

Article

Spatiotemporal Variations and Influencing Factors of Arid Inland Runoff in the Shule River Basin, Northwest China

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Abstract: Considering the possibility of increasing water supply in China in the short term and the long-term threat posed by shrinking glaciers, this paper studied the spatiotemporal evolution of runoff in typical arid areas and the influence of hydrometeorological elements on runoff, aiming to clarify the hydrological cycle law and provide a basis for adjusting water resource management strategies to cope with future uncertain changes. Based on hydrological data from 1956 to 2020, the spatial and temporal variation in runoff were discussed by means of wavelet analysis, MK test, RS analysis, and spatial interpolation. The influencing factors of runoff evolution in the Shule River Basin were determined. The results showed that the runoff in the Shule River Basin showed an increasing trend in the past 60 years. Five hydrological stations (Changmabao Station, Panjiazhuang Station, Shuangtabao Reservoir, Dangchengwan Reservoir, and Danghe Reservoir) were selected as the research objects. Among them, the runoff of Changmabao Station increased the most, which was $1.202 \times 10^8 \text{ m}^3/10 \text{ a}$. Future projections suggest a continued rise in runoff, particularly at Shuangtabao Reservoir. The runoff exhibited positive persistence and varying degrees of mutation, with most mutations occurring in the early 21st century. The runoff in the basin has a periodicity of multiple time scales (there are 2–3 main cycles), and the main cycle of annual runoff is concentrated in 58 years. This comprehensive analysis provides valuable insights for the sustainable management of water resources in inland river basins amidst changing environmental conditions. The spatial variation in runoff in summer and autumn and the whole year showed a significant southeast to northwest decreasing pattern. During the study period, accelerated glacier melting caused by rising temperatures had the most significant impact on runoff change ($p < 0.01$), and the upstream of the study area also complied with this rule (temperature contribution rate [25.96%] > precipitation contribution rate [23.91%]). The contribution of temperature and precipitation changes caused by human activities in the middle stream to runoff was relatively large, which showed that the contribution rate of temperature in Guazhou Station to runoff was 34.23% and the contribution rate of precipitation in Dangchengwan to runoff was 60.27%. The research results provide a scientific basis for the rational and efficient utilization of water resources in the arid area of Northwest China.



Academic Editors: Leszek Sobkowiak, Arthur Mynett and David Post

Received: 29 November 2024

Revised: 31 January 2025

Accepted: 3 February 2025

Published: 6 February 2025

Citation: Zhang, W.; Sun, D.; Niu, Z.; Wang, Y.; Shu, H.; Wang, X.; Cui, Y. Spatiotemporal Variations and Influencing Factors of Arid Inland Runoff in the Shule River Basin, Northwest China. *Water* **2025**, *17*, 457. <https://doi.org/10.3390/w17030457>

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Keywords: Shule River Basin; temporal and spatial variation in runoff; climate factors

1. Introduction

As an important part and form of water resources, runoff is an important part of the surface water cycle [1–3]. It can directly reflect the impact of climate change and human activities on the water cycle of the basin. Secondly, as an important part of the

watershed ecosystem and the main water source for the socio-economic development of the watershed, runoff change has a profound impact on the management and sustainable use of water resources in the watershed [4]. Significant changes in global or regional runoff seriously threaten the regional water resource status, and the runoff variation pattern has suddenness, periodicity, determinism, and randomness. Based on extensive research, the annual average runoff of many northern basins in China is obviously decreasing, including the Haihe River Basin [5], the Shiyang River Basin [6], and the Hanjiang River Basin [7]. Especially in arid regions, the drastic reduction in water resources has seriously affected socio-economic development and the destruction of ecological integrity. For the Shule River Basin in Northwest China, runoff dynamics are closely related to social and economic activities in the Shule River Basin. It is manifested in the following aspects: the abundance and decline of runoff directly affect the water supply of agricultural irrigation. In dry years, reduced runoff may lead to insufficient irrigation water sources, affecting crop yield and quality. Runoff reduction may lead to an industrial water shortage, affecting the normal operation of industrial production and residents' domestic water shortage, affecting the normal life of residents. In addition, runoff changes have an important impact on the fragile ecosystem of the region. For example, when the river runoff decreases, on the one hand, due to the lack of sufficient water scour, pollutants are easy to stay in the water, resulting in the deterioration of water quality. On the other hand, it leads to an insufficient supply of dissolved oxygen in the water body, posing a threat to the survival of fish and other aquatic organisms. Analyzing the spatiotemporal variation and distribution pattern of runoff, understanding the evolution rule of basin water resources, and revealing the characteristics of basin water resource changes can provide a decision-making basis and data support for the comprehensive management and efficient allocation of regional water resources.

At present, scholars in the field of hydrology have explored the evolution of runoff on different spatial and temporal scales, focusing on the study area of the diversity of geographical, climatic, and hydrological features. For example, China has analyzed runoff evolution models under complex climatic conditions in the source areas of the Yangtze River, Yellow River, Lancang River, Salween River, northwest arid area, southeast coastal area, inland lakes, and river basins, while foreign countries have analyzed runoff evolution models in the Mississippi River basin, Colorado River basin, Rhine River, Danube River basin, Ganges River basin, Indus River basin, and other research areas. For the study of runoff models in arid areas, foreign countries use hydrological models to simulate and forecast runoff and remote sensing technology to monitor vegetation cover and soil moisture. Statistical analysis, time series analysis, and hydrological model simulation are used in China. For example, a research team from the Northwest Institute of Ecology, Environment and Resources of the Chinese Academy of Sciences studied the annual distribution variation in mountain runoff from 13 rivers in the three major river basins in Hexi and compared and analyzed its influencing factors. The methods of the non-uniformity coefficient, complete adjustment coefficient, concentration degree and concentration period, skewness coefficient, and kurtosis coefficient are applied comprehensively. China has also conducted valuable research on the runoff evolution model in arid northern China. For example, by establishing the TVP-SV-VAR model [8] in response to meteorological variability, combined with the geographic information system (GIS), remote sensing (RS), and the artificial neural network (ANN) [9], the daily runoff series in arid and semi-arid areas was analyzed. The establishment of a runoff model is very important for the scientific and effective management of water resources. According to previous studies, the common methods used to study the interannual and intra-year variation trends of hydrological elements include linear regression, cumulative anomaly, the Mann–Kendall (MK) test, Pettitt test, seasonal trend analysis, and adaptive noise empirical mode decomposition [9,10].

For example, Dinpashoh et al. used the Mann–Kendall and the Sen estimator to analyze the monotonic trend of evaporation in the Urmia Lake basin [11], and Jerin et al. used an improved Mann–Kendall test, wavelet analysis, and Kriging model to study the spatiotemporal changes in evaporation, and used linear regression analysis and the partial correlation coefficient to determine the factors controlling these changes [12]. Considering that hydrological processes are affected by various climate factors, such as the decrease in wind speed leading to a reduction in surface evaporation, and changes in precipitation impacting runoff size [13], analyzing the influencing factors of hydrological processes under the drive of human activities has become a hot topic for experts and scholars. The main research methods in this area fall into two categories: the first involves the use of the Budyko model to quantify the influencing factors of runoff change [14,15], and the second is to simulate runoff processes using hydrological models under the premise of no human interferences [16]. At the same time, the Pearson correlation coefficient can also be used to explore the degree of interaction between runoff variation and related hydrological factors [17].

Considering the potential future impacts of climate warming and glacier retreat, the study of runoff in arid areas is still a hot spot in the rational management of water resources. The Shule River Basin in the study area of this paper is a typical arid area in Northwest China, located in the western section of the Qilian Mountains. Due to the unreasonable utilization of water resources, the ecological environment has deteriorated to varying degrees. The specific ecological and environmental problems are mainly reflected in two aspects: firstly, the increasingly severe ecological environment issues resulting from excessive water resource development, with examples such as the shrinking of the Dunhuang Basin highlighted by the decline in the water levels of crescent springs and the contraction of the West Lake Nature Reserve; secondly, due to population growth and rapid socio-economic development, excessive water resource development in the basin has led to a significant encroachment on ecological environment water use, threatening the oasis ecological environment, and subsequently impacting the stability of the oasis, seriously impeding the healthy development of the oasis ecosystem and the sustainable development of society, economy, and the environment. Therefore, this area has always been the focus of numerous studies aimed at ensuring abundant water resource supply and a balanced ecological environment. The current research results show that the runoff depth of the Shule River Basin is mainly affected by precipitation, followed by the total amount of extreme precipitation and temperature [18]. By increasing the precipitation data of 40 years by 10%, 15% and 25%, respectively, on the basis of average, it is found that when the precipitation increases from 15% to 25%, the annual runoff will hardly increase [19]. It can be seen that although precipitation will have an impact on runoff changes, it cannot play a decisive role. In order to grasp the law of runoff changes, it is necessary to pay close attention to the melting of glaciers caused by temperature changes.

This study focuses on the runoff data of the major hydrological stations in the Shule River Basin spanning from 1956 to 2020. Specifically, long-term runoff data from five hydrological stations, namely Changmabao, Panjiazhuang, Shuangta Reservoir, Danghe Reservoir, and Dangchengwan, are selected for analysis. This study applied a combined analytical method that employs quantitative calculations and traditional qualitative analyses to investigate the temporal and spatial evolution of runoff and its influencing factors. The three main objectives of the study are as follows: (1) Linear regression, moving average, and cumulative distance equality were used to determine the interannual and annual changes in runoff. (2) Qualitative analysis methods such as the MK test, wavelet analysis, RS analysis, and spatial interpolation were used to reveal the spatiotemporal evolution of annual and seasonal runoff. (3) The Pearson correlation coefficient method and cumulative

slope comparison method were used to explore the relationship between hydrological factors and runoff. The research results have significant importance for the sustainable utilization of water resources in the basin.

