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Article

Study on the Characteristics and Attribution Analysis of Runoff Changes in the Zuli River Basin of Northwest China

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Abstract: The consequence of climatic change and anthropogenic environmental modifications is a notable diminution in runoff across arid and semi-arid regions. For the sustainable management of regional water resources, it is crucial to comprehend the impacts of climatic and anthropogenic factors on runoff patterns. The Zuli River was designated as the study area for this study, and the Mann–Kendall test, double cumulative curve method, slope change ratio of cumulative quantity method, and elasticity coefficient method were employed to identify mutation points and to quantify the relative impacts of climatic variation and human activities on runoff. The results revealed a statistically insignificant downward trend in mean annual precipitation, a significant declining trend in runoff, and an evident increasing trend in potential evapotranspiration and temperature between the years 1957 and 2019. The analysis revealed that the point of sudden change in runoff at Huining station occurred in 1992, whereas the mutation point at Guo Chengyi station was identified in 1985 and that at Jingyuan station in 1995. The contribution of climate change to runoff was found to range from 28.7% to 58.5%, while the contribution of human activities to runoff ranged from 41.5% to 71.3%, based on different methodologies. Therefore, human activities were recognized as the main factor affecting the variations in runoff within the Zuli River Basin, while climate change acts as a secondary contributor. The results of the study hold considerable importance for enhancing the scientific understanding of hydrological processes within the basin and for guiding regional water administration strategies.

Keywords: climate change; human activities; cumulative slope change method; elasticity coefficient method; Zuli River Basin

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1. Introduction

The cycle of hydrology refers to the cyclical processes of matter and energy within Earth's system, including precipitation, evapotranspiration, and runoff [1]. Runoff represents a fundamental component of the cycle of hydrology, and its fluctuations are influenced by a diverse array of factors; the most significant alterations are primarily influenced by climate variation and anthropogenic activities [2]. Climate change refers to the continuous alteration in temperature over a prolonged period. This can result in alterations in precipitation, soil water content, and potential evapotranspiration, which can subsequently influence runoff [3]. Human actions exert a direct effect on the distribution of water resources in both spatial and temporal dimensions by interfering with the underlying hydrological processes. These actions involve, particularly, land use alteration, the operation and administration of water engineering projects, and the extraction and reflux of surface and groundwater [4]. In recent decades, the phenomenon of global warming, coupled with the escalation of anthropogenic factors, has brought about diverse changes in the processes that define the water cycle. The rising prevalence of extreme phenomena related to hydrography, such as droughts and floods, has presented a significant challenge to the normal functioning of urban areas and the utilization of water resources [5,6]. Therefore, an in-depth comprehension of the patterns and determinants of runoff evolution is critical to the effective scientific management and utilization of water within these regions.

A prominent topic of discussion within the domain of hydrological science is the analysis of attribution concerning river runoff. Researchers have undertaken numerous analyses and investigations into the factors contributing to variations in runoff across diverse geographic regions and temporal contexts [7–10]. The objective of these studies has been to systematically elucidate the primary mechanisms driving changes in runoff over recent years. Many researchers have performed further studies on the contribution of runoff in changing environments by employing a range of methodologies, including empirical statistics, the elasticity coefficient method, and hydrological modeling [11–13]. Li et al. [14] carried out an attribution study of the factors influencing runoff in the Lancang–Mekong Basin from 1954 to 2000 based on the soil and water assessment tool model, and the findings demonstrated that the influence of human activities on runoff exhibited a gradual increase, whereas the effect of climatic change demonstrated a gradual decline. Jalali et al. [15] adopted three distinct methodologies to estimate the influence of climatic change and anthropogenic activity on streamflow variability: climatic elasticity, a least-squares support vector machine, and a soil and water assessment tool. The findings indicated that climatic change accounted for a reduction in runoff ranging from 38% to 67%, while human activities contributed to a decrease in runoff of between 33% and 62%. Although they have obtained better results in different places using different methods, compared to the different methods, empirical statistical analyses have the benefit of requiring fewer input data and a relatively simple computational process. They lack physical mechanisms [16]. In contrast to statistical analysis techniques, hydrological models are founded upon discernible physical mechanisms, mirror the dynamics of runoff processes, and can be deployed across a range of temporal scales [17]. However, they necessitate precise data, are computationally intricate, and are marred by considerable uncertainty. The elasticity analysis methods are founded upon the assumptions posited by Budyko; they are extensively utilized to ascertain the causes of alterations in runoff in a variety of watersheds. This is due to the method's advantages, which include a limited number of parameters, a simple structure, high interpretability, and high accuracy, but this method does not fully encompass the runoff change process [18]. The integration of statistical techniques and elasticity coefficients to identify the reasons for runoff variations can not only reflect the process of runoff change but also have high accuracy and strong interpretation.

Most of the studies examining the influence of climatic environmental change and human actions on runoff have employed a single assessment methodology, which has resulted in a notable degree of uncertainty in the resulting findings. For example, Gao et al. [19] and Zuo et al. [20] conducted attribution analysis studies on runoff from the same catchment using different methodologies, resulting in conflicting conclusions. Gao et al. [19] concluded that the principal factor influencing runoff reduction is climate change, while Zuo et al. [20] suggested that anthropogenic factors were dominant in the evolution of runoff. It can be observed that there is frequently a considerable degree of ambiguity in the findings derived from disparate methodologies applied to the same geographical area. In the past few years, numerous studies have utilized diverse methodologies to assess the contribution of climate alteration and anthropogenic actions in relation to runoff, with the aim of minimizing uncertainty and improving the reliability of their findings [21–23]. Wu et al. [21] employed ten distinct methodologies to assess the influence concerning the variation of climate and anthropogenic actions with respect to changes in the runoff within the Yanhe River Basin. Their findings reveal that elasticity-based approaches and hydrological modeling yielded comparable outcomes, whereas estimates derived from empirical statistics exhibited inconsistencies. To gain a deeper comprehension of the impact regarding climatic alterations and the human element on alterations with respect to runoff, it is of the utmost importance to carry out a comparative investigation of the diverse methodologies employed in a given catchment area.

The influences of climatic variation and anthropogenic actions on hydrological processes are particularly pronounced in semi-arid regions, resulting in significant environmental degradation and water crises in these areas. The Zuli River is an important first-class tributary of the Yellow River. It is situated within an arid and semi-arid climate zone. The Zuli River Basin has experienced rising temperatures and human influence for the last few years, which has resulted in changes to the runoff. Current studies concentrate on the drivers of the change in water quality, vegetation change, and patterns of water–sediment evolution [24–26]. Few scholars have conducted comprehensive attribution analyses; moreover, scholars have not employed diverse methodologies for the comparison and examination regarding the effect of disparate elements on runoff. Therefore, this study aimed to (1) analyze the trends in precipitation, temperature, potential evapotranspiration, and runoff from 1957 to 2019 and study the sudden change points of the runoff at different hydrological stations, (2) apply empirical statistical methodologies and elasticity coefficients to carry out a quantitative evaluation regarding the effect of various factors on runoff, and (3) compare of uncertainties in results drawn through different methods and identify the anthropogenic and climatic elements that generate changes in runoff. This research offers useful pointers for the scientific management of the Zuli River.

2. Materials and Methods

2.1. Study Area

The Zuli River is situated in the northwest of China, within the province of Gansu. It constitutes a tributary in the upper part of the Yellow River. The geographic extent ranges are 35°16′ N~36°34′ N and 104°13′ E~105°35′ E. The basin encompasses an area of 10,647 km^2, with the main stream measuring 220 km in length [27] (Figure 1). The region possesses semi-arid climatic features, including a persistent shortage of rainfall and significant spatial as well as temporal variability of rainfall, which gradually diminishes from south to north. The annual rainfall is 301 mm, with over 70% occurring during the rainy season [28]. The mean annual temperature is 3.6~8.8 °C, the annual sunshine hours are between 2430~2680 h, and the frost-free period is 130~170 days [29].

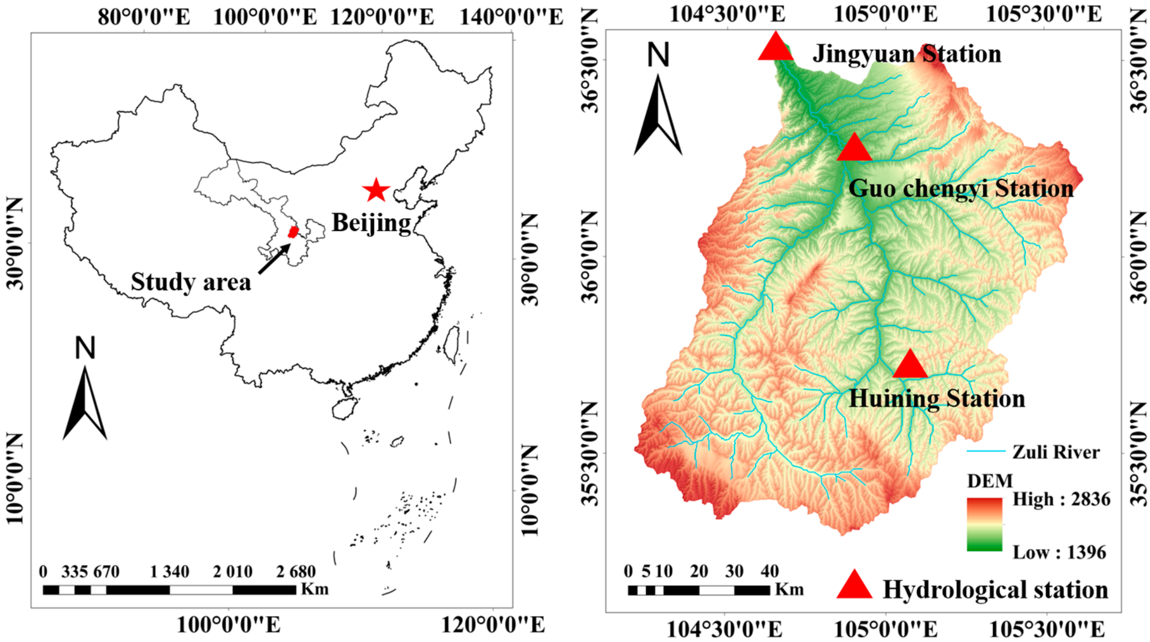

Figure 1. Map of the study area.

