

Dear Editors and Reviewers:

Thank you for your letter and for the reviewers' comments concerning our manuscript entitled "Development of a revised IHA method for the cumulative impacts of cascade reservoirs on flow regime" (No.: hess-2019-694). Those comments are all valuable and very helpful for revising and improving our paper. We have studied comments carefully and have made correction which we hope meet with approval. The main corrections in the paper and the responds to reviewer's comments are as flowing:

Responds to reviewer's comments:

Referee #1

1. "The idea of this study is innovative, and many researchers have used the principal component method to analyze the correlation among indicators. What are the advantages of this method proposed compared with the principal component method?"

Response: The Principal Component Analysis is to find a way to replace the old variables with fewer new variables and keep as much information as possible, unfortunately, a small amount of information will be lost, which will affect the evaluation to some extent. The Projection Pursuit (PP) method is a technique of falling high dimension and the Real-coded Accelerated Genetic Algorithm (RAGA) is a method of optimum. Through combining the PP and RAGA, the high-dimensional data are easily changed into low- dimensional space and the characteristics of high-dimensional data can be summarized almost no loss of information.

Special thanks to you for your good comments.

Referee #2

1. "In Results and discussion section, the paper presents the results for the Jinsha River Basin but the results of this study were not properly discussed based on the previous literature."

Response: The relevant discussion has been supplemented from line 296 to 308.

2. "The content written in Section 4.5 only introduces the existing ecological regulation, which is not relevant to the research results and lacks sufficient discussion. It is suggested that the relevant content in Section 4 be polished"

Response: The discussion on the impact of reservoir construction on fish reproduction in May and the restoration of ecological regulation have been added in Section 4.5 from line 379 to 387.

3. "In Method section, there is no application description of the real-coded accelerated genetic algorithm (RAGA) method using in this study, which is suggested to be supplemented."

Response: The application description of RAGA method has been supplemented from Line 147 to Line 170.

4. "It is recommended to add the relevant description of the Mann–Kendall test method in Method section."

Response: The relevant description of the Mann–Kendall test method has been added from Line 202 to Line 212.

5. "Please check the original expression, it is recommended to replace Table 2 with Table 3 at line 146."

Response: We have made correction according to referee's comment at Line 174.

6. "The first row and column in Table 1 are all bold, but not in other tables. Please be consistent in the format of all tables"

Response: The format of all tables has been unified.

7. “It is recommended to add the name of related station in the titles of Figure 6, Figure 7, Table 7, and Table 8”

Response: The names of related station have been added in the titles.

Special thanks to you for your good comments.

Referee #3

1. “In the section of discussing the reliability of data length, we could see that the evaluation results of different data lengths showed obvious uncertainties. Therefore, does this uncertainty appear differently at different stages (pre- and post-impact periods)?

Response: Richter et al. (1997) suggested collecting >20 years of pre- and post-impact flow data when using IHA to assess hydrological alteration. Otherwise, the interannual climate change would cause great interference in the statistical results. Therefore, in order to capture the characteristics of hydrological changes, a long series of data is necessary. During the pre-impact period, the uncertainty is mainly caused by climate change. With the continuous construction of dams, the uncertainty is jointly determined by dam operation and climate change simultaneously, the former usually play import role in altering the flow regime.

Special thanks to you for your good comments.

Referee #4

1. “section 2.1 could be simplified, Make it concise please.”

Response: The descriptions about reservoirs construction and the national nature reserve have been simplified in section 2.1.

2. “The m-k method used in this paper, which is the basis distinguishing method, please adding some distinguishing methods to make readers more convinced.”

Response: Actually, some different methods have been used to verify and support the result of MK method in the previous manuscript. In section 4.1, the annual precipitation change between two periods was discussed by using MK method, and the result showed no significant trends, meanwhile, in section 4.3.2, the precipitation in summer and winter during three periods were compared (Table 7), and the relative changes were very slight, and in section 4.4, the LOR method was used to analyze whether the length of the collected data can eliminate the interference of climate on the IHA statistical results, and the result showed thar the data collected in this study basically satisfy the requirements for the analysis.

3. “The cascade reservoirs are built, the flow regime would be altered and not suited for spawning. Please clarify how and to what extent the former will impact the latter in your study area.”

Response: After the construction of cascade reservoirs, the runoff averaging effect became more evident, which effected the transmission of fish spawning signals. The discussion on the impact of reservoir construction on fish reproduction in May and the restoration of ecological regulation have been added in Section 4.5 from line 379 to 387.

Special thanks to you for your good comments.

Referee #5

1. “In Table 6, the overall degree of alteration of group 1-4 is increased from 1998-2012 to 2013-2017, but the fifth group is decreased, please explain the reasons.”

Response: In general, the impacts on the flow regime are further aggravated with the continuous construction of reservoirs, the averaging effect of runoff became more obvious, therefore, the group 5 (Rise Rate, Fall Rate and Number of Reversals) showed a decreasing trend in alteration degree during the period of 2013-2017. And The relevant discussion has been supplemented from line 296 to 306.

Special thanks to you for your good comments.

The list of all relevant changes:

Line 1: “analysing” was added

Line 2: “cascade” was corrected as “cascading”

Line 10: The method that we refer to is the conventional method of evaluating IHA parameters, and the relevant statement was added.

Line 15: The statement of “the continuous construction of reservoirs” was corrected as “the increase in the number of reservoirs”.

Line 16: The explanation of different groups was added in the abstract.

Line 17: This statement of “a head drop and tail lift” was modified.

Line 19-21: The impact of ecological regulation has been added in the abstract.

Line 26: The estimated area was clearly stated.

Line 28: “was” was deleted.

Line 28: “from 1949” was added in the sentence, and 98795 is the number of dams built from the year when New China was founded to 2017.

Line 29-30: the values of the exponent was corrected.

Line 31: The correct citation has been provided, and the reference in the list has also been modified at line 461.

Line 32, 34, 57, 61, 63: The references were listed chronologically.

Line 77: “with” was corrected as “of”

Line 77: This statement was modified

Line 84: “mm” was corrected as “mm/yr”

Line 85: “1/3” was corrected as “a third”

Line 99: “ecological” was corrected as “flow”

Line 110: This statement of “that larger values are better and that smaller values are better” was modified.

Line 114: “n” and “m” were defined, and the indicator and sample have been explained.

Line 120: This m is the same as the one above

Line 129: z_i was defined at line 121.

Line 132: n is the length of daily streamflow data, and it was defined at line 114.

Line 136: t is the independent variable of the unit step function $u(t)$.

Line 147-170: The application description of RAGA method was added.

Line 174: “Table 2” was corrected as “Table 3”

Line 142: s.t. is short for “subject to”, and this means that the optimal projection direction must satisfy this condition.

Line 186: The repeated i was replaced to k and the repeated n was replaced to y .

Line 202-212: The relevant description of the Mann–Kendall test method was added.

Line 240: “Table 3” was corrected as “Table 4”.

Line 246: “formula” was corrected as “Equation”.

Line 262: “of” was added.

Line 263: “when” was added and “is” was added.

Line 296-308: The relevant discussion based on the previous literature was supplemented.

Line 325 : The statement of precipitation anomalies was supplemented.

Line 379-387: The discussion on the impact of reservoir construction on fish reproduction in May and the restoration of ecological regulation was added.

Line 485: A reference was added (quoted at line 212 of the manuscript).

Line 526: A reference was added (quoted at line 299 of the manuscript).

Development of a revised IHA method for analysing the cumulative impacts of cascading reservoirs on flow regime

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Abstract. The impacts of reservoirs, especially multiple reservoirs, on the flow regimes and ecosystems of rivers have received increasing attention. The most widely used metrics to quantify the characteristics of flow regime alterations are the indicators of hydrologic alteration (IHA) which include 33 parameters. Due to the difference in the degree of alteration and the intercorrelation among IHA parameters, the conventional method of evaluating IHA parameters that assigns the same weight to each indicator is obviously inadequate. A revised IHA method is proposed by utilizing the projection pursuit (PP) and real-coded accelerated genetic algorithm (RAGA). Data reliability is analysed by using the length of record (LOR) method. The projection values reflecting the comprehensive characteristics of the evaluation parameters are calculated. Based on these methods, a scientific and reliable evaluation of the cumulative impacts of cascading reservoirs on the flow regime was made by examining the Jinsha River. The results showed that with the increase in the number of reservoirs, the alteration degrees of IHA parameters gradually increased in Groups 1, 2, 3, and 4, but decreased in Group 5 (each group addresses the magnitude, timing, frequency, duration, and rate of change in turn), and the flow duration curves showed a declining trend at the high flow part and an increasing trend at the low flow part. The flow regime alteration of the outlet section was more stable than before. This change had a negative impact on downstream fish reproduction and ecological protection. An attempt at ecological regulation was made to simulate the natural rising process of water, and four major Chinese carps have a positive response to the flood peak process caused by manual regulation.

1 Introduction

Free-flowing rivers (FFRs) support diverse, complex and dynamic ecosystems globally, providing important societal and economic services (Grill et al., 2019). Humans have extensively altered river systems through impoundments and diversions to meet their water, energy, and transportation needs (Nilsson et al., 2005). Only 37% of rivers longer than 1,000 km remain free-flowing over their entire length and 23% flow uninterrupted into the ocean around the world. Very long FFRs are largely restricted to remote regions of the Arctic and of the Amazon and Congo basins. From 1978 (when China's reform and opening up began) to 2017, China experienced an unprecedented boom in the construction of dams. From 1949 to 2017, 98795

reservoirs and dams were built in China with a total storage capacity of $9.035 \times 10^{11} \text{m}^3$, accounting for 32% of the annual runoff of all rivers and streams in China, of which 732 reservoirs are large reservoirs with a total capacity of $7.21 \times 10^{11} \text{m}^3$, accounting for 79.8% of the total capacity. (Ministry of Water Resources, 2018). Flow regulation and fragmentation of large global river systems have received increasing attention (Nilsson et al., 2005; Winemiller et al., 2016; Chen and Olden, 2017; Schmitt et al., 2018; Best, 2019). Flow variability is widely recognized as a primary driver of biotic and abiotic conditions in riverine ecosystems (Poff et al., 1997; Poff and Zimmerman, 2010). However, fully understanding the cumulative impacts of multiple dams on flow regime remains a challenge in both the scientific and management communities.

