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Comprehensive analysis on the hydrologic alteration and causes of river runoff in Min River of the Yangtze River, China

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Abstract: The construction of water conservancy projects has changed the hydrological situation of rivers and has an essential impact on the river ecosystem. The influence modes of different factors on runoff alteration are discussed to improve the development and utilization of water resources and promote ecological benefits. The ecological, hydrological index change range method (IHA-RVA) and hydrological alteration degree method were comprehensively used to evaluate Min River's hydrological situation. Based on six budyko hypothesis formulas, the contribution rates of climate change and human activities to runoff change are quantitatively analyzed. The study showed that the runoff of Min River basin showed a significant decreasing trend from 1960 to 2019 and a sudden alteration around 1993; The overall alteration in runoff conditions was 45% moderate, and the overall alteration in precipitation was 37% moderate; Precipitation and potential evapotranspiration also showed a decreasing trend within the same period, but the overall trend was not significant; The contribution of climate alteration to runoff alteration is 30.2%, and the contribution of human activities to runoff alteration is 69.8%, human activities are the dominant factor affecting the alteration of runoff situation in Min River basin.

Keywords: Min River; IHA-RVA; Budyko; Climate Alteration; Human Activities

Introduction

Hydrological conditions are critical drivers of riverine ecosystems and play an essential role in maintaining the energy processes, biological interactions, and physical habitat conditions¹. Climate alteration and human activities are two critical factors influencing runoff alterations. The runoff formation is closely related to climate alteration in terms of precipitation and potential evapotranspiration; the impact of human activities can also cause alterations in runoff in the watershed^{2,3}. In recent decades, extreme weather and climate events have brought frequent floods to the Min River basin area. In contrast, the superimposed effects of many human activities and the construction of large water conservancy projects have played a regulatory role in river runoff, changing the river's runoff and its original seasonal and intra-annual distribution^{4,5}. These alterations will directly or indirectly affect the habitat waters and habits of biological resources in the watershed, thus affecting the distribution of habitat quality in the watershed⁶. The Min River is one of the important tributaries of the upper reaches of the Yangtze River and has very rich resources. In recent years, as my country's comprehensive national strength has increased, the construction of the Min Reservoir has gradually been paid attention to, and a group of cascade reservoirs including series-parallel mixed-connection has been formed^{7,8}. The construction of the reservoir will have an impact on the climate in the Min River Basin, which will inevitably alter the runoff and cause certain disturbances to the ecosystem in the basin^{9,10}. The study of hydrological alterations in the Min River basin is essential for ecological restoration and sustainable development of the upper Yangtze River basin.

43 With the development and construction of large-scale reservoirs in the Min River basin, there
44 is a tendency for its runoff to decrease. The extent of runoff alteration and its influencing factors
45 have been a hot research topic by scholars and abroad. The most widely used method is the Range
46 of Variability Approach (RVA), which Richter^{11,12} proposes to analyze the overall hydrological
47 alterations of rivers. In recent years, many scholars have discussed this issue. Gao et al.¹³ used
48 ecological streamflow indicators and IHA indicators to analyze the alterations in the Yangtze
49 River's hydrological conditions and quantitatively separate the effects of reservoir operation and
50 climate alteration on runoff. Guo et al.¹⁴ used the cumulative slope alteration method to investigate
51 climate alteration and anthropogenic factors in the Yangtze River mainstem, and this study did not
52 consider climate factors such as wind speed and temperature, lacking accuracy. Xia et al.¹⁵
53 quantitatively estimated runoff alterations in the upper reaches of the Han River based on the
54 elastic coefficient method and hydrological simulation method and discussed the differences in
55 runoff caused by natural and artificial factors, studies have shown that human activities have a
56 more significant impact on runoff. In recent years, for the attribution analysis of river runoff
57 alterations, there are mainly hydrological simulation methods, climate elasticity coefficient
58 methods, and double cumulative curve methods to explore the influence of climate alteration and
59 human activity factors on runoff alterations. Many scholars have used hydro-meteorological data
60 to fit the empirical relationships of water-heat balance in different basin types to confirm the
61 validity of Budyko's hypothesis, and the method is widely used in globally important river
62 basins^{16,19}. This study mainly focuses on the methods of IHA-RVA and elasticity coefficient
63 method, and the results can better reflect the degree of runoff alteration and influencing factors.

