Journal of
Water & Climate Change

IWA PUBLISHING

Journal of Water and Climate Change Vol 14 No 10, 3596 doi: 10.2166/wcc.2023.210

Analysis of hydrological regime evolution and ecological response in the Min River, China

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ABSTRACT

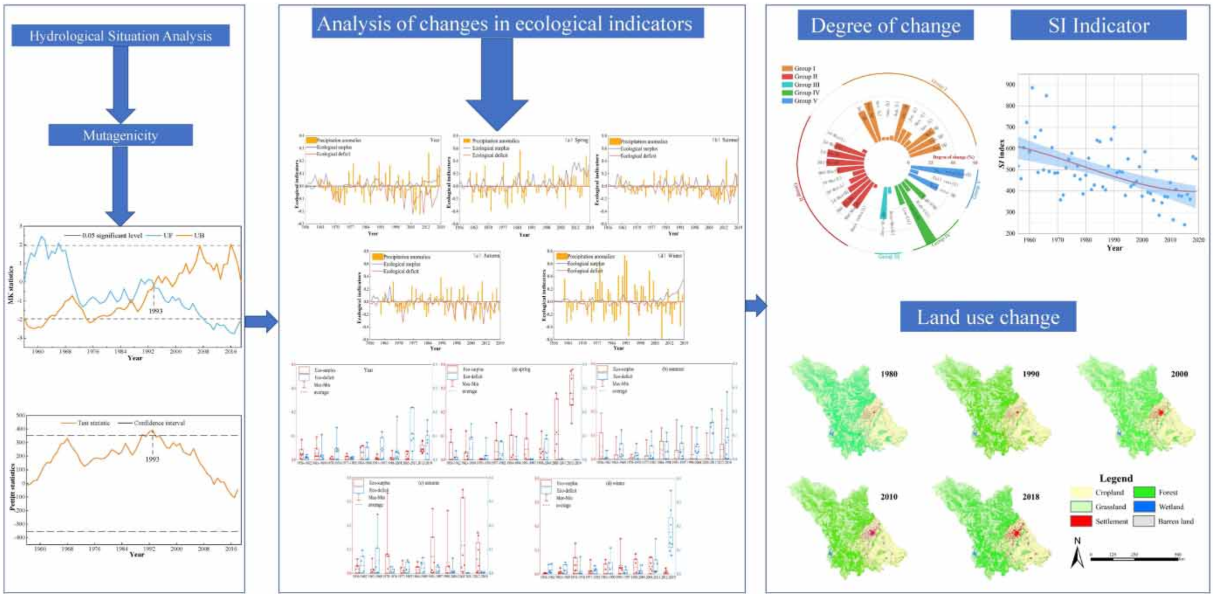
Natural fluctuation of the hydrological regime is the key to maintaining river ecosystem function. Given the shortcomings of previous studies on hydrological regime change and the ecological response of the Min River, this study combined two change degree evaluation methods and Budyko theory to quantify the degree of ecohydrological change and its driving factors. Ecological significance indicators (ecosurplus and ecodeficit) and the Shannon index (SI) were used to identify the characteristics of ecohydrological variation and ecological response mechanisms. The results showed the following: (1) The hydrological regime in the Min River basin had an abrupt change in 1993, with the overall alteration degree reaching 44%, which further led to a decrease in ecological surplus and an increase in the ecological deficit in ecological indicators. (2) Budyko's theoretical results show that climate change and human activities together lead to an 83.83 mm reduction in Min River runoff, with human activities contributing 54.20% of the change in the mean annual runoff, while rainfall and evapotranspiration contribute 43.88 and 1.92%, respectively. (3) The SI index indicates a decreasing trend in Min flow biodiversity. The results of the study can provide a reference for enhancing ecological protection and restoration in the Min River basin.

Key words: attribution analysis, Budyko, ecological response, ecosurplus and ecodeficit, IHA-RVA method, Min River

HIGHLIGHTS

- Quantitative assessment of the overall degree of change in the hydrological situation of the Min River.
- Quantitative assessment of the hydrological situation of the Min River using ecohydrological indicators (ecosurplus, ecodeficit).
- Quantitative analysis of the contribution of climate change and human activities to the hydrological changes of the Min River.

GRAPHICAL ABSTRACT



1. INTRODUCTION

The river's hydrological regime is the key index to ensuring the ecological function of the river. It can maintain the sustainable development and utilization of water resources and is also the basis for the survival, reproduction, and development of many organisms (Zalewski 2000; Sun *et al.* 2014). In recent years, many factors such as climate change and human activities have led to the degradation of river ecological functions, especially the construction of large water conservancy projects such as reservoirs and dams, which have significantly changed the hydrological regime in the Min River basin and further affected the stability and health of the hydrological regime in the upper reaches (Zhang *et al.* 2016; Sun *et al.* 2019; Bo *et al.* 2020). Therefore, it is important to evaluate the changes in the hydrological system in tributary watersheds and analyze the ecological response.

Currently, scholars at home and abroad have had a lot of discussions on the quantitative analysis of river hydrological regimes; there are more than 170 indicators describing river ecological flow (Girolamo *et al.* 2017; Zhuo *et al.* 2021). Richter *et al.* (1996) proposed the indicator of hydrologic alteration (indicators of hydrologic alteration [IHA]), which is the most widely used. The indicator system contains 33 indicators divided into five groups (flow, event, frequency, duration, and rate of alter) and further simplifies the common 170 hydrological indicators. It uses alterations in the river flow and the degree of external ecological change to determine the overall degree of alteration in the basin. Later, to better measure the level change, Richter *et al.* (1998) put forward the range of variability approach (RVA) method for a single variable and comprehensive hydrology change evaluation. Lv *et al.* (2020) made a comprehensive assessment of the changes in sediment transport and runoff caused by reservoir construction in the Min River basin and concluded that the hydrological regime changes in the basin were related to reservoir construction. Although the 33 indicators have been greatly simplified, the correlation between the indicators has not been well solved and cannot reflect the specific changes in ecological flow in the river channel. To solve this problem, Vogel *et al.* (2007) evaluated the surplus and deficit of river flow based on the dimensionless ecological index analysis (ecological surplus and ecological deficit) of the flow duration curve (FDC) and established targets and thresholds for each index (25th percentile and 75th percentile). Zhang *et al.* (2015) evaluated the change process of total surplus and deficit ecological water demand targets in the Dongjiang River basin after being affected by the reservoir based on ecological index analysis. In addition, Black *et al.* (2005) developed D_0 (degree of hydrologic alteration) and DHRAM (Dundee hydrological regime assessment method) to evaluate the degree of overall change of the reservoir to river flow and the risk of causing river ecosystems.

The attribution analysis of river hydrological regime evolution is a key link in the global assessment of river hydrological status. On the basis of Budyko's theory, Choudhury (1999) and Yang *et al.* (2008a, 2008b) proposed a coupled water–heat balance equation in the basin and divided the impact of climate change into rainfall and potential evaporation to more accurately and easily study the contribution rate of climate change and human activities to watershed runoff change over a long time series. The impact of river hydrological regime changes on biodiversity is an important objective of ecosystem assessment (Vilardy *et al.* 2011; Bing *et al.* 2022). Yang *et al.* (2008b) proposed the biodiversity index (SI) concept, which has been widely applied in river ecology. Pettersson (1998) further proved that SI is a convenient and reliable method to test the change in biodiversity. YongWei *et al.* (2021) used the Budyko hydrothermal coupling balance equation and biodiversity index (SI) to analyze the attribution and ecological impact of Dongting Lake. It was found that the main reason for the change in the hydrological regime in Dongting Lake was the influence of human activities (50–60%), and rainfall and evaporation were secondary (20–30%).

Different scholars have achieved good results in evaluating the hydrological conditions of different river basins using different hydrological evaluation methods. However, the evaluation of the Min River hydrological situation by many scholars is limited to the analysis of the degree of hydrological change and lacks a quantitative analysis of the attribution and ecological response to the change in the Min River hydrological situation. In this article, based on the quantitative analysis of the degree of hydrological change in the Min River, a suitable hydrological research method is selected to quantitatively evaluate the attribution and ecological response to the change. A comprehensive assessment of the hydrological changes in the Min River is carried out in the logical sequence of 'abrupt points analysis – hydrological change analysis – attribution analysis – ecological response analysis'. Specifically, the following five aspects were identified: (1) The Mann–Kendall and Pettitt tests were used to find out the abrupt runoff points under the natural flow patterns of the middle Gaochang station in the Min River basin, study the trend of runoff change, and analyze the influence of runoff on ecological indicators in different periods before and after the abrupt runoff points. (2) Ecological index analysis (ecosurplus and ecodeficit) and the hydrological change index (IHA) were adopted to evaluate the hydrological situation in this region. (3) A quantitative evaluation was made on the change degree of the hydrological regime in the Min River by combining DHRAM and D_0. (4) Using the Budyko hydrothermal coupling equilibrium theory, the attribution analysis of hydrological regime changes in the Min River was carried out. (5) Use the biodiversity index (SI) to assess and analyze the ecological response of the Min River.