To evaluate the characteristics and ecological effects of flow regime changes, indicators are often needed to quantify the extent of hydrological alterations caused by reservoirs or dams. Olden and Poff (2003) found more than 170 hydrological indicators that can describe the different components of the flow regime and capture the ecologically relevant streamflow attributes. However, large numbers of hydrologic metrics are too complicated to use, and many metrics are intercorrelated, resulting in statistical redundancy (Gao, et al., 2009; Poff, and Zimmerman., 2010). Studies have sought to explore redundancy among hydrological indicators. For example, Olden and Poff (2003), Yang et al. (2008), Gao et al. (2009) and Fantin - Cruz et al. (2015) used principal component analysis (PCA) to evaluate the patterns of statistical variation for each parameter and identified a small subset of hydrological indicators as the most representative of the ecological flow regimes. Yang et al. (2017) used the criteria importance through intercriteria correlation (CRTTIC) algorithm to remove repetition and identify the weights of indicators. The weight of each hydrological indicator is assumed to be proportional to the standard deviation and inversely proportional to its correlation with other indicators. Then, high-weight indicators and some low-weight indicators that have important effects on aquatic ecology are used as representative indicators. Obviously, this selection is subjective and arbitrary. The most widely used metrics for characterizing river flow regime changes are the indicators of hydrologic alteration (IHA), which were developed based on 33 hydrological parameters in five groups, namely, the magnitude of monthly streamflow, the magnitude and duration of annual extreme flows, the timing of annual extreme flows, the frequency and duration of high and low pulses, and the rate and frequency of flow changes (Richter et al. 1996; Mathews and Richter, 2007). Richter et al. (1997) proposed the range of variability (RVA) method for evaluating the degree of alteration of the hydrological flow regime with IHA metrics. Nevertheless, intercorrelation still exists among the 33 parameters (Olden and Poff, 2003; Gao et al., 2012). Vogel et al. (2007) proposed a small set of representative indicators, i.e., the nondimensional metrics of ecodeficit and ecosurplus, which are based on flow duration curves (FDCs) and are computed over any time period of interest (month, season, or year). Ecodeficit and ecosurplus reflect the overall loss or gain of streamflow resulting from flow regulation. Some studies (Gao et al., 2009; Gao et al., 2012; Zhang et al., 2015) have demonstrated that the ecodeficit and ecosurplus metrics provide a simplified and adequate representation of hydrological impacts, compared with the use of the more complex IHA and RVA hydrological approaches.

Scholars have become increasingly concerned with the cumulative effects of multiple dams deriving from individual dams on hydrological processes (Santucci et al., 2005; Deitch et al., 2013; Wang et al., 2017a; Wen et al., 2018; Wang et al., 2018; Huang et al., 2018). The combined effect of cascade reservoirs on hydrological processes is cumulative and greater than that associated with individual reservoirs (Huang et al., 2010; Dos Santos et al., 2018). In comparison, Santucci et al. (2005) found little evidence on the cumulative effects of low head dams (< 15 in height). There are few existing studies that compare the effects of single versus multiple dams on the hydrologic regime. (Zhao et al., 2012). Are the effects of multiple dams additive, multiplicative, or largely insignificant? These fundamental problems always cause disturbances to scientific and management communities (Timpe and Kaplan, 2017).

In summary, previous studies on method improvement were based on the statistical reduction in the dimensionality of multi-index data and evaluated the hydrological alterations of rivers. The disadvantage is that retaining most of the information, also leads to the loss of some information. For example, a PCA usually only maintains 80% of the data information. In this study, a very different idea was employed. Data mining and optimization methods were used to identify the characteristics of the indicator system and identify the difference weight of each indicator to overcome the deficiency in the comprehensive evaluation given the same weight for each indicator. At the same time, global optimization also reduced the deviation in the evaluation caused by intercorrelation among indicators.

Based on previous studies, the objectives of the present study are as follows: 1) to develop an updated weight determination method for IHA indicators and precisely evaluate hydrological alteration; 2) to analyze cumulative effects on the flow regime of the construction of cascade reservoirs; and 3) to simulate the process of natural flooding, implement reservoir flow regulation, and provide recommendations for water resources management.

2 Study area and data

2.1 Study area

The Jinsha River comprises the upper reaches of the Yangtze River in China and originates from the northern foot of the Tanggula Mountains in the Tibetan Plateau. The Jinsha River flows along a distance of approximately 3500 km and has a drainage area of 502,000 km², which is approximately 27.8% of the entire basin area of the Yangtze River. The mean annual precipitation in the Jinsha River basin is 710 mm/yr and the average annual runoff is 4471 m³/s. The largest tributary of the Jinsha River is the Yalong River, and its inflow accounts for a third of the total discharge of the Jinsha River. At present, 20 reservoirs have been planned for development along its mainstream, and 21 reservoirs have been planned along the Yalong River (Fig. 1). Among the 13 reservoirs built, most have the weak regulation capacity while the Ertan, Xiangjiaba and Xiluodu reservoirs have large capacities, strong regulation abilities and great effects on the flow regime (Table 1).

89 There is a national nature reserve in China that protects rare fish from 1.8 km downstream of the Xiangjiaba reservoir to
 90 the main stream of the Yangtze River in Masangxi, Chongqing municipality (355 km in length). The nature reserve's main
 91 protection targets include three rare fish, i.e., paddlefish (*Psephurus gladius*), Yangtze sturgeon fish (*Acipenser dabryanus*),
 92 and Chinese sucker fish (*Myxocyprinus asiaticus*), and 67 unique fish. This region is also an important habitat for four major
 93 Chinese carps, i.e., black carp (*Mylopharyngodon piceus*), grass carp (*Ctenopharyngodon idellus*), silver carp
 94 (*Hypophthalmichthys molitrix*), and big head carp (*Aristichthys mobilis*). With the successive construction of the Jinsha River
 95 cascade reservoirs, flow regime changes will have an impact on downstream fish habitats.

96 2.2 Data

97 The daily streamflow data of the Panzhihua, Huatan, Pingshan and Xiangjiaba hydrological gauges were collected (Table 2).
 98 The climate data used in this study are daily precipitation data at 28 stations from 1966-2017, and the daily inflow and outflow
 99 data of the Xiangjiaba Reservoir and Xiluodu Reservoir were collected to analyze the effects of flow regulation. The Pingshan
 100 station is located approximately 28 km upstream of the Xiangjiaba Reservoir and covers 99.96% of the controlled drainage
 101 area of the reservoir, but it has been out of service since 2012 due to construction of the Xiangjiaba Reservoir. Therefore, data
 102 from Xiangjiaba station, which was newly built in 2012 and is located close to the Xiangjiaba Reservoir, were supplemented
 103 with Pingshan station data (Huang et al., 2018).

104 3 Method

105 3.1 Projection pursuit method

106 Projection pursuit (Friedman and Tukey, 1974; Wang et al., 2017b; Wang et al., 2019) uses data mining and optimization
 107 methods to project high-dimensional data into low-dimensional space and analyze the characteristics of high-dimensional data
 108 through the distribution structure of low-dimensional projection data. The main steps are as follows:

109 Step 1: We normalize all of the indicators since the dimensions of some indicators are not the same or the data ranges are
 110 quite different. For the indicators that larger is better are pre-processed by Eq. (1) and for the indicators that smaller is better
 111 are pre-processed by Eq. (2) :

$$112 \quad x_{ij} = \frac{x_{ij}^o - x_{jmin}^o}{x_{jmax}^o - x_{jmin}^o} \quad (1)$$

$$113 \quad x_{ij} = \frac{x_{jmax}^o - x_{ij}^o}{x_{jmax}^o - x_{jmin}^o} \quad (2)$$

114 where $x_{ij}^o (i = 1, \dots, n; j = 1, \dots, m)$ is the j-th indicator value of the i-th sample, and n and m are the length of daily
 115 streamflow data and number of IHA indicators(in this paper, the number is 32), respectively. For example, the Mean flow in

January (the first IHA indicator) in 1966(the first year of data collection) at Panzhihua Station is 705 m³/s, so the $x_{11}^o = 705$.
 $x_{j\min}^o$ and $x_{j\max}^o$ are the minimum and maximum values of the j-th indicator, respectively. x_{ij} is the normalized indicator value.

Step 2: The projection pursuit method projects high-dimensional data into one-dimensional linear space for research; therefore, we construct a projection index function for linear projection. $a_j(j = 1, \dots, m)$ is the projection direction, and $z_i(i = 1, \dots, n)$ is the one-dimensional projection value of x_{ij} which is defined as follows:

$$z_i = \sum_{j=1}^m a_j x_{ij} \quad (3)$$

Step 3: The projection value is selected by constructing an objective function, and its scattering characteristics should be as follows: local projection points should be as dense as possible and it is better to concentrate the points into several clusters. At the same time, the overall projection points should be spread as much as possible. Therefore, the projection objective function $Q(a)$ is defined as follows:

$$Q(a) = S_z D_z \quad (4)$$

where S_z is the standard deviation of the projection value $z_i(i = 1, \dots, n)$ (Pearson,1900); D_z is the local density of the projection value $z_i(i = 1, \dots, n)$. S_z and D_z are defined as follows:

$$S_z = \sqrt{\frac{\sum_{i=1}^n (z_i - E_z)^2}{n-1}} \quad (5)$$

$$D_z = \sum_{i=1}^n \sum_{j=1}^n (R - r_{ij}) \cdot u(R - r_{ij}) \quad (6)$$

where E_z is the average of all projection values $z_i(i = 1, \dots, n)$ and R is the window density of the local density. Through experiments, it was found that using $0.1S_z$ as the value of R could ensure that the average number of projection points contained in the window was not too small, which could make the deviation in the sliding average as small as possible. At the same time, it could also prevent the value of R from increasing too much as n increased; r_{ij} is the distance between projection values(i.e., $r_{ij} = |z_i - z_j|$); $u(t)$ is unit step function that equals 0 if $t < 0$ or equals 1 if $t \geq 0$.

Step 4: For the projection objective function(Q_a),its function value changes when the projection direction (a_j) changes. To obtain an optimal projection direction, and ensure that the structural features of the high-dimensional data are displayed as much as possible, the maximum value of the projection objective function should be solved, therefore, it is an optimization problem:

$$\text{Max}Q(a) = S_z D_z \quad (7)$$

$$\text{subject to } \sum_{j=1}^m a_j^2 = 1 \quad (a_j \in [0,1]) \quad (8)$$

It is very difficult to solve this complicated nonlinear optimization problem by using the traditional optimization method. Therefore, the real-coded accelerated genetic algorithm (RAGA) was used to address this problem, and the RAGA, which

145 simulates the survival of the fittest and the intragroup chromosome information exchange mechanism, is a general global
146 optimization method (Yang et al., 2005). It includes the following 8 steps:

147 Step 1: Encoding by real number coding. For example, the general optimization problem is as follows:

148
$$\begin{cases} \text{Max } F(X(1), X(2) \cdots X(M)) \\ A(j) \leq X(j) \leq B(j), j = 1, 2 \cdots M \end{cases} \quad (9)$$

149 Where $X(j)$ represents the j -th optimization variable; $[A(j), B(j)]$ represents the interval of change of $X(j)$; M represents
150 the number of optimization variables; F represents the objective function.

