

Study of the dynamic evaluation model of overall hydrological alteration degree based on the RVA and set pair analysis–Markov chain methods

Jinping Zhang, Xin Zhang and Honglin Xiao

ABSTRACT

The concept of overall hydrological alteration degree in the traditional range of variability approach is no longer suitable for the requirements of the current changing environment. First, by introducing the analytic hierarchy process and including the concept of deviation in the range of variability approach, the traditional range of variability approach is improved. Second, by using the daily flow data from the Guide gauging station in the lower reaches of Longyangxia reservoir from 1954 to 2017 and by combining the concept of connection degree in set pair analysis, a more comprehensive overall hydrological alteration degree is obtained. Finally, based on the results of overall hydrological alteration degree in each period, a dynamic evaluation model of overall hydrological alteration degree is established based on a set pair analysis–Markov chain method. The results show that the overall hydrological alteration degree of the Longyangxia reservoir in the postimpact period is at the second level; its average is -0.43 , but its identity tends to increase. Furthermore, the dynamic evaluation model shows that the overall hydrological alteration degree of its stable state will be 0.1726 , its impact flow changes and its stable state will be at the third level. This is a positive developing trend.

Key words | dynamic evaluation model, Markov chain, overall hydrological alteration degree, range of variability approach, set pair analysis

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INTRODUCTION

Dam building remains an important means of water resources utilization in modern society. While bringing economic benefits, dams seriously affect the natural flow of riverine water and thus impact the ecological environment of the downstream river (Graf 1999). Due to these concerns, ecological considerations have become more and more influential in the regulation of reservoirs. The range of variability approach (RVA) method can assess the flow changes caused by human disturbance using 32 indicators of hydrological alteration (IHA). Thus, this method is commonly used to study changes in ecological and hydrological indicators before and after dam

construction (Alrajoula *et al.* 2016; Sojka *et al.* 2016), and it also has made many great achievements (Mittal *et al.* 2016; Lin *et al.* 2017). Yu *et al.* (2016) proposed a revised RVA method to better reveal the alteration of hydrological characteristics over a hydrological year, thus enhancing the accuracy of estimates of flow regime changes. In addition, these cited studies have mostly focused on changes in each individual indicator, while studies of the overall hydrological alteration degree (OHAD) are rare. In fact, in the traditional RVA method, there is a simple three-level evaluation system that uses a simple average weight for each indicator. This does not accurately reflect flow

changes because it fails to fully weigh the degree of influence of each indicator. Furthermore, current research on hydrological regime changes using the RVA method has not considered the temporal uncertainty of hydrological information (Kumar & Sen 2017). As hydrological time series lengthen, studies of changes in flow during preimpact and postimpact periods must consider the uncertainty and dynamics of hydrological data in a changing environment. The analytic hierarchy process (AHP) method is commonly applied to solve the hierarchically structured and complex evaluation and decision problems of hydrology and water resources (Wang *et al.* 2003). By introducing the concept of deviation from the RVA method into the AHP method, the mutual influence of different hydrological indicators can be determined more effectively and the estimation of the OHAD made more reliable and reasonable.

The characteristics of hydrological events become more uncertain in a changing environment, and this will lead to greater uncertainty. After dam construction, consequently altered hydrological indicators will have unpredictable influences on the OHAD. In 1989, the Chinese scholar Zhao (1994, 1997) proposed the set pair analysis (SPA) method to explain the uncertainty between two variables with the identity, discrepancy, and contrary. SPA is widely used and was developed in the field of hydrology, and it makes hydrological studies more objective and effective (Gang *et al.* 2018; Shu *et al.* 2018).

Furthermore, current studies on hydrological regimes influenced by human activities emphasize a static evaluation at a single time: potential future dynamic trends are not evaluated or predicted. A Markov chain (MC) is a stochastic process used to analyze the variation characteristics of time series, and it can be used to project the dynamic transformation of hydrological variables (Dong *et al.* 2012). Using a combination of SPA and MC, the uncertainty and dynamic features of variables can be better displayed. In recent years, the SPA-MC dynamic assessment method has been gradually developed in the field of security risk dynamic assessment, and many scholars have used it in the study of safety status, protection performance status, and safety management ability (Zhang *et al.* 2016; Yang *et al.* 2017) to solve problems involving information uncertainty and the dynamic analysis of data. There are occasional applications

in hydrology, but the SPA-MC method is still evaluated as seriously insufficient.

