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Attribution Identification of Runoff Changes Based on the Budyko Elasticity Coefficient Method: A Case Study of the Middle and Upper Reaches of the Jinghe River in the Yellow River Basin

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Abstract: The impacts of climate change and human activities on water resources are a complex and integrated process and a key factor for effective water resource management in semi-arid regions, especially in relation to the Jinghe River basin (JRB), a major tributary of the Yellow River basin. The Sen's slope estimator and the Mann–Kendall test (M–K test) are implemented to examine the spatial and temporal trends of the hydrological factors, while the elasticity coefficient method based on Budyko's theory of hydrothermal coupling is employed to quantify the degree of runoff response to the various influencing factors, from 1971 to 2020. The results reveal that the runoff at Pingliang (PL), Jingchuan (JC), and Yangjiaping (YJP) hydrological stations shows an obvious and gradual decreasing trend during the study period, with a sudden change in about 1986, while precipitation shows a fluctuating and increasing trend alongside a potential evapotranspiration-induced fluctuating and decreasing trend. Compared to the previous period, a change of −29%, in relative terms, in the runoff at the YJP hydrological station is observed. The interaction of human activities and climate change in the watershed contributes to the sharp decrease in runoff, with precipitation, potential evapotranspiration, and human activities accounting for −14.3%, −15.1%, and 70.6% of the causes of the change in runoff, respectively. Human activities (e.g., construction of water conservancy projects), precipitation, and potential evapotranspiration are the main factors contributing to the change in runoff.

Keywords: attribution identification; runoff change; Budyko elasticity coefficient method; Jinghe River; Yellow River basin

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1. Introduction

The IPCC6 report indicates that global warming has become a major trend in climate change [1]. Climate change leads to temperature increases, rainfall increases or decreases, and evapotranspiration changes at the regional scale, and also causes changes in regional water cycle processes. According to the influence of the warming trend in China in the last century [2–4], new characteristics of changes in the runoff volume of major rivers in China and in the water resources of the Yangtze River, Yellow River, and Yarlung Zangbo River, all of which originate from the Tibetan Plateau, have emerged in the last 60 years [5,6]. However, with respect to the JRB in the Loess Plateau, where the ecological environment is relatively fragile, meteorological and hydrological factors such as temperature, precipitation, potential evapotranspiration, and runoff have quietly changed and attracted widespread attention [7,8]. Human activities such as water conservancy projects and land use have also changed in the past few decades, resulting in new trends and characteristics of runoff and water resources in the basin and attracting the scientific interest of many scholars [9,10].

As runoff change is influenced by a combination of factors, it is also a complex and integrated process. It is a comprehensive response to climate change and human activities in the catchment. Currently, the impact of climate change and human activities on the processes of the hydrological cycle has become a popular topic of research [11–13]. At present, many scholars have used statistical analysis methods [14,15], hydrological modeling methods [16,17], and elasticity coefficient methods based on the Budyko framework [18,19] to investigate the effects of climate change and human activities on the hydrological balance of water resources. The elasticity coefficient method based on the Budyko framework, which has attracted much attention, integrates the coupled water–heat balance of the watershed, constructs the relationship among runoff, precipitation, evapotranspiration, and surface characteristics in the catchment area, is easily calculable, and has been used and validated in many watersheds [14,20,21].

