

Article

Analysis of Alterations of the Hydrological Situation and Causes of River Runoff in the Min River, China

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Abstract: Construction of water conservancy projects has changed the hydrological situation of rivers and has an essential impact on river ecosystems. The influence modes of different factors on runoff alterations are discussed to improve the development and utilization of water resources and promote ecological benefits. The ecological hydrological indicator change range method (IHA–RVA) and the hydrological alteration degree method were integrated to evaluate the hydrological situation of the Min River in China. Based on six Budyko hypothesis formulas, the rates of contribution of climate change and human activities to runoff change are quantitatively analyzed. The results show that (1) the runoff of the Min River basin showed a significant decreasing trend from 1960 to 2019 and a sudden alteration around 1993; (2) the overall alteration in runoff conditions was 45% moderate and the overall alteration in precipitation was 37% moderate; (3) precipitation and potential evapotranspiration also showed a decreasing trend within the same period but the overall trend was not significant; (4) the contribution of climate variability to runoff alterations is 30.2% and the contribution of human activities to runoff alterations is 69.8%; human activities are the dominant factor affecting the alteration of the runoff situation in the Min River basin.



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Keywords: Min River; IHA–RVA; Budyko; climate variability; human activities

1. Introduction

Hydrological conditions are critical drivers of river ecosystems and play an essential role in maintaining energy processes, biological interactions, and physical habitat conditions [1]. Climate variability and human activities are two critical factors influencing runoff alterations. Runoff formation is closely related to climate change, such as precipitation and potential evapotranspiration. Land use change and construction of large-scale water conservancy projects can change a river's runoff and its original seasonal and annual distribution by affecting rainfall interception and actual evapotranspiration [2,3]. Runoff is severely disturbed in many parts of the world [4,5]. Liu et al. [6] found significant changes in the flow of 24% of the world's large rivers. Li et al. [7] summarized long-term runoff records from 22 subbasins of the Yangtze River in China. They concluded that the construction of dams would impact hydrological factors such as water level, flow, and sand content in the downstream basin. The study of climate change and impact of human activities on runoff has become an essential scientific issue due to the importance of avoiding and reducing economic losses caused by frequent floods and severe drought disasters [8,9].

Effects of development and construction of large reservoirs on the degree of runoff change and its influencing factors have been a hot research topic at home and abroad. The most widely used method is the range of variability approach (RVA), which analyses the variability of the overall hydrological situation of a river [10,11]. This method, proposed by Richter [12], allows the river to be divided into different periods by human activity, climate change, etc. The extent to which the river's hydrology changes in a sudden change year can be obtained by exploring hydrological indicators, which has been discussed by

many scholars. Eum et al. [13] suggested that changes in flow magnitude and timing may lead to changes in reservoir operations using the range of variability approach (RVA) to assess each hydrological indicator to investigate the impact of changes in these indicators on the reservoir. Tonina et al. [14] suggested that changes in the vital hydrological indicators can significantly affect aquatic organisms' diversity and population dynamics, with implications for habitat quality within a watershed. Pfeiffer et al. [15] found that changes can influence the water balance in river catchments in precipitation. Human activities such as dam construction, irrigation, and land use changes have significantly altered the hydrological state of rivers.

Changes in meteorological factors such as precipitation, temperature, and radiation are inextricably linked to alterations in the runoff. Many scholars have used hydrometeorological data to fit empirical relationships between the water and heat balances of different watershed types, confirming the validity of the Budyko hypothesis, which is that changes in river runoff are mainly caused by climate change and human activities [16]. The method is widely used in globally significant river basins [17,18]. Dividing the United States into seven study regions, Heidari et al. [19] concluded that the southern and southwestern United States are likely to experience prolonged droughts in future periods. At the same time, the western part is likely to experience more humid conditions. Xia et al. [20] quantitatively estimated runoff alterations in the upper reaches of the Han River based on the elastic coefficient method and the hydrological simulation method. They discussed the differences in runoff caused by natural and artificial factors, which showed that human activities have a more significant impact than natural factors. Exploring the assessment of changes in river runoff characteristics and the causes of their alterations is essential to understanding and predicting the impact of changes in river flow regimes on the ecology within river basins.

The Min River is a first-class tributary of the upper reaches of the Yangtze River. In recent years, construction of Min reservoirs has gradually gained attention, forming a cluster of terraced reservoirs containing strings and mixed links [21,22]. The construction of a reservoir impacts the climate within the Min River basin, which will inevitably cause changes in runoff and some disturbance to the ecosystem within the basin [23]. The existing studies on runoff changes and their factors in the Min River basin are limited to the study of trends and abrupt changes, lacking an understanding of the causes of changes in hydrological indicators before and after abrupt changes in runoff and the impact of changes in habitat quality on runoff. Composition, structure, and function of ecosystems, such as rivers and wetlands, are inextricably linked to their hydrological characteristics. Changes in habitat quality and land use can affect hydrological cycle processes of runoff, altering the spatial and temporal distribution of water resources [24]. Therefore, the study of hydrological changes in the Min River basin is essential to the ecological restoration and sustainable development of the upper Yangtze River basin.

In this paper, based on the previous studies, we use the ecohydrological indicator range of alteration (IHA–RVA) and the hydrological alteration method to evaluate the hydrological situation in the Min River basin and analyze the degree of influence of climate variability and human activities on the runoff in the Min River basin in a more objective way. FAO Penman–Monteith formula was used to calculate the potential evapotranspiration in the Min River basin. According to the long-term water balance formula, drying indicator, and six Budyko hypothesis formulas, the influence of climate change and human activities on the runoff was calculated. This study provides a reference for the Min River basin to cope with climate variability and develop and utilize water resources more rationally.