2.2. Data Source

The runoff (R) data were sourced from the "Gansu Provincial Water Resources Bulletin" (slt.gansu.gov.cn) and the Gansu Provincial Hydrological Bureau (Table 1). Runoff data belong to the annual dataset. The meteorological data utilized in this study were acquired from the National Meteorological Information Centre (http://data.cma.cn) and cover the period from 1957 to 2019. This dataset included daily precipitation, wind speed, sunshine duration, relative humidity, and maximum and minimum daily temperatures. The potential evapotranspiration (ET_0) was determined based on the principles outlined in the Penman–Monteith equation, employing ET_0 calculation software for this purpose. The mean potential evapotranspiration and precipitation (P) across the basin's surface were determined utilizing the Thiessen Polygon methodology, implemented through ArcGIS 10.6. The land use type data within the watershed were sourced from the Resource and Environment Science and Data Centre of the Chinese Academy of Sciences, with a spatial resolution of 30 m × 30 m (https://www.resdc.cn/). The land use dataset was reclassified and analyzed using ArcGIS 10.6 software.

Table 1. Data basic information statistics.

Stations	Types	Altitude/m	Years of Data
Huining Guo Chengyi Jingyuan	Hydrologic station	1710.0 1520.0 1398.0	1957~2019
Hua Jialing Huining Dingxi Jingyuan	Meteorological station	2450.6 2012.2 1897.5 1398.2	1957~2019

2.3. Methods

2.3.1. Trend and Mutation Analysis

The Mann–Kendall trend test was employed to analyze the trends of annual precipitation, annual potential evapotranspiration and annual runoff within the Zuli River. The results obtained by this method are both intuitive and accurate and are not disturbed by a few outliers [30]. The premise of the trend test [31–33] is as follows:

For the sequence $X_1, X_2, \cdots, X_n$, first determine the number of occurrences of (X_i, X_j, $j > i$). Then determine all the dual values (X_i, X_j, $j > i$). Number of occurrences of $X_i < X_j$ (set as p). If all the values in order are greater than the previous value, it is an upward trend, $p = (n-1) + (n-2) + \cdots + 1$, which is an arithmetic progression, and the sum is $\frac{(n-1)n}{2}$. If the sequence is reversed, then $p = 0$, indicating a downward trend. It can be demonstrated that for a trendless sequence, the mathematical expectation of p is $E(p) = \frac{n(n-1)}{4}$.

The statistics of this test:

$$U = \frac{\tau}{[V_{ar}(\tau)]^{\frac{1}{2}}} \tag{1}$$

where:

$$\tau = \frac{4p}{n(n-1)} - 1 \tag{2}$$

$$V_{ar}(\tau) = \frac{2(2n+5)}{9n(n-1)} \tag{3}$$

where τ is the statistic, U is a standardized statistic, $V_{ar}(\tau)$ is the variance of τ, and n is sequence length. As n increases, U tends to normalize to a normalized normal distribution.

The null hypothesis states that there is no distinguishable trend. When the significance level α is provided, the critical value $U_{\alpha/2}$ can be identified in the table of normal distribution. When $|U| < U_{\alpha/2}$, the null hypothesis is accepted, indicating that the trend is not statistically remarkable. When $|U| > U_{\alpha/2}$, the null hypothesis is rejected, suggesting that the observed trend is of significance. In the trend test, $\alpha = 0.05$.

For runoff mutation point analyses, the M-K mutation testing method was applied, with the double cumulative curve serving as an auxiliary test for the mutation point. The precise methodology in regard to the M-K test is outlined within the existing literature [34–36].

The initial step is to construct the order column, S_k, for the time series X.

$$S_k = \sum_{j=1}^{n-1} r_i,\ K = 2,\ 3,\ 4, \ldots n \tag{4}$$

$$r_i = \begin{cases} 1, & x_i > x_j \\ 0, & x_i \le x_j \end{cases} \tag{5}$$

If the sequence of time is supposed to be stochastically independent, define the statistic UF_k, the formula is as follows:

$$UF_k = \frac{[S_k - E(S_k)]}{[V_{ar}(S_k)]^{\frac{1}{2}}} \tag{6}$$

where:

$$E(S_k) = \frac{n(n-1)}{4} \tag{7}$$

$$V_{ar}(S_k) = \frac{n(n-1)(2n+5)}{72} \tag{8}$$

UF_k is the standard normal distribution statistic, $V_{ar}(S_k)$ is the variance of S_k, and n is the length of the sequence. $E(S_k)$ is the mean value of S_k.

UF_i represents the standard normal distribution, which is derived from a series of statistical calculations based on the time series data $X_1, X_2, \ldots, X_n$. Given the significance level α, if $UF_i > \alpha$, it indicates that there is a notable alteration in the trend of the series. Repeating the process again for the time series x in reverse order $X_n, \ldots, X_2, X_1$, while making $UF_k = -UB_k$ ($k = n, n-1, \ldots, 1$) and $UB_1 = 0$. Analyzing the plotted UF_k and UB_k curves, when the value of UB_k is greater than 0, it suggests an ascending tendency within the sequence, and a value of less than 0 suggests a declining tendency; when it exceeds any of the critical lines, it suggests a notable upward or declining tendency. If the UF and UB were calculated and the significance level ($\alpha = 0.05$) was taken, then the critical value $U_{\alpha/2} = \pm 1.96$; if the UF curve intersects with the UB curve and lies within the critical value range, this point is identified as the mutation point.

2.3.2. Double Cumulative Curve Method (DCC)

The double cumulative curve method is a commonly employed approach for the trend testing and mutation analysis of a long series of hydrological elements [37]. First, the time series before and after mutation was determined by mutation analysis. Prior to mutation, the data were divided into a base period, and after mutation, they were divided into a change period. Subsequently, the cumulative rainfall–cumulative runoff relationship for the base period was established as follows:

$$\sum R = K \sum P + b \tag{9}$$

where K represents the slope, b represents the intercept, $\sum R$ denotes the cumulative runoff, and $\sum P$ denotes the cumulative rainfall.

$$\Delta Q_H = R_{21} - R_{22} \tag{10}$$

$$\Delta Q_C = R_{22} - R_{11} \tag{11}$$

ΔQ_H and ΔQ_C are the quantitative effects associated with human actions and climatic variations, respectively. R_{21} is the measured value of runoff during the period of change,

R_{22} is the cumulative rainfall for the change period brought into the fitted equation to obtain the modelled value of runoff, and R_{11} is the measured value of runoff in the base period.

The effect of both human actions and climatic variations on changes in runoff is expressed as:

$$C_H = \left(\frac{\Delta Q_H}{\Delta R}\right) \times 100\% \tag{12}$$

$$C_C = \left(\frac{\Delta Q_C}{\Delta R}\right) \times 100\% \tag{13}$$

where C_c represents the contribution of climatic change to alterations in runoff and C_H represents the contribution of human activities to changes in runoff. ΔR is the difference between the measured runoff in the base period and the change period.

2.3.3. Slope Change Ratio of Cumulative Quantity (SCRCQ) Method

The SCRCQ approach, respectively, formulates a linear equation between the influencing factor and the year in the base period and the mutation period, enabling the calculation of the contribution of the influencing factor based on the ratio of the slope rate of change. The contribution of human-related activities to the change in runoff can then be estimated as 1 min the contribution of climatic variation to change in runoff. The formulae are as follows:

$$S_{KR} = [(K_{R1} - K_{R0})/K_{R0}] \times 100\% \tag{14}$$

$$S_{KP} = [(K_{P1} - K_{P0})/K_{P0}] \times 100\% \tag{15}$$

$$S_{KE} = [(K_{E1} - K_{E0})/K_{E0}] \times 100\% \tag{16}$$

where S_{KR}, S_{KP}, and S_{KE} represent the rates of variation in R, P, and ET_0 compared to the baseline period. K_{R1}, K_{P1}, and K_{E1} are the slopes of cumulative R, P, and ET_0 over time for the period of change. K_{R0}, K_{P0}, and K_{E0} are the slopes of cumulative R, P and ET_0 over time for the base period.

In general, there exists a favorable connection between runoff and precipitation, while an inverse correlation is observed among potential evapotranspiration and runoff. The contribution rate formulae for each influencing factor are as follows:

$$C_E = -[S_{KE}/S_{KR}] \times 100\% \tag{17}$$

$$C_P = [S_{KP}/S_{KR}] \times 100\% \tag{18}$$

where C_E and C_P represent the rates of contribution of ET_0 and P to runoff.