2. RESEARCH AREA AND DATASETS

2.1. Study area

The Min River is an important tributary in the upper reaches of the Yangtze River originating at the southern foot of Minshan Mountain. The total watershed area is 1.35×10^5 km^2, while the total length of the mainstream channel is 735 km, and the natural drop is 3,560 m. The annual average total water resources of the whole basin are 9.5×10^{10} m^3 (Wenxian *et al.* 2022a). The Min River as the most important water resource in Chengdu Plain has provided basic support for the formation of the 'Land of Abundance'. However, the construction of large water conservancy projects in the upper reaches and frequent human activities have changed the characteristics of water resource distribution in the Min River basin and the natural hydrological regime in the lower reaches of the Min River (Mittal *et al.* 2016). The most influential ones are Zipingpu Reservoir with its annual regulation capacity and Pubugou Reservoir with its seasonal regulation capacity on the Dadu River (Xu 2007). Gaochang station is located in Gaochang Town, Yibin City, at the junction of the Dadu River and Min River, which is considered to be the largest tributary of the Min River basin, accounting for half of the Min River basin's water content (Xiao *et al.* 2022; Zhou *et al.* 2022). Gaochang station is the control station for the outlet reach of the lower Min River. The hydrological regime changes are very representative of the study of the whole Min River basin.

2.2. Data source

In this article, daily runoff data from 1956 to 2019 were used from the 'Yangtze Basin Hydrological Yearbook'. The daily monitoring data of 14 meteorological stations in Dujiangyan, Yibin, Neijiang, Leshan, and Xiaojin during 1956–2019 were selected (data from 14 meteorological stations were processed by summing and averaging), and the data were obtained from the website of China Meteorological Data (http://data.cma.cn/). The distribution of the hydrological stations and 14 meteorological stations in the Min River basin map is shown in Figure 1.

3. METHODS

3.1. Mann–Kendall and Pettitt mutation test

The Mann–Kendall test is widely used to test the trend of long time series of precipitation, runoff, temperature, and other data, with a wide range of tests and simple calculations (Hamed & Rao 1998; Gajbhiye *et al.* 2016; Hu *et al.* 2020). The test steps are as follows:

(1) Set the time series $\{X_t\}$ and the observed value series $\{x_t, t = 1,2\ldots,n\}$, construct order column:

$$s_k = \sum_{i=1}^{k} r_i \quad (k = 2, 3, \cdots n) \qquad r_i = \begin{cases} +1 & x_i > x_j \\ 0 & \text{else} \end{cases} \quad j = 1, 2, \cdots, i \tag{1}$$

(2) Under the assumption of random independence of time series, the statistic is defined as follows:

$$\mathrm{UF}_k = \frac{[s_k - E(s_k)]}{\sqrt{\mathrm{Var}(s_k)}} \quad (k = 2, 3, \cdots n) \tag{2}$$

In this aforementioned formula, 'UF_k' is the statistic of the standard normal distribution; '$E(s_k)$' is the average of s_k; and '$\sqrt{\mathrm{Var}(s_k)}$' is the variance of s_k, where $\mathrm{UF}_1 = 0$, $x_1, x_2\ldots, x_n$ is mutually independent and continuously identically distributed:

$$E(s_k) = \frac{n(n-1)}{4} \tag{3}$$

$$\mathrm{Var}(s_k) = \frac{n(n-1)(2n+5)}{72} \tag{4}$$

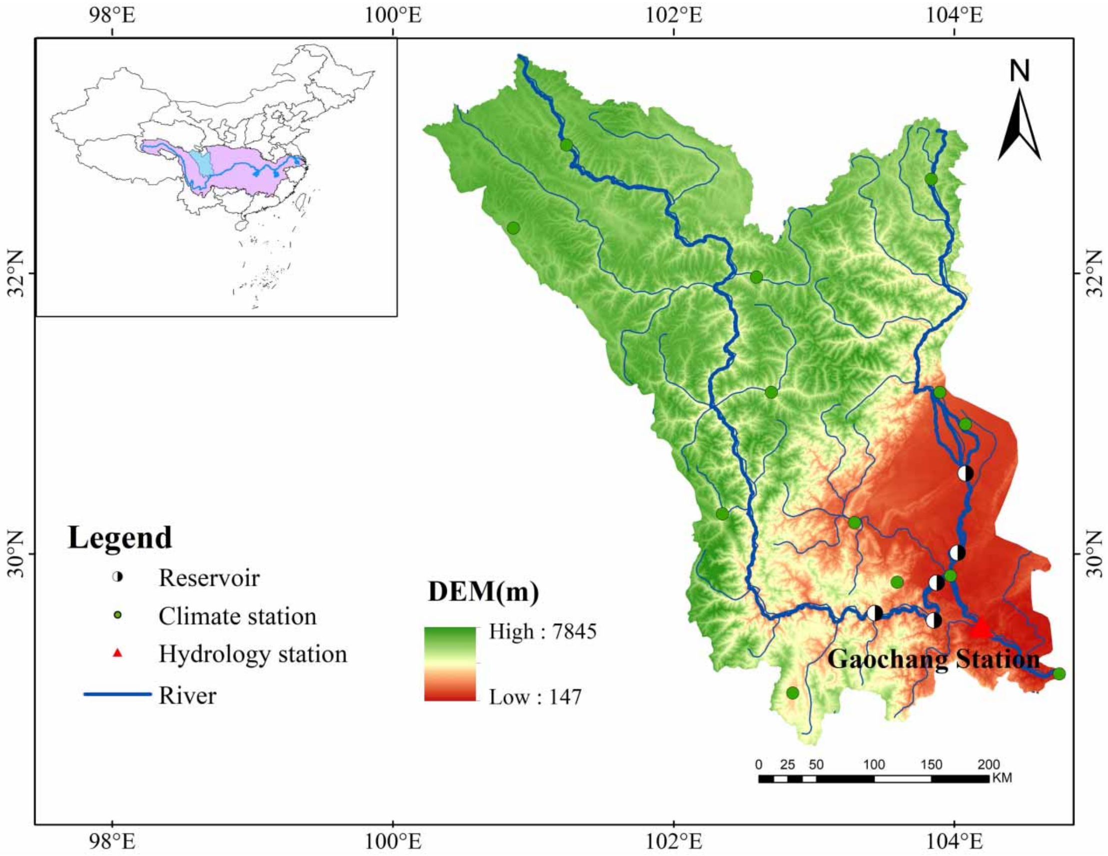


Figure 1 | Overview map of the Min River basin.

(3) Arrange the time series x in reverse order and repeat (1) and (2), while making:

$$\mathrm{UB}_k = -\mathrm{UF}_k \quad (k = n, n-1, \cdots, 1) \tag{5}$$

where $\mathrm{UB}_1 = 0$, by analyzing statistical sequences UB_k and UF_k, the time node of mutation of sequence x can be further analyzed to show the mutation region. If the UB_k and UF_k curves intersect, and the intersection is between the two critical lines, then the moment corresponding to the intersection is the moment when the mutation begins.

The Pettitt test is a method based on the Mann–Whitney nonparametric test. This method can obtain abrupt change points through abrupt change analysis on the sequence of hydrometeorological elements and quantify the statistically significant level of abrupt change points (Sun & Feng 2013; Mallakpour & Villarini 2016; Wang *et al.* 2016). The Mann–Whitney nonparametric statistic is expressed as follows:

$$U_{t,N} = U_{t-1,N} + \sum\nolimits_{i=1}^{n} \mathrm{sgn}(x_t - x_i) \qquad t = 2, 3, 4, \cdots n \tag{6}$$

According to the statistics, it can be calculated as follows:

$$K_{t,N} = \max|U_{t,N}| \quad (1 \le t \le N) \tag{7}$$

$$p = 2\exp\left[-6K_{t,N}^2/(N^3 + N^2)\right] \tag{8}$$

In general, when $p \leq 0.05$, it is considered that there are mutation points in the data.

3.2. Analysis of ecological indicators

Vogel *et al.* (2007) proposed ecological indicators (ecosurplus and ecodeficit) based on the FDC, which is used to evaluate the flow pattern changes of ecological river channels in the basin. The curve is composed of daily flow data and excess probability, whose excess probability is expressed as follows:

$$P_i = i/(n+1) \tag{9}$$

where n is the total number of days in a descending order of daily traffic data and i is the rank order.

Annual and seasonal FDC curves can also be constructed by using the daily runoff data. Gao *et al.* (2012) proposed 75 and 25% quantiles as thresholds. The critical range of river ecological health protection was defined, and the period before hydrological variation was taken as the baseline. The area bounded by a given annual or seasonal FDC and an FDC above the 75th percentile is defined as an ecological surplus, and the area bounded by a given annual or seasonal FDC and an FDC below the 25th percentile is defined as an ecological deficit (Figure 2). A river health system is considered to be in the healthy range if the river ecosystem lies between the 25th and 75th percentile of the FDC (Wang *et al.* 2017). In this study, the area below the 75th percentile FDC and the 25th percentile FDC was normalized to eliminate the effect of a large order of magnitude differences.