So the innovation of this study is to construct a dynamic evaluation model of overall hydrological alteration degree with the SPA-MC method to reveal the uncertainty and dynamic features, and also to represent the river flow change trend affected by the reservoir in the future. Based on the daily flow data of the preimpact period (1954–1985) and the postimpact period (1988–2017) from the Guide gauging station, 32 IHA indicators are considered. First, the relative weights of the indicators are determined. Second, their hydrological alterations are calculated. Third, the OHAD of the hydrological flow is estimated by the SPA method. Finally, combining the RVA and SPA-MC methods, the dynamic evaluation model of OHAD is used to analyze and predict hydrological changes and trends in the reservoir.

MATHEMATICAL METHODS

Outline of the mathematical methods

The dynamic evaluation model of the overall hydrological alteration degree includes the following steps: (1) data series are collected and prepared to be analyzed; (2) the RVA method is applied to show the hydrological alteration degree; (3) using the AHP method, the objective weighting indicators system is established and using the SPA method, the uncertain relations (including the identity, the discrepancy and the contrary) of OHAD are exhibited; and (4) with the SPA-MC method, the dynamic evaluation model of OHAD is shown. Figure 1 shows the outline of the mathematical methods.

RVA

Richter *et al.* (1998) proposed using the RVA method to assess changes in natural flow affected by human activities, considering 32 indicators called IHA. IHA can be classified into five groups (as shown in Table 1), which display the annual flow changes, the time, frequency, duration, and change rate of extreme hydrological conditions.

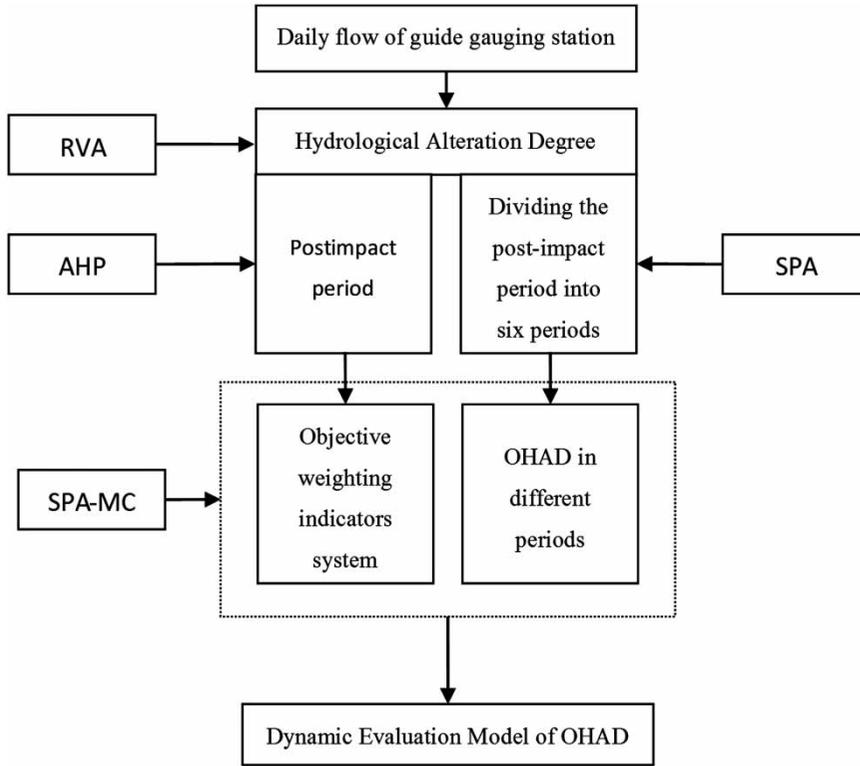


Figure 1 | The outline of the mathematical methods.

Table 1 | The indicators of hydrological alteration parameters

IHA statistics group	Regime characteristics	Hydrological parameters
Magnitude of monthly water conditions	magnitude timing	mean value for each calendar month
Magnitude and duration of annual extreme water conditions	magnitude duration	annual minima 1-day means annual maxima 1-day means annual minima 3-day means annual maxima 3-day means annual minima 7-day means annual maxima 7-day means annual minima 30-day means annual maxima 30-day means annual minima 90-day means annual maxima 90-day means number of zero-flow days base flow index: 7-day minimum flow/mean flow for year
Timing of annual extreme water conditions	timing	Julian date of each annual 1-day maximum Julian date of each annual 1-day minimum
Frequency and duration of high and low pulses	magnitude frequency duration	number of low pulses within each water year mean or median duration of low pulses (days) number of high pulses within each water year mean or median duration of high pulses (days)
Rate and frequency of water condition changes	frequency rate of change	rise rates fall rates number of hydrological reversals