2. Materials and Methods

2.1. Research Area

The Shule River Basin is one of the three major inland river basins in the Hexi Corridor of northwestern Gansu Province, China. Its geographic coordinates are between 92°10' E~99°00' E and 38°00' N~42°48' N (Figure 1). The main stream of the Shule River is 945 km long, with a catchment area of 13,015 km² and an altitude of 4737 m. Water flows from southeast to northwest. There are five hydrological stations in the study area, including Panjiazhuang, the Shuangtabao Reservoir, Danghe Reservoir, Changmabao, and Dangchengwan, as well as three meteorological stations: Dunhuang, Guazhou, and Yumen. The Shule River system is located between the Mongolian–Xinjiang Plateau and the Qinghai–Tibet Plateau, with terrain sloping from southeast to northwest and comprising three distinct topographical zones. The southern Qilian Mountains consist of a series of high mountain ranges (3000–5000 m) characterized by low temperatures and abundant precipitation. The central corridor area is irrigated by rivers and supports unconnected oases distributed in the Yumen, Tashi, Anxi, and Dunhuang river basins, with a vegetation coverage of 70%, but this is not complete forest cover, and desert vegetation such as tamarisk, alcamel, and Achnatherum is widely distributed. These areas are between 1000 and 1800 m above sea level, with high temperatures, drought, and little rainfall. The northern region includes sandy or gravel deserts and low mountains and hills, including the North Mountain range, which is between 1500 and 2000 m above sea level. The climate is extremely arid, and vegetation is scarce; especially in the desert landscape, the vegetation coverage is relatively low, mainly in the area of 5–15% vegetation coverage. The upper reaches of the Shule River are mainly located in the Qilian Mountains. The soil types in this region are mainly alpine desert soils and steppe soils, which are usually cold and wet. In the higher elevation areas, due to abundant precipitation and adequate surface water resources, the soil is well developed, and the vegetation coverage is high, which is mainly dominated by hardy vegetation. These soils provide a stable base for ecosystems in the upper reaches. The middle reaches mainly include alluvial plains and Mazong Mountain area. The soil type in this area is mainly brown desert soil. Brown desert soil is a typical soil in arid areas, with low fertility and high water permeability. Due to the relative scarcity of water resources in the middle reaches, drought-tolerant vegetation is the main vegetation, such as trees such as populus eueux and salsalis, and shrubs such as tamarisk and prickly thorn. This vegetation plays an important role in soil improvement and protection. In the lower reaches, the soil types are mainly saltsoil, meadow saltsoil, and arid saltsoil due to poor underground runoff. There are complex interactions among climate, vegetation, and runoff in the basin. Climate change will affect the growth and distribution of vegetation and then affect the process of runoff recharge and consumption. At the same time, changes in vegetation also have an impact on climate and runoff. The main water sources are glacier melt water and precipitation [20]. Due to the obstruction of high-altitude mountains, vapor is difficult to transport to inland areas, resulting in obvious temperate continental arid climate characteristics [21]. The region has low annual precipitation, strong solar, and high surface evaporation. Precipitation is concentrated from June to September, while snowmelt is concentrated from March to May. The annual average rainfall is 96.0 mm; the maximum observed monthly precipitation for the period of 1956–2020 was 76.3 mm (which occurred in August 2016); the average annual evaporation is 1751.1 mm. According to the temperature data of Shule River Basin from 1956 to 2020, the annual average temperature

of the basin is 6.98–9.82 °C, the highest annual average temperature is 11.17 °C (in 2016), and the lowest annual average temperature is 5.7 °C (in 1967) [22].

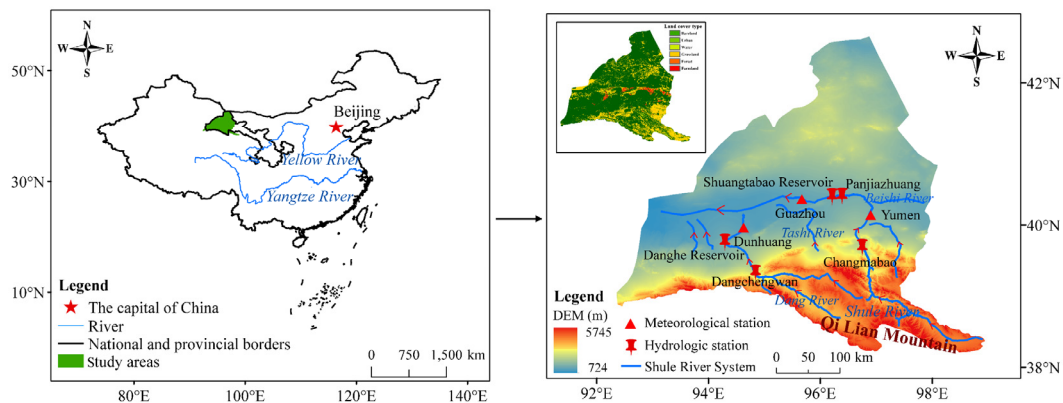


Figure 1. Schematic diagram of the study area.

2.2. Research Method

2.2.1. Data Source

This study focuses on the Shule River Basin, a typical arid region in inland China. A monthly analysis was conducted on the variables of runoff, precipitation, sediment (represents the amount of sediment passing through a cross section of a river per unit time), water surface evaporation (E601 evaporating pan was used to measure evaporation in the basin) (The E601 evaporating pan is sourced from Nanjing Research Institute of Hydraulic and Water Conservation Automation, Ministry of Water Resources, Beijing, China), and temperature (refers to the air temperature), using data from five hydrological stations (Changmabao, Panjiazhuang, Shuangtabao, Danghe Reservoir, and Dangchengwan) and three meteorological stations (Dunhuang, Guazhou, and Yumen). The detailed information about these stations is shown in Table 1. Among them, the data of Panjiazhuang Station began in 1959, Dangchengwan Station and Danghe Reservoir station began in 1966 and 1977, respectively, because of the late construction time. All data were collected from field measurements conducted by hydrological professionals in accordance with the “Specification of Hydrological Measurements”. Data compilation followed the “Guidelines for Compilation of Hydrological Data” and passed the Kolmogorov–Smirnov test and cumulative curve analysis. The months of March to May, June to August, September to November, and February were defined as spring, summer, autumn, and winter, respectively, to understand the seasonal variations throughout the year. The methodological framework of this research is shown in Figure 2.

2.2.2. Data Treatment Method

Analysis of interannual variation: By applying methods such as the Mann–Kendall (m-k) test [23] (The principle is: for time series data, calculate the size relationship between each data point and all the previous data points, and obtain a cumulative statistic S. It reflects the trend change in the data series. The statistic S is normalized to a Z-value for comparison with a preset significance level. According to the value of the standardized statistic Z and the preset significance level (such as 0.05), determine whether there is a trend change in the data series. At the same time, combining the UF (forward sequence) and UB (reverse sequence) curves, the mutation points in the data series can be further determined. When the UF and UB curves intersect at a certain time and the intersection point is outside the confidence interval corresponding to the preset significance level, the moment is considered to be the abrupt point of the data series. The criteria are as follows: If $UF > 0$, it is an upward trend; if $UF < 0$, it is a downward trend. When they exceed

the critical confidence level (± 1.96 when testing confidence level $\alpha = 0.05$), it indicates a significant upward or downward trend. If the UF curve and the UB curve intersect and the intersection point is between the critical boundary, then the moment corresponding to the intersection point is the time when the mutation begins.), rescaled range analysis (R/S) (its core principle is to evaluate the wave characteristics of the sequence by calculating the rescaled range, so as to judge whether it has long-term memory) [24], linear trend analysis, moving average method (It refers to the calculation of the average value of the data in a certain time series by taking the data of five consecutive years as a window. Then, as the data are updated, the window slides forward continuously to calculate the average value of the subsequent windows in turn. That is, by calculating the average of the data over a certain period of time (5 years), the short-term fluctuations and accidental factors in the data can be smoothed out, and the long-term trend of the data can be revealed.) [25], cumulative anomaly method [26], and wavelet analysis (The principle is to represent the signal as a series of successive approximation expressions, the core of which is to use the wavelet function to analyze the signal in multi-scale time–frequency analysis. The main periodic components of the signal can be identified according to the frequency-time diagram, time-scale diagram, and the wavelet square difference diagram. Major periods usually correspond to peaks or significant areas of energy concentration in the graph.) [27]. The annual and seasonal runoff data at five stations were analyzed to assess the persistence, abrupt changes, and cyclical characteristics of the runoff on an interannual scale.

GIS spatial interpolation was used to determine the spatial variation characteristics of runoff evolution. The principle is based on the data analysis technology of the location and the morphological characteristics of the geographic objects, which can conveniently extract and transmit the spatial information of the geographic data [28]. In this paper, Kriging interpolation is used for spatial analysis. The concrete steps are as follows: Box–Cox transformation is used to transform the original data to make them conform to the hypothesis of Kriging interpolation. The semi-variance function is used to describe the spatial correlation between known points. Finally, the accuracy and reliability of the interpolation results are evaluated by cross-validation.

Table 1. Hydrological station information.