Therefore, considering the factors of water and heat comprehensively, the contribution proportion of climatic variations to runoff alteration is as follows:

$$C_C = C_E + C_P \tag{19}$$

In cases where only the effects of climatic alteration and human actions on changes the in runoff are considered, the contribution of human actions to changes in annual runoff, excluding the effects of climatic alteration, can be quantified as follows:

$$C_H = 1 - C_C \tag{20}$$

2.3.4. Penman–Monteith Formula

In 1998, the United Nations Food and Agriculture Organization (FAO) formally proposed the Penman–Monteith formula as a standard methodology for the computation of ET_0 [38]. The formula for calculating ET_0 is as follows:

$$ET_0 = \frac{0.408\Delta(R_n - G) + r\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + r(1 + 0.34u_2)} \tag{21}$$

where ET_0 represents potential evapotranspiration (mm/d). R_n denotes the net radiation on the crop surface, MJ/(m^2·day). G represents soil heat flux, MJ/(m^2·day). T represents the average daily temperature at a height of 2 m above sea level, °C. u_2 is the wind speed at a height of 2 m, m/s. e_s is saturated vapor pressure, kPa. e_a represents the actual water vapor pressure, kPa. $e_s - e_a$ is the saturated vapor pressure difference, kPa. Δ is the slope of saturated water vapor pressure curve. r is the humidity meter constant, kPa/°C [39].

2.3.5. Elasticity Coefficient Method

The Budyko framework is a valuable tool for examining the interplay between climate variables and long-term water balance [40,41]. The model was initially developed as a non-parametric model but has since given rise to a multitude of formulas in diverse functional forms, many of which are based on the Budyko assumptions. The purpose of these formulas is to integrate the effects of other elements on the balance of water. The Budyko equation, in conjunction with a water balance equation, enables runoff depth to be characterized as a function of other parameters. Assuming that potential evapotranspiration and precipitation are mutually independent, the elasticity coefficients of runoff with respect to each of these variables can be defined, enabling the determination of the contribution of each factor to the variation in runoff [42]. Although all Budyko-type equations are designed to describe the partitioning of P into E and R under two distinct physiological constraints, the specific form of the Budyko equation differs from those of the others. There are three empirical equations that have been widely used in different regions of China owing to their simplicity and ease of implementation [43]. The calculation framework is as follows:

Climatic alteration results in variations in P and ET_0, which subsequently result in alterations in runoff dynamics. Through the examination of the elasticity coefficients pertaining to runoff in relation to P and ET_0, the quantitative reaction of runoff to climatic change can be articulated as follows:

$$\Delta Q_c = \frac{\varepsilon_p \Delta P R}{P} + \frac{\varepsilon_{E_0} \Delta ET_0 R}{\mathrm{ET}_0} \tag{22}$$

In the equation, ΔQ_c represent the variation of runoff response to climatic variation; ε_p and ε_{E_0} are the elastic coefficients of runoff to P and ET_0, respectively. ΔP and ΔET_0 represent the variations in P and ET_0, respectively.

According to the long-term water balance equation, runoff depth is expressed as $Q = P - E_a$; along with the Budyko hypothesis, the actual evapotranspiration E_a is a function of the dryness index $\varnothing = \frac{\Delta ET_0}{P}$.

The elastic coefficient is calculated as follows:

$$\varepsilon_p = 1 + \frac{\varnothing F'(\varnothing)}{1 - F(\varnothing)};\ \varepsilon_p + \varepsilon_{E_0} = 1 \tag{23}$$

Among them, $F(\varnothing)$ and $F'(\varnothing)$ can be computed using the Budyko hypothesis [44–46], as shown in Table 2.

Table 2. $F(\varnothing)$ and $F'(\varnothing)$ based on the Budyko hypothesis.

Source Literature	$F(\varnothing)$	$F'(\varnothing)$
OL'DEKOP	$\varnothing\tanh\left(\frac{1}{\varnothing}\right)$	$\frac{\tanh\left(\frac{1}{\varnothing}\right)-1}{\left\{\varnothing\left[\cosh\left(\frac{1}{\varnothing}\right)\right]^2\right\}}$
PIKE	$(1 + \varnothing^{-2})^{-0.5}$	$\frac{1}{\left\{\varnothing^3\left[1+(1/\varnothing)^2\right]^{1.5}\right\}}$
FU	$1 + \varnothing - (1 + \varnothing^\alpha)^{\frac{1}{\alpha}},\ \alpha = 2.5$	$1 - (1 + \varnothing^\alpha)^{\frac{1}{\alpha}-1}\varnothing^{\alpha-1}$

3. Results

3.1. Trend Analysis of Hydrometeorological Elements

The *R* at the Guo Chengyi station showed a fluctuating downward trend from 1957 to 2019 (Figure 2), with a reduction rate of 0.0075 × 10^8 m^3/a. After the trend test, ∣U∣ = 3.0783 > U (0.05/2) = 1.96; the *R* at the Guo Chengyi station exhibited a notable decreasing tendency. The *R* at Jingyuan station showed a fluctuating downward trend from 1957 to 2019, and the mean annual *R* exhibited a decline at a rate of 0.016 × 10^8 m^3/a. The trend test revealed that ∣U∣ = 3.8615 > U (0.05/2) = 1.96; therefore, the *R* at the Jingyuan station presented a remarkable downward tendency (Figure 2). The *R* at the Huining station showed a fluctuation downtrend tendency from 1957 to 2019, with a decline rate that was 0.0035 × 10^8 m^3/a. After the trend test, ∣U∣ = 6.0929 > U (0.05/2) = 1.96, so the *R* at the Huining station showed a notable declining trend. Therefore, the *R* presented a significant downward from 1957 to 2019.

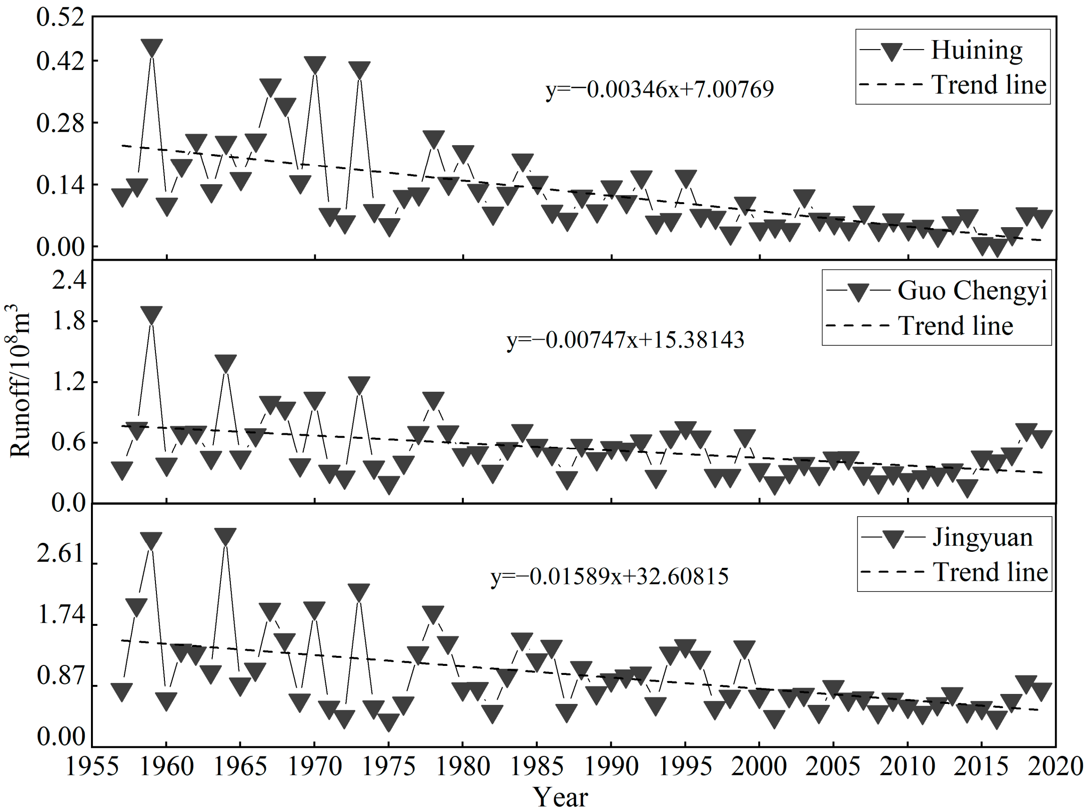

Figure 2. Inter−annual variability of runoff from different hydrological stations.

The *P* from 1957 to 1967 and from 2009 to 2019 showed a fluctuating upward trend and from 1968 to 2008 showed a fluctuating downward trend. Overall, there is a decreasing trend in *P* from 1957 to 2019; the rate of decline is 0.95 mm/a (Figure 3a). The trend test value ∣U∣ = 1.7622 < U (0.05/2) = 1.96, indicating that the *P* did not show a significant plunging trend in this study area. ET_0 showed a sliding trend in 1957~1967 and 1972~1992, an upward trend in 1968~1971, and a fluctuating upward and downward trend from 1993 to 2019. In general, the ET_0 indicator exhibited an upward trend from 1957 to 2019, with a growth rate of 0.78 mm/a. The trend test value ∣U∣ = 2.8061 > U (0.05/2) = 1.96, indicating that ET_0 showed a significant upward trend in this study area (Figure 3b). The annual mean *T* demonstrated an upward trajectory, with a rate of increase of 0.045 °C/a. In terms of stages, the average annual *T* change trend from 1957 to 1995 was relatively stable, and the upward trend from 1996 to 2019 was more obvious (Figure 3c). The trend test value ∣U∣ = 6.2818 > U (0.05/2) = 1.96, indicating that the average annual *T* showed a significant upward trend.