Longyangxia reservoir has no zero-flow days. According to the RVA method, the change in the natural flow regime can be calculated by the following steps. (1) Calculate the annual 32 IHAs in the preimpact and postimpact periods. (2) Classify the RVA target range according to the annual 32 IHA parameters in the preimpact period. Based on the natural flow conditions, the RVA target range spans the 25th and 75th percentile values, assumed to be the lowest and highest limit for each IHA, respectively. In the postimpact period, if IHAs fall within the RVA target range, it means that dam construction has had little impact on the hydrology of the river. (3) Obtain the data for the years in which IHA indicators in the postimpact period fell within the RVA target range. (4) Measure the degree of hydrological alteration (HAD) of each IHA. The HAD of each IHA is measured by:

$$D_i = [(N_i - N_e)/N_e] \times 100\% \quad (1)$$

where D_i is the HAD of the i -th IHA, N_i is the number of years in which the i -th IHA falls within the RVA target range in the postimpact period, $N_e = \gamma N_T$ is the expected number years falling within the RVA target range in the postimpact period, and γ is the proportion of IHAs falling within the RVA in the preimpact period. If the RVA target range includes the 25th and 75th percentiles values, $\gamma = 0.5$; N_T is the total number of years in the postimpact period.

$D_i \in [0, 33\%)$ indicates no alteration or low HAD, $D_i \in [33\%, 67\%)$ indicates moderate HAD, and $D_i \in [67\%, 100\%)$ indicates high HAD.

Thus, if the 32 IHA indicators are given specific weights, the OHAD can be obtained by summing them.

SPA

For two interrelated sets A and B, the basic idea of the SPA method is to analyze N characteristics of the setting pair (A, B) and then to sort these characteristics into three classes: identity characteristics, discrepancy characteristics, and contrary characteristics. Thus, the connection degree of the set pair (A, B) can be expressed as:

$$\mu_{AB} = O/N + (P/N)i + (Q/N)j \quad (2)$$

where μ_{AB} is the connection degree, O is the number of identity characteristics, P is the number of discrepancy characteristics, Q is the number of contrary characteristics, and N is the total number of characteristics.

Suppose $a = O/N$ is the identity degree, $b = P/N$ is the discrepancy degree, and $c = Q/N$ is the contrary degree; then, Equation (2) is written as:

$$\mu_{AB} = a + bi + cj \quad (3)$$

where $a + b + c = 1$ and $a, b, c \in (0, 1)$, $i \in [-1, 1]$ is the coefficient of discrepancy, and j is specified as -1 .

MC

Denote $\{C(n), n \geq 0\}$ as an integrated random stochastic process in the probability space E ; if for any $m \geq 1$ at time $t_1, t_2, \dots, t_m (t_1 < t_2 < \dots < t_m)$, the corresponding values $C(t_1), C(t_2), \dots, C(t_m)$ satisfy the following requirement:

$$P(C(t_m)|C(t_{m-1})) = P(C(t_m)|C(t_{m-1}), C(t_{m-2}), \dots, C(t_1)) \quad (4)$$

$\{C(n), n \geq 0\}$ is called the MC. The MC explores the observation that the value of $\{C(n), n \geq 0\}$ at time t_m is only related to the value at time t_{m-1} and has no relation to the observation value of earlier times. $P(C(t_m)|C(t_{m-1}))$ is the conditional probability, also called the state transition probability.

DYNAMIC EVALUATION MODEL OF THE OHAD

Evaluation indicator system and indicator weight

The evaluation indicator system of the OHAD is defined by five groups of hydrological parameters and 32 secondary IHA indicators in the RVA method (as shown in Table 1).

As described above, if the 32 IHA indicators are given defined weights, the OHAD can be obtained by summing them. Shiao & Wu (2007) developed an equal weight method to calculate the OHAD. Obviously, assuming that the IHA indicators have equal weights is not reasonable.

The AHP method is commonly used to obtain the weights of indicators by constructing a judgment matrix. In this study, the assumed weight of each indicator in the AHP method is improved by the introduction of the concept of deviation in the RVA method. The first step is to calculate the deviation of the i -th IHA in the preimpact and postimpact periods as follows:

$$P_i = (|I_{pre-i} - I_{post-i}|) / I_{pre-i} \times 100\% \tag{5}$$

where P_i is the deviation of the i -th IHA, I_{pre-i} is the i -th IHA in the preimpact period, and I_{post-i} is the i -th IHA in the postimpact period.