Observation Station Type	Station Name	No. Station	East Longitude	North Latitude	Location in the Watershed	Ground Elevation/m	Length of Data Series	Provide Information
Hydrographic station	Changmabao	01420800	96°51′	39°49′	Upstream	2112.0	1956–2020	Precipitation, runoff, sediment, water surface
	Panjiazhuang	01421400	96°31′	40°33′	Midstream	1340.0	1959–2020	Precipitation, runoff, sediment
	Shuangtabao Reservoir	01421600	96°20′	40°33′	Midstream	1300.0	1956–2020	Precipitation, runoff
	Dangchengwan	01423600	94°53′	39°30′	Primary tributary	2176.8	1966–2020	Precipitation, runoff, sediment, water surface
	Danghe Reservoir	01424000	94°20′	39°57′	Downstream	1375.5	1977–2020	Precipitation, runoff, sediment, water surface
Meteorological station	Dunhuang Station	52418	94°40′	40°9′	Downstream	1139.0	1960–2020	Temperature
	Yumen Station	52436	97°1′	40°16′	Upstream	1526.0	1960–2020	Temperature
	Guazhou Station	52424	95°46′	40°31′	Midstream	1170.9	1960–2020	Temperature

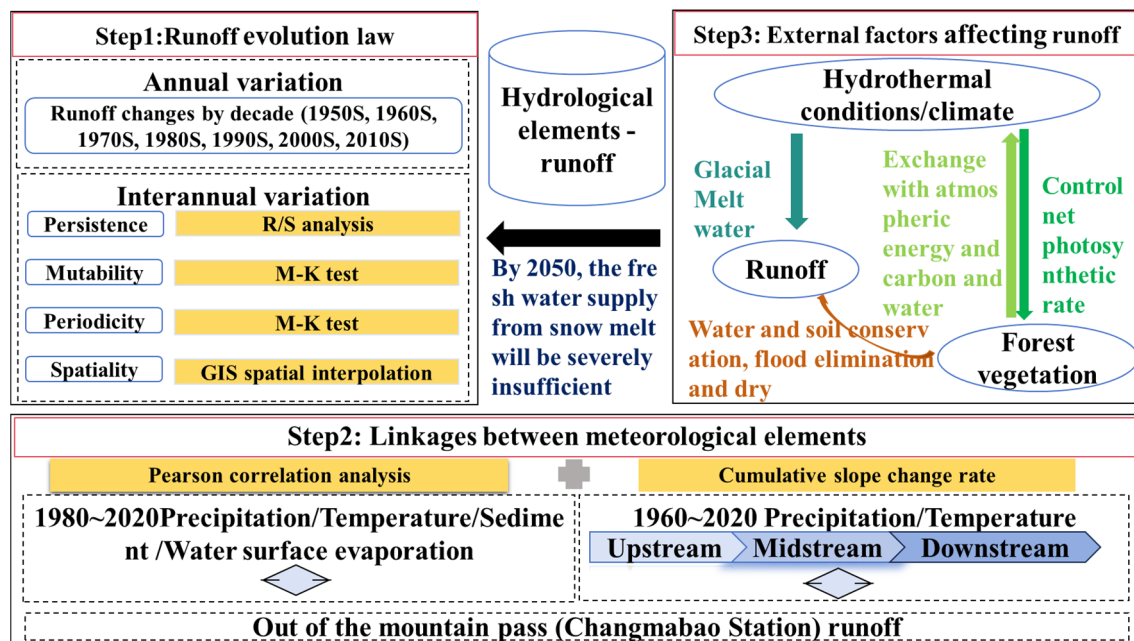


Figure 2. The methodological framework of this research.

Analysis of factors influencing: By using Pearson correlation analysis [29], the contribution of hydrological factors such as temperature and precipitation to the variation in runoff at the outlet of a river in different periods is analyzed through correlation analysis with the Pearson correlation coefficient and cumulative slope change rate. The reasons for choosing precipitation, air temperature, surface evaporation, and sediment as factors to study the interaction with runoff change are as follows: Precipitation, temperature, and evaporation directly affect the process of runoff change by changing the exchange and transfer of water and energy between the surface and the atmosphere. These changes ultimately lead to the redistribution of water resources in both time and space. Sediment changes are also influenced by runoff, which washes the land surface and rivers, causing sediment accumulation.

3. Results

3.1. Shule River Basin Intra-Annual Distribution Characteristics

Due to climate change and human activities, the water cycle in the Shule River Basin exhibits significant seasonal variations, and the temporal distribution of seasons at the five hydrological stations shows different patterns. By averaging the monthly runoff values for different years, as shown in Figure 3, Changmabao Station and Shuangtabao Reservoir have the least even distribution within a year, showing a single-peak pattern and relatively high values for the coefficient of variation. Danghe Reservoir, on the other hand, shows a relatively even distribution with a triple-peak pattern. Panjiazhuang Station and Dangchengwan Station both exhibit a double-peak pattern. The peak runoff at Changmabao Station occurs during the flood season (June to September, accounting for 68.53% of the annual runoff), while the peak runoff at Panjiazhuang Station occurs in March (9.85%), July to August (23.13%), and November (6.23%). The peak runoff at Shuangtabao Reservoir occurs from May to September (63.59%). The peak runoff at Dangchengwan Station occurs in April (11.70%), and June to August (35.26%). The peak runoff at Danghe Reservoir occurs in April (11.47%), June to August (37.15%), and November (7.54%). The interdecadal average difference between the wet and dry periods was the largest in the 2010s and the smallest in the 1970s [30]. The main reason for these phenomena is that the runoff in the

basin is influenced by climate, with a concentration of flow occurring mainly in July and August. However, the winter flow remains relatively stable due to the fact that winter precipitation is mostly in solid form, and river recharge primarily relies on deep groundwater sources in the mountainous areas. After the temperature rises in April and May, snowmelt and thawing gradually increase the amount of runoff. Then, it enters the season with the most concentrated rainfall. In addition, the melting of the mountain snow and ice further contribute to the peak flow in July and August. After October, with decreasing temperatures and weakened warm and humid air masses, the flow gradually decreases.

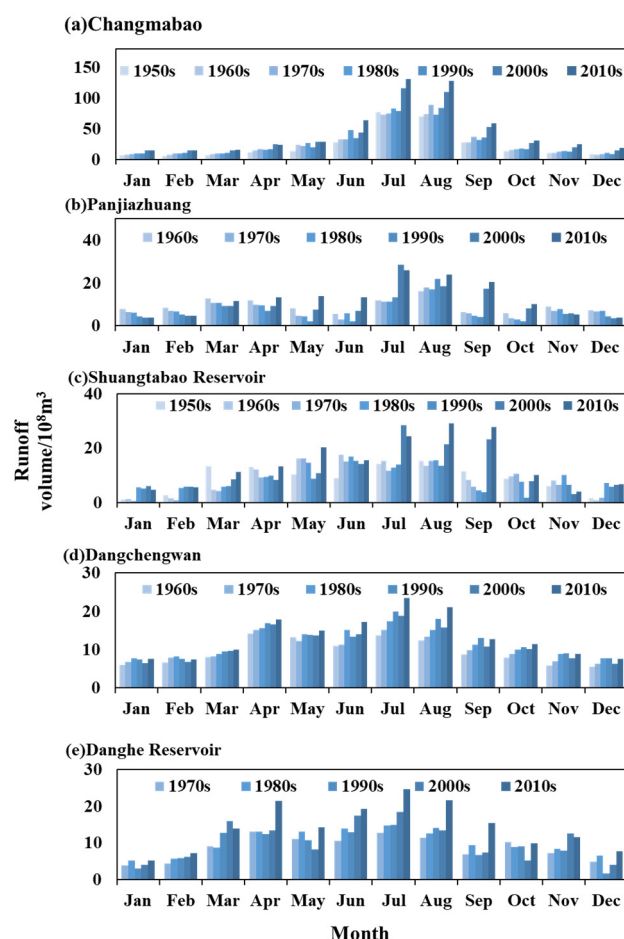


Figure 3. Interannual distribution of monthly runoff in Shule River Basin.

3.2. Shule River Basin Trends in Annual Runoff Variables

The average rate of change for the annual runoff at the five hydrological stations in the Shule River Basin was further calculated using linear regression, and the trend analysis was carried out using the Mann–Kendall method. Due to the influence of time series length, significant trends were observed at each station. This analysis, as shown in Figure 4, presented that all stations exhibited an increasing trend through the five-year moving average and cumulative anomaly analyses. From the five-year moving average curve, the Dangchengwan and Danghe Reservoir stations showed a slow increasing–decreasing fluctuation trend, while the other three stations exhibited more pronounced fluctuations. The statistical table of specific periods of abundance and low water in Shule River Basin obtained from the cumulative anomaly is shown in Table 2 and Figure 2, and its range is consistent with the change trend in Figure 4. Overall, the trend rates of the runoff in the Shule River Basin were ranked as follows: Changmabao Station [$1.202 \times 10^8 \text{ m}^3 \cdot (10 \text{ a})^{-1}$] > Danghe Reservoir [$0.437 \times 10^8 \text{ m}^3 \cdot (10 \text{ a})^{-1}$] > Shuangtabao Reservoir [$0.293 \times 10^8 \text{ m}^3 \cdot (10 \text{ a})^{-1}$] > Dangcheng-

wan Station [$0.021 \times 10^8 \text{ m}^3 \cdot (10 \text{ a})^{-1}$] > Panjiazhuang Station [$0.0202 \times 10^8 \text{ m}^3 \cdot (10 \text{ a})^{-1}$]. According to the Mann–Kendall trend test, the calculated Z-values for the five stations were 6.09, 2.56, 4.64, 4.36, and 3.02, respectively. The significance test with a 95% confidence level showed that $|Z| > 1.96$, indicating a significant increasing trend in the runoff. The maximum runoff values occurred in the 2010s, showing consistency across the stations.