2. Study Area and Data Input

2.1. Study Area

The Min River is a first-class tributary on the upper left bank of the Yangtze River, originating at the southern foot of Min Mountain in Songpan, Sichuan, and is rich in freshwater fishery resources. As an essential source of water resources for the Chengdu

Plain, the Min River has the Dujiangyan Water Conservancy Project, which provides the foundation for forming the “Land of Abundance”. It covers an area of 23,037 square kilometers. The Min River basin is composed of the main stream of the Min River, the Qingyi River, and the Dadu River (Figure 1). The lower reaches of the Min River are an essential habitat for fish and an important channel to communicate with the middle and upper reaches of the Min River and the Dadu River [25]. The Gaochang hydrological station, which is the subject of this study, is located at the confluence of the Dadu River and the Min River and is situated in the lower reaches of the Min River [26]. With the development of science and technology and the improvement of human living standards, the development of the Min River basin has increased dramatically in recent years. Significant changes have taken place in the water environment of the Min River basin, which has irreversible consequences for the ecological environment. In particular, the gradual construction of cascade hydropower stations in the Min River basin has brought a series of impacts on the runoff and fish resources in the lower reaches of the Min River. The Tongjiezi Reservoir in the Min River basin started to operate in 1993, which caused obvious original changes in the hydrological sequence in the high station control area.

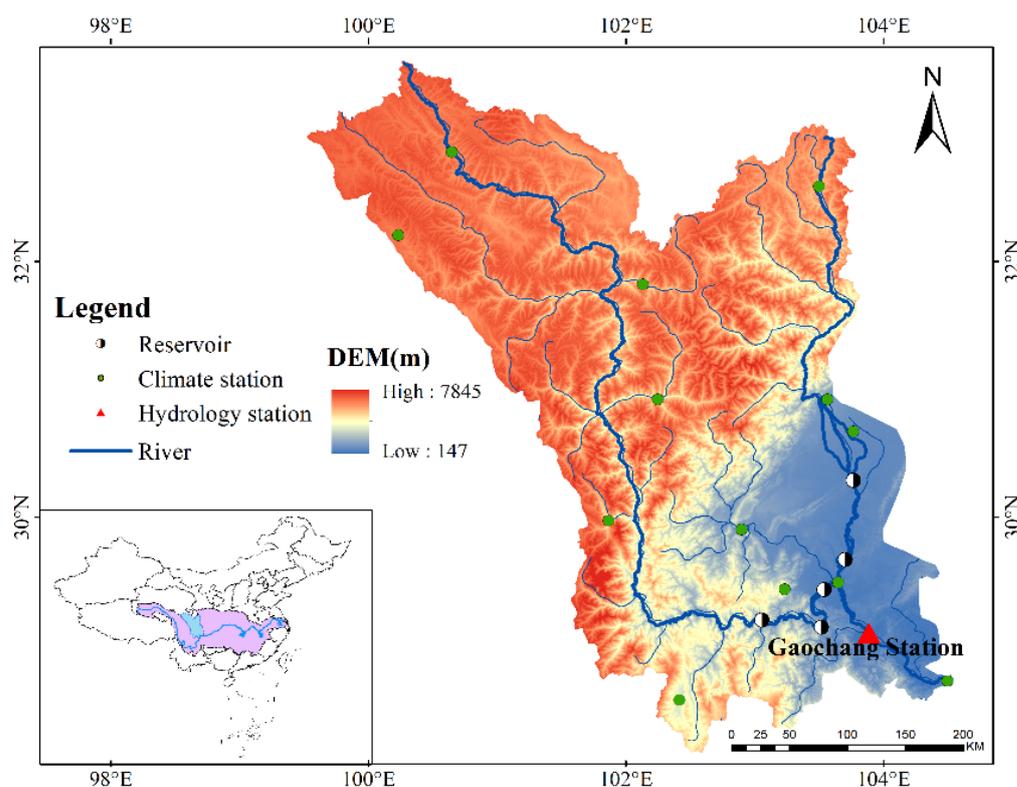


Figure 1. Min River basin map, first-class tributaries of the Yangtze River in China.

2.2. Data Input

In the study, we used the daily meteorological element data from 1960 to 2019 of 13 basic stations of the Min River basin released by the Meteorological Observation Center of the China Meteorological Administration. The basic stations of the meteorological stations were distributed all over the Min River basin (Figure 1). The meteorological data are from the China Meteorological Data Network (<http://data.cma.cn>) (accessed on 1 August 2020). Considering the distribution of rivers in the Min River basin, the daily flow data from 1960 to 2019 of the Gaochang hydrological station at the confluence of the Dadu River, a tributary of the Min River, and the lower reaches of the mainstream were selected. The data come from the “Yangtze River Basin Hydrological Yearbook”.

3. Methods

3.1. Trend and Alteration Analysis

The hydrological alteration process of the river is very complex, and in order to analyze the trend and sudden alteration tests of runoff alterations at the Gaochang hydrological station and precipitation conditions within the Min River basin, the Mann–Kendall test, the cumulative distance level method, and the sliding t -test method were mainly used in this study [27–29]. Three test methods were used to test the runoff and precipitation series alteration to select the alteration year.

The Mann–Kendall test (M–K) is a nonparametric statistical test method widely used in hydrometeorological time series. In the M–K trend test, a positive statistic indicates an increasing trend, otherwise—a decreasing trend. Statistical variables are defined as follows:

$$UF_K = \frac{|S_K - E(S_K)|}{\sqrt{Var(S_K)}} (K = 1, 2, \dots, n) \quad (1)$$

where S_K is the cumulative number of sample symbols; $E(S_K)$ is the sample mean; $Var(S_K)$ is the sample variance. Variable UB_K is calculated according to the sequence's reverse time sequence, and the curves formed by the two statistical sequences are recorded as UF and UB , respectively.

The sliding t -test divides the original sequence into two sequences (before and after) and judges whether there is an alteration in the original time series by judging whether the mean of the two sequences is different. Set a specific moment as the reference point, and the capacities of the two samples before and after the reference point are n_1 and n_2 , respectively, and the statistic t is constructed as follows:

$$t = \frac{\bar{X}_1 - \bar{X}_2}{S \cdot \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}} \quad (2)$$

$$S = \sqrt{\frac{n_1 S_1^2 + n_2 S_2^2}{n_1 + n_2 - 2}} \quad (3)$$

where X_1, X_2 is the sample mean, S_1, S_2 is the sample variance. The statistic t obeys the t distribution with degrees of freedom $V = n_1 + n_2 - 2$. Given a significant level α , if $|t| > t_{1-\frac{\alpha}{2}}$, it is considered that an alteration occurred before and after the reference point. There is a significant difference between the two subsequences before and after the reference point. If the alteration time t is positive, a decreased alteration occurs. Otherwise, an increased alteration occurs.