The second step is to sum the deviations N_i ($i = 1, 2, \dots, 32$) of the 32 indicators in the RVA method to obtain the comprehensive deviation P_c . The relative importance of each indicator is:

$$N_i = P_i / P_c \tag{6}$$

Using the actual calculated N_i and the classification of each indicator on the judgment matrix 1–9 scale range, as determined by experts, the weights of the secondary indicators are finally achieved.

Determination of OHAD

Combined with the SPA method, the OHAD of the hydrological streamflow can be determined. Suppose that the indicator system is set A and indicator change degree is set B . The indicator system and indicator alteration degree can form a set pair for OHAD evaluation; then, the indicator weights are introduced into the SPA method. Assuming that at time t , within the total of 32 hydrological indicators, H_t indicators have a high change degree, M_t indicators have a moderate change degree, L_t indicators have a low change degree, and, all together, the indicators satisfy $H_t + M_t + L_t = 32$. Thus, the connection degree of set A and set B can be expressed as:

$$\begin{aligned} \mu_o &= a(t) + b(t)i + c(t)j \\ &= \sum_{k=1}^{H_t} \omega_k(t) + \sum_{k=H_t+1}^{H_t+M_t} \omega_k(t)i + \sum_{k=H_t+M_t+1}^{13} \omega_k(t)j \end{aligned} \tag{7}$$

where $\omega_k(t)$ is the weight of the secondary indicators in different states, $\sum_{k=1}^{H_t} \omega_k(t) + \sum_{k=H_t+1}^{H_t+M_t} \omega_k(t) + \sum_{k=H_t+M_t+1}^{13} \omega_k(t) = 1$, $i = 0, j = -1$, and $\mu_o \in [-1, 1]$ is the connection degree. The connection degree μ_o is the OHAD.

The values of OHAD can be divided into five classes using the equipartition method and are expressed from high to low as fifth level, fourth level, third level, second level and first level. Therefore, $OHAD \in [-1, -0.6]$ represents fifth level; $OHAD \in (-0.6, -0.2]$ represents fourth level; $OHAD \in (-0.2, 0.2]$ represents third level; $OHAD \in (0.2, 0.6]$ represents second level; $OHAD \in (0.6, 1]$ represents first level.

DYNAMIC EVALUATION MODEL ESTABLISHMENT OF THE OHAD

State transition probability matrix

Assume that H_t IHA indicators at time t show high alteration and that after time Δt , there are H_{t1} IHA indicators still showing high alteration, H_{t2} IHA indicators showing moderate alteration, H_{t3} IHA indicators showing low alteration, and $H_{t1} + H_{t2} + H_{t3} = H_t$, the state transition probability matrix of H_t IHA indicators in the time interval $[t, t + \Delta t]$ is:

$$[P_{11}, P_{12}, P_{13}] = \left[\sum_{k=1}^{H_{t1}} \omega_k(t), \sum_{k=H_{t1}+1}^{H_{t1}+H_{t2}} \omega_k(t), \sum_{k=H_{t1}+H_{t2}+1}^{H_t} \omega_k(t) \right] / \alpha(t) \tag{8}$$

where $P_{11} + P_{12} + P_{13} = 1$ and $\alpha(t) = \sum_{k=1}^{H_t} \omega_k(t)$.

Similarly, the state transition probability matrix of M_t IHA indicators with moderate alteration in the time interval $[t, t + \Delta t]$ is:

$$[P_{21}, P_{22}, P_{23}] = \left[\sum_{k=H_t+1}^{H_t+M_{t1}} \omega_k(t), \sum_{k=H_t+M_{t1}+1}^{H_t+M_{t1}+M_{t2}} \omega_k(t), \sum_{k=H_t+M_{t1}+M_{t2}+1}^{H_t+M_t} \omega_k(t) \right] / \beta(t) \tag{9}$$

where $P_{21} + P_{22} + P_{23} = 1$, $M_{t1} + M_{t2} + M_{t3} = M_t$, and $\beta(t) = \sum_{k=H_t+1}^{H_t+M_t} \omega_k(t)$.