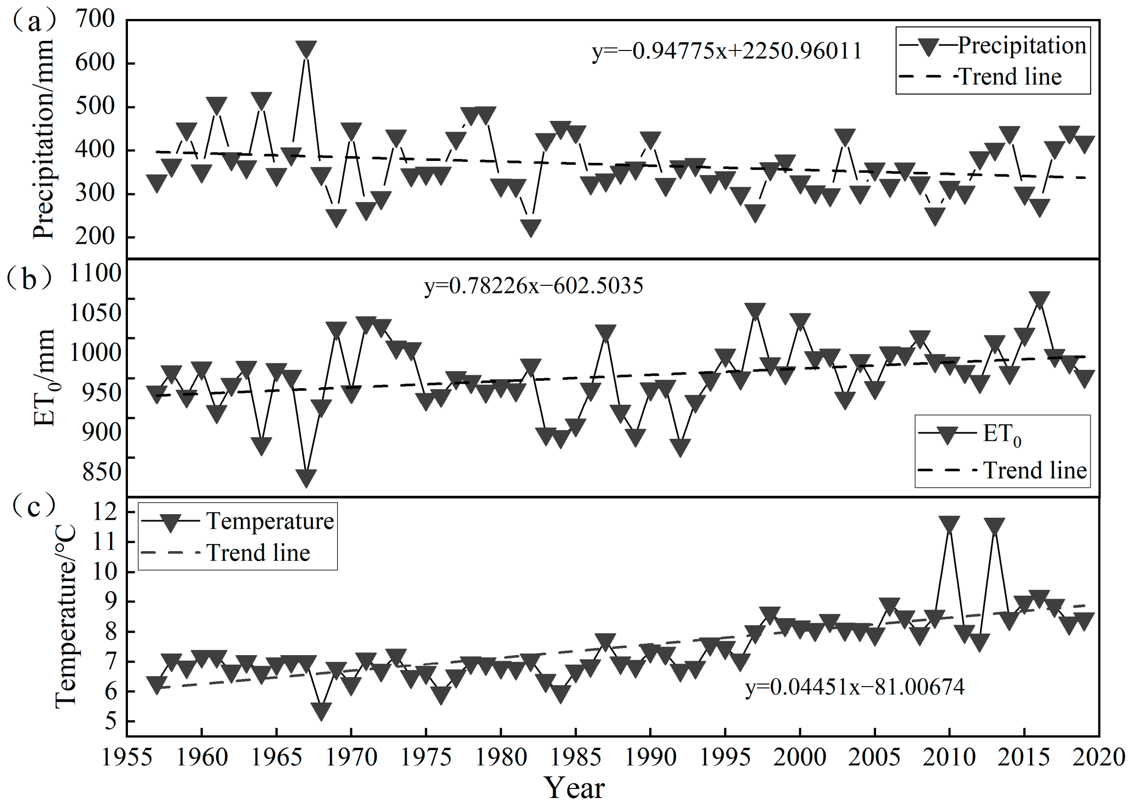

Figure 3. Internal variation of hydro−meteorological factors: (**a**) precipitation, (**b**) ET_0, and (**c**) temperature.

3.2. Runoff Mutation Analysis

During 1957–1970, the statistical value of the UF was greater than 0, indicating that *R* at this stage demonstrated an increasing trend. The UF statistics were less than 0 from 1971 to 2019, indicating that the *R* followed a decreasing trend. The statistics exceeded the 0.05 significance level of 2001~2009, proving that a significant downward trend was observed in the *R* levels during this period. The statistical distributions of UF and UB converged in 1985, with the juncture occurring within the range of critical value testing (α = 0.05). Consequently, it is posited that 1985 represents a point of mutation at the Guo Chengyi station (Figure 4b). The UF statistics of *R* were greater than 0 at Huining Station from 1957 to 1974, indicating that *R* in this stage manifested a growth trend. The UF statistics were less than 0 from 1975 to 2019, confirming that the *R* exhibited a declining trend. The statistics exceeded the significance level of 0.05 between 1993 and 2019, evidencing that the *R* showed a notable declining trend throughout this period. The statistical curves for UF and UB intersected in 1992, with the intersection point located within the critical value's test range (α = 0.05); therefore, it was considered that a mutation point occurred at Huining station in 1992 (Figure 4a). The *R* was greater than 0 for the Jingyuan station during 1957–1965, indicating that the *R* manifested a rising tendency in this period of time. The statistical UF was less than 0 in 1966~2019, indicating that the runoff demonstrated a declining trend. The statistical value for 2003~2019 exceeded the significance level of 0.05, indicating that *R* showed a significant decreasing trend during this period. The two statistical distributions corresponding to the variables UF and UB converged in 1995, with the point of intersection falling within the critical value test range (α = 0.05); therefore, it was considered that 1995 was the year in which a mutation was observed in the *R* from Jingyuan station (Figure 4c). Huining station is situated in the upper part of the Zuli River, with the *R* change point occurring in 1992. The Guo Chengyi station is situated in the central part of the Zuli River, with the *R* change point occurring in 1985. The Jing Yuan station is situated in the downstream area of the Zuli River, with the *R* change point occurring in 1995. The abrupt alterations observed at various hydrological monitoring stations can primarily be attributed to the impact of anthropogenic activities. The JingHui Irrigation Project represents the most critical human activity with the potential to impact R abruptness. This project is situated in the middle and lower reaches of the Zuli River. Irrigation was initiated in 1973, which had a definite influence regarding the annual *R* of the downstream Guo Chengyi Hydrological Station, so the mutation point of the Guo Chengyi Station was related to this project earlier.

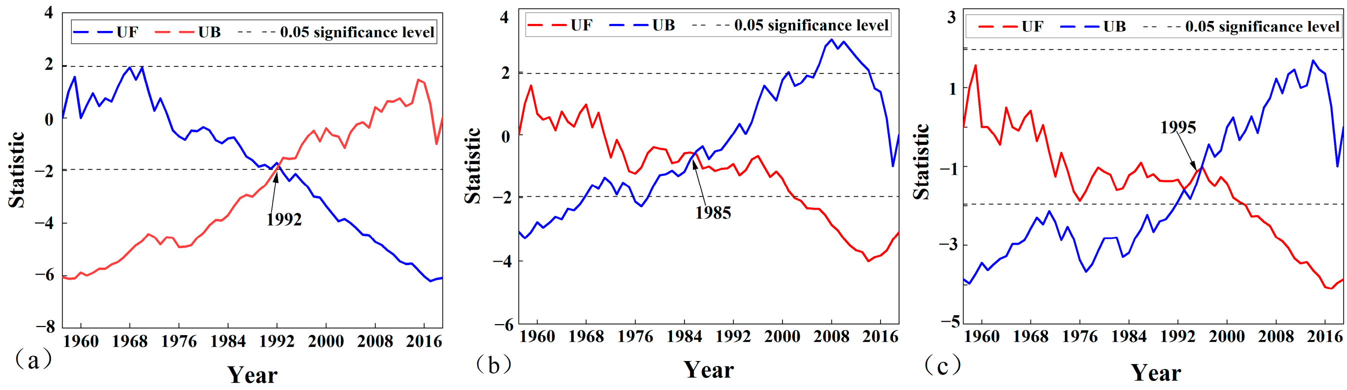

Figure 4. M−K mutation test: (**a**) Huining, (**b**) Guo Chengyi, and (**c**) Jingyuan.

The abrupt point of R in the Zuli River basin appeared after 1980. To determine the rationality of the mutation, the mean values of the annual *R* pre- and post-mutation of the three stations and the rate of change of the mean value (compared with the previous period) are given (Table 3). The *R* changed significantly from the fore-and-aft to the mutation point. The average change rate anteroposterior to the mutation at Huining station was as high as 64.7%, Jingyuan station was 38.8%, and Guo Chengyi station was 37.3%; this indicated that the results of the mutation analyses conducted at the three stations were reliable.

Table 3. Mean value and its change rate before and after runoff mutation.

Station	Mutational Site	Pre-Mutation Mean/10^8 m^3	Mean After Mutation/10^8 m^3	Mean Change Rate Before and After Mutation/%
Huining	1992	0.17	0.06	64.7
Guo Chengyi	1985	0.67	0.42	37.3
Jingyuan	1995	1.21	0.74	38.8

3.3. Attribution Analysis

The Jingyuan hydrological station is positioned in the downstream area of the Zuli River Basin, and it is also the last important control station of the Yellow River outbound section in Gansu and is representative. Therefore, Jingyuan Hydrological Station was chosen as the control station for the attribution analysis of the Zuli River, and the runoff mutation point of Jingyuan Station was 1995, so the base period was 1957~1994 and the change period was 1995~2019.

3.3.1. DCC Method

The linear fitting curve for each stage exhibited an R^2 value exceeding 0.99 (Figure 5), indicating a markedly high degree of correlation and satisfactory fitting effect. For the base period, the regression formula related to *P* and *R* was: $\sum R = 0.00305 \sum P + 2.6081$. Additionally, the calculated *R* can be obtained by taking the accumulated P in the change period into the regression equation of the base period. To calculate the climate and human impacts on runoff, the annual average values are used, considering the different durations of the baseline and change periods. Compared with the base period, the runoff volume decreased by 0.47×10^8 m^3/a during the change period. Human factors were responsible for 66.0% of the decline in runoff, while climatic factors contributed 34.0% (Table 4). Therefore, human activities are the main factors causing R changes.