151 Then, introducing a random number with $W \in [0,1]$ and using the following linear transformation:

152
$$X(j) = A(j) + W_j(B(j) - A(j)) \quad (10)$$

153 Step 2: Random generation of initial parent groups. Generating N groups uniform random number, each group has m
154 numbers in range $[0,1]$ (that is $W(j), j = 1, 2 \cdots m$). The $W(j)$ is used as the parent individual value of each initial group,
155 and then, plugging $W(j)$ into Equation (10) to get the optimized variable value $X(j)$. The corresponding objective function
156 value $F(X)$ is obtained in Equation (9).

157 Step 3: Evaluation of the fitness of the parent population. According to step 2, the corresponding fitness function $F(X)$
158 is obtained, and the larger the function value is, the higher the individual adaptability is.

159 Step 4: The probability of selection of the parent individual. Selection is the key to genetic algorithm, which reflects
160 the idea of survival of the fittest. The excellent parent individuals are directly added to the child group.

161 Step 5: Performing a hybridization of parent individual. The new population selected in step 4 is hybridized according to
162 the random linear combination with crossover probability to generate a second child generation.

163 Step 6: Performing a mutation of descendant individual. The second child generation is mutated according to the
164 probability of mutation to generate the third child generation. If the fitness function value of any parent is small, the probability
165 of variation of the parent is larger.

166 Step 7: Evolution iteration. The excellent descendant individuals are obtained after steps 6, and the RAGA algorithm is
167 transferred to step 3 and enters the next round of evolution.

168 Step 8: Accelerated circulation. The algorithm jumps to step 1 and the variable change interval of the excellent individuals
169 is taken as the new initial change interval. The acceleration is not ended until the algorithm runs to a predetermined number of
170 accelerations.

171 3.2 Evaluation method for the hydrological alteration degree

172 The IHA system, consisting of 33 hydrological indicators, is employed to assess hydrological alteration. The 33 IHAs are
173 categorized into five groups addressing the magnitude, timing, frequency, duration, and rate of change (Shiau and Wu., 2010)
174 and each group has a different ecological significance (Table 3). For the IHA statistics of the pre-impact period, its range of

variation between the 75th and 25th percentiles is considered as the ecological target range. The alteration degree (D_i) of the post-impact flow regime for the i -th IHA parameter is calculated as follows:

$$D_i = \left| \frac{N_{oi} - N_e}{N_e} \right| \times 100\% \quad (11)$$

where $N_{oi} (i = 1, \dots, m)$ and N_e are the observed and expected number of years during which the "post-impact" values of the i -th IHA parameters should fall within the ecological target range, respectively. Ranges of 0-33%, 33%-66%, and 66%-100% are defined as the evaluation boundaries of low, medium, and high alteration degrees, respectively. Then, the overall hydrological alteration degree is calculated as follows:

$$D = \frac{1}{c} \sum_{i=1}^c D_i \quad (12)$$

where c is the number of parameters. In this study, 32 parameters were considered since there was no zero-flow day. As seen from Equation (10), the conventional method gives the same weight for each IHA parameter.

3.3 FDC method and LOR analysis

A flow duration curve is simply a plot of the ordered daily streamflow observations $Q(k)$ (where $k = 1$ is the largest flow) as a function of their exceedance probability (p_k) (Vogel et al., 2007) and is defined as follows:

$$p_k = \frac{k}{y+1} \quad (13)$$

where y is the number of flow days (365 or 366 days in this paper) and k is the rank of flow. In this study, two typical annual FDCs during the pre-impact period (the 25th percentile FDC and the 75th percentile FDC) were used as the comparison objects.

The length of record (LOR) method is used to provide quantitative advice on the length of record required for each IHA parameter. The result of the LOR for a station is considered as a reference for other stations with similar hydrologic regimes; therefore, the station with the smallest anthropogenic impact and longest record length in the study area was chosen for LOR analysis. For each IHA parameter, we calculate its statistics for each year in a data set along with the long-term mean as the reference for LOR analysis. Then, the statistics of each parameter are ordered randomly and grouped into record-length increments ranging from two years to the full LOR. The mean of each increment is calculated for a comparison with the long-term mean. This process is repeated 50,000 times, from which 95%, 90%, and 85% confidence intervals (CIs) are calculated. Finally, we calculate the LOR required within 5% and 10% long-term mean errors at a specified confidence interval for the river in the study. For convenience of discussion, the LOR result within 10% of the long-term mean with a CI of 85% is abbreviated as 10/85 (Timpe and Kaplan, 2017).

201 3.4 Mann–Kendall test method

202 When we evaluate the effect of reservoirs on the hydrological regime, it is necessary to consider the potential impacts of
203 climate change on hydrological data since here may be different climatic conditions in the pre-and post-stages (Wang et al.,
204 2017a). Therefore, the Mann–Kendall (hereafter referred to as MK) test method was used to analyze the trend in the annual
205 precipitation time series 1966-2017(52 years) for 28 stations in the Jinsha River basin. The MK test is based on statistics S
206 defined as follows :

$$207 S = \sum_{i=1}^{N-1} \sum_{j=i+1}^N \text{sgn}(Y_j - Y_i) \quad (14)$$

208 Where Y_i and Y_j are the sequential data values of annual precipitation, N is the data set record length, and sgn is the
209 signum. The standardized statistics Z is computed by:

$$210 Z = \begin{cases} \frac{S-1}{\sqrt{\text{Var}(S)}} & S > 0 \\ 0 & S = 0 \\ \frac{S+1}{\sqrt{\text{Var}(S)}} & S < 0 \end{cases} \quad (15)$$

211 Where Var is the variance, and at the 5% significance level, the null hypothesis of no trend is rejected if $|Z| > 1.96$ and
212 rejected if $|Z| > 2.33$ at the 1% significance level (Tao et al., 2011).

213 4.Results and discussion

214 4.1 Characteristic analysis of annual precipitation change

215 In the study area, annual precipitation showed no significant trend or trend below the 10% significance level at 21 stations,
216 and only 2 and 3 stations showed increasing trends at 1% and 5% significance levels, respectively. A decreasing trend was
217 found at only 1 station with 1% significance level (Fig. 2). The moment estimation method was used to calculate the
218 characteristic values of precipitation from two short time series (1966-1998 and 1999-2017) and one long time series (1966-
219 2017). Compared with the value of the long time series, the relative errors of the mean of two short time series did not exceed
220 $\pm 3\%$ at 22 and 16 stations respectively, and the absolute errors of coefficient of variation do not exceed ± 0.03 at 26 and 18
221 stations. The results imply that the precipitation series from 1999-2017(post-impact period) and 1966-1998(pre-impact period)
222 have the same meteorological conditions, and show no significant trends.

223 4.2 Projection pursuit analysis

224 4.2.1 Applying data mining to identify indicator weights

225 The IHA statistics software developed by the US Nature Conservancy (<http://www.nature.org/>) was used to analyze the daily

streamflow data of the Panzhihua, Huatan and Pingshan hydrological stations from 1966 to 2017, and a matrix of 32 IHA statistics with long time series was obtained. According to the principle that the optimal pattern for a flow regime occurs in a natural state with no interference (Bayley, 1995), that is, the characteristics of intra-annual cyclical changes in wet and dry situations in a river are maintained, we first preprocessed the indicator system and transferred the high-dimensional data to low-dimensional subspaces using the PP method, and then, obtained the optimal projection direction of each indicator by the optimizing projection objective function and model parameters with the RAGA. In this paper, the population number was 400, the probability of crossover was 0.8, the probability of mutation was 0.8, the number of excellent individuals was 20, and the acceleration time was 10.

The larger the optimal projection direction value is, the greater the contribution to the flow regime evaluation, that is, the higher the weight of the indicator. As shown in Fig. 3, at the Pingshan and Huatan stations, the weight allocations are similar(Fig. 3b and 3c), and the parameters with similar high weight values (greater than 0.04) are mean flow in January, April, May, annual minimum discharge(one-day mean, seven-day mean, 90-day mean), base flow index, duration of high flow pulse, rise rate, fall rate, and number of reversals, while at Panzhihua station(Fig. 3a), the high weight parameters are mean flow in January, February, March, June, September, November, annual minimum discharge(three-day mean and thirty-day mean), base flow index, date of minimum, count and duration of high pulse(Table 4). This result indicates that the data structure of the characteristics of the flow regime characterized by IHA parameters has both similar and different parts upstream and downstream, and it also implies that different weights may be related to tributary imports, reservoir constructions or interval water supplies.

4.2.2 Projection value calculation

The projection values of the flow regime from the 1966-2017 hydrological series (Fig. 4) were obtained by substituting the optimal projection directions into Equation (3) at three stations. The results of the trend analysis on the projection values by the MK test suggest that at Panzhihua station, the projection values fluctuated periodically without any significant change trend(Fig. 4a), while the significant decreasing trends were found at the 1% significance level at the Huatan and Pingshan stations (Fig. 4b and 4c), especially at Pingshan station, where the decreasing trend was more intense after 2012. The projection value is a comprehensive evaluation result of flow regime changes and takes into account the monthly flow condition, the magnitude and duration of extreme discharge conditions, the occurrence time of extreme discharge conditions, the frequency and duration of high/low flow pulse, and the frequency and rate of hydrological process changes. The larger the projection value is, the more distinct the intra-annual cyclical change in wet and dry situations, and the smaller the interference caused by human activities. As shown in Fig. 4b and 4c, the projection values both began to show a significant decline in 1999, and a more significant decreasing trend was found at Pingshan station from 2013 to 2017(Fig. 4c). The timing of the two drastic

changes coincides with the time when the Ertan Reservoir in the Yalong River(tributary) and the Xiangjiaba and Xiluodu Reservoirs in the lower reaches of the Jinsha River (main stream) were first put into operation. This finding also implies that the impact of giant reservoirs on the flow regime is substantial, and that the degree of impact is further aggravated with the continuous construction of reservoirs.

4.2.3 Evaluation of the hydrological alteration degree with a revised method

According to the commissioning time of the first generator set in the Ertan Reservoir, the period of 1966-1998 is considered as the natural state of hydrological series unaffected by human activities(pre-impact period), and the period of 1999-2017 is considered as when the series is affected by human activities(post-impact period).The alterations and weights of the 32 IHA parameters are shown in Table 4. As shown in Table 4, the alteration degree calculated by the revised IHA method is larger than that by the traditional method. For the Panzhihua, Huatan and Pingshan stations, the overall alteration degrees calculated by the revised method are 0.29, 0.57, 0.54, and those by the traditional method are 0.28, 0.50 ,0.49 by the traditional method with relative changes 3.57%, 14%, and 10.20%, respectively. The traditional IHA method, analyzing overall hydrological alteration with the same weight for each parameter, constantly underestimates or overestimates actual hydrological changes since many parameters are intercorrelated (Yang et al., 2019).