Additionally, the state transition probability matrix of L_t IHA indicators with low alteration in the time interval $[t, t + \Delta t]$ is:

$$[P_{31}, P_{32}, P_{33}] = \left[\sum_{k=H_t+M_t+1}^{H_t+M_t+L_{t1}} \omega_k(t), \sum_{k=H_t+M_t+L_{t1}+1}^{H_t+M_t+L_{t1}+L_{t2}} \omega_k(t), \sum_{k=H_t+M_t+L_{t1}+L_{t2}+1}^{32} \omega_k(t) \right] / \gamma(t) \tag{10}$$

where $P_{31} + P_{32} + P_{33} = 1$, $L_{t1} + L_{t2} + L_{t3} = L_t$, $H_t + M_t + L_t = 32$, and $\gamma(t) = \sum_{k=H_t+M_t+1}^{32} \omega_k(t)$.

Thus, the state transition probability matrix of the 32 IHA indicators in the time interval $[t, t + \Delta t]$ is constructed:

$$P = \begin{bmatrix} P_{11} & P_{12} & P_{13} \\ P_{21} & P_{22} & P_{23} \\ P_{31} & P_{32} & P_{33} \end{bmatrix} \tag{11}$$

Establishment of dynamic evaluation model

Combining SPA with the MC, the dynamic evaluation model of SPA-MC is established. According to the traversal properties of the MC, it is known that the model will eventually become stable after $n\Delta t$ times; thus, the connection degree $(\hat{a}, \hat{b}, \hat{c})$ at the stable state can be described as:

$$\begin{cases} (\hat{a}, \hat{b}, \hat{c})(E - \bar{P})(1, i, j)^T = 0 \\ \hat{a} + \hat{b} + \hat{c} = 1 \end{cases} \tag{12}$$

where $\hat{a}, \hat{b}, \hat{c} > 0$, E is the identity matrix, and \bar{P} is the average state transition probability matrix.

By solving this equation, the steady-state value of the overall hydrological alteration degree can be obtained as follows:

$$\hat{\mu}_{A \sim B} = \hat{a} + \hat{b}i + \hat{c}j \tag{13}$$

where $i = 0$, $j = -1$, and $\hat{\mu}_{A \sim B}$ is the overall hydrological alteration degree.

Study area and data

The Longyangxia reservoir is located on the main stream of the Yellow River in Republic County and Guide County of

Qinghai Province. This reservoir is the first large-scale hydropower station in the upper reaches of the Yellow River and is the leading reservoir of the Yellow River Main Reservoir Group. The Guide gauging station is the first gauging station in the lower reaches of the Longyangxia reservoir (as shown in Figure 2). In October 1986, the Longyangxia reservoir began to store water, which greatly changed the river's flow conditions and had an important influence on the river basin ecosystem.

To analyze the flow variations impacted by reservoir operation clearly, the 1986 and 1987 flow data from the Guide gauging station are removed because 1986.10–1987.02 is the reservoir storage period. Thus, the daily flow data from the Guide gauging station is divided into two periods: the preimpact period (1954–1985) and the postimpact period (1988–2017).

RESULTS AND DISCUSSION

Weights of the 32 IHA indicators

According to the adjustment matrix, the weights of the 32 IHA indicators at the Guide gauging station are shown in Table 2.

It can be seen from Table 2 that after the beginning of reservoir operation, the deviations in the mean monthly flows in January, February, and March, as well as the low pulse count, high pulse count, rise rate, and fall rate, have been larger. Except for the mean monthly flows of May and November, which are 1-day maximum flows, the deviations are generally greater. Therefore, just estimating from the deviations, it can be roughly seen that the hydrological flow of the postimpact period is in a state of high alteration.

Hydrological alteration of the 32 IHA indicators

The postimpact period is divided into six periods: 1988–1992, 1993–1997, 1998–2002, 2003–2007, 2008–2012, and 2013–2017. According to the RHA method, the hydrological alteration of the 32 IHAs in these six periods can be calculated as shown in Figure 3. Number 3 represents high HAD, number 2 represents moderate HAD, and number 1 represents low HAD.