3.3. Evaluation of hydrological change degree

Richter *et al.* (1996) put forward the hydrological regime change index (IHA) to reflect the river ecohydrological regime, including five indicators from discharge, event, frequency, duration, and rate of change (Table 1), which can quantitatively analyze the degree of influence of climate change and human activities on the hydrological regime of the Min River and provide a basis for estimating the river ecological flow sequence.

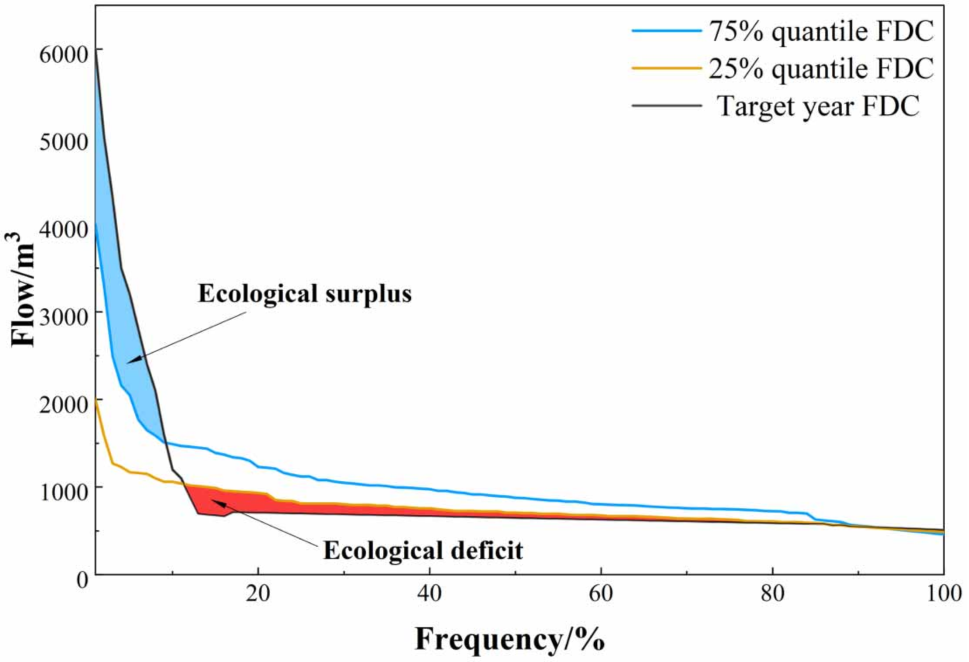


Figure 2 | Definition of ecological surplus and ecological deficit based on FDC.

Table 1 | Indexes of IHA

Group	IHA parameters	Parameter index description
1	Median month ($m^3 \cdot s^{-1}$)	Median monthly streamflow
2	Annual pole size ($m^3 \cdot s^{-1}$)	Annual average 1, 3, 7, 30, 90-day minimum and maximum streamflow (sand content), baseflow index[a]
3	Time of occurrence of annual extreme value condition (ds)	The date on which the maximum and minimum 1 day of the year occurs (Roman day)[b]
4	Frequency and duration of high and low pulses (times)	Number of high and low pulses per year[c] and an average of pulse durations
5	Rate and frequency of alteration in conditions($m^3 \cdot d^1$)/(times)[d]	Median annual values of increase (rate of increase) and decrease (rate of decrease) and number of reversals[e]

[a] The ratio of the annual minimum continuous 7-day streamflow to the annual median.

[b] Roman day indicates the number of days in the calendar year.

[c] Low pulse is defined as the median of the day lower than 25% of the frequency before the disturbance, and high pulse is defined as the median of the day higher than 75% of the frequency before the disturbance.

[d] The units of rise rate and fall rate are $m^3 \cdot d^{-1}$, and the unit of number of reversals is 'times'.

[e] The number of reversals refers to the number of times the daily streamflow turns from increasing to decreasing or decreasing to increasing.

Richter *et al.* (1998) proposed the variation range method (RVA) based on IHA to assess the change in the river hydrological regime. For the change degree of a single hydrological index (Di), the following formula is used to calculate it:

$$D_i = \frac{P_0 - P_e}{P_e} \times 100\% \tag{10}$$

$$P_e = rP_t \tag{11}$$

where D_i is the change degree of the ith index; P_0 and P_e represent the actual number of years and the predicted number of years when the ith index falls within the RVA threshold, respectively; 'r' is the proportional coefficient, usually 50%; P_t represents the total number of years after being affected.

$$D_0 = \left(\frac{1}{32}\sum_{i=1}^{32} D_i^2\right)^{0.5} \tag{12}$$

where to objectively describe the change degree of each hydrological index, the value of D_0 is divided into three stages: less than 33% is unchanged or low change; 33–67% are moderate changes, and more than 67% are height changes.

Black *et al.* (2005) proposed another hydrological change index (DHRAM), which aims to assess the degree and scope of hydrological regime change caused by human activities. Each of the 32 hydrological indicators for the IHA produces an absolute percentage change in the mean and an absolute percentage change in the coefficient of deviation. DHRAM has reassigned the weight of the hydrological indicators based on the IHA hydrological indicators. The degree of change was divided into three levels: 1 for low change, 2 for moderate change, and 3 for high change. DHRAM classifies the impact degree into five levels (Table 2). According to the score calculated by DHRAM, higher score values indicate higher levels of hydrological change and a greater likelihood that ecosystems will be at risk. The combination of DHRAM and D_0 is used to assess the degree of change in the hydrological situation (Dyer *et al.* 2014; Lu *et al.* 2018; Xiaoming *et al.* 2021).

3.4. Budyko hydrothermal coupling equilibrium theory

For attribution analysis of runoff change, Budyko hydrothermal coupling balance theory was adopted in this article, and the long-term water balance of the basin is expressed as follows:

$$R = P - E - \Delta S \tag{13}$$

Table 2 | Classification of DHRAM

Grade	Score range	Description
1	0	No impact
2	1–4	Low impact
3	5–10	Moderate impact
4	11–20	Highly impact
5	21–30	Serious impact

where R is the average runoff depth (mm), P is the average precipitation (mm), E is the average actual evaporation (mm), and ΔS is the change in water storage (mm). In the long-term runoff change, ΔS is 0.

Choudhury (1999) and Yang *et al.* (2008a, 2008b) derived the water balance equation on an annual average scale based on Budyko's hypothesis, combined it with an empirical formula for annual evaporation, and applied dimensional analysis and mathematical statistics.

$$R = P - \frac{P \times ET0}{(P^{n} + ET_0^{n})^{1/n}} \tag{14}$$

where n represents the characteristic parameters of the subbasin of the basin. Given R, P, and ET_0, n can be derived.

Because P, ET_0, and n are independent variables, the total differential form of annual runoff is expressed as follows:

$$dR = \frac{\partial R}{\partial P}dP + \frac{\partial R}{\partial ET_0}dET_0 + \frac{\partial R}{\partial n}dn \tag{15}$$

The sensitivity of runoff R to each factor can be expressed by the elastic coefficient as follows:

$$\varepsilon_x = \frac{\partial R}{\partial x}\frac{x}{R} \tag{16}$$

where x can be expressed as P, ET_0, or n.

Assumption: Then, the elastic coefficient is calculated as follows:

$$\varepsilon_{\mathrm{P}} = \frac{(1+\varphi^{n})\frac{1}{n+1} - \varphi^{n+1}}{(1+\varphi^{n})\left[(1+\varphi^{n})\frac{1}{n} - \varphi\right]},\ \varepsilon_{\mathrm{ET_0}} = \frac{1}{(1+\varphi^{n})\left[1-(1+\varphi^{-n})\frac{1}{n}\right]},\ \varepsilon_{n} = \frac{\ln(1+\varphi^{n}) + \varphi^{n}\ln(1+\varphi^{-n})}{n\left[(1+\varphi^{n}) - (1+\varphi^{n})\frac{1}{n+1}\right]} \tag{17}$$

According to the elastic coefficient of runoff for each influence factor, the variation in runoff depth caused by the corresponding factor can be calculated:

$$\Delta R_x = \varepsilon_x \frac{R}{x}\Delta x \tag{18}$$

The obtained additive sum calculated the runoff depth variation$\Delta R'$, which are expressed as follows:

$$\Delta R' = \Delta R_P + \Delta R_{\mathrm{ET_0}} + \Delta R_n \tag{19}$$

The contribution rate of each factor to runoff change is calculated according to the following formula:

$$\eta_p = \frac{\Delta R_p}{\Delta R'} \times 100\%$$
$$\eta_{\mathrm{ET}_0} = \frac{\Delta R_{\mathrm{ET}_0}}{\Delta R'} \times 100\% \tag{20}$$
$$\eta_n = \frac{\Delta R_n}{\Delta R'} \times 100\%$$

3.5. Ecological response assessment

SI is widely used in the evaluation of ecological diversity (Kwang-Tsao *et al.* 2001):

$$\mathrm{SI} = -\sum_i p_i \times \log p_i \tag{21}$$

where p_i is the percentage of a kind of biota to the ith species.