64 Many scholars from different perspectives have discussed the impact of Min river runoff
65 alteration. Hou et al.²⁰ used a dual-mass mean curve (DMC) and distributed time-varying gain
66 hydrological model (DTVGM) to distinguish the effects of climate alteration and human activities
67 on water resources. Mao et al.²¹ used soil and water assessment tools to develop a regional model
68 to divide the Min River basin into 236 sub-basins, through GIS-based image display, simulations
69 showed the spatial runoff of each sub-basin distribution. They analyzed the impact of land-use
70 alteration on runoff. Guo et al.²² firstly restored the natural runoff process at Gaochang station in
71 the Min River basin, simulated the commissioning scenario of Shuangjiangkou reservoir, and
72 predicted the variability of the hydrological situation at Gaochang station. The analysis of runoff
73 alterations and their factors in the Min River basin has been limited to the study of trends and
74 abrupt alterations, but there is a lack of in-depth research on the causes of alterations in
75 hydrological indicators before and after abrupt alterations in runoff and the effects of alterations in
76 habitat quality on runoff. The composition, structure, and function of ecosystems such as rivers
77 and wetlands are inextricably linked to their hydrological characteristics, and alterations in land
78 use can impact the spatial and temporal distribution of water resources by altering the hydrological
79 cycle of runoff^{23,24}. At the same time, further research is needed on such issues because of the lack
80 of qualitative analysis of the effects of alterations in hydrological conditions on organisms in the
81 Min River basin due to the lack of information on aquatic biota in the basin.

82 In this paper, based on the previous studies, we use the ecohydrological index range of
83 alteration (IHA-RVA) and hydrological alteration method to evaluate the hydrological situation in
84 the Min River basin and analyze the degree of influence of climate alteration and human activities
85 on runoff in the Min River basin in a more objective way. FAO Penman-Monteith formula was
86 used to calculate the potential evapotranspiration in Min River Basin. According to the long-term

water balance formula, drying index, and six Budyko hypothesis formulas, the influence of climate change and human activities on runoff was calculated. This study provides a reference for the Min River basin to cope with climate alteration and develop and utilize water resources more rationally.

Results and Analysis

Mutagenicity analysis

The Mann-Kendall nonparametric test, the sliding t-test, and the cumulative distance level method were applied to the annual runoff and annual precipitation to test the abrupt alterations of their intra-annual long series (Figure 1). The intersection of the UF and UB statistics of runoff and precipitation is at 0.05 significant level, and that of precipitation is at 0.1 significant level, which indicates that the hydrological situation of the Min River basin may have changed abruptly in 1993 and 1997. The results of the sliding t-test method can be concluded that the intra-annual distribution uniformity of runoff volume passes the 0.05 significant level, and the intra-annual distribution uniformity of precipitation volume does not pass the 0.1 significant level. From the figure, 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. The cumulative anomaly method shows that the annual runoff had a maximum value in 1993 and 2002, and the annual precipitation had a maximum value in 1974. Combining the above three methods, 1993 was chosen as the year of the sudden alteration in annual runoff and annual precipitation in this study. The daily runoff data from Gaochang hydrological station and daily precipitation data from the Min River basin were divided into a base period T_a (1960~1993) and a alteration period T_b (1994~2019).

Fig.1 Mutation test analysis curve

Table.1 Years of sudden alteration in uniformity of runoff and precipitation distribution throughout the year

Method	Mann-Kendall	Sliding T-test	Cumulative distance level	Mutation year
Runoff	1993、1997	1968、1993	1993、2002	1993

Precipitation	1987、1993	1990、1993	1974	1993
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IHA hydrological index alteration degree analysis

As climate alteration 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 a macroscopic level, and to further analyze the causes of runoff alterations in a more detailed way, the recording, and analysis of climate alteration data are essential. Precipitation has a direct impact on runoff alterations in climate alteration. Considering daily precipitation data, it can reflect not only the rise and fall of rivers directly but also the alterations of aquatic organisms and riparian habitats. Therefore, in this study, the RVA method was used to analyze the daily streamflow data of Gaochang Station, a representative hydrological station of Min River, and the daily precipitation data of 13 meteorological stations in the Min River basin for variability analysis. Combining the above analyses, the daily streamflow data from the Gaochang station and the daily precipitation data from the Min River basin were divided into the base period T_a (1960~1993) and the abrupt alteration period T_b (1994~2019), and the alteration rates and degrees of alteration of 32 parameters were calculated (Table 2) to quantitatively assess the alterations in the streamflow situation in the Min River basin.