Fig. 5 illustrates boxplots of the correlation coefficients between each IHA parameter and the remaining 31 IHA parameters at the three hydrological stations mentioned above. At the Panzhihua station, the absolute values of the correlation coefficients among the IHA parameters range from 0.0016 to 0.9976, with a mean of 0.2852(Fig. 5a). The absolute values of the correlation coefficients at the Huatan station range from 0.0 to 0.9876 with a mean of 0.2931(Fig. 5b). The absolute values of the correlation coefficients at the Pingshan station range from 0.0012 to 0.9972 with a mean of 0.2920(Fig. 5c). Fig. 5 shows that the correlations among parameters at the Huatan and Pingshan stations are stronger than that at the Panzhihua station, which suggests that the correlations among parameters has an impact on the evaluation of the hydrological alteration when combined with the results of the above two methods. The stronger the correlation among parameters, the greater the impact is. The Panzhihua station is located 10 km upstream of the junction of the Yalong River and the Jinsha River; therefore, operation of the Ertan Reservoir does not affect its hydrological streamflow series. This is also confirmed by the fact that the overall hydrological alteration at the Panzhihua station is low.

4.3 Cumulative impacts of cascade reservoirs on the flow regime

4.3.1 Hydrological alteration degree

The large reservoirs of the Ertan, Xiluodu and Xiangjiaba were successively built along the Jinsha River. Three periods were

utilized for studying the cumulative impacts of cascade reservoirs. The Ertan Reservoir was put into operation in 1999, and the Xiluodu and Xiangjiaba Reservoirs were both put into operation in 2013. Therefore, the first period is 1966-1998 with natural flow regime conditions; the second period is 1999-2012 with the effects of individual reservoir; and the third period is 2013-2017 with the effects of the cascade reservoirs of Ertan, Xiluodu and Xiangjiaba. A total of 32 IHA statistics at the Pingshan station were calculated, and the weights of each parameter were obtained by PP and RAGA. For the three different periods, the alteration degrees of each parameter and the overall alteration degrees are shown in Table 5 and Table 6, respectively. The cumulative impacts on the flow regime are very obvious with the successive construction of the reservoirs. During the period of 1999-2012, the number of high alteration degree parameters was eight, with an overall alteration degree of 47%, while during the period of 2013-2017, the number of high alteration degree parameters increased to thirteen, with an overall alteration degree of 70%. In particular, for the parameters of the mean flow in May (5), base flow index (23), and low pulse count(26), the alteration degrees of the three parameters were low during the period of 1999-2012, but they became high alteration degrees during the period of 2013-2017.

Huang et al. (2018) found the cumulative effect of cascade reservoirs was not a simple additive effect. Since the joint operation of cascade reservoirs for guaranteed output, flood regulation, and hump modulation was complicated, a decreasing trend in the impact of reservoir operation on downstream hydrological conditions along the direction of flow of the Jinsha River could be found, while the runoff averaging effect became more evident. Zhang et al. (2020) found the impacts of anthropogenic factors on water discharge were more significant than the impacts of precipitation, especially for the high discharge during flood season. In this paper, the increasing trends in the alteration degree were shown in the group 1, 2, 3, and 4, especially for the indicators of maximum/minimum flow in the group 2, the change of extreme flow was the main reason for the averaging effect of the river. However, the group 5 showed decreasing trend in alteration degree, and this could mainly result from the joint operation of cascade reservoirs. For the single reservoir, its limited regulation ability made the rate of change and reversals show dramatic and uncertain changes, while for the cascade reservoirs, their joint operation with strong regulation ability enhanced the averaging effect and also made the rate of change stable, especially for the ecological regulation that has been implemented in recent years, trying to maintain the flow changes under similar natural conditions during the spawning period of fish.

As shown in Table 7, compared with the period of 1966-1998, the changes in winter precipitation during the periods of 1999-2012 and 2013-2017 were very small, -1.5% and 1.6%, respectively, but the minimum flow values of the two periods increased by approximately 11-25% and 30-38%, respectively. However, slightly different changes in the flow regime were found in summer. Precipitation in summer had slight increases during the two periods, 2.5% and 2.7%, respectively. Significant decreases in maximum flow values were found during the period of 2013-2017, approximately 17-24%. However, during the period of 1999-2012, the maximum flow values increased by 4%-8%, which is basically consistent with the increase in

precipitation. These findings suggest that during the period of 1999-2012, only the Ertan Reservoir was operating in the tributary; therefore, its ability to control runoff and the impact on hydrological conditions on the outlet section of the basin were limited. In summer, the changes in the flow regime were mainly influenced by precipitation. However, in winter, the regulation of the Ertan Reservoir was still relatively obvious. With the operation of the Xiluodu and Xiangjiaba Reservoirs in the main-stream, the impacts of reservoir regulation on the flow regime were greater in summer than before.

4.3.2 FDC analysis

To better compare and analyze the cumulative effect of cascade reservoirs on the flow regime, two years were selected at Pingshan station, that is 2004 and 2016, based on the annual flow of periods of 1999-2012 and 2013-2017(Fig. 6). These years represent the years with an annual flow in the 50th percentile, and their annual mean discharges are 4796 m³/s and 4063 m³/s, respectively. Compared with the annual FDC above the 20th percentile in 2016, the high flow in 2004 was larger. The high flow above the 20th percentile of the FDC typically occurred in summer (Gao et al., 2012), and the precipitation anomalies (the deviation from the mean) in summer were 0 mm in 2004 and -29 mm in 2016. The summer runoff was basically consistent with precipitation in the same period, indicating that summer runoff changes are mainly caused by seasonal precipitation changes. By analyzing the annual FDCs between the 20th and 60th percentiles, we found that the flow in 2016 was smaller than that in 2004. This flow occurred mostly in fall, and the fall precipitation anomalies were -3mm in 2004 and -47mm in 2016. We analyzed the consistency of the underlying surface in the two pre- and post-impact periods, and the results indicate that the precipitation-runoff correlation trend lines for the two periods nearly coincide (Fig. 7). Therefore, the main reason for the phenomenon in fall is the accumulation of the impact of reservoir storage after the Xiangjiaba and Xiluodu Reservoirs were put into operation. The cumulative impact was much larger than the single impact of the Ertan Reservoir before 2012. At the same time, even if there was a large increase in precipitation in fall of 2016, the impact of precipitation on the flow was also weakened by cumulative impact of water storage. The low flows below the 80th percentile of the FDC occurred in winter, and two typical annual FDCs during the pre-impact period (the 25th percentile FDC and the 75th percentile FDC) were almost coincident during the low flows. This indicates that the changes in runoff in the dry season were slight during the pre-impact period. The winter precipitation anomalies were -3 mm in 2004 and 3 mm in 2016. Therefore, the reservoir water release was the main reason that the annual FDCs below the 80th percentile in 2004 and 2016 were generally above two typical annual FDCs. Due to the cumulative effect, the low flow in 2016 was even higher than the low flow in 2004.

4.4 Data reliability analysis

The characterization of natural and altered flow regimes using IHA requires adequate flow data (Zhang et al., 2018). Richter et al. (1997) suggested using >20 years of pre- and post-impact data to characterize the hydrologic regime. Timpe and Kaplan

(2017) found that fewer than 20 years of data could be used to yield statistically significant IHA results for a number of rivers across the Amazon by using the length of record (LOR) method. Given this uncertainty, further research is needed to determine the reliability of the data required by IHA. We chose 47 years from 1952 to 1998 at the Huatan station as the LOR calculation period with the smallest anthropogenic impact and the longest record length in the study area. Table 8 shows the length of record required for the 32 IHA parameters within 5% and 10% long-term mean errors at different specified confidence intervals at the Huatan station. Comparing the results between different groups, it is observed that the data volume requirement in group 4 is the highest, while when comparing and analyzing within the same group, it is observed that the amount of data required to describe the parameters for low flow is less than that required to describe the parameters for a relatively high flow. For example, the amount of data required for monthly mean flow in the flood season is higher than that for the monthly mean flow in the dry season in group 1. Zhang et al. (2018) found that the amount of data required has a consistent relationship with the amount of average monthly flow and the variability in hydrological data. Both the Huatan and Pingshan stations are located downstream of the Jinsha River with similar hydrologic regimes (Fig.3). Referring to the results of Table 8, the 33-year daily streamflow data from 1966 to 1998 at the Pingshan station fully satisfy the highest requirement (31 years) to produce a 10/85 LOR result for all parameters. These data also satisfy the requirement to produce a 10/90 LOR result except that the parameter of high pulse duration requires 34 years for analysis. Furthermore, the number of the IHA parameters that satisfy the requirement to produce 10/95, 5/85, 5/90, and 5/95 LOR results are 30, 30, 28, and 28, respectively. This indicates that the 33-years daily streamflow data at the Pingshan station could capture intra- and interannual flow variations. At the same time, the 19 years of post-impact data we collected from 1999 to 2017 could mainly satisfy the data requirement for analysis. Therefore, the data collection in this study basically satisfies the requirements for the analysis, and the overall evaluation of the hydrological alteration degree is basically reasonable.

4.5 Attempts at ecological regulation

Li et al., (2006) found that the total number of days with rising water from May to June in the Yangtze River is an important environmental driving factor that determines the amount of spawn produced by fish with pelagic eggs. Four major Chinese carps are typical fish with the pelagic eggs and the most widely distributed species in protected areas. The cumulative impact of the construction and operation of cascade reservoirs on the flow regime in the downstream nature reserve of the Jinsha River has aroused widespread concern. During the period from May 15 to May 18, 2018, the management institution conducted a joint eco-hydrological regulation test of the Xiluodu-Xiangjiaba Reservoirs for 4 days (Fig. 8). On May 15, the outflow discharge of the Xiluodu Reservoir was 2770m³/s, and it increased to 3420m³/s on May 16. After that, it increased slightly to 3470m³/s in the next two days. On May 14, the outflow discharge of the Xiangjiaba Reservoir was 2740m³/s, and it increased to 3330m³/s on May 15. Then, it evenly increased 300m³/s every day and reached 4320m³/s. Ecological regulation promoted

the spawning of fish. The Yibin monitoring section showed obvious spawning during the ecological regulation period, and fish spawning under the reservoir was stimulated obviously. The spawning peak was found at the Jiangjin monitoring section on the 6th day after the end of the regulation. Before the regulation, the amount of spawning was much lower in the Jiangjin monitoring section, but a significant increasing trend was found during the regulation and after the regulation. During the period of joint regulation, the number of fish eggs was 3 million in the Yinbin section, 7 million in the Luzhou section, and 173 million in the Jiangjin section. The result of joint regulation test indicates that the spawning of four major Chinese carps generally took place along with the artificial flooding process, and there was a delay of several days between the peak of spawning and the peak of flood. Before the operation of the Xiluodu and Xiangjiaba reservoirs from 1966 to 2012, the average coefficient of variation (CV) value of runoff at Pingshan Station in May was 0.204, while after the operation of the two reservoirs, the CV values in 2013,2014,2015 and 2016 were 0.138, 0.134, 0.245 and 0.174 (with an average of 0.173), respectively. The joint ecological regulation was implemented in 2017 and 2018, and the CV values at Pingshan Station in May were 0.243 and 0.181. It indicates that the ecological regulation in May has a positive repairing effect on fish reproduction signal and the artificial flood process caused by manual regulation can promote the spawning of these four major Chinese carps. In addition to the natural reproduction of the four major Chinese carps, the feasibility of studying for other important species is still in progress.