A larger SI indicates higher ecological diversity. Yang *et al.* (2008b) proposed the SI index. Based on the IHA index, the regression equation of the biodiversity index and the IHA index was constructed by the genetic programming method:

$$\mathrm{SI} = \frac{D_{\min}/\mathrm{Min7} + D_{\min}}{W_3 + W_5 + \mathrm{Min3} + 2 \times \mathrm{Max3}} + R_{\mathrm{rate}} \tag{22}$$

where $D_{\min}$ is the Julian day with the minimum water level; W_3 and W_5 are the average flows in March and May, respectively; Min3 and Min7 are the minimum annual average flows of 3 and 7 days, respectively; Max3 is the maximum annual 3D average flow; R_{rate} is the rate of water rise.

4. RESULTS AND ANALYSIS

4.1. Test and analysis of annual mean flow mutation

The trend and mutation point of runoff at the Gaochang station from 1956 to 2019 were calculated (Figure 3) using the Mann-Kendall (MK) trend test. The analysis results showed that, at the significant level of 0.05, the value of statistic Zc was −2.02, indicating that the runoff in this region showed a significant decreasing trend in this time series. The absolute

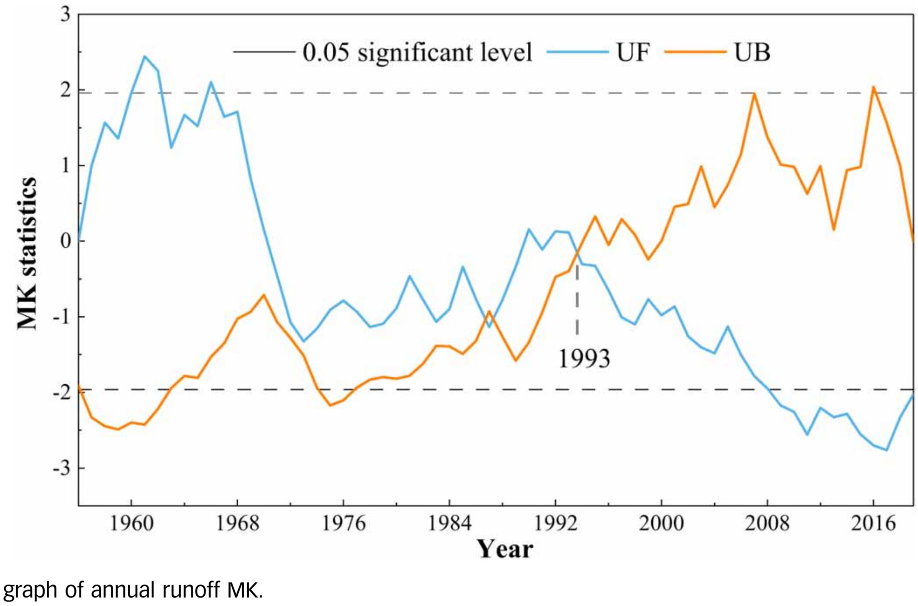


Figure 3 | Statistical graph of annual runoff MK.

value of *Zc* was greater than 1.96, indicating that it passed the 95% significance test. In this figure, there are three intersection points of the UF and UB curves, and the years of mutation are 1983 and 1987, respectively.

According to the calculation results of the Pettitt mutation analysis, the abrupt change test results of runoff at the Gaochang station from 1956 to 2019 were obtained (Figure 4). The value of '*p*' for the mutation test was 0.04 (less than 0.05), so a significant mutation occurred in this region, and the significant mutation point occurred in 1993.

The combination of the Mann–Kendall test and the Pettitt test can accurately identify mutation points, solve the absence of mutation points, and improve the drawbacks of a single test method. Based on the two test methods, it was determined that 1993 was the hydrological variation year of the Min River. By analyzing the influence of human activities on runoff in this region before and after the abrupt change point, it can be seen that under the natural flow state (before 1993), the construction of reservoirs was few and slow, and most of them were small- and medium-sized reservoirs, which had a little change to the discharge of the Min River. In 1993, Tongjiezi Reservoir within the control range of the Min River basin was put into use, which significantly changed the hydrological sequence within the control area of the Gaochang station, resulting in abrupt changes in the annual discharge of the Gaochang station in the lower reaches of the Min River. After the sudden change (since 1993), the number of medium and large reservoirs continued to increase. In 2003, Pubugou Reservoir in the upper reaches of the Min River and Zipingpu Reservoir in 2005 was put into use, resulting in an increased average storage capacity far exceeding the sum of previous periods and forming a series of reservoirs. This indicates that the construction of large- and medium-sized reservoirs in the Min River basin has had a significant impact on the variation of its discharge since the 1990s.

4.2. Analysis of ecological index change

In the study of hydrological changes at Gaochang station, this article referred to the improvement made by Gao *et al.* (2012), took the year of abrupt change as the cutoff point, and took the daily discharge date at Gaochang station from 1956 to 1993 as the base period, representing natural runoff. On this basis, we obtained the long-term variation results of runoff at annual and seasonal scales at the Gaochang station from 1956 to 2019 (Figure 5). It can be seen that there is a significant correlation between the annual scale FDC ecological index and precipitation anomaly; the annual ecological surplus and precipitation anomaly present a significant positive correlation; while the annual ecological deficit and precipitation anomaly present a good negative correlation. At the seasonal scale, it can be seen that the correlation between runoff change and the ecological index is different in different seasons.

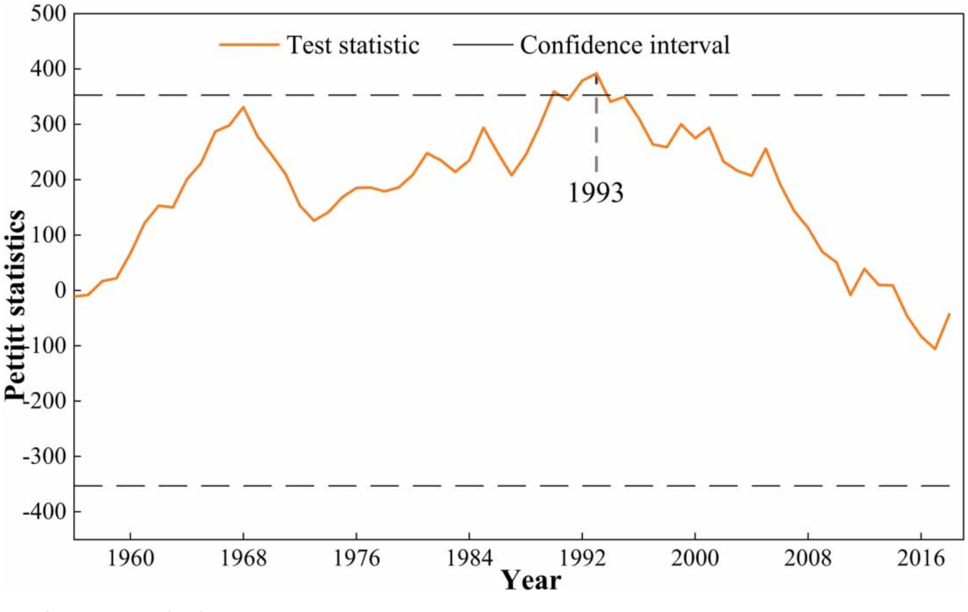


Figure 4 | Pettitt mutation test result plot.

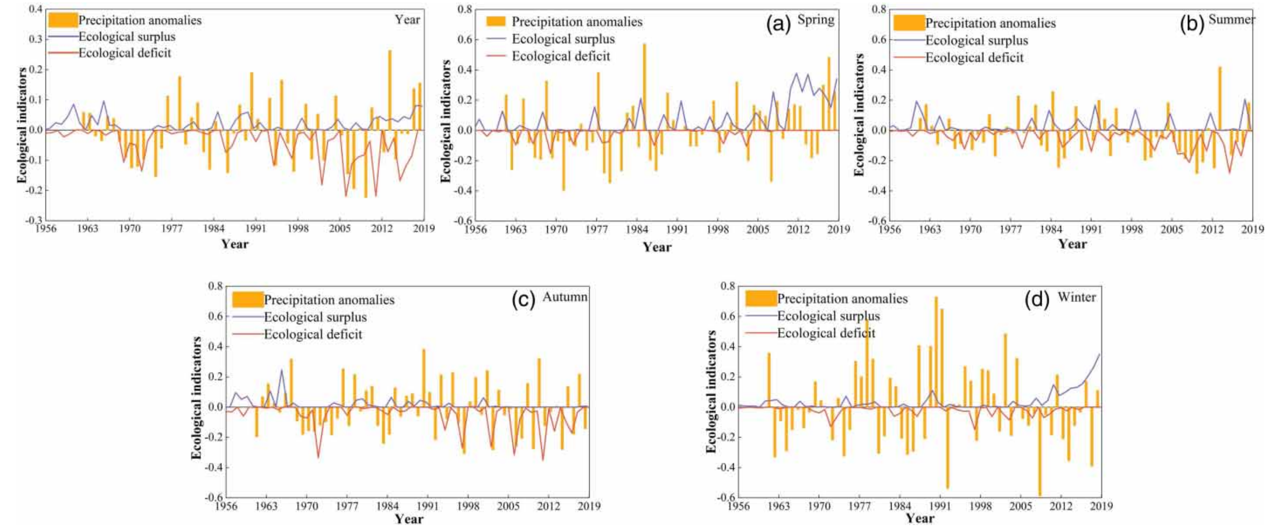


Figure 5 | Results of annual scale precipitation distance average and ecological indicators.