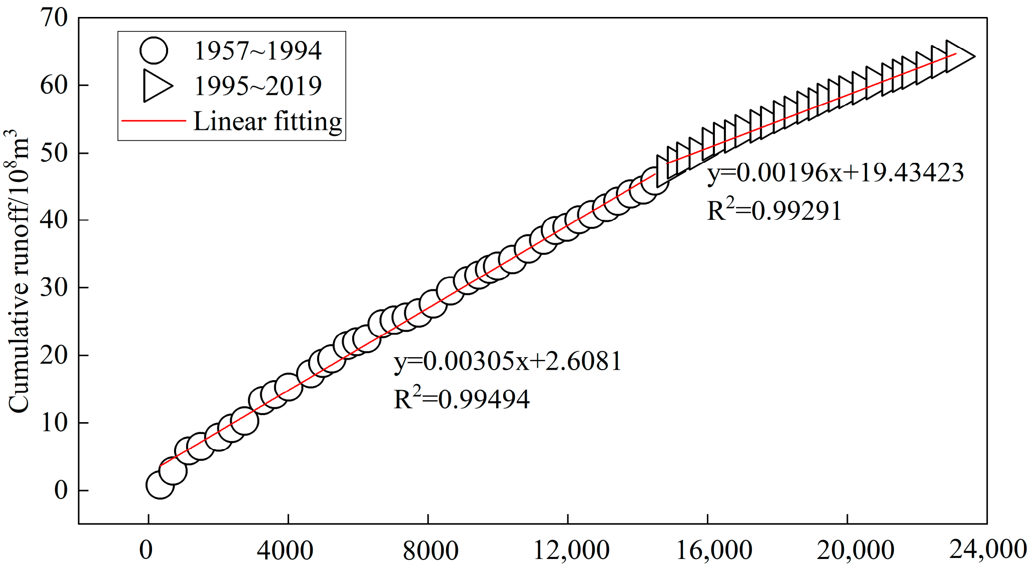

Figure 5. Precipitation–runoff double cumulative curve.

Table 4. Contribution rate of climate change and human activities to runoff change.

Time	Precipitation/mm	Runoff and Its Variation/10^8 m^3				Human Activities	Climatic Change
		R_{11}	R_{21}	R_{22}	ΔR	C_H/%	C_C/%
1957~1994 1995~2019	381.41 344.66	1.21	0.74	1.05	0.47	66.0	34.0

3.3.2. SCRCQ Method

The cumulative P slope changed from 381.74 mm/a before 1995 to 340.98 mm/a, with a change rate of −10.7% (Figure 6a). The slope of cumulative R prior to 1995 was 1.16×10^8 m^3/a. Moreover, the slope after 1995 was 0.67×10^8 m^3/a, with a change rate of −42.2% (Figure 6b). The slope of cumulative ET_0 anteroposterior to 1995 changed from 940.11 mm/a to 975.32 mm/a, with a change rate of 3.8% (Figure 6c), and the impact rate on runoff was 8.9% (Table 5). The R was influenced by climatic variation at a rate of 34.2%, with human actions contributing 65.8%. Therefore, human activity represents a significant contributing factor to alterations in runoff patterns.

3.3.3. Elasticity Coefficient

During the base period, the average yearly P was 381.41 mm, compared to 244.66 mm during the change period. During the base period, the yearly average ET_0 was 936.63 mm, while it was 976.96 mm during the period of change. The R for the base period was 11.3 mm, and that in the change period was 6.9 mm. The impact of various factors on R variation was quantified using three functional forms aligned with the Budyko hypothesis. The contribution rate of climatic factors to R was approximately 28.7~58.5%, and the contribution rate of human factors was approximately 41.5~71.3% (Table 6). It can be inferred that human actions were the primary cause of the decrease in R, aligning with the findings from empirical statistical analysis.

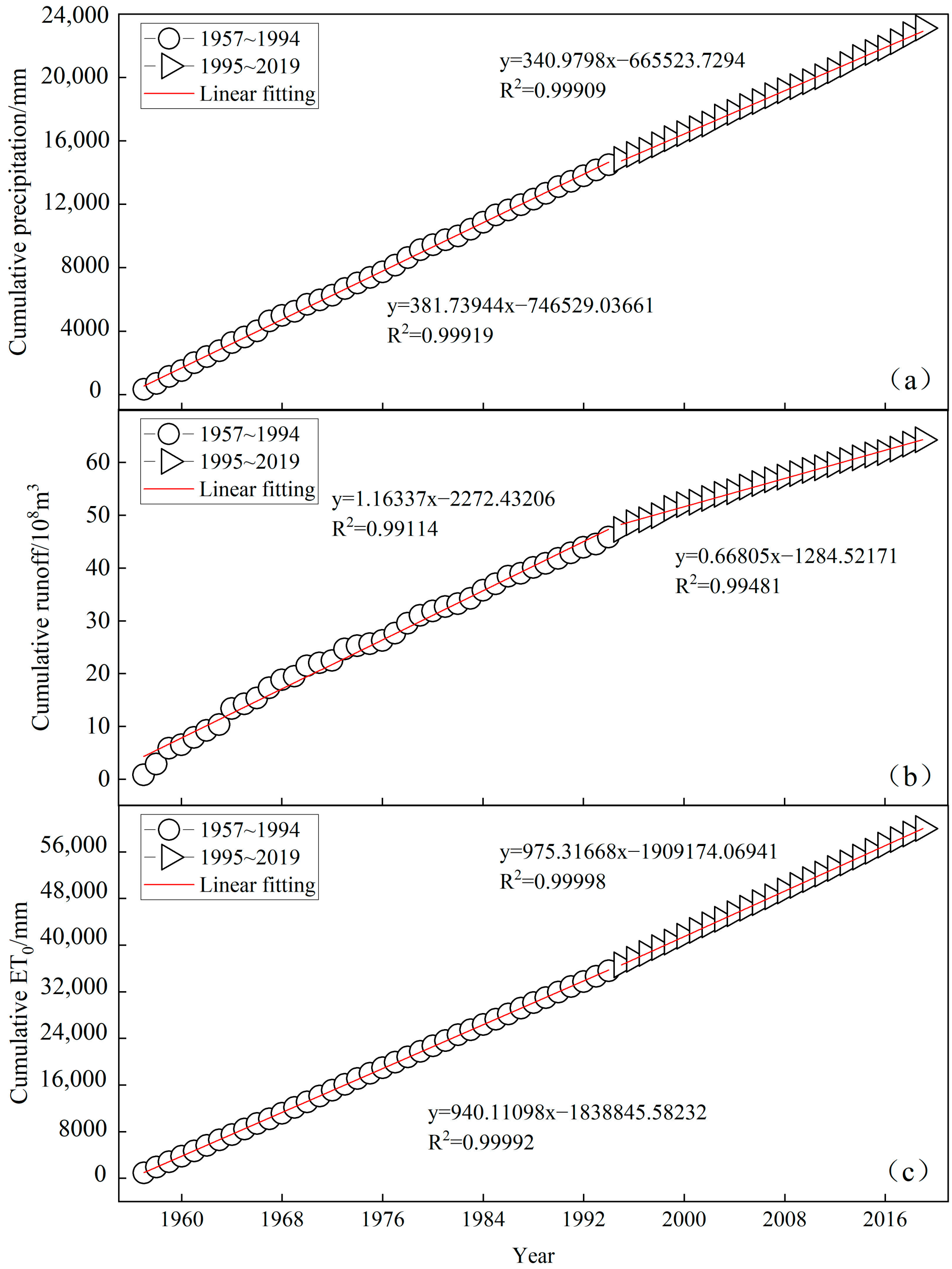

Figure 6. Accumulation curve of hydro−meteorological factors: (**a**) cumulative precipitation, (**b**) cumulative runoff, and (**c**) cumulative ET_0.

Table 5. Contribution rate of climatic change and human activities to runoff change.

Time	**Runoff**		**Climate Change**						C_C (/%)	C_H (/%)
	K_R (10^8 m^3/a)	S_{KR}/%	**Precipitation**			**ET_0**				
			K_P (mm/a)	S_{KP}/%	C_P/%	K_E (mm/a)	S_{KE}/%	C_E/%		
1957~1994 1995~2019	1.16 0.67	−42.2	381.74 340.98	−10.7	25.28	940.11 975.32	3.8	8.9	34.2	65.8

Table 6. Contribution rate of climatic change and human activities to runoff change.