5 Conclusions

In this study, a revised IHA method is presented by combining projection pursuit (PP) with a real-coded genetic algorithm (RAGA) to obtain the weight of each IHA parameter. The method is applied to assess the cumulative impacts of cascade reservoirs on the flow regime in the Jinsha River. The main points can be summarized as follows:

- (1) The impacts of the construction and operation of the cascade reservoirs on the flow regime are huge. Using the revised IHA method to analyze the cumulative effects of Ertan, Xiangjiaba and Xiluodu Reservoirs on the flow regime of the outlet section of the Jinsha River, we found that with the continuous construction of the reservoir, the alteration degrees of IHA parameters in Groups 1, 2, 3, and 4 are gradually increasing, but are decreasing in Group 5(rise rate, fall rate, number of reversals). Due to reservoir water storage and release, the FDC shows decreasing trends in high flow, and increasing trends in low flow. The whole curve shows the characteristics of a head drop and the tail lift. The maximum flow is reduced, and the minimum flow is increased. The rate and frequency of discharge changes tend to be subtle. As the cascade reservoirs are completed, the flow regime alteration at the outlet section is more stable. This change has a negative impact on downstream fish reproduction and ecological protection.
- (2) The traditional IHA method employs 33 parameters to quantify the characteristics of flow regime changes, and analyze the overall hydrological alteration with the same weight for each parameter. The revised IHA method gives each

parameter its own weight by applying a projection pursuit model to project high-dimensional data into a low-dimensional space and optimizing the projection direction of each parameter. This method achieves a more reasonable evaluation of hydrological alterations and overcomes the problem of underestimating the hydrological alterations in the study area due to the difference in the degree of alteration and the intercorrelation among IHA parameters.

(3) Previous studies have suggested using >20 years of pre- and post-impact data to characterize the hydrologic regime. In this study, we chose 47 years from 1952 to 1998 at the Huatan station as the LOR calculation period. As a reference, the 33-years daily streamflow data from 1966 to 1998 at Pingshan station fully satisfy the highest requirement (31 years) to produce a 10/85 LOR result. These data also satisfy the requirement to produce a 10/90 LOR result except that the parameter of high pulse duration requires 34 years for analysis. In summary, the data collected in this study basically satisfy the requirements for the analysis, and the overall hydrological alteration degree evaluated by the IHA method is essentially reliable and reasonable.

Author contribution

Xingyu Zhou and Xiaorong Huang suggested the idea and formulated the overarching research goals and aims. Xingyu Zhou, Hongbin Zhao and Kai Ma corrected and managed the data. Xingyu Zhou and Xiaorong Huang employed statistical method to analyze study data. Xingyu Zhou prepared the manuscript with contributions from all co-authors

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Competing interests

The authors declare that they have no conflict of interest.

References

- Bayley, P. B.: Understanding large river floodplain ecosystems, *Bioscience.*, 45, 153-158, <https://doi.org/10.2307/1312554>, 1995.
- Best, J.: Anthropogenic stresses on the world's big rivers, *Nat. Geosci.*, 12(1),7-21, <https://doi.org/10.1038/s41561-018-0262-x>, 2019.

Chen, W. and Olden, J. D.: Designing flows to resolve human and environment water needs in a dam-regulated river, *Nat. Commun.*, 8:2158, <https://doi.org/10.1038/s41467-017-02226-4>, 2017.

Deitch M.J., Merenlender A.M., and Feirer S.: Cumulative effect of small reservoirs on streamflow in northern coastal California catchments, *Water Resour. Manag.*, 27, 5101-5118, <https://doi.org/10.1007/s11269-013-0455-4>, 2013.

Dos Santos, N.C.L., Lopes, T.M., and Gomes L.C.: Cumulative ecological effects of a Neotropical reservoir cascade across multiple assemblages, *Hydrobiologia.*, 819(1): 77-91, <https://doi.org/10.1007/s10750-018-3630-z>, 2018.

Fantin - Cruz, I., Pedrollo, O., Girard, P., Zeilhofer, P., and Hamilton, SK.: Effects of a diversion hydropower facility on the hydrological regime of the Correntes River, a tributary to the Pantanal floodplain, Brazil. *J. Hydrol.*, 531, 810–820, <https://doi.org/10.1016/j.jhydrol.2015.10.045>, 2015.

Friedman J. H., and Tukey J.W.: A projection pursuit algorithm for exploratory data analysis. *IEEE Trans. Comput.*, 23 (9):881-890, <https://doi.org/10.1109/t-c.1974.224051>, 1974.

Gao, B., Yang, D. W., Zhao, T. T. G., and Yang, H. B.: Changes in the eco-flow metrics of the upper Yangtze River from 1961 to 2008, *J. Hydrol.*, 448, 30–38, <https://doi.org/10.1016/j.jhydrol.2012.03.045>, 2012.

Gao, Y., Vogel, R. M., Kroll, C. N., Poff, L. R., and Olden, J. D.: Development of representative Indicators of Hydrologic Alteration, *J. Hydrol.*, 374, 136–147, <https://doi.org/10.1016/j.jhydrol.2009.06.009>, 2009.

Grill, G., Lehner, B., Thieme, M., Geenen, B., Tickner, D., Antonelli, F., Babu, S., Borrelli, P., Cheng, L., Crochetiere, H., Macedo, H. E., Filgueiras, R., Goichot, M., Higgins, J., Hogan, Z., Lip, B., McClain, M. E., Meng, J., Mulligan, M., Nilsson, C., Olden, J. D., Opperman, J. J., Petry, P., Liermann, C. R., Saenz, L., Salinas-Rodriguez, S., Schelle, P., Schmitt, R. J. P., Snider, J., Tan, F., Tockner, K., Valdujo, P. H., van Soesbergen, A., and Zarfl, C.: Mapping the world’s free-flowing rivers, *Nature*, 569(5), 215-221, <https://doi.org/10.1038/s41586-019-1111-9>, 2019.

Huang, W., Chen, J., and Wang, B.: Study on averaging effect of cascade hydropower development on flow and water temperature process, *Resources and Environment in the Yangtze Basin*, 19(3): 335-339, <https://doi.org/10.3724/SP.J.1088.2010.00432>, 2010. (In Chinese)

Huang, X.R., Gao, L.Y., Yang, P.P., and Xi, Y. Y.: Cumulative impact of dam constructions on streamflow and sediment regime in lower reaches of the Jinsha River, China, *J Mt. Sci.*, 15(12), 2752-2765, <https://doi.org/10.1007/s11629-018-4924-3>, 2018.

Li, C., Peng, J., and Liao, W. G.: Study on the eco-hydrological factors and flow regime requirement on spawning of four major Chinese carps in the middle reaches of Yangtze River, *Journal of China Institute of Water Resources and Hydropower Research*, 4(3), 170-176, <https://doi.org/10.3969/j.issn.1672-3031.2006.03.002>, 2006. (In Chinese)

Mathews, R., and Richter, B. D.: Application of the indicators of hydrologic alteration software in environmental flow setting, *J. Am. Water Resour. Assoc.*, 43, 1400–1413, <https://doi.org/10.1111/j.1752-1688.2007.00099.x>, 2007.

Ministry of Water Resources, People's Republic of China. 2017 Statistic Bulletin on China Water Activities. China WaterPower Press, Beijing, 2018.

Nilsson, C., Reidy, C.A., Dynesius, M., and Revenga, C.: Fragmentation and flow regulation of the world's large river systems, *Science*, 308(4), 405-408, <https://doi.org/10.1126/science.1107887>, 2005.

Olden, J. D., and Poff, N. L.: Redundancy and the choice of hydrologic indices for characterizing streamflow regimes, *River Res. Appl.*, 19(2), 101-121, <https://doi.org/10.1002/rra.700>, 2003.

Pearson, K.: On lines and planes of closest fit to points in space, *Philos. Mag.*, 2(11), 559-572, <https://doi.org/10.1080/14786440109462720>, 1900.

Poff, N. L., and Zimmerman, J. K. H.: Ecological responses to altered flow regimes: A literature review to inform the science and management of environmental flows, *Freshw. Biol.*, 55, 194-205, <https://doi.org/10.1111/j.1365-2427.2009.02272.x>, 2010.

Poff, N. L., Allan, J. D., Bain, M. B., Karr, J. R., Prestegard, K. L., Richter, B. D., Sparks, R. E., and Stromberg, J. C.: The natural flow regime: A paradigm for river conservation and restoration, *Bioscience*, 47(11), 769-784, <https://doi.org/10.2307/1313099>, 1997.

Richter, B.D., Baumgartner, J.V., Powell, J., and Braun, D. P.: A method for assessing hydrologic alteration within ecosystems, *Conserv. Biol.*, 10, 1163-1174, <https://doi.org/10.1046/j.1523-1739.1996.10041163.x>, 1996.

Richter, B.D., Baumgartner, J.V., Wigington, R., and Braun, D. P.: How much water does a river need? *Freshwater Biol.* 37 (1), 231-249, <https://doi.org/10.1046/j.1365-2427.1997.00153.x>, 1997.

Santucci, J., Gephard, S.R., and Pescitelli, S.M.: Effects of multiple low-head dams on fish, macroinvertebrates, habitat, and water quality in the Fox River, Illinois, *North Am. J. Fish Manage.*, 25, 975-992, <https://doi.org/10.1577/M03-216.1>, 2005.

Schmitt, R.J.P., Bizzi, S., Castelletti, S.B., and Kondolf, G.M.: Improved trade-offs of hydropower and sand connectivity by strategic dam planning in the Mekong, *Nature Sustainability*, 1, 86-104. <https://doi.org/10.1038/s41893-018-0022-3>, 2018.

Shiau, J. T., and Wu, F. C.: Assessment of hydrologic alterations caused by chi-chi diversion weir in chou-shui creek, taiwan: opportunities for restoring natural flow conditions, *River Res. Appl.*, 20(4), 401-412, <https://doi.org/10.1002/rra.762>, 2010.