The cumulative distance level method is a nonlinear statistical method that reflects sequence changes through a curve. From the fluctuation of the cumulative anomaly curve, the evolution trend and change of the series can be judged, and the abrupt change point can be judged according to the turning point of the cumulative anomaly curve. The cumulative distance level method can better distinguish the interannual variation of runoff and precipitation, help calculate the annual runoff and precipitation anomalies and accumulate them year by year to obtain the cumulative anomaly curve.

3.2. IHA–RVA Method

To quantitatively analyze the influence degree of reservoir construction on river hydrology, in 1996, Richter et al. proposed five groups of 32 indicators of hydrological alteration (IHA) from the five dimensions of change rate, duration, frequency, size, and time of occurrence (Table 1), whose sequence information is easy to collect and easy to use. The IHA was combined with the range of variability approach (RVA) to analyze the degree

of change in the hydrological regime before and after abrupt changes [30]. The formula is as follows:

$$D_i = \left| \frac{N_{oi} - N_e}{N_e} \right| \times 100\% \quad (4)$$

where D_i is the degree of hydrological alteration of the i IHA indicator; N_{oi} is the number of years that fall within the RVA target threshold for the i IHAs observed after the disturbance (the IHA threshold range is the number of years of observation); N_e is the number of years after the alteration. D_i of 0–33% belongs to low change; 33–67%—moderate change; 67–100%—high change.

Table 1. Summary of hydrological parameters used in the IHA.

IHA Statistics Group	Hydrological Parameters
Group 1: Monthly average	Monthly average streamflow (precipitation)
Group 2: Size and duration of annual extremes	Annual average 1, 3, 7, 30, 90 d minimum and maximum streamflow (precipitation), base index
Group 3: Time of year when extreme conditions occur	Date of occurrence of the maximum and minimum one day of the year (Roman day)
Group 4: Frequency and duration of high and low pulses	Average number of high and low pulses per year and the duration of the pulses
Group 5: Rate and frequency of change	Annual average rates of increase and decrease and the number of reversals

Note: The base index is the ratio of the annual minimum seven-day flow (precipitation) to the annual mean. The number of reversals refers to the number of times the daily flow or precipitation changes from increasing to decreasing.

The degree of hydrological alteration of individual indicators cannot reflect the overall degree of alteration, so this paper uses the overall degree of hydrological alteration D_o to reflect the overall alteration of runoff and precipitation; the calculation principle is detailed in the literature; the formula is as follows [31]:

$$D_o = \left(\frac{1}{n} \sum_{i=1}^n D_i^2 \right)^{0.5} \quad (5)$$

where n is the number of indicators and the judgment standard of D_o is the same as that of D_i .

3.3. Estimation of Potential Evaporation

In this study, the potential evapotranspiration was calculated using the FAO Penman–Monteith formula, which has been widely used by domestic and international scholars:

$$ET_0 = \frac{0.408(R_n - G) + \gamma \frac{900}{T+273} \mu_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34\mu_2)} \quad (6)$$

where ET_0 is the potential evaporation (mm/d); Δ is the slope of the saturation water pressure curve (Kpa/°C); R_n is the net surface radiation (MJ/m² d); G is the soil heat flux (MJ/m² d); γ is the dry and wettable constant (Kpa/°C); T is the average daily air temperature (°C); μ_2 is the wind speed at 2 m (m/s); e_s is the saturation water pressure (KPa); e_a is the actual water pressure (KPa). The above meteorological data were obtained from the China Meteorological Data Network, and the specific calculation process is shown in [32].

3.4. Quantitative Analysis of Runoff Situation Alterations

Alterations in the runoff within the Min River basin should take both climate and human activities into account, calculated as follows:

$$\Delta Q = \Delta Q_C + \Delta Q_H \tag{7}$$

$$\eta_C = Q_C / \Delta Q \times 100\% \tag{8}$$

$$\eta_H = \Delta Q_H / \Delta Q \times 100\% \tag{9}$$

where ΔQ is the difference between streamflow alterations; ΔQ_C and ΔQ_H are the amounts of runoff alteration caused by climate variability and human activities; η_C and η_H are the contribution rates of climate variability and human activities [33].

The elasticity coefficient method was chosen to calculate ΔQ_C and ΔQ_H based on the basin long-time water balance equation ($Q = P - E_a$), the dryness index ($\phi = E_0 / P$) calculation, and six formulas based on the Budyko hypothesis (Table 2), with the following equations:

$$\Delta Q_C = \varepsilon_P \frac{Q}{P} \Delta P + \varepsilon_{E_0} \frac{Q}{E_0} \Delta E_0 \tag{10}$$

$$\varepsilon_P = 1 + \frac{\phi'(\phi)}{1 - F(\phi)}, \text{ and } \varepsilon_{E_0} = 1 - \varepsilon_P \tag{11}$$

where Q , E_0 , and P are the multiyear average runoff, potential evapotranspiration, and precipitation, respectively; ΔE_0 and ΔP are the alterations in potential evapotranspiration and precipitation before and after the impact, respectively; ε_P and ε_{E_0} are the elasticity indices of runoff to precipitation and potential evapotranspiration, respectively [34]. Budyko considers $F(\cdot)$ a universal function, a hydrothermal coupling balance equation independent of water balance and energy balance. The research has attracted widespread attention and spawned many similar theoretical explorations of multiyear water balances. In this study, six widely used hydrothermal coupling balance equations were used to quantitatively analyze the rate of contribution of climate change and human activities to the runoff change. As shown in Table 2, $F(\phi)$ and $F'(\phi)$ are the six Budyko hypothesis formulas and their derivation formulas.

Table 2. Common expressions based on the Budyko hypothesis.