Budyko	ε_P	$\Delta Q_c/mm$	$\Delta Q_H/mm$	$C_C/\%$	$C_H/\%$
OL'DEKOPE	2.18	−2.58	−1.82	58.5	41.5
PIKE	1.60	−1.78	−2.62	40.5	59.5
FU	1.22	−1.26	−3.14	28.7	71.3

4. Discussion

4.1. Comparison of the Quantitative Results

The combined effect of anthropogenic factors and climatic variation has resulted in distinctive features and differences in the process of hydrological changes within the basin, which have a notable influence on the evolution of water within the basin [47]. In exploring the reasons for the variations in runoff, the quantitative outcomes computed by the elasticity-based and empirical methods were found to be largely consistent. The rate of contribution of climatic factors on runoff decrease was found to range from 28.7% to 58.5% (with an average of 39.2%), whereas the rate of contribution of human actions was observed to range from 41.5% to 71.3% (with an average of 60.8%) (Figure 7). The foundations and frameworks of the disparate quantitative techniques vary. Consequently, an integrated methodology that incorporates a multitude of techniques is likely to be more compelling than the exclusive reliance on a single technique. It is clear that human actions are the leading cause of runoff alterations in the Zuli River during the period from 1957 to 2019. The outcomes of our study align with prior findings. For example, in the arid Shiyang River Basin of northwestern China, Xue et al. [16] used the double mass curve method for an attribution analysis, which showed that anthropogenic actions were the principal element affecting runoff changes, followed by climatic variations and upstream runoff. Bai and Zhao [48] conducted an analysis of the impacts of climate change and human activities on runoff from major river basins in China since 1950; the results demonstrated that reduced precipitation was the primary factor contributing to the decline in runoff in the southern regions, whereas in the northern regions, human activities were the primary reason for the decrease in runoff.

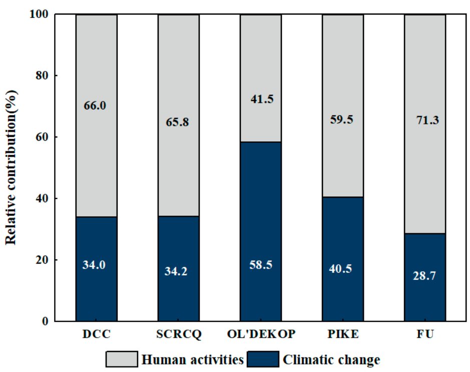

Figure 7. Comparison of the quantitative results. DCC denotes the double cumulative curve method. OL'DEKOP, PIKE, and FU denote three assumptions of the elasticity coefficient method.

In this study, the contribution of anthropogenic actions to runoff, as calculated by the two empirical statistical methods, was 66.0% and 65.8%, respectively. The calculations are essentially identical. In contrast to empirical statistics, the elasticity-based method employs a more physically plausible mechanism for calculating runoff and is more consistent with the actual hydrological cycle. Furthermore, the conclusions derived from different Budyko-based methods may vary (Figure 7). The Budyko assumption of OL'DEKOP differs from the other two assumptions, and it is possible that the parameter estimation results in disparate outcomes. However, some uncertainty remains in these estimates. The purpose of elasticity-based modeling is to analyze the long-term consequences of climate change and human activities on water balance. However, such modeling is not capable of accounting for the impact of inter- and intra-annual climate change, including extreme weather conditions, seasonal variations, and the impact of snowpack variability [49]. The uncertainty associated with the structure and parameters of the models used can also influence the accuracy of the quantitative results obtained from hydrological model calculations. Another factor contributing to uncertainty is the quality of the meteorological and hydrological data [50]. Collectively, these uncertainties affect the results of model calculations to some extent. To achieve a more refined understanding of how climatic variation and human activities influence runoff, it would be advantageous for future research to utilize hydrological models.

4.2. Impact of Human Activities on Runoff

Human activities have direct and indirect impacts on the hydrological cycle, and the effects of human activities are multifaceted [51]. Some human activities result in increased runoff, whereas others lead to decreased runoff. These effects occur concurrently, which makes it challenging to discern individual contributions. Land cover change is a significant factor that influences runoff, reflecting the far-reaching impact of human activities on this process [52]. Consequently, a comprehensive investigation of the processes governing land use change and its impact on runoff is of paramount importance in the context of the Zuli River Basin. Accordingly, high-resolution (30 m) land use data for three time periods (1980, 2000, and 2015) were selected to facilitate the comprehension of the impact of land use change on runoff between 1957 and 2019 (Figure 8).

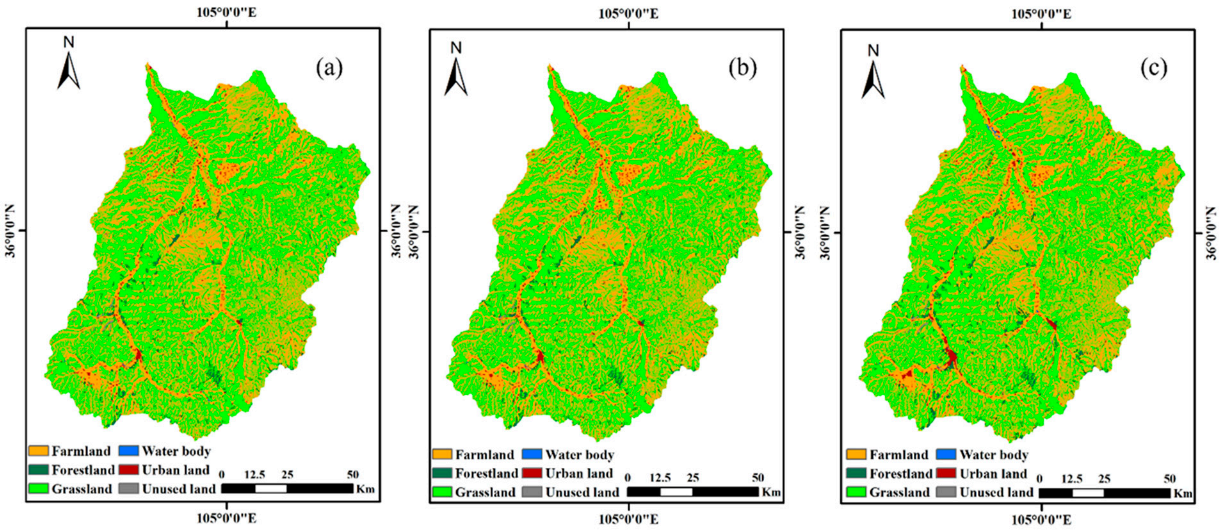

Figure 8. LUCC information of the Zuli River (**a**) 1980 (**b**) 2000 (**c**) 2015.

The results of the statistical analysis indicated that the predominant land cover type in the Zuli River area was grassland, which accounts for approximately 57% of the total area. This was followed by farmland, which accounted for approximately 40% of the total area. As evidenced by the data presented in Table 7, the areas of forestland, farmland, and urban land, increased by 0.4%, 0.2%, and 0.3%, respectively, between 1957 and 2019. Conversely, the area of grassland decreased by 0.9%, respectively (Table 7). The characteristics of the water cycle vary according to the specific land use type, with corresponding differences in the hydrological effects [53]. An increase in forestland can effectively enhance soil infiltration and retention capacity, ensure soil integrity and water retention capacity, and also decelerate the flow of rainfall water, thus inhibiting surface runoff. In semi-arid regions, evapotranspiration from forestlands is considerably higher than that from the surface [54]. Moreover, it has been demonstrated that afforestation will result in an increase in the average annual evapotranspiration rate by between 2.7% and 11.1% [55]. Consequently, it can be concluded that the expansion of forestland contributed to a reduction in runoff from the Zuli River. The expansion of urbanization and human activity has resulted in a notable increase in the extent of built-up areas within cities. This is likely to further intensify the urban heat island effect, thereby reducing the runoff from watersheds [56]. However, the prevalence of extensive impermeable surfaces on built-up land, coupled with the diminished permeability and water retention capacity of soils, will likely contribute to an increase in surface runoff. It can be observed that the Zuli River Basin is subject to a complex array of influencing factors. A more comprehensive examination of the contextual environment of the basin and the interplay between these factors is essential for a nuanced understanding of the response of runoff to land use change.

Table 7. Land use change from 1980 to 2015 in the Zuli River Basin.

Land Use Type	Area Variation/Km^2					
	1980	**Percentage**	**2000**	**Percentage**	**2015**	**Percentage**
Farmland	4199.6	39.2%	4247.7	39.7%	4214	39.4%
Forestland	165.4	1.5%	168.0	1.6%	210.9	1.9%
Grassland	6163.5	57.6%	6101.6	57.0%	6064.8	56.7%
Water body	6.1	0.1%	4.5	0.04%	10.2	0.1%
Urban land	147.5	1.4%	160.2	1.5%	183.5	1.7%
Unused land	19.8	0.2%	19.8	0.2%	18.2	0.2%

The primary anthropogenic influences on runoff within the basin include the adoption of integrated soil and water conservation management practices, as well as the functioning of inter-basin water transfer initiatives. Soil and water conservation strategies primarily encompass the establishment of silt dams, the implementation of afforestation initiatives, and the cultivation of grass. The initiatives aimed at soil erosion protection and ecological construction within the basin commenced in the 1970s. Subsequently, during the 1980s and 1990s, there was a notable increase in both the extent of vegetation and the quantity of silt dams in the region. As of 2016, the degree of erosion control in the watershed reached 60.3% [57]. The large-scale implementation of these measures has reduced the rate of erosion on subsurface slopes, resulting in an improvement in the soil's infiltration capacity and an augmentation of the storage capacity for surface rainwater runoff. These alterations have resulted in a suppressive effect on runoff generation, which has indirectly facilitated a decrease in the runoff volume within the basin [58]. The Jinghui Irrigation Project is the initiative that exerts a more significant influence on the runoff of the Zuli River and facilitates the transfer of water from various regions in the upper reaches of the Yellow River into the basin. The initiation of the project occurred in 1971, with its completion achieved in 1973, facilitating the irrigation of 20,000 ha of agricultural land within the basin. Since the irrigation project began, the irrigated area and the amount of water transferred have increased considerably. The total volume of irrigation water increased from 2.973×10^7 m^3 in the 1970s to 8.365×10^7 m^3 at the beginning of the twenty-first century, and the extent of irrigated land increased from 0.2×10^4 ha in 1973 to 1.68×10^4 ha in 2005 [59]. By the end of 2013, the amount of water transferred from the Yellow River to the Zuli River Basin was about 2.86 billion m^3**.** The water supply to the Jinghui Irrigation Project in 1973 provided a significant level of compensation for the surface water deficit in the receiving area. However, despite the diversion of surface water, natural precipitation in the region has not led to a substantial increase in runoff, primarily due to the impacts of population growth [60]. As a result, the relationship between anthropogenic alterations to the surface and regional runoff is distinctly evident.