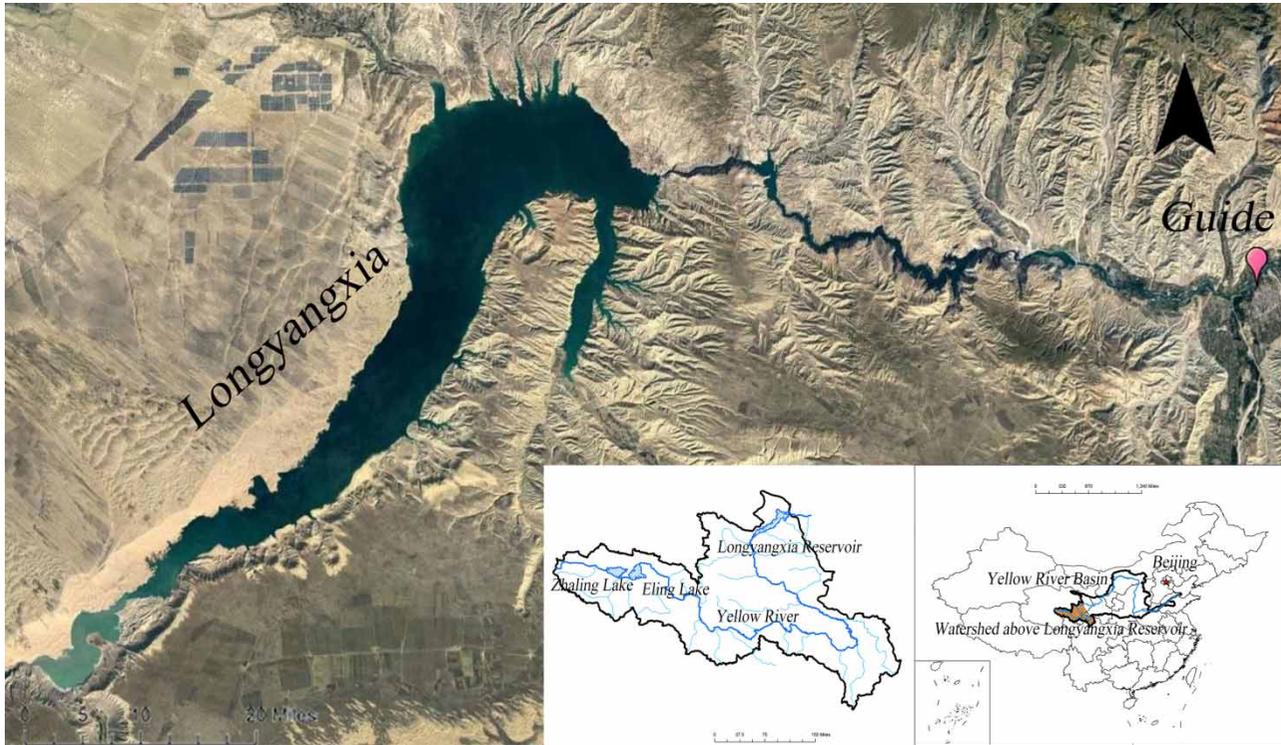


Figure 2 | The location of the Longyangxia reservoir.

Table 2 | The weight of the 32 IHA indicators

IHA indicators	Sequence number	Weight	IHA indicators	Sequence number	Weight
Jan	ω_1	0.0077	90-day min	ω_{17}	0.0156
Feb	ω_2	0.00844	1-day max	ω_{18}	0.0344
Mar	ω_3	0.01286	3-day max	ω_{19}	0.02072
Apr	ω_4	0.05113	7-day max	ω_{20}	0.01797
May	ω_5	0.07783	30-day max	ω_{21}	0.0156
Jun	ω_6	0.06273	90-day max	ω_{22}	0.0156
Jul	ω_7	0.03942	Base flow	ω_{23}	0.02736
Aug	ω_8	0.0503	Date min	ω_{24}	0.03942
Sep	ω_9	0.0344	Date max	ω_{25}	0.07235
Oct	ω_{10}	0.03942	Low pulse count	ω_{26}	0.00328
Nov	ω_{11}	0.08799	Low pulse duration	ω_{27}	0.0231
Dec	ω_{12}	0.02025	High pulse count	ω_{28}	0.00518
1-day min	ω_{13}	0.06273	High pulse duration	ω_{29}	0.0181
3-day min	ω_{14}	0.04634	Rise rate	ω_{30}	0.01286
7-day min	ω_{15}	0.02519	Fall rate	ω_{31}	0.00481
30-day min	ω_{16}	0.0181	No. of reversals	ω_{32}	0.0288