At the annual scale, the change range of the annual ecological surplus is small and presents a decreasing trend, while the change range of the annual ecological deficit is large and presents an increasing trend. In the period before and after the abrupt change, the ecological surplus was greater than the ecological deficit in the natural flow state during the period before the abrupt change (1956–1993), while in the period after the abrupt change (1994–2019), the ecological deficit was greater than the ecological surplus due to the influence of multiple factors such as climate change and human activities. The most obvious change was in the period 2005–2012 when the ecological deficit reached its highest (0.24). The main reason was that the runoff decreased due to less precipitation in this period, which led to an increase in the ecological deficit. In this way, it is confirmed that the ecological indicators and runoff changes caused by the precipitation anomaly have a significant synchronized change rule; that is, when the runoff increases, the ecological surplus increases, while when the runoff decreases, the ecological deficit increases.

At the seasonal scale, the FDC ecological indicators correlate differently with their precipitation spacing in different seasons. As shown in Figure 5, the precipitation distance level correlates best with the ecological indicator in any given period in summer and weakest in winter, with spring and autumn in between, because precipitation levels are much greater in summer than in winter, and when precipitation is high enough, precipitation can be a major factor in changing its flow. The results also show a concentration of peak ecological surpluses in 2000, 2006, and 2010, consistent with the annual variability results. These peaks occurred after the year of the abrupt change (1993), suggesting that climate change and human activities are interfering with changes in ecological flows in the basin. Compared to the sudden change period, it can be concluded that the ecological surplus shows an unusually increasing trend, especially in winter (2019 maximum value of 0.37) and spring (2012 maximum value of 0.41), which never occurred before the sudden change. Figure 5(b) also shows that precipitation patterns in summer are consistent with annual scale variability, while Figure 5(a)–5(d) show that precipitation in spring, autumn, and winter is less consistent with precipitation variability over the whole year, which together suggests that the variability of precipitation and ecological indicators in summer is most representative of the whole year.

Box plots were drawn to further show the relationship between annual and seasonal ecological indicators (Figure 6). We can see that there is a strong similarity between annual scale ecological indicators and summer ecological indicators from 1956 to 2019. The ecological deficit showed a trend of ‘high – low – high’, while the ecological surplus showed a trend of ‘low – high – low’. During 1960–1970, the ecological surplus was significantly larger than the ecological deficit. Especially from 1990 to 2010, the increase in the ecological deficit was the most obvious, which was related to the construction and use of reservoirs in the Min River basin. The main flood season in the Min River basin usually lasts from June to August, covering the whole summer. During this period, Pubugou Reservoir played an important role in flood control, while Zipingpu Reservoir played an auxiliary role. It can alleviate the trend toward a significant increase in the ecological deficit. After the flood season, to meet the water demand in the dry season, the cascade reservoir needs to be switched to storage, resulting

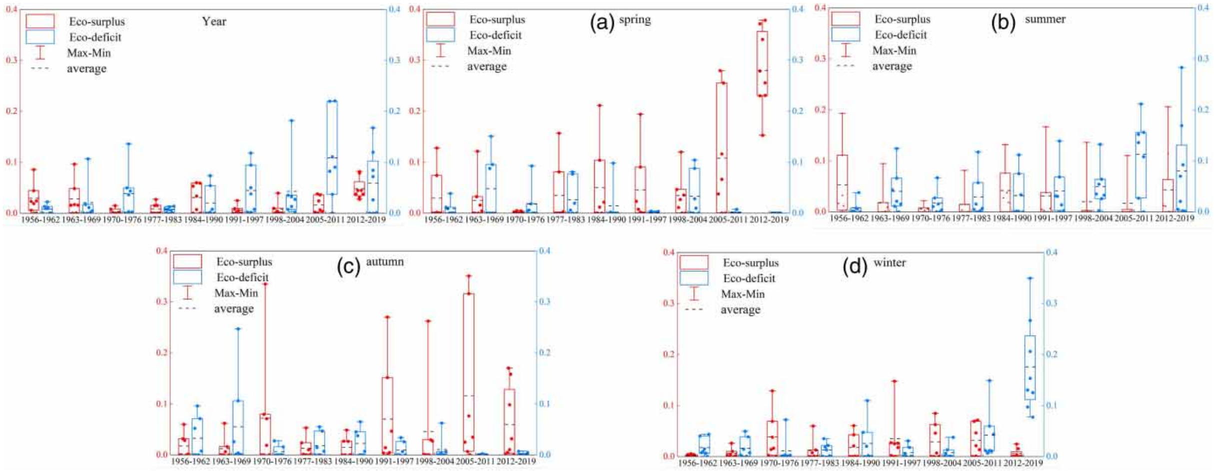


Figure 6 | Seasonal FDC ecological indicator change box diagram. **Note:* The edge of the box is the 25th percentile and 75th percentile of the ecological indicators.

in the ecological deficit continuing to fluctuate. Due to the water replenishment of the reservoir, the runoff keeps increasing, resulting in the ecological deficit in the dry season (winter and spring) staying around zero during the whole adjustment period. Based on the aforementioned ecological index analysis, it is further verified that precipitation is the main factor affecting runoff change at the annual scale. At the seasonal scale, the operation of the reservoir and the existence of a tandem reservoir are the main factors affecting the runoff change.

4.3. Analysis of overall hydrological change

In the analysis of the degree of change of hydrological indicators, the RVA method was used to obtain quantitative results for the degree of change of hydrological indicators (Figure 7 and Tables 3 and 4). Among the 32 hydrological indicators, 14 were moderately changed and 14 were lowly changed, each accounting for 44%. There are four hydrological indicators with height changes, accounting for 12%. It can be seen that the change of hydrological indicators for the Min River is mainly dominated by moderate and low change, which further indicates that the hydrological situation of the Min River has undergone a significant change. Among the highly altered hydrological indicators, the largest degree of change in the rate of decline reached 100%. This is followed by the number of reversals, which reach 90%, which has a very negative impact on the ecosystem's response to external changes. Moderately changed hydrological indexes were as follows: minimum flow in January, February, July, September, November, and December; annual average 3-, 30-, and 90-day minimum flow; annual average 1- and 90-day maximum flow; fundamental current index; and several high and low pulses. The remaining hydrological indicators were all low-level changes.

Two calculation methods, DHRAM and D_0, were used to obtain the results of the hydrologic change degree (Table 5). From the overall score and results of DHRAM, the total DHRAM score of the Gaochang station was three points, and the change level was 2, which belonged to a low change degree; D_0 was 45%, which belonged to a moderate change degree. Considering that the proportion of moderate and low changes among the 32 hydrological change indicators in the IHA was 44%, the degree of hydrological regime change in the Gaochang was determined to be a moderate change by combining the results of the two methods.

4.4. Budyko result analysis

The attribution analysis of the change in the hydrological situation of the Min River mainly adopts the Budyko hydrothermal coupling balance theory. We obtain the calculation results of the multiyear average rainfall, multiyear average potential evapotranspiration, multiyear average runoff depth, underlying surface parameters n, rainfall, evaporation, and elastic coefficients of human activities in the Min River basin (Table 6).

According to the calculation results, compared with before the dam construction, P, R, and ET_0 in the Min River basin decreased after the dam construction, with a rate of 8.44, 7.75, and 1.54%, respectively. n is increased, and the growth