(1) The average flow and precipitation of each month. As can be seen from Table 2, the average monthly flow at the Gaochang hydrological station increased to different degrees after the abrupt alteration, while the average monthly precipitation in the Min River basin increased and decreased, but the increase and decrease were more moderate; the flood season of the Min River was concentrated in June to September, and the rate of alteration of streamflow and precipitation in this period was relatively large; the alteration of average monthly flow was high in May, and medium and low in the rest of the month; for the alteration of average monthly precipitation, July was high. After 1993, the number of reservoirs and their capacity increased significantly, which increased the post-surge flow and caused some disturbance to aquatic organisms' reproduction.

(2) Annual extreme flow and precipitation. The annual mean extreme minimum flow at the Min River basin high field hydrological stations generally increased after the abrupt alteration, while the extreme values showed different degrees of decrease, of which the minimum 7-day flow was highly altered, and the rest were moderately and lowly altered. The reservoir construction and operation after 1993 affected the original flow polarity alteration process of the river. The range of annual extreme precipitation alteration is more drastic, which influences the flow alteration. Such extreme daily alterations in precipitation are frequent and unpredictable, and extreme alterations in precipitation can lead to alterations in natural river hydrologic processes, causing disturbances to species that are not adapted to frequent alterations in water flow.

(3) The timing of annual extreme flow and precipitation occurrence. After the sudden hydrology alteration at the high field hydrological station, the occurrence time of annual maximum flow and 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 alteration had no significant effect on the occurrence time of annual extreme flow.

(4) Frequency and ephemeris of high and low flows with precipitation. After the abrupt alteration, the number of low flow pulses and the rate of alteration of flow low pulse ephemeris is increased by 25%. The number of flow pulses is moderately altered, and the pulse ephemeris is lowly altered. The rate of alteration of precipitation is less than 10% in all cases, which is a small

	30-day maximum	7436	7.182	5927	7.309	28%	2%	-32(L)	-11(L)
	90-day maximum	5857	6.028	4802	5.81	3%	4%	-43(M)	11(L)
	Baseflow index	0.2272	5	0.291	12	1%	140%	-43(M)	-81(H)
3	Date of minimum	37.5	9	38.5	4	3%	56%	9(L)	-29(M)
	Date of maximum	212.5	208	214.5	210	69%	1%	-21(L)	-29(M)
4	Low pulse count	4	35	8	34	25%	3%	-43(M)	-33(M)
	Low pulse duration	5	2	2	2	25%	0	-21(L)	3(L)
	High pulse count	8	36	10	38	8%	6%	-38(M)	-39(M)
	High pulse duration	4	2	3	2	38%	0	-9(L)	-3(L)
5	Rise rate	141	0.8	130	0.811	22%	1%	-21(L)	-22(L)
	Fall rate	-108.5	-0.79	-150	-0.789	17%	0	-100(H)	78(H)
	Number of reversals	151	218	184	215	21%	1%	-89(H)	-38(M)

Note: H-High Variability; M-Moderate Variability Limit; L-Low Variability.

(6) The overall degree of alteration of flow and precipitation. Figure 3 shows the diagram of the hydrological alteration degree of the high field station. It can be seen from the figure that there are four high alterations, 15 medium alterations, and the rest are low alterations in the hydrological alteration degree index in the Min River basin. Among the precipitation alteration indexes in the Min River basin, except for the average precipitation in July, the baseflow index, and the decline rate, which was highly altered, the rest were all moderate and low altered.

According to the above equation, the 32 hydrological indicators of alteration are integrated (Figure 2) to find out the overall hydrological alteration of the lower Min River basin. The overall degree of alteration in flow is moderate alteration. The overall alteration of precipitation is 37% moderate alteration, and the degree of alteration is small. It shows that climate alteration is not the dominant factor affecting the alteration of Min River streamflow (Table 3; Figure 3).

Fig.2 Schematic diagram of hydrological alteration degree of Gaochang Station

Fig.3 Schematic diagram of precipitation alteration degree in Min River Basin

Table.3 Min River discharge and precipitation overall alteration degree

Category	Hydrology, precipitation alteration degree					Overall degree of alteration D_0
	Group 1	Group 2	Group 3	Group 4	Group 5	
Gaochang Station	43(M)	43(M)	16(L)	31(M)	78(H)	45(M)
Min river precipitation	32(L)	39(M)	29(L)	26(L)	52(M)	37(M)

Note: H-High Variability; M-Moderate Variability; L-Low Variability.