Serial No.	$F(\phi)$	$F'(\phi)$	Literature Source
1	$(1 + \omega\phi) / (1 + \omega\phi + 1/\phi), \omega = 1$	$(\omega + 2\omega/\phi - 1 + 1/\phi^2) / (1 + \omega\phi + 1/\phi)^2$	Zhang [35]
2	$1 + \phi - (1 + \phi^a)^{1/a}, a = 2.5$	$1 - (1 + \phi^a)^{1/a-1} \phi^{a-1}$	Fu [36]
3	$\frac{1}{1 - e^{-\phi}}$	$\frac{e^{-\phi}}{e^{-\phi}}$	Schreiber [37]
4	$[\phi \tanh(1/\phi)(1 - e^{-\phi})]^{0.5}$	$0.5[\phi \tanh(1/\phi)(1 - e^{-\phi})]^{-0.5} \times [\tanh(1/\phi) - \text{sech}^2(1/\phi) / \phi(1 - e^{-\phi}) + \phi \tanh(1/\phi)e^{-\phi}]$	Budyko [38]
5	$(1 + \phi^{-2})^{-0.5}$	$1 / \left[\phi^3 (1 + (1/\phi)^2)^{1.5} \right]$	Pike [39]
6	$\phi \tanh(1/\phi)$	$\tanh(1/\phi) - 4 / \left[\phi (e^{-1/\phi} + e^{1/\phi})^2 \right]$	Ol'dekop [40]

3.5. Land Use Transfer Matrix

The land use transfer matrix mainly describes the mutual transformation relationship between various land types, which can reflect the quantity and direction changes of different land types in a specific and comprehensive manner [41]. The formula is as follows:

$$S_{ij} = \begin{pmatrix} S_{11} & \cdots & S_{1n} \\ \vdots & \ddots & \vdots \\ S_{n1} & \cdots & S_{nn} \end{pmatrix} \tag{12}$$

where S represents the land type area, n is the land type, and S_{ij} represents the area of land type i converted to type j ($i, j = 1, 2, 3, \dots, n$).

This study uses five periods of remote sensing data (1980, 1990, 2000, 2010, 2020) in the study area to analyze its changes. According to the characteristics of land use types, the realm study area is divided into six categories: forest, grassland, cropland, wetland, barren land, and construction land.

4. Results and Analysis

4.1. Mutagenicity Analysis

Using the M–K test method, it can be seen that the intersection of the runoff and precipitation statistics of the two curves of UF and UB is at the 0.05 significance level, which indicates that the hydrological situation of the Min River basin may have changed abruptly in 1993 and 1997 (Figure 2a,d). From the results of the sliding t -test method, it can be concluded that the intra-annual distribution uniformity of the runoff volume passes the 0.05 significance level and the intra-annual distribution uniformity of the precipitation volume does not pass the 0.05 significance level. It can be seen that the annual runoff volume showed abrupt alterations in 1968 and 1993, and the years of abrupt alterations in annual precipitation were 1990 and 1993 (Figure 2b,e). The cumulative distance level method shows that the annual runoff had the maximum value in 1993 and 2002, and the annual precipitation had the maximum value in 1993 (Figure 2c,f). Combining the above three methods, 1993 was chosen as the year of the sudden alteration in the annual runoff and the annual precipitation in this study. The daily runoff data from the Gaochang hydrological station and the daily precipitation data from the Min River basin were divided into base period T_a (1960–1993) and alteration period T_b (1994–2019).

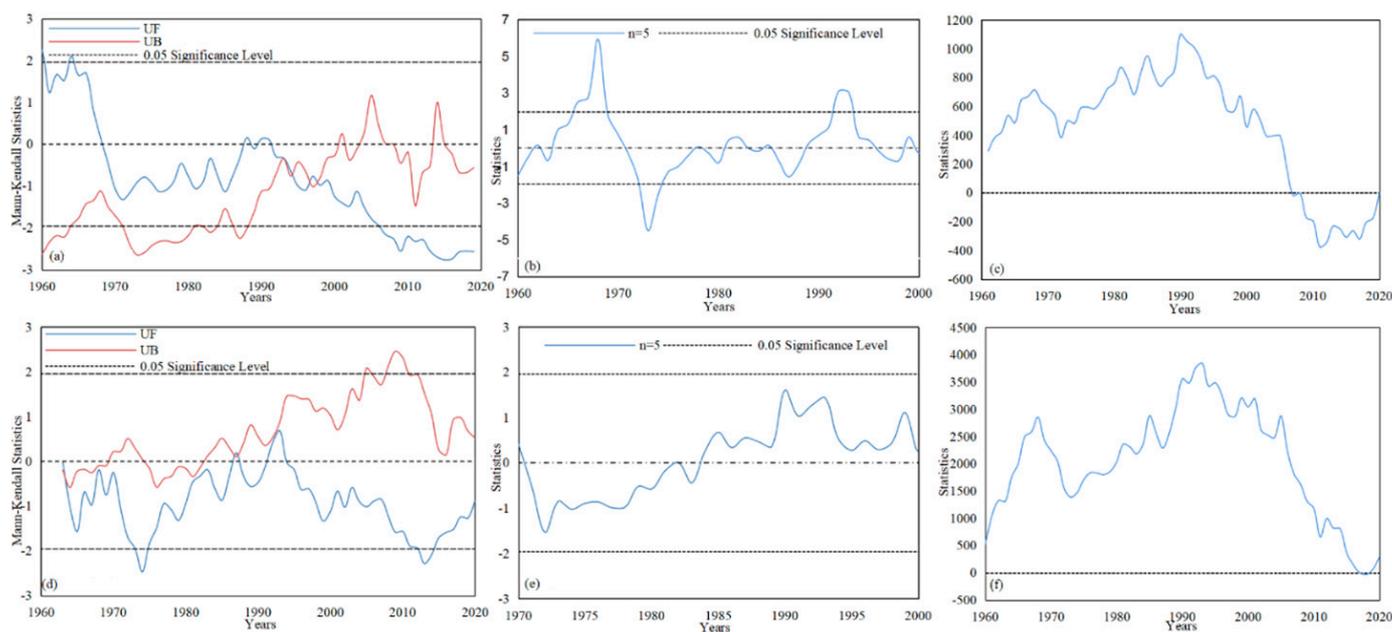


Figure 2. Alteration test analysis curve. (a) Runoff: M–K; (b) runoff: sliding t -test; (c) runoff: cumulative distance level; (d) precipitation: M–K; (e) precipitation: sliding t -test; (f) precipitation: cumulative distance level.

4.2. IHA Hydrological Indicator Alteration Degree Analysis

As climate variability and human activities are important factors affecting runoff alterations, considering only daily flow alterations can only describe the changing state of the Min River basin at the macroscopic level, and to further analyze the causes of the runoff alterations in a more detailed way, recording and analysis of the climate variability data are essential. Precipitation has a direct impact on runoff alterations in climate variability.