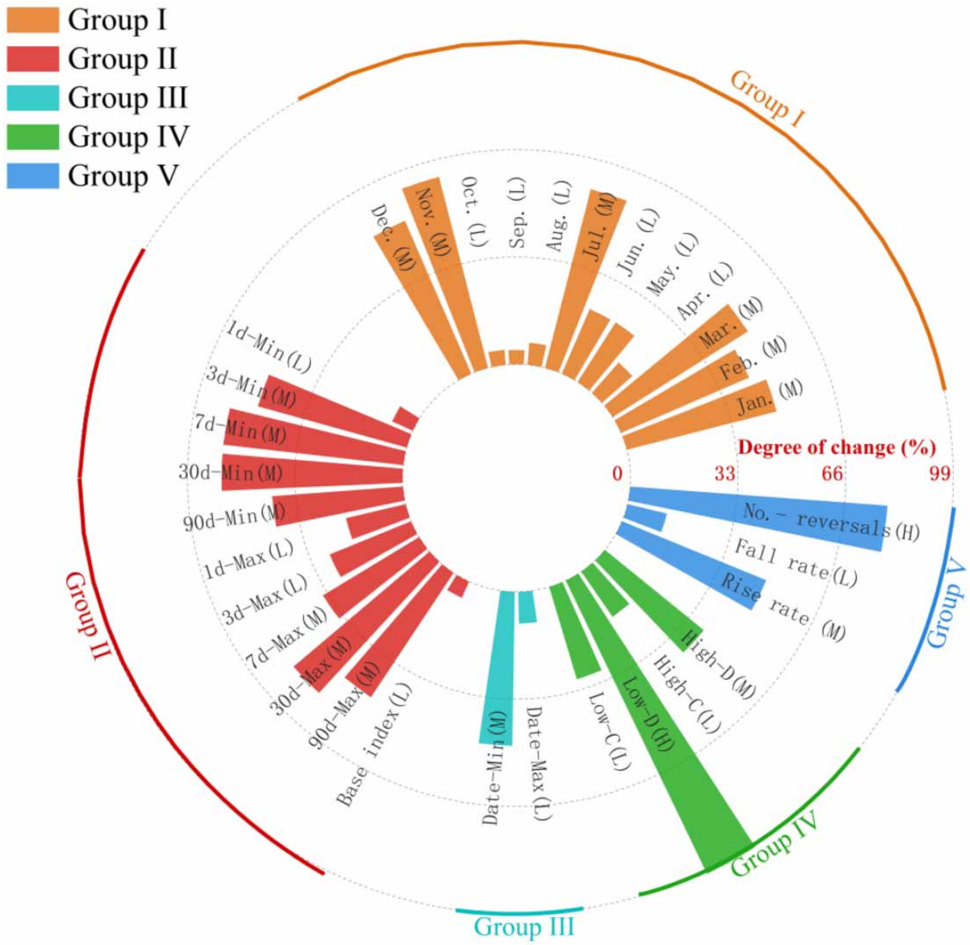


Figure 7 | Schematic diagram of the degree of hydrological change of the Min River.

rate was 47.33%. The dryness index (ET_0/P) and runoff coefficient (R/P) increased slightly compared with the base period. The elastic coefficients of runoff on rainfall, potential evaporation, and underlying surface parameters after dam construction in the Min River basin are 1.53, −0.40, and −0.31, respectively, indicating that when rainfall, potential evaporation, and underlying surface parameters increase by 1%, the runoff depth will increase by 1.53%, decrease by 0.40%, and decrease by 0.31%, respectively. The change in the runoff depth in the Min River basin is positively correlated with P but negatively correlated with ET_0 and n. As the absolute value of the elastic coefficient reflects the sensitivity of runoff to the influencing factors, the results show that runoff depth is most sensitive to the change in P and least sensitive to the change in n.

We further studied and obtained the contribution rate of each influencing factor to runoff change in the Min River basin (Table 7). The results show that the variation in runoff caused by rainfall is −83.83 mm. The potential for evapotranspiration increased to 3.68 mm in runoff depth. The underlying surface parameter resulted in a 103.54 mm decrease in runoff at the Gaochang station. The contribution rate of underlying surface parameter change to runoff change in the Gaochang station is the largest, which is 54.20%. The contribution rate of rainfall to the runoff change at Gaochang station was 43.88%. The contribution rate of potential evapotranspiration to runoff change at the Gaochang station was the lowest, which was 1.92%. Therefore, the change of the underlying surface parameter is the main factor leading to the decrease of runoff at the Gaochang station, followed by precipitation and the least by potential evapotranspiration.

4.5. SI indicator analysis

The ecological response assessment of hydrological regime changes in the Min River basin mainly analyzed the change in the flow biodiversity index and obtained the interannual variation results of the flow biodiversity index in the Min River from 1956 to 2019 by using the SI index analysis (Figure 8). According to the results of the method to detect Trend Free

Table 3 | Calculation results of ecohydrological indicators of Gaochang hydrological station

	Hydrological indicators	**Before the mutation**	**After the mutation**	**Degree of change**
1 group	Jan.	769.2	971.2	47% (M)
	Feb.	706.8	905.4	43% (M)
	Mar.	834.4	1,039	49% (M)
	Apr.	1,234	1,331	12% (L)
	May.	2,127	2,049	22% (L)
	Jun.	4,019	3,792	22% (L)
	Jul.	6,255	5,420	57% (M)
	Aug.	5,872	5,130A	7% (L)
	Sep.	4,973	4,063	4% (L)
	Oct.	3,263	2,845	5% (L)
	Nov.	1,821	1,678	61% (M)
	Dec.	1,129	1,218	51% (M)
2 groups	1 d-Min	557.8	617.2	7% (L)
	3 d-Min	606.9	675.3	47% (M)
	7 d-Min	633.9	731	56% (M)
	30 d-Min	680.1	828.7	56% (M)
	90 d-Min	766.5	617.2	40% (M)
	1 d-Max	17,050	675.3	19% (L)
	3 d-Max	13,230	731	27% (L)
	7 d-Max	10,450	828.7	34% (M)
	30 d-Max	7,410	959.1	55% (M)
	90 d-Max	5,922	13,260	46% (M)
	Base index	0.2312	0.2905	6% (L)
3 groups	Date-Min	50.26	56.77	47% (M)
	Date-Max	214.8	215.8	10% (L)
4 groups	Low-C	0.05263	0	30% (L)
	Low-D	1	0	100% (H)
	High-C	9.447	8.154	17% (L)
	High-D	5.493	4.312	39% (M)
5 groups	Rise rate	539.9	411.1	48% (M)
	Fall rate	−374.8	−355.9	12% (L)
	No. of reversals	138.4	184.3	79% (H)

Table 4 | Overall hydrological change of discharge sequence

	Hydrologic variation of each group of indicators					
Hydrographic station	**Group 1**	**Group 2**	**Group 3**	**Group 4**	**Group 5**	**Global hydrologic variation (D_o)**
Gaochang station	42 (M)	41 (M)	16 (L)	35 (M)	79 (H)	45 (M)

H indicates height change, *M* indicates moderate change, and *L* indicates low change.

Table 5 | The overall evaluation of hydrology alteration before and after completion of the reservoirs: DHRAM and D_o values

		Mean change ratio		**Influence number**			
Hydrographic station	**IHA grouping**	**Mean value**	**Coefficient of deviation (C_V)**	**Mean value**	**Coefficient of deviation (C_V)**	**Total points**	**D_o (%)**
Gaochang station	1	14.1	64.4	0	1	3 (4)	45
	2	25.3	67.5	0	0		
	3	2.1	18.9	0	0		
	4	45.1	55.4	1	1		
	5	20.7	25.2	0	0		

Table 6 | Hydrometeorological characteristic values of the Min River

Period	P/mm	ET_0/mm	R/mm	n	R/P	ET_0/P	ε_P	ε_{ET_0}	ε_n
Before dam construction	1,100.82	466.34	643.55	1.31	0.58	0.51	1.56	−0.39	−0.29
After dam construction	1,007.88	459.18	593.70	1.93	0.59	0.52	1.53	−0.40	−0.31

Table 7 | Attribution analysis of runoff change in the Min River basin

Hydrographic station	Base period	Change period	ΔR_P (mm)	$\Delta\Delta R_{ET_0}$ (mm)	ΔR_n (mm)	ΔR (mm)	C_P (%)	C_{ET_0} (%)	C_n (%)
Gaochang station	1956–1993	1994–2019	− 83.83	3.68	− 103.54	− 49.85	43.88	1.92	54.2

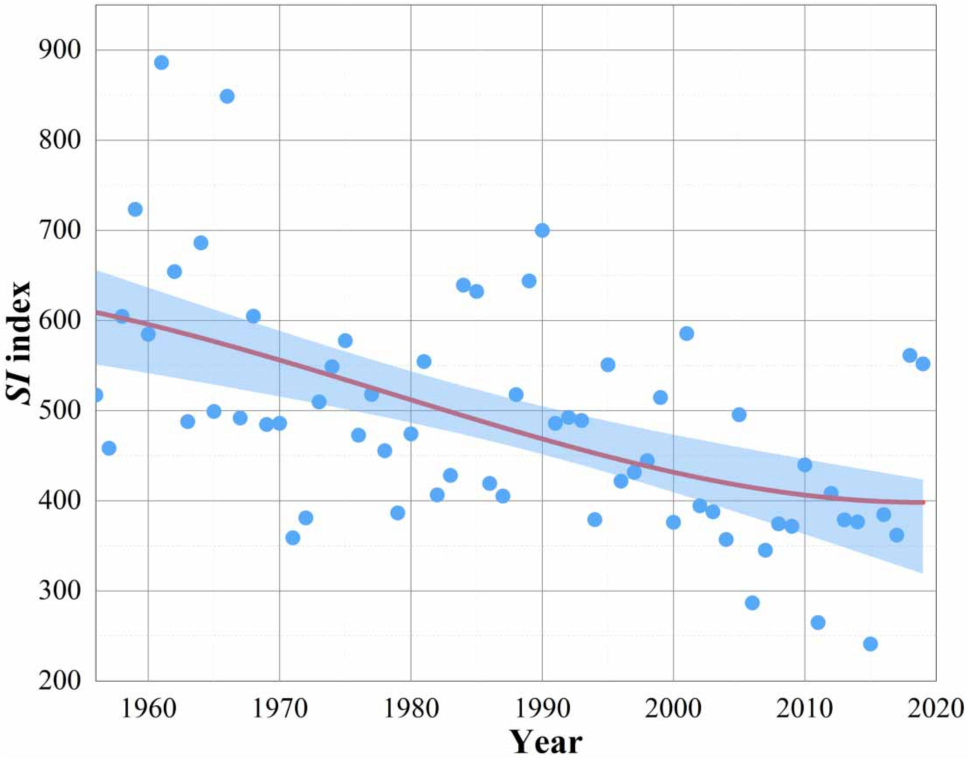


Figure 8 | SI index of the Min River.