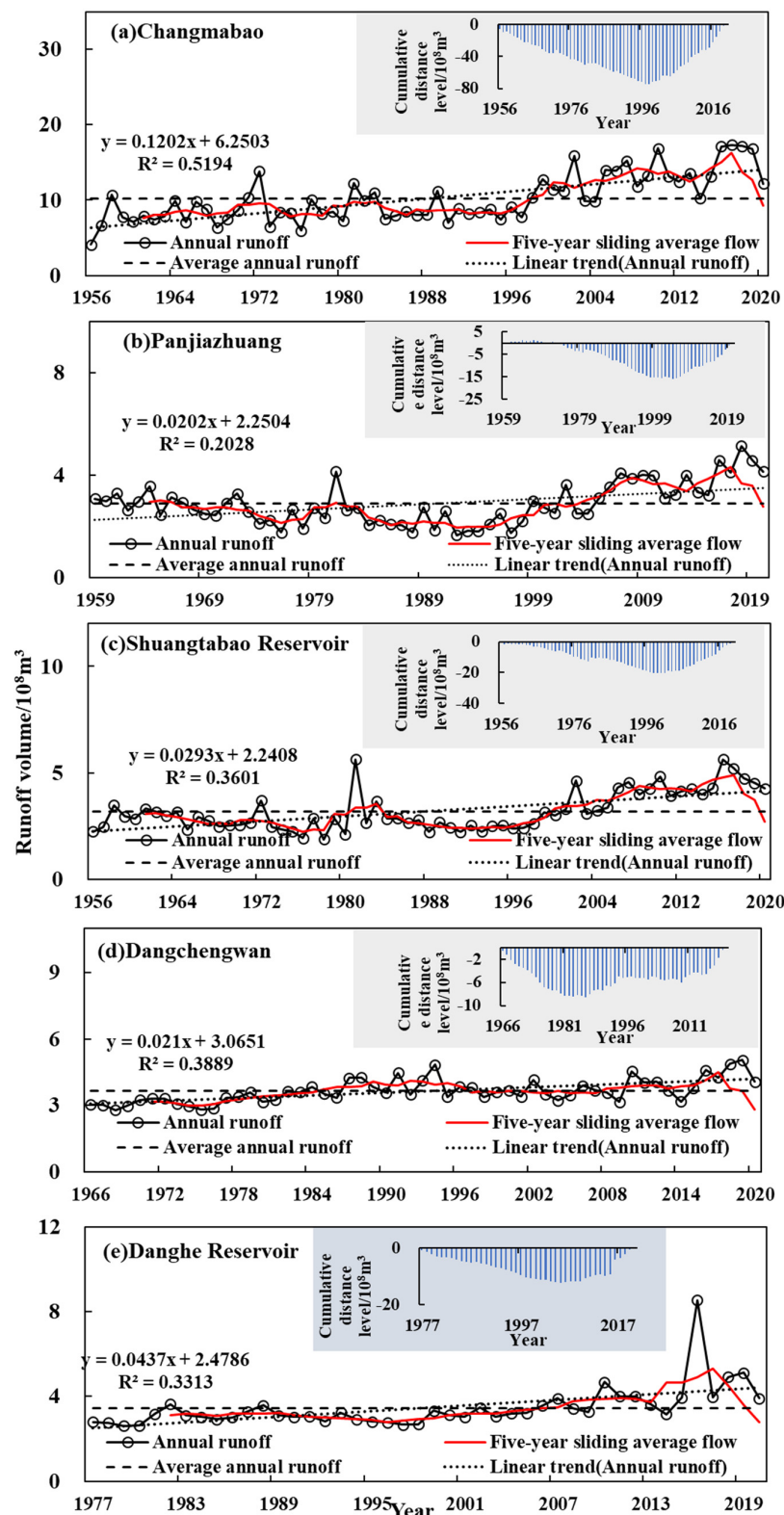


Figure 4. Annual runoff and cumulative distance level of runoff variation at each hydrological station in this study.

Table 2. Statistical table of abundant and low-water period in Shule River Basin.

Hydrographic Station	The Period of Low Water	The Period of Normal Water	The Period of Abundant Water
Changmabao	1959–1996	-	1997–2020
Panjiazhuang	1966–2003	1959–1965	2004–2020
Shuangtabao Reservoir	1956–2003		2004–2020
Dangchengwan	1966–1980	1997–2007	1981–1996, 2008–2020
Danghe Reservoir	1977–2007	-	2008–2020

3.3. Shule River Basin Runoff Persistence Analysis and Mutation Detection

The calculation results of the Hurst index based on the R/S analysis are shown in Tables 3 and 4. The overall Hurst exponent values, for both the annual and seasonal runoff at all five stations in the Shule River Basin, are greater than 0.5. This indicates that these five stations exhibit positive persistence characteristics, with the runoff sequences showing a tendency to continue their past behavior in the future. Additionally, the memory property of the sequences does not vary with different time scales.

Table 3. Hurst index scale.

Level	Index Range	Sustained Strength
I	$0.50 < H \leq 0.55$	Very weak
II	$0.55 < H \leq 0.65$	Weaker
III	$0.65 < H \leq 0.75$	Stronger
IV	$0.75 < H \leq 0.80$	Strong
V	$0.80 < H \leq 1.00$	Very strong

Table 4. Analysis of the persistence of runoff throughout the year and in all seasons.

Hydrological Stations	All Years	Spring	Summer	Autumn	Winter
Changmabao	0.8280	0.8127	0.7353	0.8155	0.9422
Panjiazhuang	0.9194	0.9939	0.7716	0.9581	0.9999
Shuangtabao Reservoir	0.7425	0.9134	0.7243	0.9241	0.9999
Dangchengwan	0.9316	0.8307	0.9030	0.9642	0.9142
Danghe Reservoir	0.7685	0.8358	0.7958	0.7522	0.8857

Detecting the sudden changes in hydrological data can assist in the analysis and prediction of hydrological data. Reliable sudden change detection can identify the factors that affect the effectiveness of hydrological forecasting and analyze the phase change characteristics of hydrological data. This is of great significance for the in-depth analysis of hydrological data change characteristics and improving the timeliness of hydrological data prediction [31]. Using the M-K test to determine the abrupt change points in annual runoff for the five stations, as shown in Figure 5, the intersection of U_{fk} and U_{bk} within the 95% confidence interval is considered a change point [32]. The annual and seasonal runoffs at Changmabao, Panjiazhuang, Shuangtabao Reservoir, Dangchengwan, and Danghe Reservoir stations in the Shule River Basin show varying degrees of abrupt changes and exhibit different change points in different time periods. The change points of annual runoffs at the five stations were in 2000, 2016, 2006, 1982 and 2007, respectively.

3.4. Shule River Basin Runoff Periodicity Analysis

Using wavelet analysis, the real part time–frequency and wavelet variance of the annual runoff wavelet coefficients for the five stations in the Shule River Basin were computed, as shown in Figure 6. It can be observed that the lower contour lines (the time scale is 0–20 years) are relatively dense, representing high-frequency curves corresponding to

small-scale oscillations. Conversely, the upper contour lines (the time scale is 50–60 years) are relatively sparse, representing low-frequency curves corresponding to large-scale periodic oscillations. The annual runoff of the five sites showed obvious periodic changes, and the annual runoff of the five sites changed on the time scale of 56–60 years. The wavelet variance further indicates that the runoff exhibits significant multi-scale variations, with a primary period of 58 years for the annual runoff throughout the year. These results suggest that the changes in runoff in the Shule River Basin occur in a non-fixed periodical form. Table 5 shows the main cycle statistics. Overall, the periodical variations in the Shule River runoff from 1956 to 2020 show large-scale changes of 28–38 years and 5–16 years. In summary, the alternation of abundance and drought in the Shule River Basin has undergone a significant change in the early 21st century.