Analysis of alterations in runoff conditions

In the selected hydrological series of the Min River basin, the annual runoff volume alterations with 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 annual runoff volume is $1004.54 \times 10^8 \text{m}^3/\text{s}$ (1990), and the minimum value is $635.17 \times 10^8 \text{m}^3/\text{s}$ (2006); compared with the T_a period, the annual runoff in the T_b period decreases by 10.46%. The yearly precipitation is falling in both T_a and T_b periods, and according to the trend test statistic of -1.52, the trend is not significant, and the decrease is 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 T_b period decreases by 6.33%. The fluctuation of annual evapotranspiration is more dramatic, with an apparent decreasing trend in the T_a stage and a slight increase in the T_b stage after the breakthrough, with an overall decreasing trend (Figure 4; Figure 5).

Fig.4 Trend chart of annual runoff and annual precipitation in Min River Basin before and after the sudden alteration

Fig.5 Trend chart of annual runoff and annual evapotranspiration in the Min River Basin before and after the breakthrough

The calculated results of runoff situation alterations in Table 4 show the degree of influence of climate alteration and human activities on annual dimensions. The elasticity coefficient of runoff to precipitation is 0.83; the contribution of climate alteration and human activities to the runoff alteration is 30.20% and 69.80%, respectively.

Table.4 Calculation results of alterations in runoff regime

Index	Zhang	Fu	Schireiber	Budyko	Pike	Ol'dekop	Mean
εp	0.59	0.92	0.93	0.63	0.94	0.96	0.83
$\Delta Q_c / \text{mm}$	-22.94	-28.16	-28.54	-23.79	-28.68	-28.89	-26.83
$\Delta Q_H / \text{mm}$	-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

The multi-year 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 will have a certain impact on the annual runoff. The Min River is rich in water and ecological resources. In recent years, the number of human exploitation of the Min River's hydropower resources has increased significantly, and the number of reservoirs and their capacity has gradually risen. People have made full use of the abundant water resources in the Min River basin to build reservoirs, store water during the flood season and release water during the dry season for the benefit of both sides of the river. By the end of 2019, Min River has built more than 870 large and small reservoirs, with a cumulative total capacity of about 15.3 billion m³, and 22 reservoirs are currently under construction in the basin, with a total capacity of about 3.88 billion m³. In the high field control area, Gongzui and Tongjiezi Reservoirs were put into operation in 1972 and 1993; Zipingpu Reservoir and Waterfall Ditch Reservoir were put into operation in 2006 and 2009, respectively. The terraced power station has brought a more significant impact on the ecological environment in the watershed and has a more significant impact on runoff. Water storage in reservoirs often leads to seepage, which causes certain losses, and reservoir storage will lead to increased water use, and part of the water will evaporate in the process of water use, changing the intra-annual distribution and hydrological pattern of runoff in the Min River basin. The human activity factor dominates the runoff alteration process. The use of human activities for water allocation, power generation, and shipping in the study area should be actively considered to promote the water's ecological benefits.

Discussion

Impact of climatic factors on runoff

Precipitation is the main source of runoff, and its variability has a direct impact on runoff. The rainfall-runoff depth double accumulation curve is a straight line in the natural state, which will be shifted if natural alterations such as extreme precipitation occur. Relative to the base period, the slope of the abrupt alteration period in the Min River basin shows a decreasing trend, i.e., the rainfall-runoff depth double accumulation curve is shifted downward, indicating that the runoff decreases under the same rainfall (Figure 6), so precipitation has a particular influence on the alteration of runoff in the basin, but it is not a key influencing factor²⁵. The slope of the potential evapotranspiration also tends to decrease after the abrupt alteration, and the potential evapotranspiration-runoff depth double accumulation curve shifts downward somewhat (Figure 7). The correlation coefficient between runoff depth and potential evapotranspiration has a decreasing trend, which shows that the correlation between potential evapotranspiration and runoff depth is weak, so the influence of potential evapotranspiration on runoff alterations is small^{26,27}. It shows that the runoff alteration in the watershed is mainly caused by human activities.

Fig.6 Precipitation-Runoff depth double

Fig.7 Potential evaporation-Runoff depth

Impact of land-use change on runoff changes in the watershed

Using five phases of remote sensing data in the study area, ArcGIS was applied to map the land-use changes in the Min River basin in different periods (1980, 1990, 2000, 2010, 2020) (Figure 8) and analyze the changes in land-use area increase and decrease in different periods. 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. 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 basin²⁸.