Pre-Whitening (TRPW)-MK for flow biological diversity index, the standardization of test statistics $Z = 2.02$, $|Z| > 1.96$ (the critical value of alpha is 0.05) shows that traffic from 1956 to 2019 biological diversity index is on the decline and its significance.

We can see that under the natural flow regime (1956–1993), the declining trend of the Min River flow biodiversity index is in a stable change phase. In the posttransformation period (1993–2019), the decline in the Min flow biodiversity index accelerated slightly, followed by a slow change from 2010 onward. It can be shown that the construction of reservoirs under the influence of human activities has changed the hydrological situation of the Min River in its natural state, causing a further decrease in its biodiversity, but with the protection of the ecological environment in recent years, the decreasing trend of the biodiversity index has been alleviated, which also indicates that the protection of the Min River's biodiversity has played an important role.

5. DISCUSSION

5.1. Changes in the hydrological situation and attribution analysis

Quantitative analysis of the influence of climate change and human activities on hydrological regime change is not only a hot topic in the field of hydrology but also a difficult one (Wu *et al.* 2017; Li *et al.* 2020). As an important tributary of the Yangtze River basin, the Min River has been affected by multiple factors, such as climate change and human activities, for a long time, and its hydrological regime has changed significantly (Shao *et al.* 2021; Wang *et al.* 2022). Therefore, the change and attribution of the hydrological regime in the Min River are discussed in depth from five aspects: runoff change, interannual change, ecological index change, hydrological degree change, and Budyko change result.

This article used the MK and Pettitt tests to find that 1993 was the year of hydrological abrupt in the Min River. Before the abrupt change (before 1993), the runoff in the Min River basin was in a stable change stage; after the abrupt change (after 1993), the natural hydrological regime of the Min River changed significantly, and the runoff showed a downward trend. The attribution analysis proves that the construction of tandem reservoirs in human activities is an important factor leading to its change. We studied the relationship between ecological indicators and precipitation anomalies at the annual scale and the seasonal scale, respectively, and found that the annual scale FDC ecological indicators and precipitation anomalies showed a significant correlation, in which the ecological surplus increased with the increase of precipitation and decreased with the decrease of precipitation. At the seasonal scale, the relationship between ecological indices and precipitation anomaly changes in summer is most similar to that between annual changes, which is related to more precipitation in summer. By analyzing the attribution, we know that the change of runoff at the annual scale is mainly influenced by precipitation, and the change of runoff at the seasonal scale is mainly regulated by the reservoir. The combined effects of climate change and human activities lead to a decreasing trend of ecological surplus and an increasing trend of ecological deficit in the Min River basin. The overall change degree of the Min River hydrological regime reached 44%, which was a moderate change, indicating that the Min River ecosystem was facing a moderate risk of destruction. The Budyko results quantitatively analyzed the degree of each influencing factor on the runoff change, in which the change in rainfall caused the runoff decrease of 83.83 mm, and the change in the underlying surface parameter caused the runoff decrease of 103.54 mm. It can be seen that runoff changes are mainly affected by rainfall and underlying surface parameter changes, and with the rapid development of the social economy in recent years, underlying surface parameter changes have become an increasingly important factor affecting runoff changes.

To further discuss the rationality of the paper's conclusions on hydrological regime changes of the Min River and attribution, we further elaborate on the relevant conclusions of existing scholars on the Min River and other river basins. Du *et al.* (2022) made a systematic analysis of the precipitation of the Min River and observed that the precipitation of the Min River basin decreased year by year from 1956 to 2020 with a slight change rate of 1.028 mm/10a and showed a decreasing spatial distribution pattern from the southeast to the northwest. Zhao *et al.* (2020) evaluated the hydrological situation of Panzhihua Station based on the FDC ecological index and found that the main reason for the change in the hydrological situation at the seasonal scale was the influence of the reservoir, and for any season, the ecological surplus and ecological deficit showed a parabolic law of 'low-high-low'. Zhang *et al.* (2021) used the ecological runoff index system composed of a 12-month ecological surplus and a 12-month ecological deficit on the basis of a new evaluation method for hydrological regime change of the ecological runoff index and confirmed that each month before and after the reservoir construction would have varying degrees of influence on the change of the ecological runoff. Wenxian *et al.* (2022b) used Budyko to analyze the attribution of hydrological regime changes in the Jialing River and observed that the contributions of precipitation, potential evapotranspiration, and human activities to runoff changes were 61, −16, and 55%, respectively, among which precipitation and climate change were the main influencing factors. Duan *et al.* (2016) used the IHA-RVA method to study the hydrological regime changes in the middle and lower reaches of the Yangtze River and observed that the degree of hydrological change at Yichang Station was high, while that at Datong Station was moderate change. Guo *et al.* (2022) conducted a quantitative analysis of the hydrological regime of the Min River and observed that the degree of hydrological change was 45%, which was not much different from the results of the study in this article.

After further discussion of the changes in the hydrological regime of the Min River and its attribution, it is not difficult to find that the research results of this article are more comprehensive than the previous research results on the Min River basin. Previous research results have been limited to the analysis of the hydrological change of the Min River and have not quantitatively evaluated the contribution rate of climate change and human activities to the change in the hydrological regime. In this article, while calculating the contribution rate, the proportions of each impact factor are considered separately, which makes the research results more rigorous and scientific, and indirectly indicates that the research results in this article are more reasonable.

5.2. Ecological responses to changes in hydrological situations

Ecological response analysis is an important form of assessment to cope with the adverse effects of river hydrological regime changes on ecosystems (Döll & Zhang 2010; Alban *et al.* 2021). In this article, the SI index was used and it was found that the biodiversity index of the Min River was in stable change under the natural flow state. The biodiversity index decreased significantly with the influence of human activities after the mutation, and the more intense the interference of human activities, the faster the declining trend. The conclusion of this study is also confirmed by the research results of many researchers on the water environment, species diversity, and fish in the Min River. Chen *et al.* (2019b) observed that the ammonia nitrogen content in the Min River basin was low and showed a slowly increasing trend under natural hydrological conditions, and the water quality was good. However, the construction and use of reservoirs and the increase of ammonia nitrogen discharge by many enterprises along the Min River basin destroyed a natural hydrological regime, which led to the deterioration of the Min River's water environment. Chen *et al.* (2019a, 2019b) used the image element decomposition method to conclude that the overall vegetation cover of the Min River basin shows a fluctuating downward, decreasing trend. In 2008, with the increasing frequency of human activities such as reservoir maintenance and power station reconstruction in Min River basin, the vegetation coverage changed significantly, and the decreased area accounted for 26.4% of the study area, which further led to the deterioration of the vegetation coverage structure in Min River basin. In 1957, Zhang & Liu (1957) conducted a preliminary survey of fish resources in the Min River and found 92 species of fish in 68 genera in the study area. Lv *et al.* (2018) surveyed the main flow of the Min River in 2015 and found 71 species of fish in the study area. He *et al.* (2021) conducted field surveys on the Dadu River, the largest tributary of the Min River, from 2017 to 2019, and fish sampling showed that 24 species of fish were collected in the upper reaches of the Dadu River. This indicates that the construction of water conservancy projects has caused certain barriers to the migration and spawning of fish and even changed the community structure and functional groups, bringing adverse effects on the reproduction of fish in the Min River basin.

Although nature has a certain ability to adjust to changes in the external environment, the ecology and water environment have undergone drastic changes in recent years under the long-term influence of human activities, and the original ecological environment of the Min River has been intensified by the continuous invasion of alien species (Buytaert *et al.* 2011). Especially, the construction of the cascade reservoir has seriously affected the species and quantity of fish in the Min River area. To reduce the negative impact of changes in hydrological conditions on the ecological environment, many researchers have used hydrological distribution models and neural networks to predict changes in runoff. The results of these studies have helped to improve the accuracy and reliability of long-term runoff probability predictions in multisite systems, and have helped to improve the efficiency of integrated water resources development and use, and to reduce uncertainty and risk (Minglei *et al.* 2020; Ebtehaj *et al.* 2021; Wang *et al.* 2022). Therefore, the hydrological distribution model should be applied to the hydrological study of the Min River basin in future research, so that relevant managers can develop and utilize the Min River basin resources scientifically and rationally and thus achieve ecologically sustainable development within the Min River basin.