Considering daily precipitation data, they can reflect not only the rise and fall of rivers directly, but also the alterations of aquatic organisms and riparian habitats. Table 3 shows the degree of change of 32 hydrological indicators in five groups before and after abrupt changes in the runoff and precipitation. The influence of reservoir construction on rivers is discussed by changing 32 hydrological indicators.

Table 3. Statistical table of IHA indicators before and after the alteration of the Min River.

IHA Indicators	Pre-Alteration, 1960–1993		Post-Alteration, 1994–2019		Change D_i (%)		
	Flow	Precipitation	Flow	Precipitation	Flow	Precipitation	
I	January	758.5	0.135	836.5	0.117	43 (M)	30 (L)
	February	709	0.27	788.5	0.229	43 (M)	22 (L)
	March	819	0.558	965.5	0.535	10 (L)	11 (L)
	April	1053	1.282	1268	1.423	21 (L)	11 (L)
	May	1990	2.535	1840	2.435	77 (H)	44 (M)
	June	3470	4.314	3390	4.509	21 (L)	22 (L)
	July	5615	5.077	4710	4.405	55 (M)	78 (H)
	August	5230	4.805	4310	3.988	43 (M)	22 (L)
	September	4875	3.965	3905	3.573	36 (M)	11 (L)
	October	3095	1.464	2725	1.3	21 (L)	56 (M)
	November	1755	0.323	1540	0.311	55 (M)	11 (L)
	December	1130	0.125	1145	0.1	44 (M)	33 (M)
II	1-day minimum	578.5	0	598.5	0	21 (L)	3 (L)
	3-day minimum	601.8	0.007	645.5	0	55 (M)	56 (M)
	7-day minimum	625.4	0.041	705.1	0.0241	67 (H)	22 (L)
	30-day minimum	677.2	0.180	760.7	0.142	43 (M)	22 (L)
	90-day minimum	780.9	0.472	864.3	0.511	43 (M)	22 (L)
	1-day maximum	16,050	23.41	12950	23.47	47 (M)	44 (M)
	3-day maximum	12,620	14.58	9967	13.27	32 (L)	44 (M)
	7-day maximum	9877	10.34	7886	10.17	32 (L)	44 (M)
	30-day maximum	7436	7.182	5927	7.309	32 (L)	11 (L)
	90-day maximum	5857	6.028	4802	5.81	43 (M)	11 (L)
Base index	0.2272	5	0.291	12	43 (M)	81 (H)	
III	Date of the minimum	37.5	9	38.5	4	9 (L)	29 (M)
	Date of the maximum	212.5	208	214.5	210	21 (L)	29 (M)
IV	Low pulse count	4	35	8	34	43 (M)	33 (M)
	Low pulse duration	5	2	2	2	21 (L)	3 (L)
	High pulse count	8	36	10	38	38 (M)	39 (M)
	High pulse duration	4	2	3	2	9 (L)	3 (L)
V	Rise rate	141	0.8	130	0.811	21 (L)	22 (L)
	Fall rate	−108.5	−0.79	−150	−0.789	100 (H)	78 (H)
	Number of reversals	151	218	184	215	89 (H)	38 (M)

Note: H—high change; M—moderate change; L—low change. Unit description: flow rate (m^3/s); precipitation (mm); rate of rise, fall rates ($\text{m}^3 \text{s}^{-1} \text{d}^{-1}$); low pulse count, high pulse count, number of reversals (times); low pulse duration, high pulse duration, date of the minimum, date of the maximum (day).

Average flow and precipitation of each month: As can be seen from Table 3, the average monthly flow at the Gaochang hydrological station increased to different degrees after an abrupt alteration, while the average monthly precipitation in the Min River basin increased and decreased, but the increase and decrease were more moderate; the alteration of the average monthly flow was high in May and medium and low in other months; the alteration of the average monthly precipitation was high in July. After 1993, the number and storage capacity of reservoirs increased significantly, which increased the runoff after the alteration and caused specific disturbance to the reproduction of aquatic organisms.

Annual extreme flow and precipitation: The annual mean extreme minimum flow at the Min River basin's Gaochang hydrological station generally increased after an abrupt alteration, while the extreme values showed different degrees of decrease, of which the

minimum seven-day flow was highly altered, and the rest were altered to a moderate or small degree. The reservoir construction and operation after 1993 affected the original flow polarity alteration process of the river. The annual extreme precipitation alteration range is more drastic, which influences the flow alteration. Such extreme daily alterations in the precipitation are frequent and unpredictable, and extreme alterations in the precipitation can lead to alterations in the natural river hydrological processes, causing disturbances to species that are not adapted to frequent alterations in the water flow.

Timing of the annual extreme flow and precipitation occurrence: After the sudden hydrology alteration at the Gaochang hydrological station, the time of occurrence of the annual maximum flow and the annual minimum flow was changed at a low degree, indicating that the alteration of hydrological indicators in this group had a little alteration on biological abundance. The annual precipitation alterations were low, and climate variability had no significant effect on the time of occurrence of the annual extreme flow.

Frequency and duration of high and low flow (precipitation): After the alteration, the number of flow pulses changed moderately, and the pulse duration changed to a small degree. The precipitation indicators are all low-level changes, and the impact is negligible. The high and low diachronic changes of runoff and precipitation affect the structure and function of the river ecosystem, change the soil water content on both sides of the river, and make the riparian vegetation disappear [42].

The rate of alteration and frequency alteration of flow and precipitation. After the abrupt alteration, the rate of flow increases, and the number of reversals have different degrees of increase, and the rate of flow decrease reaches 100% as high change, which makes the allowable range of flow alteration decrease. The annual precipitation decline rate of 78% is highly altered, and the annual precipitation reversal number of 38% reaches moderate change, indicating that climate variability has a certain impact on the flow alteration rate and frequency alteration. The rate and frequency of flow alterations affect the pattern of river rise and fall, thus affecting the survival and reproduction of aquatic organisms. The ecosystem has a limited ability to withstand external alterations, and a reduced range of flow alterations can affect the growth of organisms on both sides of the river, while too frequent flows can destabilize flora and fauna.