Fig.8 Land use map in different periods of the Min River Basin

The land cover change in Min River Basin from 1980 to 2020 shows fluctuating changes, the grassland area coverage increases from 42.15% to 42.58, and the increased area is 105km²(Table 5); the increase in construction land changes more between 1980 and 2020, and the area increase rate is 0.23%, which indicates that with the continuous development of industrialization and urbanization, the construction land area increases gradually with time; the un The trend of decrease and then increase in a barren land, 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^{29,30}.

Table.5 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 (Table 6). the watershed area decreases by 9 km² during 1980-2020, 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 of human activities, the total forested area remained in a decreasing change, decreasing by 230km². Grassland and construction land increased by 100km² and 321km², respectively, with the most dramatic increase in the construction area during 1980-2020.

Table.6 Transfer matrix of land use from 1980 to 2020 (km²)

Period	Land Type	2020						
		Cropland	Grassland	Forest	Construction land	Wetland	Barren land	total
1980	Cropland	21112	24	32	316	16	0	21500
	Grassland	12	56302	1129	4	18	381	57846
	Forest	53	1347	50519	4	14	10	51947
	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	21189	57946	51717	1375	959	2898	136084

The mechanisms by which land-use change affects runoff processes in a watershed are complex. One of the most direct effects of land-use change on runoff is soil erosion and implementing soil and water conservation measures to protect against water and sand reduction. Land-use changes have a direct impact on the watershed substrate and are related to the process of watershed flow production and confluence, which leads to changes in the watershed runoff. The decrease of cropland and forest, and the increase of construction land, i.e., the increase of impermeable layer in the watershed sub-base, will impact runoff, precipitation, and evaporation, thus changing the spatial and temporal distribution of water resources^{31,32}. Land-use change in the Min River basin is an essential factor in the change of runoff in the basin, but the extent of its influence due to is less than the extent of the influence of the construction of water conservancy projects on the change of runoff in the Min River basin³³.

Conclusion

(1) Through the Mann-Kendall method, the cumulative anomaly method, and the sliding T-test method combined with the reservoir construction, the abrupt year of runoff and precipitation was 1993. Annual runoff, precipitation, and evapotranspiration show a downward trend.

(2) Using the RVA method to conduct a comprehensive analysis of 32 hydrological indicators and 32 precipitation indicators in the Min River basin hydrological stations, the overall hydrological alteration at the Gaochang hydrological station is 45% is a moderate alteration. Considering the influence of precipitation on the alteration of runoff, the overall alteration of rain in the Min River basin is 37%, which is a moderate alteration. Climate factors have less influence on runoff alterations. At the same time, human activities such as water conservancy 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 rivers and alterations to the habitat of aquatic organisms.

(3) The contribution rates of climate alteration and human activities to the Min River runoff

were 30.20% and 69.80%, respectively. Human activities were the dominant factors influencing the Min River basin runoff situation.

(4) The Min River basin has seen an increase of 321 km² in a built-up area and a corresponding decrease in the water area, forest area, and cropland area in the land use type 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.

Materials and Methods

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. A large tributary of the Min River basin is the Dadu River, which is formed by the confluence of the upper reaches of the Min River, the Qingyi River, and the Dadu River³⁴. 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. 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, so the streamflow data from the Gaochang hydrological station are representative³⁵. 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, and the water environment in the Min River basin has undergone significant alterations, with irreversible consequences on the ecological environment, especially the gradual construction of the upper Min River basin step-by-step power stations have brought a series of impacts on the runoff and fish resources of the lower Min River. Gongzui Reservoir was built on the Dadu River and started to store water in 1972, Tongjiezi Reservoir began to operate in 1993, causing significant alterations to the hydrological sequence within the control area of the high field station, and Zipingpu Reservoir, located in the upper reaches of the Min River, was put into operation in 2006, operating in parallel with the original reservoirs in the Min River basin.

Data

Combining the distribution of hydrological and meteorological stations in the Min River basin, the study uniformly selected day-by-day meteorological element data from 13 meteorological stations in the Min River basin from 1960 to 2019, which are distributed throughout the Min River basin (Figure 9) and can represent the spatial alteration of hydro-meteorology in the basin. The meteorological data were obtained from the China Meteorological Data Network (<http://data.cma.cn>), and there were missing daily data from individual meteorological stations, and the study interpolated the missing data. Considering the distribution of rivers within the Min River basin, the daily flow data from 1960-2019 at Gaochang Station, a representative hydrological station at the confluence of the Dadu River, a tributary of the Min River, with the lower reaches of the mainstream, were selected from the Hydrological Yearbook of the Yangtze River Basin.