4.3. Impact of Climate Change on Runoff

Climatic change has significant impacts on hydrological processes in watersheds, and its impacts on runoff are mainly reflected in changes in P and ET_0 [61]. P contributes positively to runoff, whereas ET_0 has a negative contribution. Based on the results of this study, it was shown that the Zuli River exhibited an overall decline in P, accompanied by an increase in ET_0, this has resulted in a corresponding reduction in runoff (Figures 2 and 3). The meteorological factors considered in this study are P and ET_0, and if a more comprehensive analysis is required, other factors such as insolation, temperature, and wind speed need to be taken into account. Moreover, the evaluation of the impact of anthropogenic activities and climatic variation on runoff variability is contingent upon an assumption of independence between these two factors. Indeed, there is an interconnection between these factors, and the role of P and ET_0 in affecting runoff cannot be entirely ascribed to natural phenomena [62]. The influence of human actions on the land surface also indirectly affects the contribution of meteorological factors, including P and ET_0, to the formation of runoff; this suggests that the theoretical value of the impact of human activities on runoff is relatively low [63]. Therefore, additional research is required to accurately quantify the effects of diverse human activities and their interactions with the climate.

5. Conclusions

This research conducted an examination of the trends associated with hydro-meteorological parameters regarding the Zuli River over the period from 1957 to 2019. Furthermore, the contributions of climate change and human activities to runoff changes were quantified by employing a range of methodological approaches. The results of this research offer a significant reference point for the administration of water within the Zuli River Basin. The principal conclusions are as follows:

(1) The results indicated a notable decline in the annual runoff within the Zuli River Basin; precipitation showed an insignificant downward trend. In contrast, the ET_0 and the average annual temperature demonstrated a notable increasing trend.

(2) The analysis of M-K mutations revealed that 1992 was the year when runoff at Huining station experienced a mutation point, the mutation point for runoff at Guo Chengyi station occurred in 1985, and the point of mutation for runoff at Jingyuan station occurred in 1995.

(3) The three attribution analysis methods indicated that the influence of climatic change on the reduction in runoff in the Zuli River ranged from 28.7% to 58.5%, whereas the activities of humans contributed to a diminution in runoff, with effects ranging from 41.5% to 71.3%. Therefore, human interventions were the predominant factor in the decrease in runoff from the Zuli River. The assessment of the impacts of human activities and climate change on runoff variability is contingent upon the assumption of independence between the two factors, which are in fact interlinked. Consequently, to accurately determine the impacts of diverse factors on runoff, the role and interconnections between these factors need to be further investigated.

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References

1. Dimitriadis, P.; Koutsoyiannis, D.; Iliopoulou, T.; Papanicolaou, P. A global-scale investigation of stochastic similarities in marginal distribution and dependence structure of key hydrological-cycle processes. *Hydrology* **2021**, *8*, 59. [CrossRef]
2. Gao, C.; Ruan, T. The influence of climate change and human activities on runoff in the middle reaches of the Huaihe River Basin, China. *J. Geogr. Sci.* **2018**, *28*, 79–92. [CrossRef]
3. Zhai, R.; Tao, F. Contributions of climate change and human activities to runoff change in seven typical catchments across China. *Sci. Total Environ.* **2017**, *605*, 219–229. [CrossRef] [PubMed]
4. Alifujiang, Y.; Abuduwaili, J.; Groll, M.; Issanova, G.; Maihemuti, B. Changes in intra-annual runoff and its response to climate variability and anthropogenic activity in the Lake Issyk-Kul Basin, Kyrgyzstan. *Catena* **2021**, *198*, 104974. [CrossRef]
5. Xiong, J.; Yang, Y. Climate Change and Hydrological Extremes. *Curr. Clim. Change Rep.* **2024**, *11*, 1. [CrossRef]
6. Fischer, E.; Knutti, R. Anthropogenic contribution to global occurrence of heavy-precipitation and high-temperature extremes. *Nat. Clim. Change* **2015**, *5*, 560–564. [CrossRef]
7. Li, B.; Shi, X.; Lian, L.; Chen, Y.; Chen, Z.; Sun, X. Quantifying the effects of climate variability, direct and indirect land use change, and human activities on runoff. *J. Hydrol.* **2020**, *584*, 124684. [CrossRef]
8. Wu, L.; Zhang, X.; Hao, F.; Wu, Y.; Li, C.; Xu, Y. Evaluating the contributions of climate change and human activities to runoff in typical semi-arid area, China. *J. Hydrol.* **2020**, *590*, 125555. [CrossRef]
9. Rankinen, K.; Gao, G.; Granlund, K.; Grönroos, J.; Vesikko, L. Comparison of impacts of human activities and climate change on water quantity and quality in Finnish agricultural catchments. *Landsc. Ecol.* **2015**, *30*, 415–428. [CrossRef]
10. Saedi, J.; Sharifi, M.R.; Saremi, A.; Babazadeh, H. Assessing the impact of climate change and human activity on streamflow in a semiarid basin using precipitation and baseflow analysis. *Sci. Rep.* **2022**, *12*, 9228. [CrossRef]
11. Wang, X.; He, K.; Dong, Z. Effects of climate change and human activities on runoff in the Beichuan River Basin in the northeastern Tibetan Plateau, China. *Catena* **2019**, *176*, 81–93. [CrossRef]
12. Wu, J.; Miao, C.; Wang, Y.; Duan, Q.; Zhang, X. Contribution analysis of the long-term changes in seasonal runoff on the Loess Plateau, China, using eight Budyko-based methods. *J. Hydrol.* **2017**, *545*, 263–275. [CrossRef]
13. Yan, X.; Bao, Z.; Zhang, J.; Wang, G.; He, R.; Liu, C. Quantifying contributions of climate change and local human activities to runoff decline in the upper reaches of the Luanhe River basin. *J. Hydro-Environ. Res.* **2020**, *28*, 67–74. [CrossRef]
14. Li, R.; Huang, H.Q.; Wang, Z.; Zhao, R. Quantitative assessment of the impacts of climate and human activities on streamflow of the Lancang-Mekong river over the recent decades. *Front. Earth Sci.* **2023**, *10*, 1024037. [CrossRef]
15. Jalali, J.; Ahmadi, A.; Abbaspour, K. Runoff responses to human activities and climate change in an arid watershed of central Iran. *Hydrol. Sci. J.* **2021**, *66*, 2280–2297. [CrossRef]
16. Xue, D.; Zhou, J.; Zhao, X.; Liu, C.; Wei, W.; Yang, X.; Li, Q.; Zhao, Y. Impacts of climate change and human activities on runoff change in a typical arid watershed, NW China. *Ecol. Indic.* **2021**, *121*, 107013. [CrossRef]
17. Cao, Y.; Fu, C.; Wang, X.; Dong, L.; Yao, S.; Xue, B.; Wu, H.; Wu, H. Decoding the dramatic hundred-year water level variations of a typical great lake in semi-arid region of northeastern Asia. *Sci. Total Environ.* **2021**, *770*, 145353. [CrossRef]
18. Jiang, C.; Xiong, L.; Wang, D.; Liu, P.; Guo, S.; Xu, C.Y. Separating the impacts of climate change and human activities on runoff using the Budyko-type equations with time-varying parameters. *J. Hydrol.* **2015**, *522*, 326–338. [CrossRef]
19. Gao, G.; Fu, B.; Wang, S.; Liang, W.; Jiang, X. Determining the hydrological responses to climate variability and land use/cover change in the Loess Plateau with the Budyko framework. *Sci. Total Environ.* **2016**, *557*, 331–342. [CrossRef]
20. Zuo, D.; Xu, Z.; Wu, W.; Zhao, J.; Zhao, F. Identification of streamflow response to climate change and human activities in the Wei River Basin, China. *Water Resour. Manag.* **2014**, *28*, 833–851. [CrossRef]
21. Wu, J.; Miao, C.; Zhang, X.; Yang, T.; Duan, Q. Detecting the quantitative hydrological response to changes in climate and human activities. *Sci. Total Environ.* **2017**, *586*, 328–337. [CrossRef] [PubMed]
22. Luan, J.; Zhang, Y.; Ma, N.; Tian, J.; Li, X.; Liu, D. Evaluating the uncertainty of eight approaches for separating the impacts of climate change and human activities on streamflow. *J. Hydrol.* **2021**, *601*, 126605. [CrossRef]
23. Zhang, Q.; Liu, J.; Singh, V.P.; Gu, X.; Chen, X. Evaluation of impacts of climate change and human activities on streamflow in the Poyang Lake basin, China. *Hydrol. Process.* **2016**, *30*, 2562–2576. [CrossRef]
24. Zhang, Z.; Zhang, F.; Zhang, Z.; Wang, X. Study on Water Quality Change Trend and Its Influencing Factors from 2001 to 2021 in Zuli River Basin in the Northwestern Part of the Loess Plateau, China. *Sustainability.* **2023**, *15*, 6360. [CrossRef]
25. Liao, H.; Wei, W.; Shi, Y. Characteristics of Spatial and Temporal Evolution of Soil Erosion in Typical Watersheds in Loess Hilly Areas and Its Driving Mechanisms: A Case Study of Zuli River. *Ecol. Environ. Sci.* **2024**, *33*, 908–918. (In Chinese)
26. Zhao, X.; Zhou, R.; Zhang, F.; Hu, Y.; Li, X.; Bao, B.; Jiang, C. Change Trend of Precipitation, Runoff and Sediment in the Upper Zuli River Basin from 1957 to 2016. *Res. Soil Water Conserv.* **2020**, *27*, 83–90. (In Chinese)
27. Huang, C.; Xu, J.; Shan, L. Long-term variability of vegetation cover and its driving factors and effects over the Zuli River Basin in Northwest China. *Sustainability* **2023**, *15*, 1829. [CrossRef]
28. Liu, Z.; Tan, H.; Shi, D.; Xu, P.; Elenga, H.I. Origin and formation mechanism of salty water in Zuli River catchment of the Yellow River. *Water Environ. Res.* **2019**, *91*, 222–238. [CrossRef]
29. Zhang, F.; Zhao, C.; Deng, J.; Chen, J.; Zhang, B.; Hu, Y. Change characteristics of the precipitation, runoff and sediment discharge in Zulihe River Basin. *Arid. Land Geogr.* **2018**, *41*, 74–82. (In Chinese)