Overall degree of alteration of flow and precipitation: The change degree of 32 hydrological indicators of the runoff and precipitation is drawn as a radar map (Figure 3), which can more intuitively show the change of the hydrological situation of the Min River before and after the alteration. It can be seen from the figure that there were four high changes in the hydrological alteration degree indicator in the Min River basin, namely the average flow in May, 7-day minimum, fall rate, and reversals, 15 moderate changes; the rest are low changes. Among the precipitation alteration indicators in the Min River basin, except for the average precipitation in July, the base index, and the decline rate, which were highly altered, the rest were all altered to a moderate and small degree.

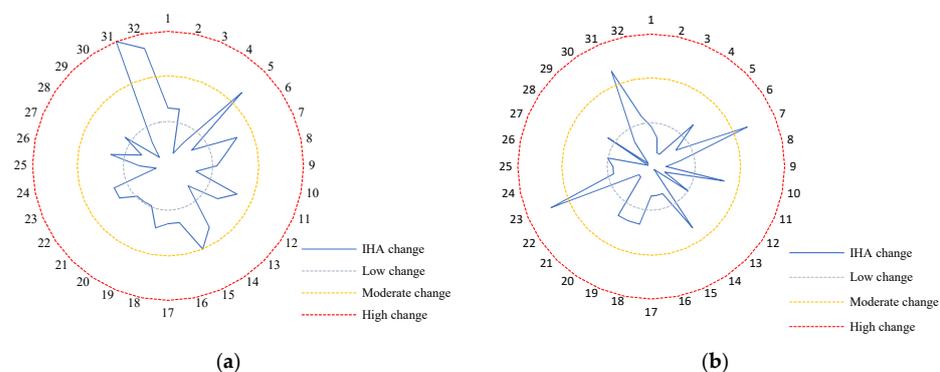


Figure 3. Schematic diagram of the hydrological change degree. (a) Schematic diagram of the hydrological change degree at the Gaochang station; (b) schematic diagram of the precipitation change degree in the Min River basin.

Equation (5) was used to calculate the change degree of hydrological indicators in five groups and the whole. It can be seen from Table 4 that the overall change of the runoff is 45% (moderate change). The overall change in the precipitation is 37% (moderate). The change of the precipitation in the Min River is small, indicating that human activities such as reservoir construction have a more significant impact on the runoff.

Table 4. Overall Min River discharge and precipitation change degree.

Category	Hydrology Precipitation Change Degree					Overall Degree of Change D_o
	Group I	Group II	Group III	Group IV	Group V	
Gaochang station	43 (M)	43 (M)	16 (L)	31 (M)	78 (H)	45 (M)
Precipitation	32 (L)	39 (M)	29 (L)	26 (L)	52 (M)	37 (M)

Note: H—high change; M—moderate change; L—low change.

4.3. Analysis of the Alterations in Runoff Conditions

In the selected hydrological series of the Min River basin, the annual runoff volume alterations has some oscillations and is unstable, with a slight upward trend in the T_a stage and a significant downward trend in the T_b stage, and the annual runoff volume has a decreasing trend in general; according to the trend test analysis, the test statistic is -2.76 , which passes the 95% significance level test; the maximum value of the annual runoff volume was $1004.54 \times 10^8 \text{ m}^3$ (1990); the minimum value was $635.17 \times 10^8 \text{ m}^3$ (2006); compared with the T_a period, the annual runoff in the T_b period decreased by 10.46%. The yearly precipitation fell in both the T_a and T_b periods, and according to the trend test statistic of -1.52 , the trend was not significant, and the decrease was not evident in many years; the maximum value of annual precipitation is 1286.78 mm (1990), and the minimum value is 808.17 mm (2006); compared with the T_a period, the yearly rainfall in the T_b period decreased by 6.33%. The annual evapotranspiration fluctuated violently, and the T_a phase showed an apparent decreasing trend. After the breakthrough, the T_b phase increased by 4.9% compared with the T_a phase, showing a general decreasing trend (Figure 4). The multiyear precipitation in the Min River basin is on a downward trend, but the overall decline is not significant. We know that the annual runoff of the Min River also shows a decreasing trend, which indicates that the alteration of precipitation has a certain impact on the annual runoff.

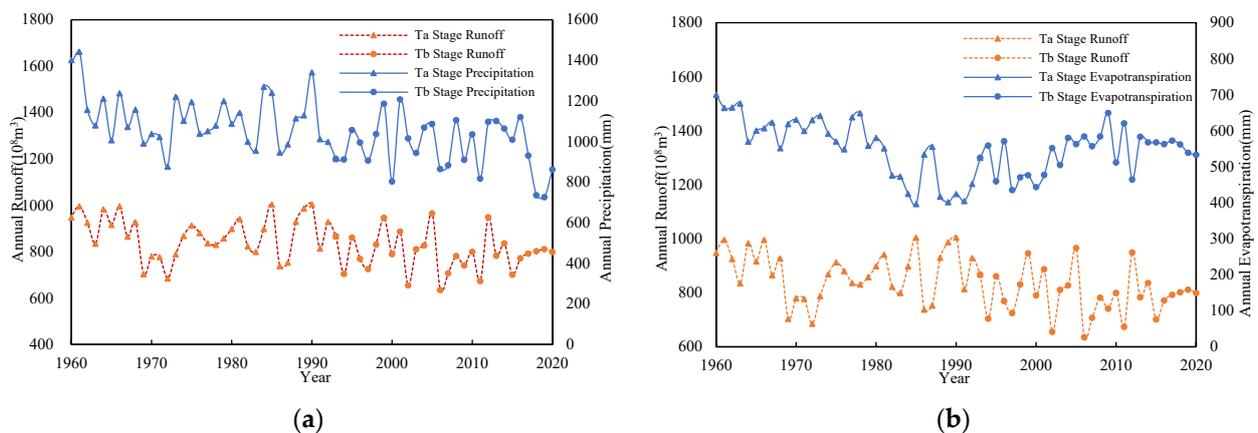


Figure 4. (a) Trend chart of the annual runoff and the annual precipitation in the Min River basin before and after the sudden alteration; (b) trend chart of the annual runoff and the annual evapotranspiration in the Min River basin before and after the sudden alteration.