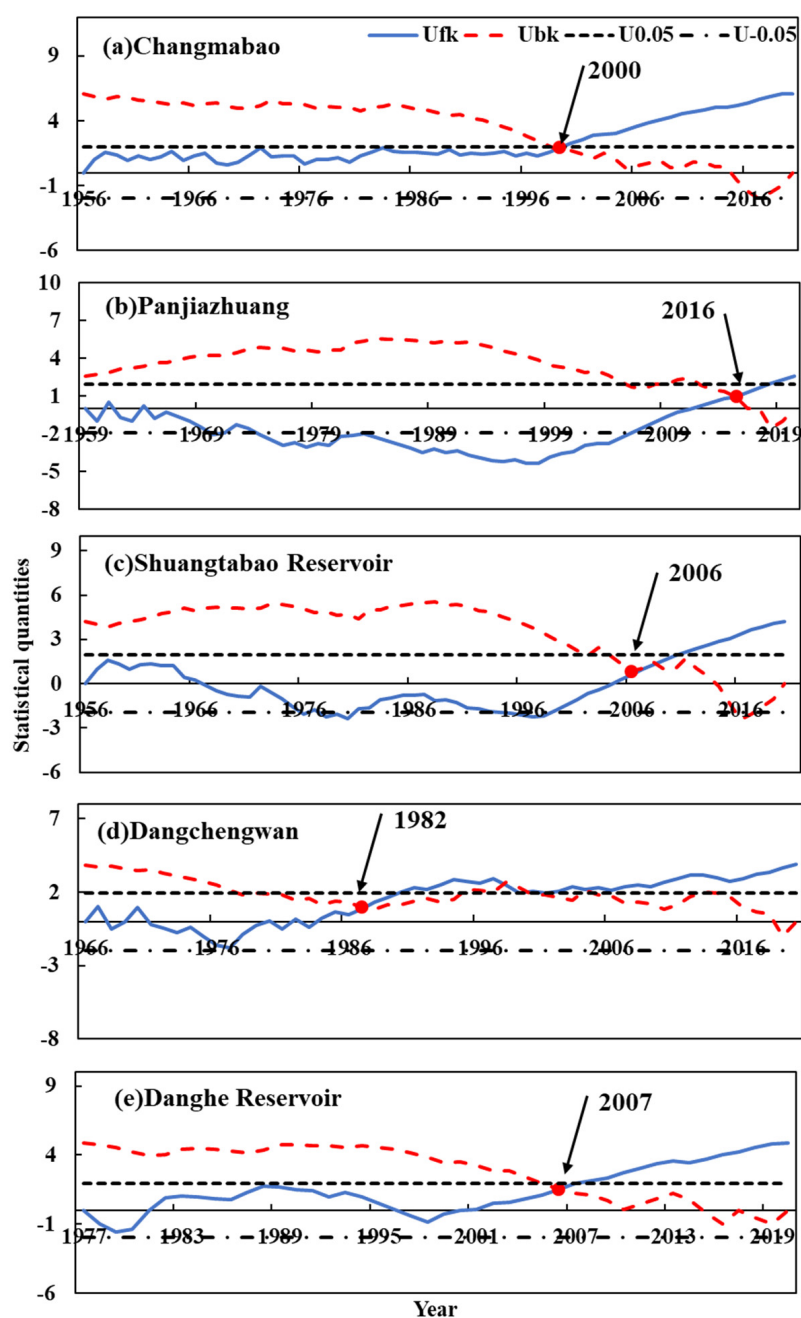


Figure 5. Analysis of abrupt changes in runoff throughout the year and in all seasons.

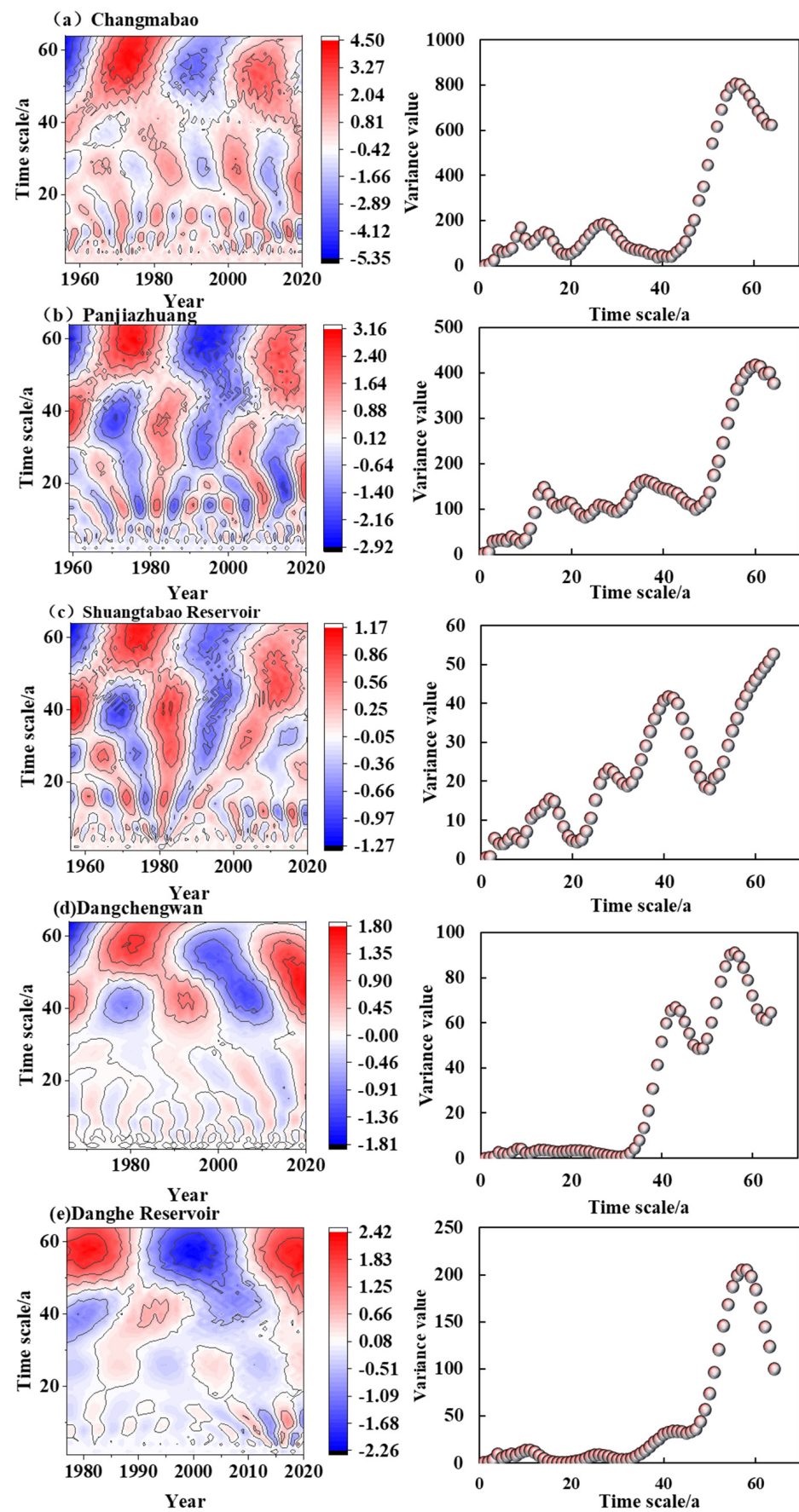


Figure 6. Real part of wavelet cycle analysis of year-round and four-season runoff.

Table 5. Statistical table of main cycle in Shule River Basin.

Hydrological Stations	First Primary Cycle	Second Primary Cycle	Third Primary Cycle
Changmabao	57 a	28 a	9 a
Panjiazhuang	59 a	38 a	13 a
Shuangtabao Reservoir	40 a	28 a	15 a
Dangchengwan	57 a	45 a	-
Danghe Reservoir	58 a	43 a	5 a

Note: “a” stands for the year.

3.5. Shule River Basin Characteristics and Patterns of Spatial Variation in Runoff

The spatial distribution of seasonal and annual runoff was obtained by interpolating the annual average values from five stations. The spatial distribution of the average values for each season and the annual average are shown in Figure 7. The average runoff values for the year, spring, summer, autumn, and winter are 4.68, 1.01, 2.19, 0.95, and $0.52 \times 10^8 \text{ m}^3$, respectively. The average values in descending order from highest to lowest are summer, spring, autumn, and winter, with summer being 4.21 times larger than winter. In summer and autumn, the runoff increases from upstream to downstream. The range of runoff values for each season is as follows: spring ($0.73\text{--}1.41 \times 10^8 \text{ m}^3$), summer ($11.28\text{--}5.94 \times 10^8 \text{ m}^3$), autumn ($0.58\text{--}1.98 \times 10^8 \text{ m}^3$), and winter ($0.33\text{--}0.86 \times 10^8 \text{ m}^3$). The annual runoff varies from 2.89 to $10.22 \times 10^8 \text{ m}^3$. According to the annual and seasonal runoff of each station, the coefficient of variation can be calculated, and the coefficient of variation in each of the five time scales is as follows: CV (annual) = 0.59; CV (spring) = 0.24; CV (summer) = 0.85; CV (autumn) = 0.55; CV (winter) = 0.41. Because the coefficient of variation can reflect the spatial heterogeneity, the greater the coefficient of variation, the more uneven the spatial distribution of the data, that is, the higher the spatial heterogeneity. Therefore, the spatial distribution of summer, autumn, and the whole year is not uniform. In general, Figure 7 also shows that the spatial distribution of runoff in summer and autumn is similar to the annual distribution, decreasing from southeast to northwest. Furthermore, the overall runoff in the watershed shows an increasing pattern from upstream to downstream.

3.6. Analysis of Factors Affecting Runoff Change in Shule River Basin

Runoff plays a crucial role in the water system structure and is closely influenced by climatic factors. To address the water resources crisis in the Shule River Basin, it is important to quantitatively assess the relationship between the mountain runoff in the Shule River and various climate influencing factors. Using Pearson correlation analysis, the correlation between temperature, rainfall, sediment, water surface evaporation, and outlet runoff (Changmabao station) from 1980 to 2020 was calculated. The results are shown in Table 6, indicating significant correlations between rainfall, sediment, water surface evaporation, temperature, and outlet runoff for all stations. Specifically, runoff is positively correlated with rainfall, temperature, and sediment, while negatively correlated with water surface evaporation.

Considering the significant changes in Shule River runoff since the 21st century, the research time scale was further divided into two stages, the baseline period (1980–2000) and the changing period (2001–2020), to explore the relationship between annual average temperature, annual average precipitation, and outlet runoff in the Shule River Basin. Figure 8 illustrates the relationship, showing that sediment is the best fit for annual runoff in both the baseline and changing periods, with R^2 values of 0.669 and 0.029. The results of this study are consistent with the conclusions of previous research [33], that the water–sediment relationship in the Shule River Basin is significant. The river is mainly replenished by melting ice and snow from the Qilian Mountains and precipitation. The vegetation cover and water conservation conditions are good above the outlet of

the mountain. However, downstream of the mountain outlet, there are impacts from activities such as the construction of reservoirs, hydroelectric power development, diversion projects, and sand mining, which have affected the relationship between sediment and water. The sediment–runoff model shows a positive correlation in the baseline and a negative correlation in the changing period. It shows that the change in the sediment transport rate in the baseline period is mainly affected by natural factors, and the change period is affected by terrain slope direction and human activities (such as water conservancy facility construction, soil and water protection measures, etc.), that is, the effect of sand control and water retention is achieved. Similar changes are observed in the temperature–runoff relationship model. With increasing temperatures, the melting of ice and snow in altitude areas increasingly supplemented river runoff.