Tao, H., Gemmer, M., Bai, Y.G., Su, B.D., and Mao, W.Y.: Trends of streamflow in the Tarim River Basin during the past 50 years: Human impact or climate change? *J. Hydrol.*, 400(1-2), 1-9, <https://doi.org/10.1016/j.jhydrol.2011.01.016>, 2011.

Timpe, K., and Kaplan, D.: The change hydrology of a dammed Amazon. *Science Advances*, 3, 1-13, <https://doi.org/10.1126/sciadv.1700611>, 2017.

Vogel, R.M., Sieber, J., Archfield, S.A., Smith, M. P., Apse, C. D., and Huber-Lee, A.: Relations among storage, yield and instream flow, *Water Resour. Res.*, 43, <http://dx.doi.org/10.1029/2006WR005226>, 2007.

Wang, L., Wang, J., and Gao, X. S.: Toward the health measure for open source software ecosystem via Projection Pursuit and

492 Real-Coded Accelerated Genetic, IEEE Access, 7, 87396-87409, <http://dx.doi.org/10.1109/ACCESS.2019.2926306>, 2019.

493 Wang, Y.K., Wang, D., Lewis, Q.W., Wu, J. C., and Huang, F.: A framework to assess the cumulative impacts of dams on
 494 hydrological regime: a case study of the Yangtze River, Hydrol. Process., 31, 3045-3055, <http://dx.doi.org/10.1002/hyp.11239>,
 495 2017a.

496 Wang, W.C., Chau, K.W., Xu, D.M., Qiu, L., and Liu, C. C.: The annual maximum flood peak discharge forecasting using
 497 hermit projection pursuit regression with SSO and LS method, Water Resour. Manag., 31, 461-477,
 498 <http://dx.doi.org/10.1007/s11269-016-1538-9>, 2017b.

499 Wang, Y.K., Zhang, N., Wang D., Wu, J. C., and Zhang, X.: Investigating the impacts of cascade hydropower development
 500 on the natural flow regime in the Yangtze River, China, Sci. Total Environ., 624,1187-1194.
 501 <http://dx.doi.org/10.1016/j.scitotenv.2017.12.212>, 2018.

502 Wen, X., Liu, Z.H., Lei X.H., Lin, R. J., Fang, G. H., Tan, Q. F., Wang, C., Tian, Y., and Quan, J.: (2018). Future changes in
 503 Yuan River ecohydrology: individual and cumulative impacts of climates change and cascade hydropower development on
 504 runoff and aquatic habitat quality, Sci. Total Environ., 633, 1403-1417, <http://dx.doi.org/10.1016/j.scitotenv.2018.03.309>,
 505 2018.

506 Winemiller, K.O., McIntyre, P.B., Castello, L. Fluet-Chouinard, E., Giarrizzo, T., Nam, S., Baird, I. G., Darwall, W., Lujan,
 507 N. K., Harrison, I., Stiassny, M. L. J., Silvano, R. A. M., Fitzgerald, D. B., Pelicice, F. M., Agostinho, A. A., Gomes, L. C.,
 508 Albert, J. S., Baran, E., Petrere, M., Zarfl, C., Mulligan, M., Sullivan, J. P., Arantes, C. C., Sousa, L. M., Koning, A. A.,
 509 Hoeinghaus, D. J., Sabaj, M., Lundberg, J. G., Armbruster, J., Thieme, M. L., Petry, P., Zuanon, J., Vilara, G. T., Snoeks, J.,
 510 Ou, C., Rainboth, W., Pavanelli, C. S., Akama, A., van Soesbergen, A., and Saenz, L.: Balancing hydropower and biodiversity
 511 in the Amazon, Congo, and Mekong, Science, 351(6269), 128-129, <http://dx.doi.org/10.1126/science.aac7082>, 2016.

512 Yang, T., Cui, T., Xu, C.Y., Ciais, P., and Shi, P. F.: Development of a new IHA method for impact assessment of climate
 513 change on flow regime, Glob. Planet. Change., 156, 68-79, <http://dx.doi.org/10.1016/j.gloplacha.2017.07.006>, 2017.

514 Yang, T., Zhang, Q., Chen, Y. Q. D., Tao, X., Xu, C. Y., and Chen, X.: A spatial assessment of hydrologic alteration caused
 515 by dam construction in the middle and lower Yellow River, China. Hydrol. Process., 22(18), 3829–3843,
 516 <http://dx.doi.org/10.1002/hyp.6993>, 2008.

517 Yang, X., Yang, Z., Lu, G. H., and Li, J.: A gray-encoded, hybrid-accelerated, genetic algorithm for global optimizations in
 518 dynamical systems, Commun. Nonlinear Sci. Numer. Simul., 10(4), 355-363, <http://dx.doi.org/10.1016/j.cnsns.2003.12.005>,
 519 2005.

520 Zhang, Z. X., Chen, X., Xu, C. Y., Hong, Y., Hardy, J., and Sun, Z. H.: Examining the influence of river–lake interaction on
 521 the drought and water resources in the Poyang Lake basin, J.Hydrol., 522,510–521,
 522 <http://dx.doi.org/10.1016/j.jhydrol.2015.01.008>, 2015.

523 Zhang, W. H., Jia, Y.W., Ge, J.J., Huang, X.R., Ni, G.H., Hou, J.M., and Wang, H., 2019. Multi-index data dimension reduction
 524 approach and its applicability in the calculation of indicators of hydrological alteration. *Hydrol. Res.*, 50(1): 231-243.
 525 <http://dx.doi.org/10.2166/nh.2018.068>, 2018.

526 Zhang, P.P., Cai, Y.P., Yang, W., Yi, Y.J., and Yang, Z.F., Climatic and anthropogenic impacts on water and sediment
 527 generation in the middle reach of the Jinsha River Basin. *River Res. Appl.*, 36(12). <http://dx.doi.org/10.1002/rra.3572>, 2020.

528 Zhao, Q.H., Liu, S.L., Deng, L., Dong, S. K., Cong, Wang, Yang, Z. F., and Yang, J. J.: Landscape change and hydrologic
 529 alteration associated with dam construction, *Int. J. Appl. Earth Obs. Geoinf.*, 16, 17-26,
 530 <http://dx.doi.org/10.1016/j.jag.2011.11.009>, 2012.

Table 1. Large reservoirs built in the Jinsha River Basin

Reservoir	Total storage capacity (10^8m^3)	Regulating storage (10^8m^3)	Installed capacity (10^4kW)	Annual energy production ($10^8\text{ kW}\cdot\text{h}$)	Pool level (m)	Basin area (10^4km^2)	First impoundment year
Ertan	58	33.7	330	170	240	11.64	1999
Xiluodu	126.7	64.6	1260	573.5	600	45.33	2013
Xiangjiaba	51.63	9.03	600	307.47	384	45.88	2013

Table 2. List of hydrological stations and their features.

Station	Longitude (E)	Latitude(N)	Drainage area (10 ⁴ km ²)	Annual discharge (10 ⁸ m ³)	Runoff data	
					Record period	Length(year)
Panzhihua	101°44'41"	26°38'19"	25.92	561.38	1966-2017	52
Huatan	102°54'03"	26°59'45"	42.59	1255.11	1952-2017	66
Pingshan	104°15'51"	28°37'29"	45.85	1426.30	1966-2012	47
Xiangjiaba	104°24'29"	28°38'00"	45.88	1286.00	2013-2017	5

(The Xiangjiaba station was also called the Pingshan Station in this study.)

Table 3. 33 Indicators of Hydrologic Alteration

Group 1		Group 2		Group 3	
1	Mean flow in January	13	1-day minimum	24	Date of minimum
2	Mean flow in February	14	3-day minimum	25	Date of maximum
3	Mean flow in March	15	7-day minimum	Group 4	
4	Mean flow in April	16	30-day minimum	26	Low pulse count
5	Mean flow in May	17	90-day minimum	27	Low pulse duration
6	Mean flow in June	18	1-day maximum	28	High pulse count
7	Mean flow in July	19	3-day maximum	29	High pulse duration
8	Mean flow in August	20	7-day maximum	Group 5	
9	Mean flow in September	21	30-day maximum	30	Rise rate
10	Mean flow in October	22	90-day maximum	31	Fall rate
11	Mean flow in November	23	Base flow index	32	Number of reversals
12	Mean flow in December	33	Zero flow day*		

*This parameter is excluded from the study

Table 4. Alteration degree and weight of 32 IHA parameters

Parameter	Panzhihua Station		Huatan Station		Pinshan Station	
	(1966-2017)		(1966-2017)		(1966-2017)	
	Alteration Degree	Weight	Alteration Degree	Weight	Alteration Degree	Weight
IHA Group 1						
1	5%	0.0513	89%	0.0529	79%	0.0519
2	16%	0.0566	100%	0.026	79%	0.0251
3	68%	0.0458	100%	0.0202	89%	0.0181
4	5%	0.0387	47%	0.0486	58%	0.0501
5	26%	0.003	68%	0.0445	37%	0.0442
6	5%	0.0492	5%	0.0113	5%	0.0157
7	16%	0.0403	26%	0.0291	47%	0.0303
8	16%	0.0042	26%	0.0221	5%	0.0201
9	26%	0.0572	5%	0.0425	5%	0.0393
10	37%	0.008	58%	0.0193	58%	0.0194
11	26%	0.0456	5%	0.0133	16%	0.013
12	16%	0.0142	16%	0.0385	16%	0.0352
IHA Group 2						
13	79%	0.0293	79%	0.0571	58%	0.0563
14	79%	0.0459	89%	0.039	68%	0.0376
15	68%	0.0123	68%	0.0608	89%	0.0598
16	47%	0.051	89%	0.0311	100%	0.0287
17	47%	0.0395	89%	0.0424	89%	0.0456
18	5%	0.0268	16%	0.0218	16%	0.0226
19	5%	0.0374	16%	0.0175	16%	0.0183
20	5%	0.0234	5%	0.0008	26%	0.0025
21	16%	0.0262	26%	0.0092	47%	0.0114
22	47%	0.0281	5%	0.0142	16%	0.0164
23	26%	0.0444	16%	0.0587	37%	0.0621
IHA Group 3						
24	16%	0.0006	68%	0.0137	58%	0.0132
25	5%	0.0503	26%	0.0396	5%	0.0432
IHA Group 4						
26	26%	0.0124	68%	0.008	47%	0.0052
27	16%	0.0042	100%	0.0273	89%	0.0274
28	5%	0.0548	5%	0.011	47%	0.0082
29	68%	0.0427	26%	0.0432	26%	0.0446
IHA Group 5						
30	16%	0.0136	68%	0.0492	37%	0.0454
31	16%	0.0131	100%	0.0474	100%	0.0449
32	37%	0.0299	100%	0.0399	100%	0.0442
mean value	28%		50%		49%	
Weighted mean value		29%		57%		54%

The values in bold mean high weights.