The calculated results of the runoff situation alterations in Table 5 show the degree of influence of climate variability and human activities on annual dimensions. The elasticity

coefficient of runoff to precipitation is 0.83; the contribution of climate variability and human activities to the runoff alteration is 30.20% and 69.80%, respectively.

Table 5. Calculation results of alterations in the runoff regime.

Indicator	Zhang	Fu	Schreiber	Budyko	Pike	Ol'dekop	Mean
εp	0.59	0.92	0.93	0.63	0.94	0.96	0.83
$\Delta Q_c(mm)$	−22.94	−28.16	−28.54	−23.79	−28.68	−28.89	−26.83
$\Delta Q_H(mm)$	−65.92	−60.70	−60.32	−65.07	−60.18	−59.97	−62.03
$\eta_C(\%)$	25.82	31.69	32.11	26.77	32.27	32.51	30.20
$\eta_H(\%)$	74.18	68.31	67.89	73.23	67.73	67.49	69.80

4.4. 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 had improved since 1989 when the state started to take various soil and water conservation engineering measures in the Yangtze River basin. Figure 5 shows the land use changes in the Min River basin in different periods (1980, 1990, 2000, 2010, 2020).

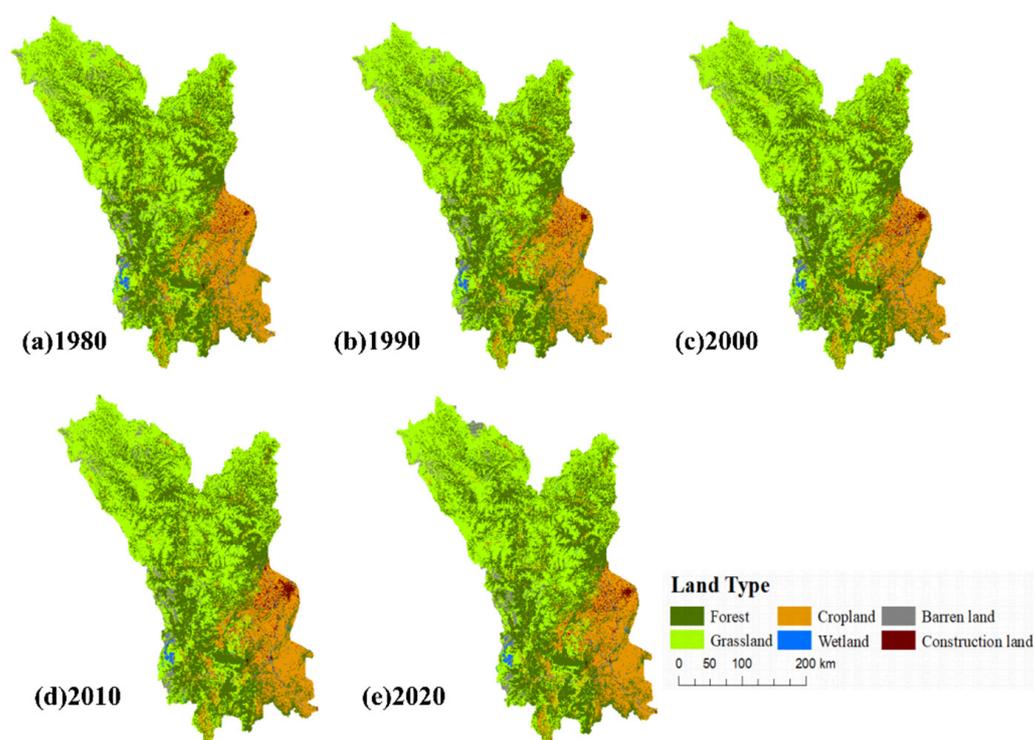


Figure 5. Land use map of the Min River basin in different periods.

The land cover change in the Min River basin from 1980 to 2020 shows fluctuating changes: the grassland area coverage increased from 42.15% to 42.58% (105 km²) (Table 6); the construction land area changed more between 1980 and 2020 (0.23%), which indicates that with the continuous industrialization and urbanization, the construction land area increased gradually with time; the decreasing and then increasing trend in barren land area and the decreasing and then increasing trend 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.

Table 6. Changes of land use types in different periods in the Yangtze River basin.

Land Type	Area Ratio (%)					Area Change Rate (%)
	1980	1990	2000	2010	2020	1980–2020
Grassland	42.51	42.54	42.64	42.76	42.58	0.07
Forest	38.17	38.14	38.04	38.01	38.00	−0.17
Cropland	15.8	15.74	15.57	15.19	15.57	−0.23
Barren land	2.03	2.05	2.05	2.07	2.15	0.12
Construction land	0.78	0.84	1.01	1.25	1.01	0.23
Wetland	0.71	0.69	0.69	0.72	0.69	−0.02

The evolution of land types and land use patterns in the Min River basin are analyzed in Table 7. The watershed area decreased by 9 km² in 1980–2020, 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 km²). Grassland and construction land increased by 100 km² and 321 km², respectively, with the most dramatic increase in the construction area during 1980–2020.

Table 7. Transfer matrix of land use from 1980 to 2020 (km²).

Period	Land Type	2020						Total
		Cropland	Grassland	Forest	Construction Land	Wetland	Barren Land	
1980	Cropland	21,112	24	32	316	16	0	21,500
	Grassland	12	56,302	1129	4	18	381	57,846
	Forest	53	1347	50,519	4	14	10	51,947
	Construction land	2	1	2	1049	0	0	1054
	Wetland	10	20	8	2	911	17	968
	Barren land	0	252	27	0	0	2490	2769
	Total	21,189	57,946	51,717	1375	959	2898	136,084

5. Discussion

5.1. Impact of Climatic Factors on the Runoff

Climatic factors are among the main reasons for the change in the runoff. Climate change directly affects evapotranspiration and distribution of its components, precipitation, water absorption, and utilization efficiency of plants, etc., which in turn affects changes in hydrological regimes such as runoff and flood processes in the basin. Precipitation is the primary source of runoff, and its changes directly impact the runoff [43]. Hasan et al. [44] calculated the effects of temperature and precipitation on the runoff. They concluded that the impact of precipitation on the runoff is five times that of temperature, and the response of the runoff to precipitation changes is strongly nonlinear compared to temperature.