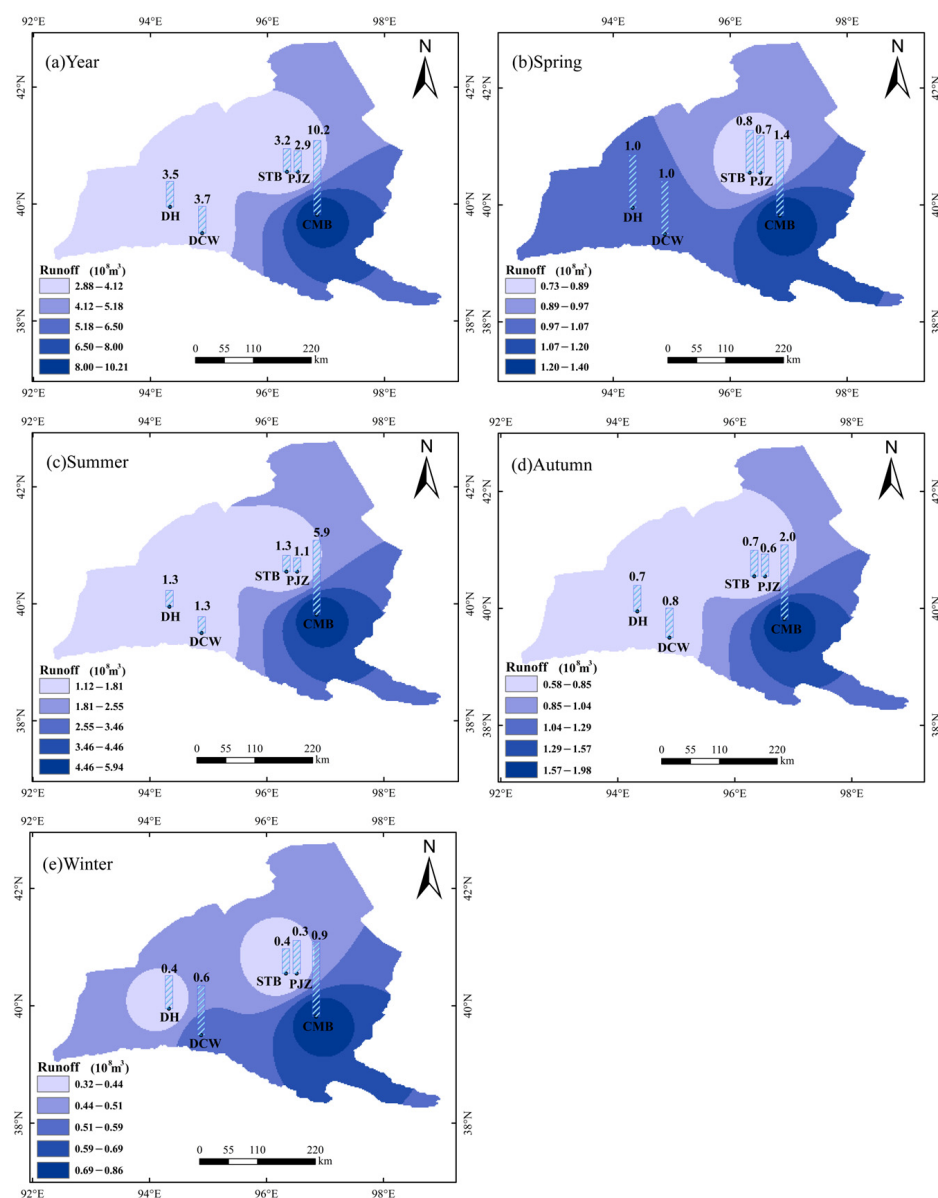
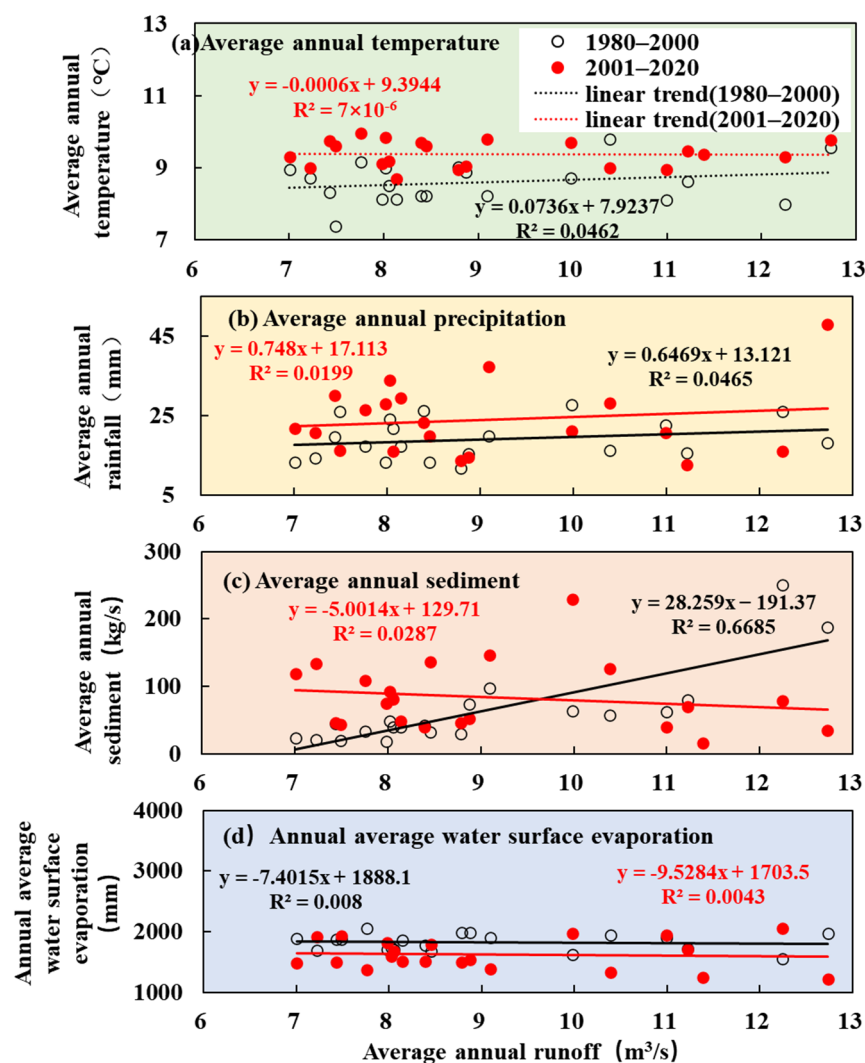


Figure 7. Spatial variation pattern of runoff in the Shule River Basin throughout the year and in all four seasons. (Note: CMB represents Changmabao, PJZ represents Panjiashuang, STB represents Shuangtabao Reservoir, DCW represents Dangcheng Wan, and DH represents Danghe Reservoir).

Table 6. Correlation coefficients between the runoff from the Shule River (Changmabao Station) and climate factors at each station.

Hydrological Stations Runoff	Average Annual Precipitation	Average Annual Sediment	Annual Average Water Surface Evaporation	Average Annual Temperature	
	Correlation Coefficient	Correlation Coefficient	Correlation Coefficient	Hydrological Stations	Correlation Coefficient
Changmabao	0.43 (0.005 ***)	0.66 (0.000 ***)	−0.28 (0.075 *)	Guazhou Station	0.68 (0.000 ***)
Panjiazhuang	0.38 (0.015 **)	0.36 (0.022 **)		Dunhuang Station	0.51 (0.001 ***)
Shuangtabao Reservoir	0.38 (0.014 **)		−0.57 (0.000 ***)	Yumen Station	0.69 (0.000 ***)
Dangchengwan	0.59 (0.000 ***)	0.30 (0.054 *)	−0.46 (0.003 ***)		
Danghe Reservoir	0.31 (0.050 **)		−0.62 (0.000 ***)		

Note: ***, **, and * represent 1%, 5%, and 10% significance levels, respectively.

**Figure 8.** Relationships between mean annual temperature, mean annual precipitation, and runoff from outlets in the Shoal River Basin.