Methods

Trend and mutation 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 high field 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 are mainly used in this study. The detailed calculation procedures are described in Ref^{36,37}.

IHA-RVA method

To quantitatively analyze the degree of influence of reservoir construction in the Min River basin on the hydrological situation of rivers, Richter et al. 1996 proposed 32 hydrological alteration indicators that can represent the relationship between river streamflow alterations and external ecological alterations, IHA indicators can express the degree of environmental influence on rivers, and then used the range of alteration method (RVA) established based on the hydrological alteration indicator method to evaluate the river Hydrological situation alteration situation. And the degree of alteration after the alteration was quantified by calculating the degree of alteration (Table 1) by the following equation³⁸.

$$D_i = \left| \frac{N_{oi} - N_e}{N_e} \right| \times 100\% \quad (1)$$

Where: D_i is the degree of hydrological alteration of the i the IHA indicator; N_{oi} is the number of years that fall within the RVA target threshold for the i IHAs observed after the disturbance; N_e is the number of years after the alteration.

The hydrological degree of 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 water temperature, the calculation principle is detailed in the literature, the following formula is calculated.

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

Where: n is the number of indicators. The comprehensive index hydrological alteration degree D_o can fully reflect the overall alteration, the absolute values of the hydrologic alteration degree (0–100%) were divided into three categories: (1) 0–33% represented low or no Variability (L); (2) 33–67% represented moderate Variability (M); and (3) 67–100% represented high Variability (H), as shown in Table 7.

Table.7 Classification of streamflow rate alterations

Method	Classification	Influence Level
RVA	0-33%	Low Variability
	33-67%	Moderate Variability
	67-100%	High Variability

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 scholars³⁹.

$$ET_0 = \frac{0.408(R_n - G) + \gamma \frac{900}{T + 273} \mu_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34\mu_2)} \quad (3)$$

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/m²d); G is the soil heat flux (MJ/m²d); 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 China Meteorological Data Network, and the specific calculation process is shown in Ref.

Quantitative Analysis of Runoff Situation Alterations

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

$$\Delta Q = \Delta Q_C + \Delta Q_H \quad (4)$$

$$\eta_C = Q_C / \Delta Q \times 100\% \quad (5)$$

$$\eta_H = \Delta Q_H / \Delta Q \times 100\% \quad (6)$$

Where: ΔQ is the difference of streamflow alteration; ΔQ_C and ΔQ_H are the amount of runoff alteration caused by climate alteration and human activities; η_C and η_H are the contribution rate of climate alteration and human activities^{40,41}.

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 Budyko's assumptions (Table 2), with the following equations.

$$\Delta Q_C = \varepsilon_P \frac{Q}{P} \Delta P + \varepsilon_{E_0} \frac{Q}{E_0} \Delta E_0 \quad (7)$$

$$\varepsilon_P = 1 + \frac{\phi F'(\phi)}{1 - F(\phi)}, \text{ and } \varepsilon_{E_0} = 1 - \varepsilon_P \quad (8)$$

Where: Q , E_0 , and P are the multi-year 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; and ε_P and ε_{E_0} are the elasticity indices of runoff to precipitation and potential evapotranspiration, respectively. For the 6 formulas $F(\phi)$ and $F'(\phi)$ based on Budyko's hypothetical formula, refer to related literature^{42,43} (Table 8).

Table.8 6 common expressions based on Budyko's hypothesis

Serial number	$F(\phi)$	$F'(\phi)$	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; 2001
2	$1 + \phi - (1 + \phi^a)^{1/a}, a = 2.5$	$1 - (1 + \phi^a)^{1/a-1} \phi^{a-1}$	Baopu Fu; 1981
3	$1 - e^{-\phi}$	$e^{-\phi}$	Schireiber; 1904

4	$\left[\phi \tanh(1/\phi)(1-e^{-\phi})\right]^{0.5}$	$0.5[\phi \tanh(1/\phi)(1-e^{-\phi})]^{0.5} \times [\tanh(1/\phi) - \operatorname{sech}^2(1/\phi)/\phi(1-e^{-\phi}) + \phi \tanh(1/\phi)e^{-\phi}]$	Budyko; 1948
5	$(1+\phi^{-2})^{-0.5}$	$1/\left[\phi^3(1+(1/\phi)^2)^{1.5}\right]$	Pike; 1964
6	$\phi \tanh(1/\phi)$	$\tanh(1/\phi) - 4/\left[\phi(e^{-1/\phi} + e^{1/\phi})^2\right]$	Ol'dekop; 1911

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