Concerning the assessment of the impacts of climate change and human activities on hydrological processes, the paired watershed approach, hydrological modeling, and statistical methods have been used [22]. Studies have shown that each method has its own advantages; for instance, the paired watershed method is superior to hydrological modeling when calculating climate change effects in small watershed applications, but it is challenging to apply it to medium or large watersheds because natural conditions are seldom similar in large watersheds [23]. Hydrological modeling, including process-based and conceptual models, is a powerful tool for studying the relationship among climate change, human activities, and water resources [24]. However, hydrological modeling is also difficult to use directly due to the lack of detailed hydrological processes with respect to components such as the lack of engineering measures [25]. Consequently, conceptual and regression-based statistical models are broadly used to quantify the effects of environmental change on runoff. Water–energy balance equations based on watershed scales, such as the Budyko hypothesis [26], have become very popular in recent years owing to their simplicity of formulation and their ability to adequately reflect changes in climate and surface characteristics [27,28]. Using the water balance equation of $P = Q + ET + \Delta S$ (where P, Q, ET, and ΔS denote changes in precipitation, runoff, actual evapotranspiration, and water storage, respectively), several analytical equations have been established to express the effects of the following environmental factors on runoff or actual evapotranspiration. Runoff elasticity can be derived from three parameters: precipitation, potential evapotranspiration, and surface conditions [29]. To isolate the contributions of different climatic variables, the elasticity of the runoff has been related to precipitation, net radiation, air temperature, wind speed, and relative humidity [30]. Assuming that ΔS is zero at the long-term water balance, the elasticity approach can effectively describe the sensitivity of the runoff to environmental factors.

Spatial and temporal differences exist in the impacts of climate change and human activities (e.g., afforestation, land use, and hydraulic engineering measures) on the hydrological cycle in the Yellow River basin and one of its sub-basins. Studies have shown that anthropogenic activities account for about 50% of the runoff changes in most watersheds [31,32], while climate change also plays an important role in some watersheds [22,33,34]. In addition, the hydrological effects of river runoff vary at different chronological scales. Since different scholars have chosen different time scales and regional scales when conducting research on the Yellow River basin, there are differences in the research results available in the literature in terms of runoff and the degree of influence of different factors on runoff changes. In addition, it is important to evaluate the runoff changes in the sub-basins of the Yellow River basin alongside their determining factors, and the results of such a study can provide important information for water resources management and high-quality development of the Yellow River basin.

In this study, the impacts of regional meteorological variables and anthropogenic factors on runoff variability in the middle and upper reaches of the JRB during the period 1971–2020 are comprehensively assessed using elements of meteorological data such as temperature, precipitation, and potential evapotranspiration, as well as anthropogenic (e.g., hydrological engineering) data. The aims of this study are to (i) analyze the spatial and temporal changes in the runoff of the middle and upper reaches of the JRB over the period 1971–2020, (ii) evaluate the interannual variability of runoff elasticity coefficients concerning climate change and anthropogenic factors, and (iii) further quantify the contribution of the two factors mentioned above to runoff variability. This study analyzes the interannual variability of elasticity coefficients and the spatial and temporal changes in runoff alongside their determining factors, and the results provide reliable scientific data to support water resource management in the region.

2. Materials and Methods

2.1. Study Area

The Jinghe River, originating from the east side of the Liupan Mountain, is a secondary tributary of the Yellow River and a primary tributary of the Weihe River, with a total catchment area of 45,421 km^2 and a total length of 455.1 km (Figure 1) [35]. The JRB is located in the temperate continental climate zone, and the precipitation level is low and concentrated around July-September, with an average annual precipitation of 517.9 mm. The runoff is mainly concentrated around July-October, accounting for more than 60% of the annual runoff. Precipitation is the main recharge source of runoff in the JRB. The middle and upper reaches of the Jinghe River are above the YJP hydrological station, with a watershed area of 14,124 km^2 and an elevation range from 902 m to 2911 m. The area above the PL hydrological station consists of the upper reaches of the Jinghe River, mainly in the Liupan Mountains, with good forest cover and meandering rivers and a watershed area of 1305 km^2. The area between the PL hydrological station and the YJP hydrological station constitutes the middle reaches of the Jinghe River, which is mainly located in the plains with the JC hydrological station. The hydrological stations in the middle and upper reaches of the mainstem of the Jinghe River were selected for our study. The upstream control station is the PL hydrological station, while the midstream station is the YJP hydrological station (Figure 1 and Table 1) [7]. The study area is located in the Loess Plateau high-intensity soil and water erosion area, which is mainly composed of two terrain types: hilly–gully terrain and terrace–gully terrain. Soil erosion in the watershed is relatively serious, and the average annual sand transport is about 6718×10^4 t, representing the main source of sediment for the Weihe River and even the Yellow River. Information on the hydrological and meteorological stations involved in the study area is provided in Tables 1 and 2.