The cumulative slope ratio method has the advantage of quantitatively analyzing the contribution of statistical quantity changes to runoff changes while partially eliminating the impact of interannual fluctuations in measured data. In comparison to other correlation analysis methods, the cumulative slope ratio method is more objective. Therefore, this method is further used to analyze the contribution rate of runoff evolution from different hydrological and meteorological stations in spatial dimensions, as shown in Table 7. Precip-

itation variation at Dangchengwan Station contributed the most to the discharge out of the mountain pass, reaching 60.27%. The temperature changes at the Guazhou Station have the greatest contribution compared to other meteorological stations, reaching a maximum of 34.23% in terms of its impact on the runoff. This indicates that the temperature change in the middle reaches of the Shule River is the main cause of the runoff evolution in the basin. The reasons are that the middle reaches of the Shule River pass through the Qilian Mountains, the altitude is relatively high, and the glaciers and snow are widely distributed. As the temperature rises, the amount of snow- and ice-melt increases and becomes an important supply source for rivers. In spring and summer, warmer temperatures lead to the faster melting of snow and ice, which in turn increases runoff. On the other hand, evaporation and transpiration may increase as temperatures rise. This results in increased water loss within the catchment, which reduces the amount of water available for runoff. However, it is important to note that evaporation and transpiration have relatively little impact on runoff, as snowmelt and watershed precipitation are the main sources of recharge. However, attention should be paid to evapotranspiration in the process of the dynamic adjustment of water resource allocation in the future, because the ecosystem structure and function of the high-vegetation zone may change, such as vegetation type transformation and biodiversity reduction, and these changes will affect the intensity and mode of evapotranspiration. For example, drought-tolerant plants may gradually replace the original vegetation, resulting in a decrease in the overall evapotranspiration efficiency. Conversely, if vegetation growth conditions improve, more evapotranspiration may be promoted. In the middle reaches of the Shule River, there are many transformations between groundwater and surface water. As temperatures rise, snowmelt water and precipitation increase, which may promote the rise in the water table. When the groundwater level rises to a certain level, it is converted back into surface runoff through springs and other forms. See Figure 9.

Table 7. Analysis of cumulative precipitation and temperature values at different time scales—annual slope, change rate, and contribution rate.

Station	Meteorological Station/(Hydrographic Station)	Period	Cumulative Temperature/(Cumulative Precipitation)			Cumulative Runoff			Contribution Rate of Temperature/(Precipitation) Variation to Runoff (%)
			Slope	Variation (°C/a)	Variation Rate (%)	Slope	Variation ((m ³ /s)/a)	Variation Rate (%)	
Meteorological station	Dunhuang Station	Base period	9.33	1.25	13.40	27.71	15.53	56.04	23.91
		Change period	10.58			43.24			
	Yumen Station	Base period	6.91	0.91	13.17	27.71	15.82	57.09	23.07
		Change period	7.82			43.53			
	Guazhou Station	Base period	8.68	1.08	12.44	43.53	−15.82	−36.34	−34.23
		Change period	9.76			27.71			
Hydrographic station	Changmabao	Base period	97.73	14.48	14.82	27.71	15.82	57.09	25.96
		Change period	112.21			43.53			
	Panjiazhuang	Base period	54.15	−0.34	−0.63	27.71	18.81	67.88	−0.93
		Change period	53.81			43.52			
	Shuangtabao Reservoir	Base period	54.28	1.14	2.10	27.71	15.82	57.09	3.68
		Change period	55.42			43.53			
	Dangchengwan	Base period	54.28	17.59	32.41	27.71	15.82	57.09	60.27
		Change period	71.87			43.53			
	Danghe Reservoir	Base period	54.28	−0.01	−0.02	27.71	15.82	57.09	−0.06
		Change period	54.27			43.53			

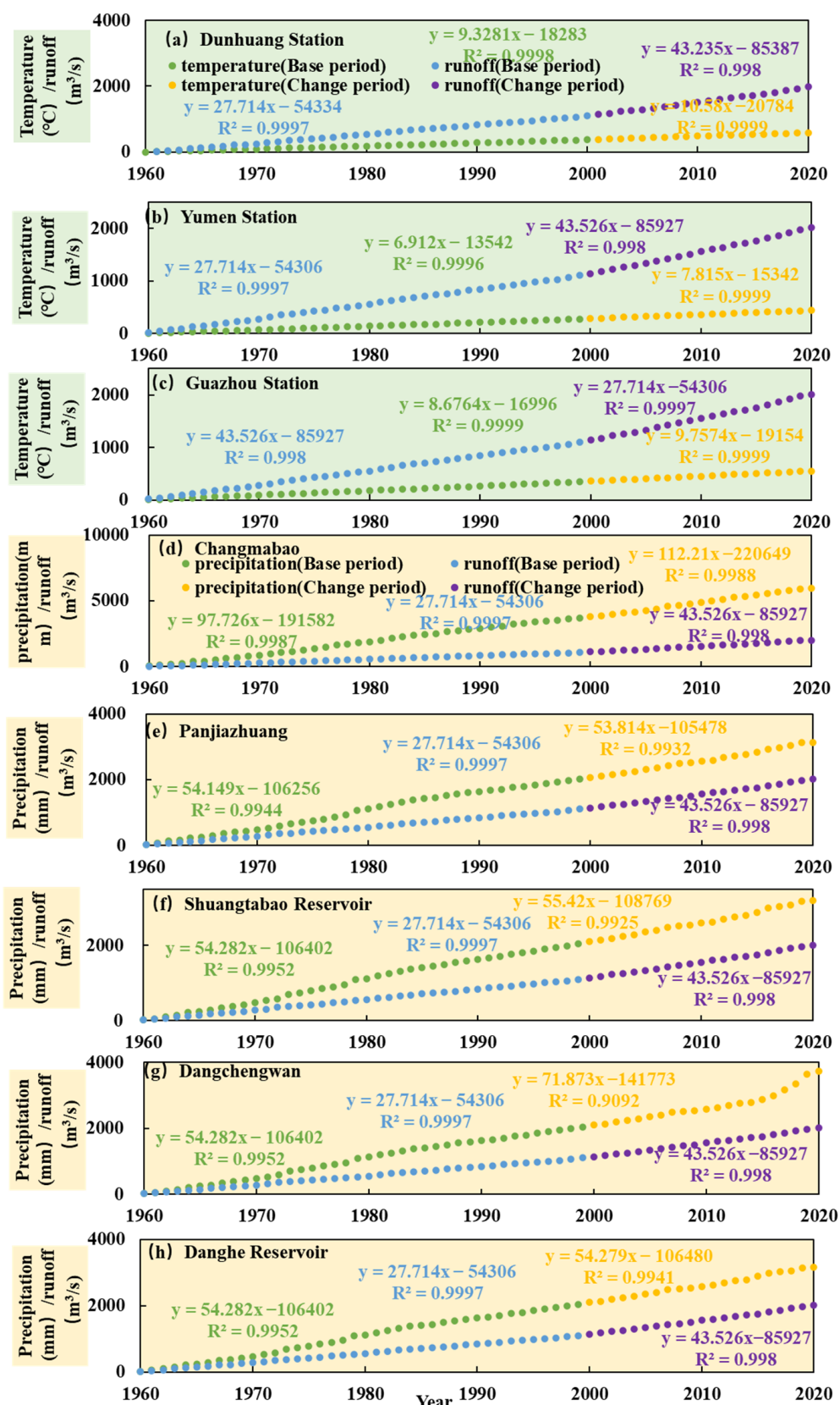


Figure 9. Relationship between cumulative precipitation, runoff and temperature and year.

4. Discussion

In summary, the Shule River Basin is affected by global warming, leading to a warmer and wetter climate in the upstream mountainous areas. According to some studies, more

than half of the global average surface temperature rise is highly likely to be due to anthropogenic factors, such as greenhouse gases (CO_2 , CH_4 , N_2O) and other human-caused factors (aerosols, land use, surface reflectivity, and ozone changes) [34]. Among them, the most important factor affecting runoff by human activities is the construction of reservoirs. Several reservoirs have been built in Shule River Basin, such as Shuangta Reservoir, Danghe Reservoir and Yulin River Reservoir. These hydraulic engineering facilities are mainly used to regulate river flow, flood control, and drought relief and meet the needs of agricultural irrigation and urban water supply. The storage and release operations of reservoirs alter the temporal and spatial distribution of natural water flows, resulting in a decrease or increase in water volume at certain periods downstream. In view of the impact of human activities on runoff, we can take into account the long-term impact of climate change on runoff and plan corresponding engineering facilities and technical solutions in advance, such as the construction of more small reservoirs and rainwater collection systems, so as to enhance the ability to cope with extreme weather events. As the main source of runoff, glacial meltwater in arid Northwest China has a greater impact on runoff dynamics in the future. The research shows that the glacier area of Qilian Mountains has decreased by about 21.20%. Overall, ice reserves decreased by about 25.86% by 2014, with a recent trend of accelerated shrinkage and thinning.

Based on this, the paper further quantitatively discussed the impact of glacier ablation on runoff change, and generally used hydrological model simulation, glacier mass balance measurement, isotope analysis, scenario prediction, and other methods for analysis. In view of the limited data acquisition, the temperature–runoff response function was selected to determine the degree of impact (Figure 10). Since the glaciers are mainly distributed in the upper reaches of the Shule River Basin, the temperature of Yumen Station and the runoff of Changmabao Station are selected for research, and the contribution rate of temperature of Yumen Station to the runoff of Changmabao Station determined above is 23.07%, and the correlation between the two is as follows: Figure 10a, based on the correlation of 0.69 between the annual mean runoff and the annual mean temperature in the Shule River Basin during 1960–2020, further visualized the changes in annual and interannual impact degrees; Figure 10b shows the correlation coefficient between monthly runoff and temperature in the Shule River Basin during 1960–2020 with a lag of 0–2 months. The blue line shows the relationship between runoff and temperature (R-T) in the same month. Green indicates that the runoff and temperature (Rmon-Tmon-1) lag by 1 month. The yellow line represents the relationship between runoff and temperature (Rmon-Tmon-2) with a lag of 1 month. From Figure 10a, it can be seen that after the 1990s, the correlation between temperature and runoff increased significantly from 0.05 in the 1960s to 0.50. At the same time, it is also known that the Shule River Basin experienced a significant warming trend from the late 1980s to the 1990s. According to the study, the average annual temperature showed a very significant warming trend, with a linear change rate of $0.0393\text{ }^\circ\text{C/a}$, and the abrupt change year was in the early 1990s. This warming accelerates the process of melting ice and snow, especially during periods of high summer temperatures, which increases the amount of melt from glaciers and snow cover, thereby increasing the amount of runoff from rivers. As can be seen from Figure 10b, runoff in spring, summer, and autumn showed a strong positive correlation with temperature in the first 0–2 months, and the correlation reached a significant level at a 99% confidence level, while the influence of temperature in the first 1–2 months of winter on runoff was greater than that in the same month, indicating that runoff in winter had a lag, and runoff in spring was positively correlated with temperature in the first 0–2 months. It shows that the temperature rises from January to May, and the snowmelt period is advanced, thus increasing the spring runoff. To sum up, glacier melting will have a great impact on runoff in the Shule River Basin. For example, the increase