As shown in Figure 6a, the precipitation–runoff depth double accumulation curve is a straight line in the natural state. If natural changes such as extreme precipitation occur, the curve shifts. Compared with the reference period, the slope of the short period in the Min River basin showed a decreasing trend. The precipitation–runoff depth double accumulation curve shifts downward, indicating that the runoff decreases under the same rainfall. Hence, precipitation has a particular impact on the runoff change in the basin. However, it is not the key influencing factor. The slope of the potential evaporation after the abrupt change also showed a downward trend. Figure 6b shows that the potential evapotranspiration–runoff depth double accumulation curve shifted to a certain extent. The correlation coefficient between runoff depth and potential evapotranspiration has a

downward trend. It can be seen that the correlation between potential evapotranspiration and runoff depth is weak, so potential evapotranspiration has little impact on runoff changes [45]. The water balance equation based on the Budyko hypothesis shows that the contribution rate of climate change to the runoff is 30.20%, and the impact of climate change on the runoff is small.

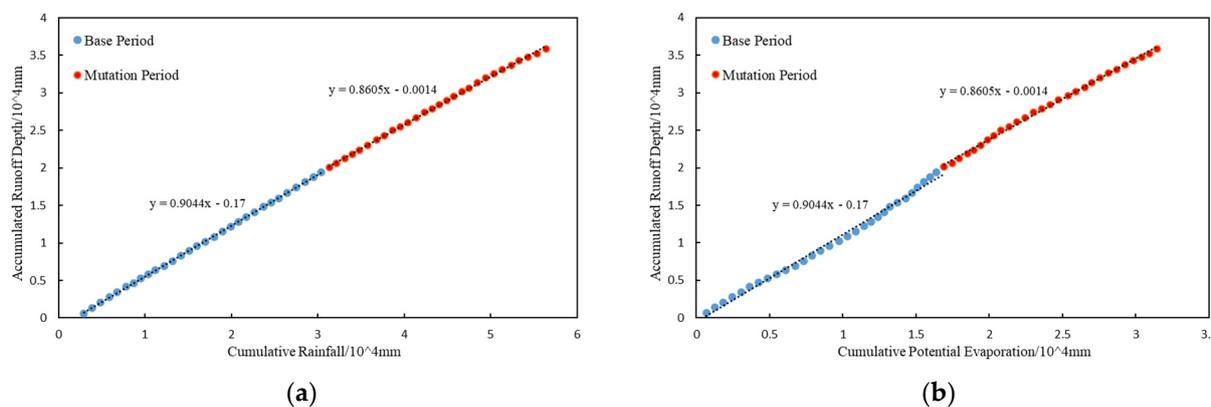


Figure 6. (a) Precipitation—runoff depth double accumulation curve in the Min River basin; (b) potential evapotranspiration—runoff depth double accumulation curve in the Min River basin.

5.2. The Impact of Human Activities on the Runoff

In addition to climate change, human activities also play a crucial role in changing hydrological regimes. The construction of water conservancy projects and the transformation of land use affect the mechanism of runoff and confluence and change the spatial and temporal distribution characteristics of water resources. The Min River is rich in water resources and ecological resources. The operation of the reservoir is an essential factor affecting the sudden change of the hydrological regime of the river. In recent years, human development of hydropower resources in the Min River has increased significantly [46]. The number of reservoirs and the storage capacity of the pools have gradually increased. By the end of 2019, more than 870 large, medium, and small reservoirs have been built in the Min River, with a cumulative total storage capacity of about 15.3 billion m^3 . Currently, there are 22 reservoirs under construction in the basin, with a full storage capacity of about 3.88 billion m^3 . Within the Gaochang control area, the Gongzui and Tongjiezi reservoirs were put into operation in 1972 and 1993, and the Zipingpu and Puegou reservoirs were put into operation in 2006 and 2009, respectively [47]. Cascade power stations have a significant impact on the ecological environment in the basin and have a substantial effect on the runoff. The impact of water conservancy projects on the aquatic ecological environment is long-term, slow, potential, and extraordinarily complex and is often the superposition of various water conservancy projects.

Land use change is the most direct manifestation of human activities. The gradual increase in land activities such as deforestation and reclamation of lakes impact the rivers in the basin [48]. Zhou et al. [49] analyzed the impacts of climate change, land use, and water conservancy projects in the Jialing River basin in China in the past 60 years. Land use change may cause environmental problems such as time and space changes in water resources in the basin, soil erosion, or low-end weather events. The reduction of cropland and forests and the increase in construction land in the Min River basin affect the runoff, precipitation, and evaporation, changing the water resources' spatial and temporal distribution [50]. Land use change in the Min River basin is one of the influencing factors of the runoff change in the basin, but its impact is smaller than that caused by the construction of water conservancy projects. The contribution rate of human activities to the runoff change was 69.80%, and the human activity factor played a dominant role in the process of runoff change. Active consideration should be given to the use of human activities in water

allocation, power generation, shipping, etc., in the study area to promote the development of ecological water benefits.

6. Conclusions

According to the Mann–Kendall method, the cumulative distance level method, and the sliding *t*-test method combined with the reservoir construction, the abrupt year of runoff and precipitation was 1993. The annual runoff, precipitation, and evapotranspiration show a downward trend.

Using the RVA method to conduct a comprehensive analysis of 32 hydrological indicators and 32 precipitation indicators at the Min River basin's hydrological stations, the overall hydrological change at the Gaochang hydrological station was 45% (moderate change). Considering the influence of precipitation on the alteration of runoff, the overall change of rain in the Min River basin was 37% (moderate change). At the same time, human activities such as water conservancy-related construction have brought resources and convenience to people and also caused alterations to the hydrological situation in the basin, thus causing damage to the ecological function of the rivers and alterations to the habitat of aquatic organisms.

The contribution rates of climate variability and human activities to the Min River runoff were 30.20% and 69.80%, respectively. Human activities were the dominant factor influencing the Min River basin's runoff situation. Climate factors have a smaller influence on runoff alterations.

The Min River basin has seen an increase of 321 km² in built-up area and a corresponding decrease in the wetland, forest, and cropland area (in terms of land use) from 1980 to 2020, and land use changes in the Min River basin have become a factor leading to runoff changes in the area that cannot be ignored.

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