5.3. Impact of land use change on runoff changes in the watershed

In recent years, the rapid development of population and economy in the Yangtze River basin has led to a change in vegetation cover. The vegetation cover has improved since 1989 when the state started to take various soil and water conservation engineering measures in the Yangtze River basin. Figure 9 shows the land use changes in the Min River basin in different periods (1980, 1990, 2000, 2010, and 2018).

The land cover change in the Min River basin from 1980 to 2018 shows fluctuating changes: the grassland area coverage increased from 42.15 to 42.58% (105 km^2) (Table 8); the construction land area changed more between 1980 and 2018 (0.23%), which indicates that with the continuous industrialization and urbanization, the construction land area increased gradually with time; and the decreasing and then increasing trend in barren land area and the decrease in the forest, cropland, and wetland area indicate that human activities have had an impact on the habitats in the watershed. In recent years, human activities in the Min River basin have increased significantly, leading to a rapid increase in the proportion of land used for construction and a decrease in wetland areas.

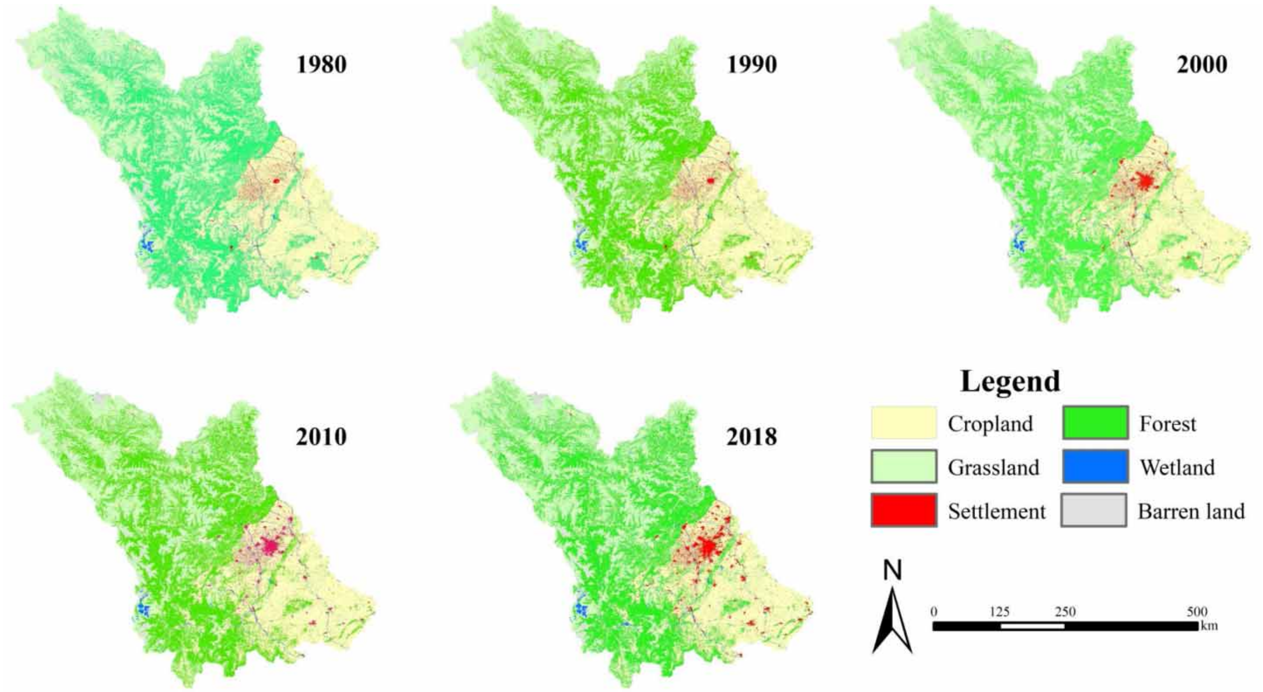


Figure 9 | Land use map of the Min River basin in different periods.

Table 8 | Changes of land use types in different periods in the Yangtze River basin

	Area ratio (%)						
Land type	**1980**	**1990**	**2000**	**2010**	**2018**	**1980**	**1980–2018**
Cropland	42.51	42.54	42.64	42.76	42.58	42.51	0.07
Grassland	38.17	38.14	38.04	38.01	38.00	38.17	– 0.17
Forest	15.8	15.74	15.57	15.19	15.57	15.8	– 0.23
Settlement	2.03	2.05	2.05	2.07	2.15	2.03	0.12
Wetland	0.78	0.84	1.01	1.25	1.01	0.78	0.23
Barren land	0.71	0.69	0.69	0.72	0.69	0.71	– 0.02

The evolution of land types and land use patterns in the Min River basin are analyzed in Table 9. The watershed area decreased by 9 km^2 from 1980 to 2018, converting mainly to grassland and barren land, indicating the severity of soil erosion. Since the implementation of soil and water conservation measures in 1980, the forested area showed a trend of growth followed by a decrease during this period. With the development of hydropower projects and the dramatic increase in human activities, the total forested area continued to decrease (230 km^2). Grassland and construction land increased by 100 km^2 and 321 km^2, respectively, with the most dramatic increase in the construction area during 1980–2018.

6. CONCLUSION

To determine the degree of influence of climate change and human activities on the hydrological regime of the Min River basin, the hydrological changes are evaluated comprehensively from the characteristics of interannual and annual changes. With the help of Mann–Kendall and Pettitt tests, the abrupt change points of the Min River runoff were found. The ecological indicator (FDC) was used to analyze the causes of runoff change in the Min River at the annual and seasonal scales. With IHA-RVA, DHRAM, and D_0, the degree of hydrological regime change in the Min River was quantified. The effects of climate

Table 9 | Transfer matrix of land use from 1980 to 2018 (km^2)

		2018						
Period	**Land type**	**Cropland**	**Grassland**	**Forest**	**Settlement**	**Wetland**	**Barren land**	**Total**
1980	Cropland	21,312	33	32	316	16	0	21,709
	Grassland	12	56,302	1,129	4	18	381	57,846
	Forest	53	1,347	50,519	7	14	10	51,950
	Settlement	2	1	2	1,049	0	0	1,054
	Wetland	10	20	8	2	911	17	968
	Barren land	0	252	27	0	0	2,490	2,769
	Total	21,389	57,955	51,717	1,378	959	2,898	136,296

change and human activities were quantitatively separated based on the Budyko hydrothermal coupling equilibrium theory. The changing trend of biodiversity in the Min River was obtained by SI index changes. The results are summarized as follows:

(1) MK and Pettitt tests comprehensively indicate that 1993 is the abrupt change point of Min River runoff under the natural flow state. At the annual scale, runoff changes in the Min River basin are mainly caused by precipitation; at the seasonal scale, runoff changes are mainly caused by reservoir regulation. Climate change and human activities have led to a decrease in the ecosurplus and an increase in the ecodeficit of the Min River.

(2) According to the comprehensive analysis of the IHA-RVA method, DHRAM, and D0 change degree analysis, the 32 eco-hydrological indicators in the Min River basin are mainly moderate and low change, and the overall change degree is 44%, which belongs to the moderate change.

(3) The elastic coefficients of runoff for the influencing factors were calculated according to the Budyko water–heat balance equation. It was found that the contribution rate of human activities was 10.32% higher than that of rainfall, indicating that human activities greatly affected the hydrological regime in the Min River basin.

(4) The change in the hydrological regime of the Min River basin resulted in a decreasing trend in the SI index, with a significance level exceeding the 95% confidence interval. The influence of human activities led to a faster decline in the alteration period (1994–2019) compared to the base period (1956–1993).

The impact of climate change and human activities on hydrological conditions in different river basins is a long-standing and complex issue. The results of this article can be well applied to river management in the Min River basin and provide reasonable guidance for changes in river hydrology in other regions. In future studies, the focus should be on the ecological response of different meteorological scenarios and reservoir operations to hydrological changes, in conjunction with hydrological modeling, to provide a further basis for water resource management and protection of the river ecosystem.

ETHICAL APPROVAL

Not required as the study did not involve humans or animals.

CONSENT TO PARTICIPATE

The authors have consented to participate in any offer by the journal.

CONSENT TO PUBLISH

The authors are giving consent to publish the article in the submitted journal.

AUTHOR CONTRIBUTIONS

H.W.: funding acquisition, project administration, resources, investigation, supervision. B.W.: conceptualization, data curation, formal analysis, investigation, methodology, resources, software, validation, visualization, writing – original draft, and writing – review and editing. H.Y.: investigation, formal analysis, methodology, validation, and visualization. H.Z.: visualization, investigation, and formal analysis. H.C.: formal analysis, investigation, and methodology. W.G.: funding acquisition and project administration.

FUNDING

This study was supported by the National Natural Science Fund of China (51779094); The 2016 Henan University Science and Technology Innovation Talent Support Plan (16HASTIT024); and The Guizhou Provincial Water Resources Department 2020 Water Conservancy Science and Technology Project (KT202008).

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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First received 18 March 2023; accepted in revised form 4 September 2023. Available online 15 September 2023