in runoff in the short term makes the peak of runoff in spring and early summer more obvious, while the low-discharge period in autumn and winter may become lower due to the decrease in glacial meltwater. In the long run, as the glacier area continues to shrink or even disappear, the role of glacial meltwater as a stable water source will gradually weaken. When small-scale glaciers melt completely, they are no longer able to provide additional meltwater, ultimately leading to a significant decrease in runoff throughout the year, especially during dry seasons. The Shule River Basin itself is an arid and semi-arid area, with scarce and unevenly distributed precipitation. Once rivers that rely on glacial meltwater become seasonal, meaning they only have enough flow during the rainy season, water shortages in the region will become more severe. Secondly, it will also affect the water demand of human society and the ecological environment. For example, shrinking wetlands, falling water tables, reduced vegetation cover, and other issues can lead to a loss of biodiversity and further affect the health of the entire ecosystem. Based on this, in order to address the above challenges, a series of adaptive measures should be taken, such as strengthening monitoring and forecasting, optimizing water resource allocation, and strengthening environmental protection.

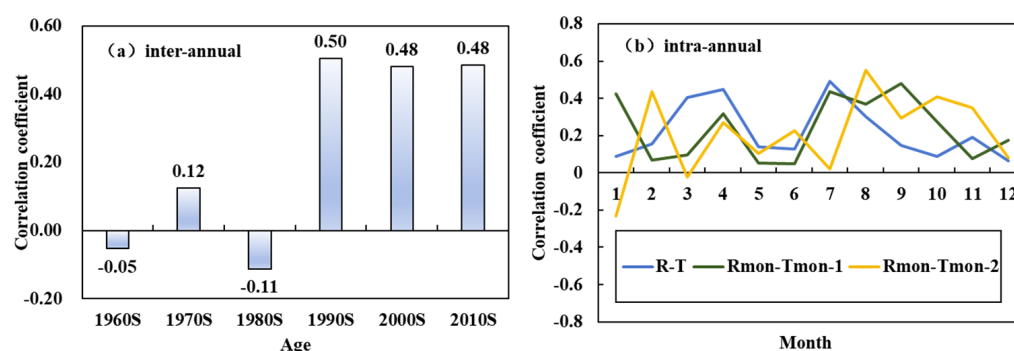


Figure 10. Figure correlations between annual and interannual temperature and runoff in Shule River Basin during 1960–2020.

Scholars have noted that in addition to the Shule River, the runoff changes in the neighboring Heihe River Basin are also affected by this phenomenon, and the Shiyang River Basin and Halten River Basin located in the arid and semi-arid regions of Northwest China are all facing the challenges brought by rising temperatures and changing precipitation patterns with the trend of glacier, snowmelt, and permafrost degradation. The trend of glacier loss in these basins is similar, with initial runoff increasing but decreasing in the long term. However, due to the differences in geographical location, runoff evolution characteristics, and water resources development and utilization, the dynamic change trend of runoff and the degree of impact of glacier ablation on rivers will be different. For example, compared with the Heihe River Basin, the Shule River Basin exhibits fewer oscillations in the wet–dry alternation and more stable periodic changes on a certain time scale. The Hurst index also shows the stronger persistence of the Shule River Basin than the Heihe River Basin. In terms of water resource development and utilization, due to the backward irrigation technology in the Shule River Basin, most of the agriculture still adopts traditional irrigation methods, making the water consumption for agriculture twice of that in other arid inland rivers. Moreover, the Shule River Basin is located in the city area where desertification is most severe, with the risk of expanding areas of land desertification and sandification. Therefore, it is urgent to develop customized water resource protection plans according to local conditions. With reference to the implementation of the IWRM framework in the Heihe River Basin, which includes cross-sectoral coordination, integrated basin management, and multi-stakeholder participation, the Shule River could consider

establishing a similar basin management body to ensure effective cooperation between the different levels of government and water departments to promote the sustainable use of water resources. Explore advanced agricultural water-saving technologies and management models in arid regions such as Israel and Australia to see how they achieve efficient water use through drip and sprinkler irrigation and intelligent irrigation control systems. The successful application of these technologies can provide new ideas and technical support for the Shule River Basin and promote the sustainable development of local agriculture. Based on the above research results, the correlation between runoff and forest vegetation under hydrothermal conditions was explored. The research results of three parts, namely, the rule of runoff evolution, the internal relations among hydrological elements, and the external factors affecting runoff changes, were reviewed. It is of practical significance to understand the pattern of water movement in the arid area of Northwest China to clarify the runoff variation rule from the perspectives of periodicity, persistence, trend, mutability, spatial character, and influencing factors.

5. Conclusions

This study analyzed the correlation between hydrological factors (such as precipitation, temperature, sediment, and evaporation) and runoff in the Shule River Basin in two different time periods (1980–2000 as the reference period, 2001–2020 as the change period), and revealed the spatiotemporal evolution pattern of runoff in the basin and the main driving factors behind it. The following is an in-depth discussion based on the above research findings:

- (1) The research shows that the seasonal adjustment capacity of Changmabao Station and Shuangtabao Reservoir is relatively weak, which is mainly manifested as the unimodal annual runoff, and the flood season is concentrated from June to September, accounting for more than 60% of the annual runoff. This phenomenon may be due to the geographical constraints of these areas, coupled with the influence of water resources management and human activities, resulting in the limited regulation of natural runoff. Changmabao Station had the highest rate of runoff change, reaching $1.202 \times 10^8 \text{ m}^3/10 \text{ years}$, and exceeded the Z-values for all regions at the 95% confidence level. This indicates that the site has experienced relatively drastic changes in runoff over the past few decades, which may be related to climate change, glacier melting, and other factors.
- (2) It is found that the annual runoff changes at different time points, and the overall trend show a strong positive continuity ($H > 0.7$), which means that the runoff has high predictability and stability. The main cycle is mostly 58 year, suggesting the influence of a longer period of climatic or geological processes on runoff. Despite 1–2 dry and wet alternations, the 2020 data show that the downstream contours are still not closed, indicating that partial abundance states will continue to occur in the future. The spatial distribution of runoff increases gradually from upstream to downstream, reflecting the difference in topographic relief and land cover types.
- (3) The attribution analysis shows that temperature has the most significant influence on outlet runoff, and the correlation coefficient reaches a significant level ($p < 0.01$). Especially in Guazhou Station, the contribution rate of temperature change to runoff reached 34.23%, which was much higher than other stations. Specifically, the temperature rises from January to May, the snowmelt period is advanced, and the spring runoff increases. This result highlights the important role of rising temperatures in accelerating glacier snowmelt, which in turn affects changes in river runoff.
- (4) Compared with the change period, the correlation between sediment and annual runoff showed a good fitting effect in the base period ($R^2 = 0.669$) but dropped sharply

in the change period ($R^2 = 0.029$). This indicates that with the change in environmental conditions, especially the intensification in glacier melting, the water–sediment effect in the basin has changed significantly, and the influence of sediment content on runoff has weakened.

- (5) Although the phenomenon of runoff decline was found, especially in all hydrographic stations around 2019, from the perspective of periodicity and continuity, the future runoff may continue to follow the original fluctuation pattern. However, this change does not mean that there is sufficient water, but rather that the dynamic characteristics of runoff remain unchanged. Related studies indicate that glacier melting in the Qilian Mountains is one of the key factors to grasp the runoff evolution in the Shule River Basin. It is expected that by 2050, the freshwater resources supplied by snow and ice meltwater will face a severe shortage, which will pose a great threat to the livelihoods and production of local residents. In order to cope with this challenge, effective water resource management measures must be taken, such as strengthening water-saving awareness, optimizing the layout of water conservancy projects, and promoting ecological restoration projects.

Author Contributions: Conceptualization, W.Z.; methodology, Y.W.; resources, Z.N.; supervision, D.S.; validation, Y.C. and X.W.; visualization, H.S. and Z.N.; writing—original draft, W.Z. and D.S.; writing—review and editing, H.S. and W.Z.; data curation, Y.W.; formal analysis, W.Z.; and software, W.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research is supported by the Scientific Research Start-up Funds for Openly Recruited Doctors of Gansu Agricultural University [Grant No. GAU-KYQD-2019-27], the Key R&D Project for Provincial Ecological Civilization Construction of Gansu Province (Grant No. 24YFFF002), the Key R&D Project of Gansu Province (Grant No. 21YF5NA015), the Gansu Province Water Conservancy Science Experimental Research and Technology Promotion Project (23GSLK084, 23GSLK087, 23GSLK088), and the Discipline Team Construction Project of GAU (GAU-XKTD-2022-08).

Data Availability Statement: The data are available from the corresponding author upon reasonable request.

Acknowledgments: Thank you to the reviewers for the comments, which greatly improved the quality of the paper.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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