Table 5. Alteration degree of 32 indicators in Pingshan station in different periods

Parameter	Pingshan Station	Pingshan Station	Parameter	Pingshan Station	Pingshan Station
	1999-2012	2013-2017		1999-2012	2013-2017
	Alteration Degree	Alteration Degree		Alteration Degree	Alteration Degree
1	71%	100%	17	86%	100%
2	86%	60%	18	0%	60%
3	86%	100%	19	0%	60%
4	43%	100%	20	14%	60%
5	14%	100%	21	43%	60%
6	14%	20%	22	0%	60%
7	43%	60%	23	14%	100%
8	0%	20%	24	57%	60%
9	14%	20%	25	14%	60%
10	57%	60%	26	29%	100%
11	0%	60%	27	86%	100%
12	0%	60%	28	57%	20%
13	43%	100%	29	14%	60%
14	57%	100%	30	57%	20%
15	86%	100%	31	100%	100%
16	100%	100%	32	100%	100%

Table 6. Overall degree of alteration of five groups of IHA parameters

	Pingshan Station 1999-2012	Pingshan Station 2013-2017
Group 1	16%	23%
Group 2	20%	28%
Group 3	1%	4%
Group 4	1%	10%
Group 5	9%	5%
Overall degree of alteration	47%	70%

(The weight of each parameter has been considered)

Table 7. Changes in the annual minimum and annual maximum flows
between the periods 1966-1998, 1999-2012 and 2013-2017 in the Pingshan Station

Indicator	Pre-impact period 1966-1998	Post--impact period 1999-2012	Relative changes (%)	Post-impact period 2013-2017	Relative changes (%)
Precipitation in winter (mm)	12.3	12.1	-1.5%	12.5	1.6%
Precipitation in summer (mm)	394.5	404.3	2.5%	405.0	2.7%
1-day minimum flow(m ³ /s)	1216	1349	11%	1588	31%
3-day minimum flow(m ³ /s)	1221	1393	14%	1591	30%
7-day minimum flow(m ³ /s)	1231	1446	17%	1605	30%
30-day minimum flow(m ³ /s)	1269	1589	25%	1753	38%
1-day maximum flow(m ³ /s)	16525	17150	4%	12580	-24%
3-day maximum flow(m ³ /s)	16000	16784	5%	12458	-22%
7-day maximum flow(m ³ /s)	14915	15854	6%	11816	-21%
30-day maximum flow(m ³ /s)	11889	12839	8%	9835	-17%

Table 8.Length of record (LOR) results for each IHA parameter in the Huatan Station

IHA Group	parameter	LOR results (years)					
		5/95	5/90	5/85	10/95	10/90	10/85
Group1	January	15	11	8	5	3	2
	February	14	10	7	5	3	2
	March	14	10	7	5	3	2
	April	16	11	8	5	3	2
	May	19	14	10	7	5	3
	June	29	23	18	13	10	7
	July	32	26	21	16	11	8
	August	33	28	23	18	13	9
	September	26	20	16	12	8	6
	October	28	22	17	12	9	6
	November	20	15	12	7	5	3
	December	17	13	9	6	4	3
Group2	1-day min	14	10	7	5	3	2
	3-day min	14	10	7	5	3	2
	7-day min	14	10	7	5	3	2
	30-day min	14	10	7	5	3	2
	90-day min	14	10	7	5	3	2
	1-day max	27	22	17	12	8	6
	3-day max	27	22	17	12	8	6
	7-day max	27	22	17	12	8	6
	30-day max	26	20	16	12	8	6
	90-day max	25	19	15	10	7	5
	Base flow	21	16	12	8	5	4
Group3	Date min	27	23	20	15	10	7
	Date max	9	6	4	3	2	2
Group4	Lo pulse #	41	35	33	27	22	18
	Lo pulse L	43	42	41	37	32	27
	Hi pulse #	40	38	35	27	20	16
	Hi pulse L	45	44	41	38	34	31
Group5	Rise rate	31	25	21	16	12	9
	Fall rate	25	21	16	12	8	5
	Reversals	11	8	6	3	2	2