30. Sun, L.; Bi, H.; Ma, Z.; Zhao, D.; Wang, N.; Liu, Z.; Wang, X. Runoff variation characteristics and attribution analysis of the upper and middle reaches of the Yellow River from 1951 to 2020. *J. Beijing For. Univ.* **2024**, *46*, 82–92. (In Chinese)
31. Mann, H.B. Nonparametric tests against trend. *Econom. J. Econom. Society* **1945**, *13*, 245–259. [CrossRef]
32. Kendall, M.G. *The Advanced Theory of Statistics*; C. Griffin and Co. Ltd.: London, UK, 1943.
33. Zhang, J.; Wang, G.; Jin, J.; He, R.; Liu, C. Evolution and variation characteristics of the recorded runoff for the major rivers in China during 1956–2018. *Adv. Water Sci.* **2020**, *31*, 153–161. (In Chinese)
34. Sang, Y.F.; Wang, Z.; Liu, C. Comparison of the MK test and EMD method for trend identification in hydrological time series. *J. Hydrol.* **2014**, *510*, 293–298. [CrossRef]
35. Liu, F.; Chen, S.; Dong, P.; Peng, J. Spatial and temporal variability of water discharge in the Yellow River Basin over the past 60 years. *J. Geogr. Sci.* **2012**, *22*, 1013–1033. [CrossRef]
36. Hamed, K.H.; Rao, A.R. A modified Mann-Kendall trend test for autocorrelated data. *J. Hydrol.* **1998**, *204*, 182–196. [CrossRef]
37. Wigbout, M. Limitations in the use of double-mass curves. *J. Hydrol.* **1973**, 132–138.
38. Allen, R.G.; Pereira, L.S.; Raes, D.; Smith, M. *Crop Evapotranspiration-Guidelines for Computing Crop Water Requirements-FAO Irrigation and Drainage Paper 56*; FAO: Rome, Italy, 1998; Volume 300, p. D05109.
39. Paredes, P.; Pereira, L.S.; Almorox, J.; Darouich, H. Reference grass evapotranspiration with reduced data sets: Parameterization of the FAO Penman-Monteith temperature approach and the Hargeaves-Samani equation using local climatic variables. *Agric. Water Manag.* **2020**, *240*, 106210. [CrossRef]
40. Wang, W.; Fu, J. Global assessment of predictability of water availability: A bivariate probabilistic Budyko analysis. *J. Hydrol.* **2018**, *557*, 643–650. [CrossRef]
41. Mo, C.; Huang, K.; Ruan, Y.; Lai, S.; Lei, X. Quantifying uncertainty sources in runoff change attribution based on the Budyko framework. *J. Hydrol.* **2024**, *630*, 130790. [CrossRef]
42. Miao, Z.; Li, N.; Lu, M.; Xu, L. Attribution analysis of runoff variations in the upper reaches of Hutuo River Basin. *J. Beijing Norm. Univ. (Nat. Sci.)* **2021**, *57*, 756–767. (In Chinese)
43. Fu, J.; Liu, B.; Wang, W.; Fei, E.X. Evaluating main drivers of runoff changes across China from 1956 to 2000 by using different budyko-based elasticity methods. *J. Environ. Manag.* **2023**, *329*, 117070. [CrossRef] [PubMed]
44. Ol'Dekop, E.M. On evaporation from the surface of river basins. *Trans. Meteorol. Obs.* **1911**, *4*, 200.
45. Pike, J.G. The estimation of annual run-off from meteorological data in a tropical climate. *J. Hydrol.* **1964**, *2*, 116–123. [CrossRef]
46. Fu, B.P. On the calculation of the evaporation from land surface. *Sci. Atmos. Sin.* **1981**, *5*, 23.
47. Liu, Z.; Rong, L.; Wei, W. Impacts of land use/cover change on water balance by using the SWAT model in a typical loess hilly watershed of China. *Geogr. Sustain.* **2023**, *4*, 19–28. [CrossRef]
48. Bai, X.; Zhao, W. Impacts of climate change and anthropogenic stressors on runoff variations in major river basins in China since 1950. *Sci. Total Environ.* **2023**, *898*, 165349. [CrossRef]
49. Farsi, N.; Mahjouri, N. Evaluating the contribution of the climate change and human activities to runoff change under uncertainty. *J. Hydrol.* **2019**, *574*, 872–891. [CrossRef]
50. Qiao, Z.; Ma, L.; Xu, Y.; Yang, D.; Liu, T.; Sun, B. Runoff change and attribution analysis in a semiarid mountainous basin. *Ecol. Eng.* **2023**, *195*, 107075. [CrossRef]
51. Luo, K.; Moiwo, J.P. Sensitivity of the land surface hydrological cycle to human activities in China. *Gondwana Res.* **2023**, *123*, 255–264. [CrossRef]
52. Zhang, H.; Meng, C.; Wang, Y.; Wang, Y.; Li, M. Comprehensive evaluation of the effects of climate change and land use and land cover change variables on runoff and sediment discharge. *Sci. Total Environ.* **2020**, *702*, 134401. [CrossRef] [PubMed]
53. Sajikumar, N.; Remya, R.S. Impact of land cover and land use change on runoff characteristics. *J. Environ. Manag.* **2015**, *161*, 460–468. [CrossRef] [PubMed]
54. Wang, S.; Zhang, Z.; McVicar, T.R.; Zhang, J.; Zhu, J.; Guo, J. An event-based approach to understanding the hydrological impacts of different land uses in semi-arid catchments. *J. Hydrol.* **2012**, *416*, 50–59. [CrossRef]
55. Wang, D.; Yu, X.; Jia, G.; Wang, H. Sensitivity analysis of runoff to climate variability and land-use changes in the Haihe Basin mountainous area of north China. *Agric. Ecosyst. Environ.* **2019**, *269*, 193–203. [CrossRef]
56. Gibson, G.R.; Campbell, J.B.; Zipper, C.E. Sociopolitical influences on cropland area change in Iraq, 2001–2012. *Appl. Geogr.* **2015**, *62*, 339–346. [CrossRef]
57. Huang, C. Analysis of Water and Sediment Evolution Law and Its Causes in Zuli River Basin. *J. China Hydrol.* **2021**, *41*, 101–108. (In Chinese)
58. Liang, S.; Niu, Z.; Jia, L. Analysis of runoff changes and attribution in the main stream of Zuli River in the past 65 years. *Arid Zone Res.* **2024**, *41*, 928–939. (In Chinese)
59. Zhang, F.; Xing, Z.; Zhao, C.; Deng, J.; Yang, B.; Tian, Q.; Herb, W.R.; Nasem, B. Characterizing long-term soil and water erosion and their interactions with various conservation practices in the semi-arid Zulihe basin, Dingxi, Gansu, China. *Ecol. Eng.* **2017**, *106*, 458–470. [CrossRef]
60. Hang, T.; Chen, S.; Qiao, L. Rainfall Variation in Zuli River Basin in the Past 50 Years and Influence of Typical Human Activities. *J. Arid. Meteorol.* **2009**, *27*, 220–226+244.
61. Wang, G.; Zhang, J.; Pagano, T.C.; Xu, Y.; Bao, Z.; Liu, Y.; Jin, J.; Liu, C.; Song, X.; Wan, S. Simulating the hydrological responses to climate change of the Xiang River basin, China. *Theor. Appl. Climatol.* **2016**, *124*, 769–779. [CrossRef]

62. Mo, C.; Ruan, Y.; Xiao, X.; Lan, H.; Jin, J. Impact of climate change and human activities on the baseflow in a typical karst basin, Southwest China. *Ecol. Indic.* **2021**, *126*, 107628. [CrossRef]
63. Huang, T.; Liu, Y.; Wu, Z.; Xiao, P.; Wang, J.; Sun, P. Quantitative analysis of runoff alteration based on the Budyko model with time-varying underlying surface parameters for the Wuding River Basin, Loess Plateau. *Ecol. Indic.* **2024**, *158*, 111377. [CrossRef]