificial Intelligence and Computational Intelligence, Shanghai, China, 7–8 November 2009; Volume 4, pp. 269–273. [[CrossRef](#)]
45. Cazelles, B.; Chavez, M.; Berteaux, D.; Ménard, F.; Vik, J.O.; Jenouvrier, S.; Stenseth, N.C. Wavelet analysis of ecological time series. *Oecologia* **2008**, *156*, 287–304. [[CrossRef](#)]
46. Torrence, C.; Compo, G.P. A practical guide to wavelet analysis. *Bull. Am. Meteorol. Soc.* **1998**, *79*, 61–78. [[CrossRef](#)]
47. Labat, D.; Ronchail, J.; Guyot, J.L. Recent advances in wavelet analyses: Part 2—Amazon, Parana, Orinoco and Congo discharges time scale variability. *J. Hydrol.* **2005**, *314*, 289–311. [[CrossRef](#)]
48. Cui, B.S.; Li, X.; Zhang, K.J. Classification of hydrological conditions to assess water allocation schemes for Lake Baiyangdian in North China. *J. Hydrol.* **2010**, *385*, 247–256. [[CrossRef](#)]

**Publisher’s Note:** MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



© 2020 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).