Fig.1

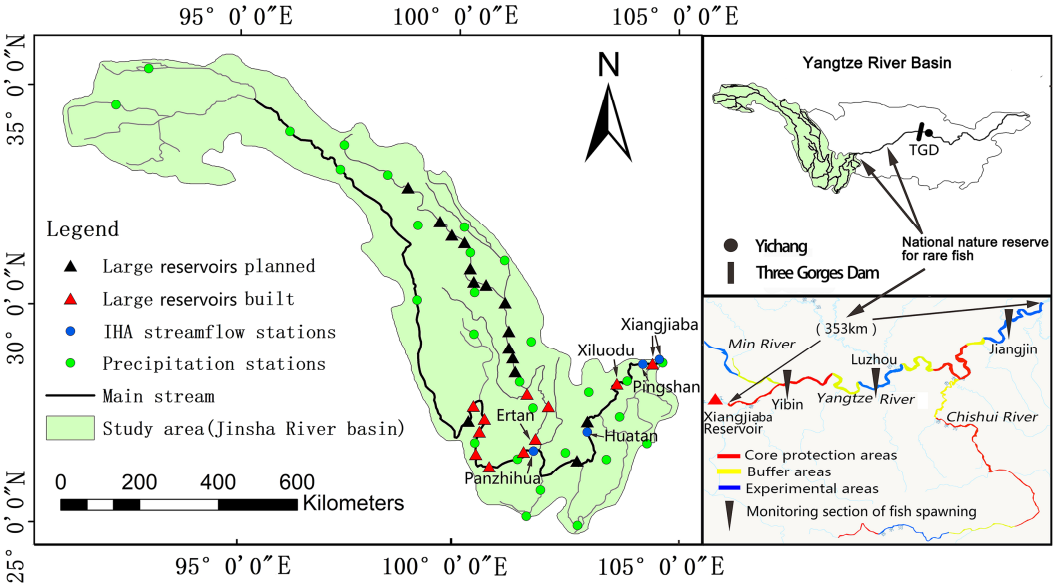


Fig.2

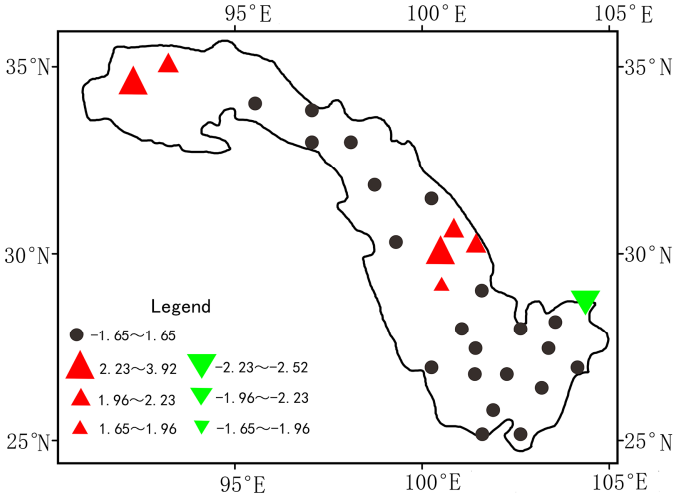


Fig.3

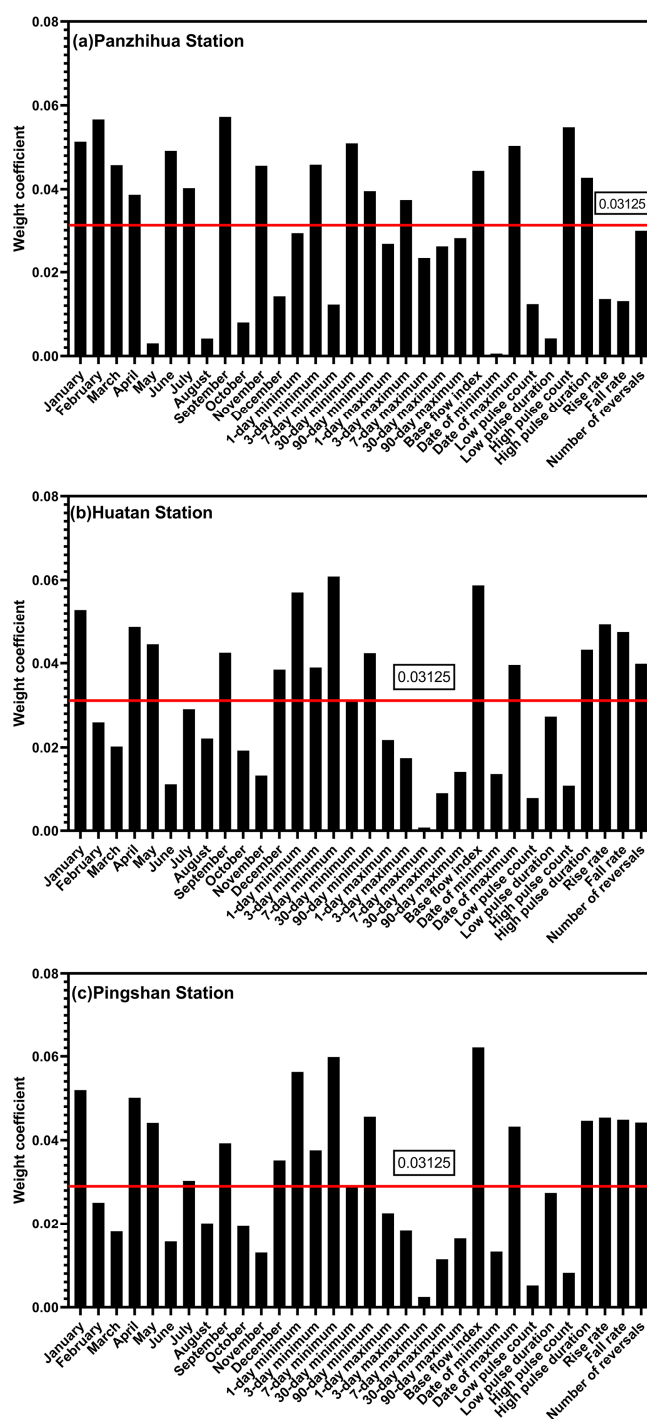


Fig.4

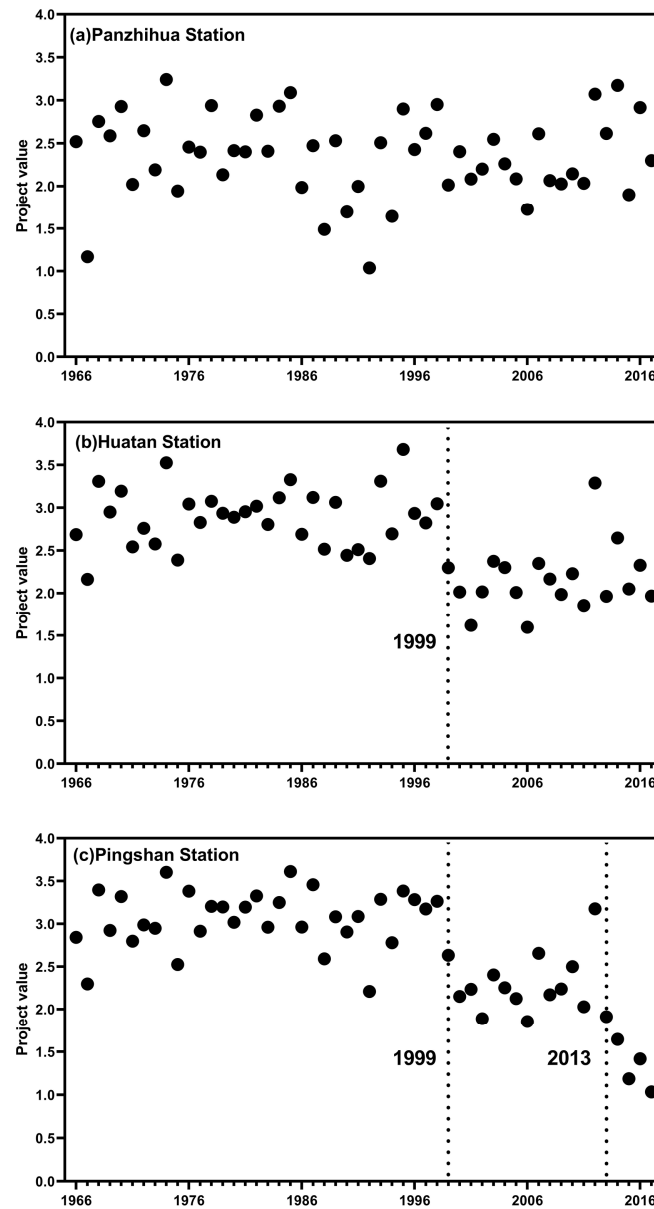


Fig.5

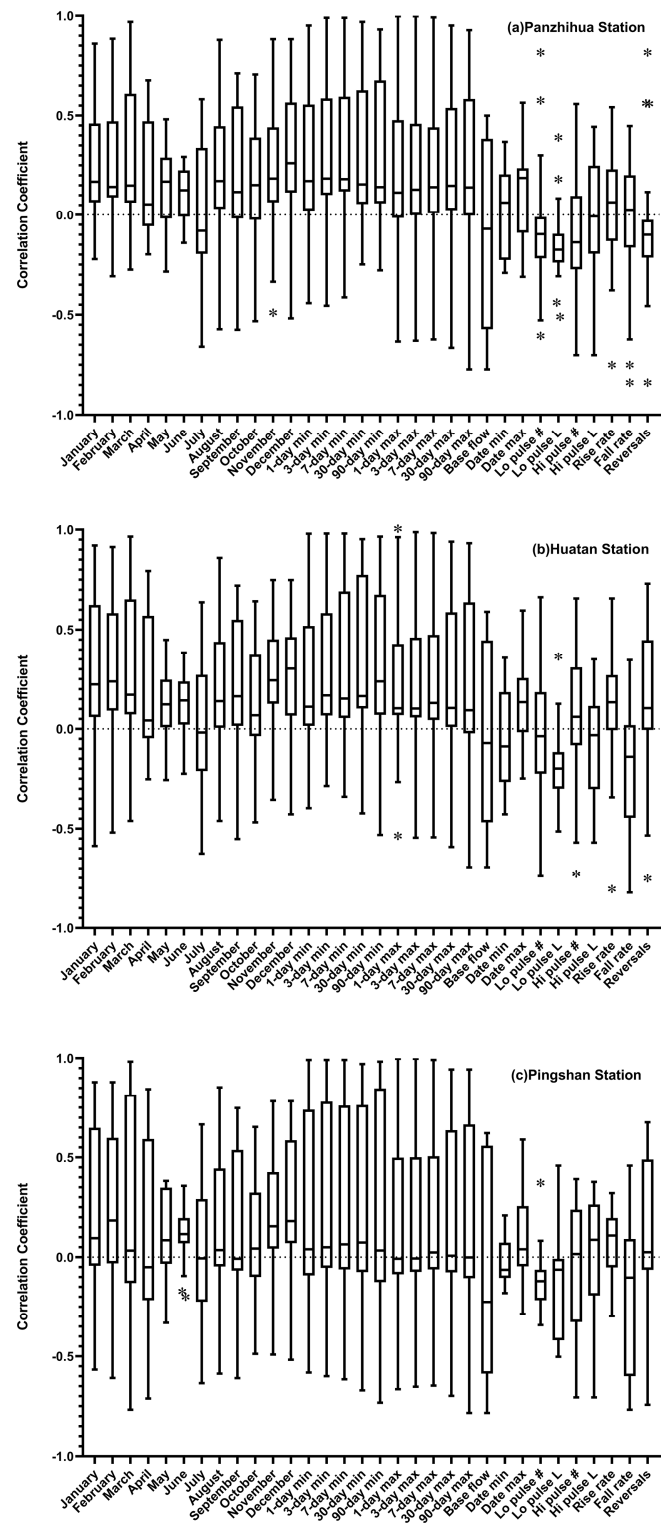


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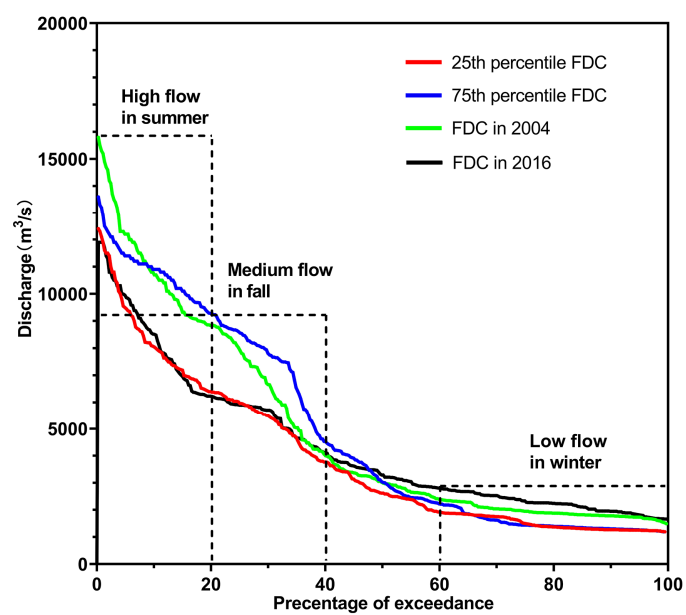


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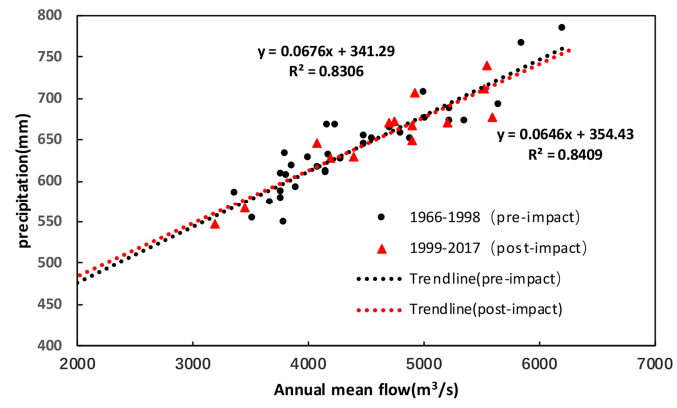


Fig.8

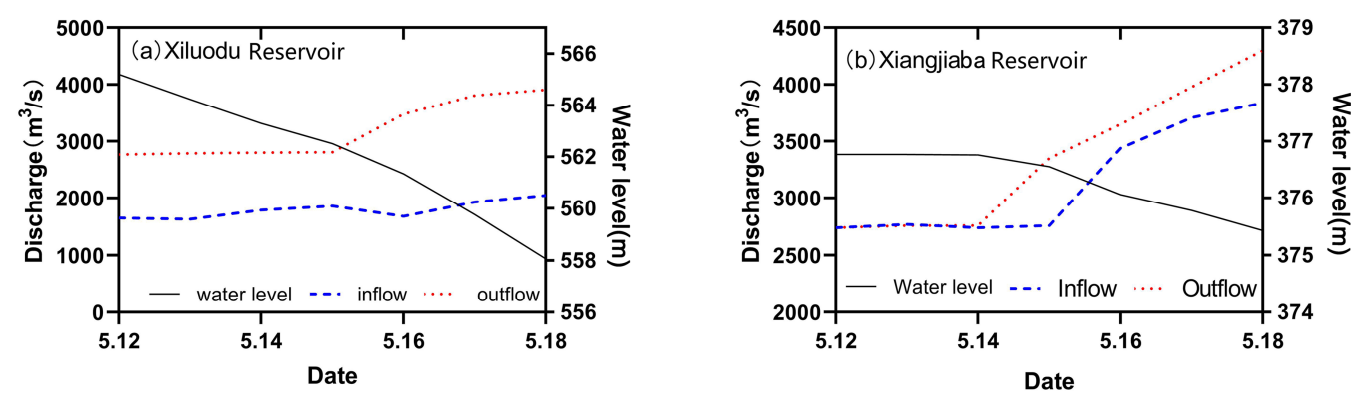


figure captions

Fig 1. Generalized map of study region.

Fig 2. Precipitation changes in the Jinsha River Basin:(a) Trend of annual Precipitation at 28 stations between 1966 and 2017(Upward (downward) triangles indicate positive (negative) trends from MK test. The size of the triangles depicts the significance levels 10% (small), 5% (medium), and 1% (large). Black dots show stations with no trends or trends below 10% significance level. Value in the legend is the standardized statistics Z value).

Fig 3. Value of weights of 32 IHA parameters in the (a) Panzhihua Station, (b) Huatan Station, and (c) Pingshan Station. The red line is equal weight line ($1/32=0.03125$).

Fig 4. Project values in the (a) Panzhihua Station, (b) Huatan Station, and (c) Pingshan Station.

Fig 5. Correlation coefficients among the IHA statistics for the observed data sets in the (a) Panzhihua Station, (b) Huatan Station, and (c) Pingshan Station. (* means outlier.)

Fig. 6 Annual flow duration curves in 2004 and 2016 in the Panzhihua Station.

Fig. 7 Correlation between runoff and precipitation for the periods of pre– and post–impact **in the Panzhihua Station.**

Fig 8. Hydrograph for daily average inflow, outflow and reservoir water level in the (a) Xiluodu and (b) Xiangjiaba Reservoirs.