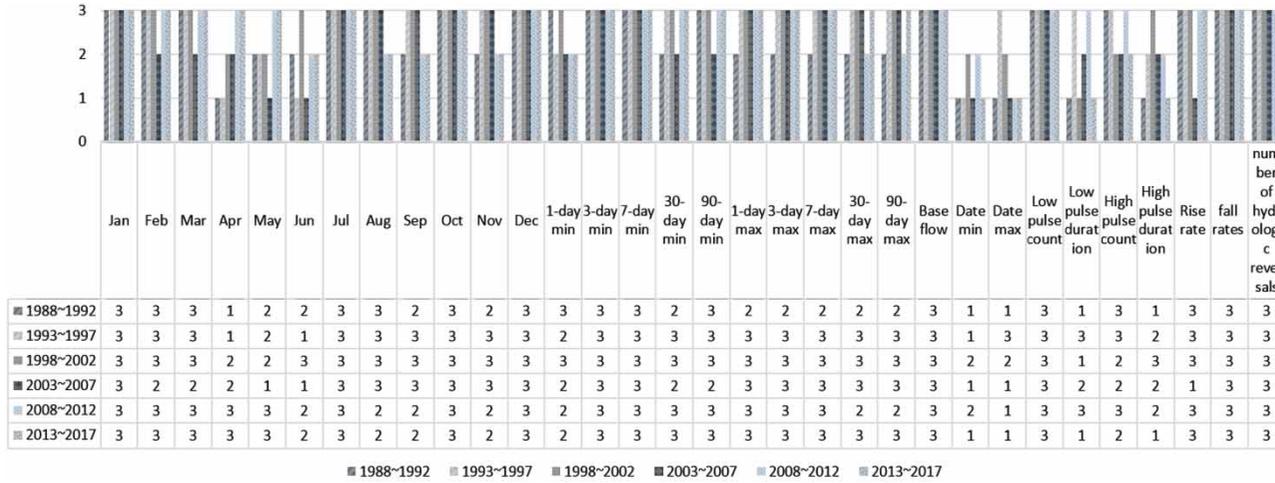


Figure 3 | The hydrological alteration of the 32 IHA indicators in six periods.

OHAD

If the IHA indicators in Table 2 are used to define A, the HA in Figure 3 defines B, and the connection degree of pair (A, B) is then calculated, the OHAD of the hydrological flow is determined as shown in Table 3.

Analyzing the trend characteristics of a and c (as shown in Figure 4), these trends will increase μ and improve the OHAD.

Predictions of the dynamic evaluation model

According to Equations (8), (9), and (10), the state transition probability matrix through the six periods during the postimpact period is as follows:

$$P_{1-2} = \begin{bmatrix} 0.808567 & 0.1914334 & 0 \\ 0.703348 & 0.176253 & 0.1203989 \\ 0.47088 & 0.0825899 & 0.4465305 \end{bmatrix}$$

$$P_{2-3} = \begin{bmatrix} 0.849982 & 0.1206846 & 0.0293333 \\ 0.531291 & 0.4687091 & 0 \\ 0.365247 & 0.6347534 & 0 \end{bmatrix}$$

$$P_{3-4} = \begin{bmatrix} 0.710782 & 0.1858141 & 0.1034042 \\ 0 & 0.228997 & 0.771003 \\ 0 & 1 & 0 \end{bmatrix}$$

$$P_{4-5} = \begin{bmatrix} 0.607571 & 0.3924294 & 0 \\ 0.624461 & 0.3755393 & 0 \\ 0.341982 & 0.3852036 & 0.2728146 \end{bmatrix}$$

$$P_{5-6} = \begin{bmatrix} 0.947695 & 0.0095863 & 0.0427184 \\ 0.080661 & 0.7706587 & 0.1486805 \\ 0 & 0 & 1 \end{bmatrix}$$

Assuming that the weight of the above state transition probability matrix is the same, the average state transition probability matrix is calculated as:

$$\bar{P} = \begin{bmatrix} 0.7849192 & 0.17999 & 0.035091 \\ 0.3879521 & 0.404031 & 0.208016 \\ 0.2356216 & 0.420509 & 0.343869 \end{bmatrix}$$

Table 3 | The OHAD of the hydrological flow

Periods	1988-1992	1993-1997	1998-2002	2003-2007	2008-2012	2013-2017	Average
a	0.204	0.153	0.023	0.265	0.072	0.153	0.145
b	0.385	0.159	0.246	0.215	0.387	0.303	0.283
c	0.411	0.688	0.731	0.520	0.541	0.544	0.572
μ	-0.207	-0.535	-0.708	-0.254	-0.468	-0.391	
OHAD	second level	second level	first level	second level	second level	second level	

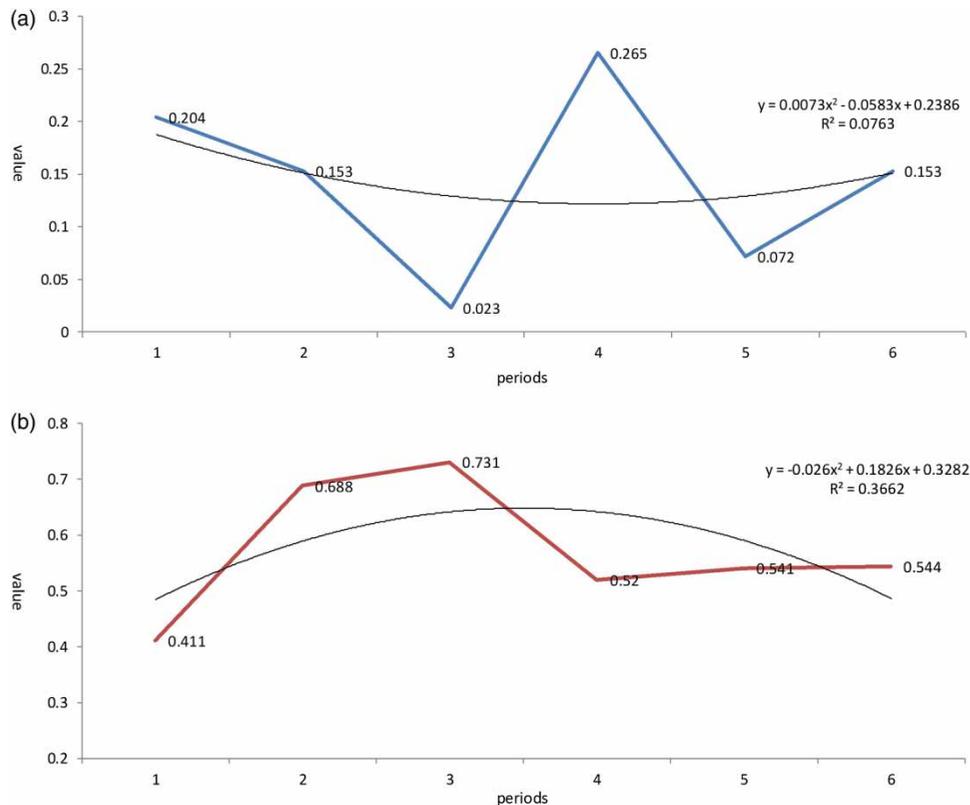


Figure 4 | The trend changes in a and c .

Assuming that the state transition probability matrix P remains unchanged, the connection degree of its stable state $(\hat{a}, \hat{b}, \hat{c})$ after a certain time can be written as:

$$\begin{cases} (\hat{a}, \hat{b}, \hat{c}) \begin{bmatrix} 0.215081 & -0.17999 & -0.03509 \\ -0.38795 & 0.595969 & -0.34387 \\ -0.23562 & -0.42051 & 0.656131 \end{bmatrix} = 0 \\ \hat{a} + \hat{b} + \hat{c} = 1 \end{cases}$$

Thus, $\hat{a} = 0.4269$, $\hat{b} = 0.3188$, $\hat{c} = 0.2543$, $\hat{\mu}_{A \sim B} = 0.1726$ and the OHAD still displays the third level.

CONCLUSIONS

Based on the RVA method and the SPA-MC method, a dynamic evaluation model of the OHAD caused by the Longyangxia reservoir is proposed. The main conclusions are drawn as follows:

- (1) The HADs of 32 IHA indicators in six periods during the postimpact period are variously different: some indicators have always been highly variable, while others change frequently between high, moderate and low states. Except for during the period of annual maximum flow, the reservoir has a strong impact on riverine flow conditions, especially for the IHA indicators in group 1 and group 2; thus, operation of the reservoir can worsen the original river habitat to some extent, and future operations should pay more attention to the hydrological parameters in these two groups to achieve greater ecological benefits.
- (2) By introducing the deviation in IHA indicators of the RVA into the AHP method, a more objective system of weighting indicators is established. Moreover, using the combined SPA and MC method, a dynamic evaluation model of HAD is built to provide a new procedure for evaluating reservoir management and guiding reasonable reservoir operation. This paper shows that the OHAD in the Longyangxia reservoir has been greater, and the

contrary has always been greater than the identity in the past six periods. The contrary and the identity have a favorable trend in the mid and late periods.

- (3) Riverine flow changes caused by the Longyangxia reservoir show a good development trend, and the connection degree of its stable state is 0.1276, and the OHAD of its stable state is at third level.

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