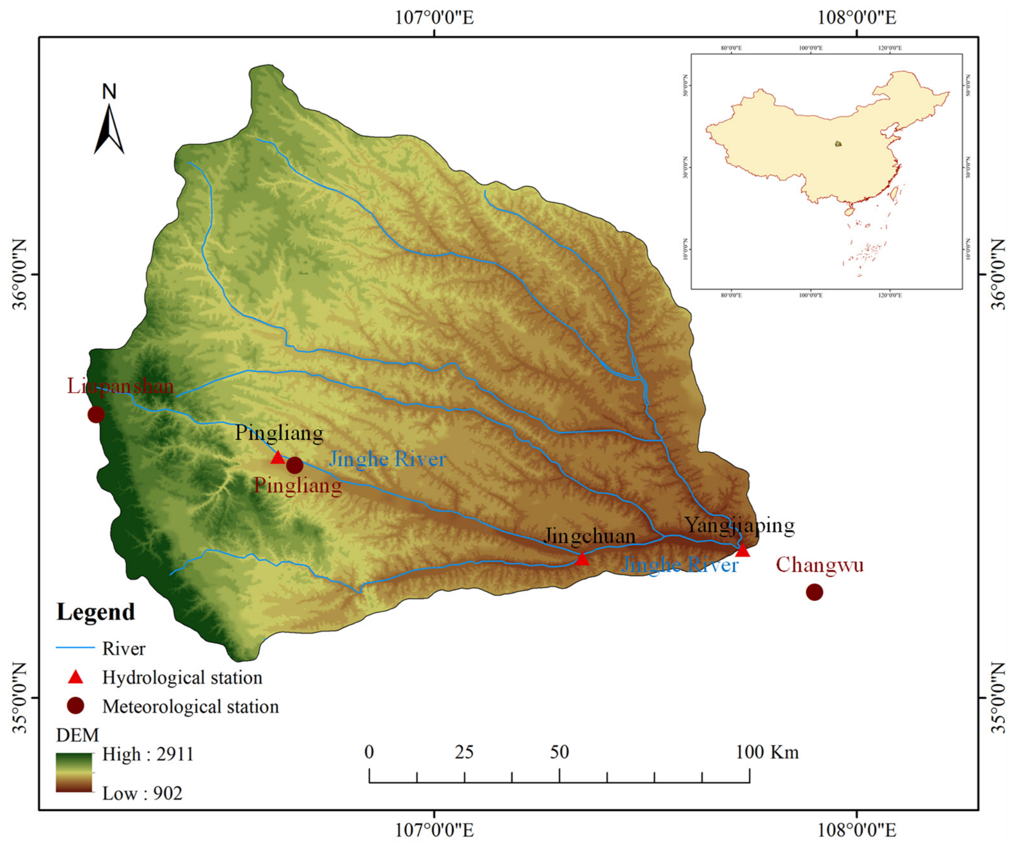

Figure 1. Distribution of hydrological and meteorological stations in the study area.

Table 1. Basic information on the hydrological stations in the upper and middle reaches of the Jinghe River.

River Name	Discharge Station	Longitude	Latitude	Basin Area (km^2)	Data Series
Jinghe River	Pingliang	106°38′	35°34′	1305	1971–2020
	Jingchuan	107°21′	35°20′	3145	1971–2020
	Yangjiaping	107°44′	35°20′	14,124	1971–2020

Table 2. Basic information on the meteorological stations in the upper and middle reaches of the Jinghe River.

Meteorological Station	Longitude	Latitude	Altitude (m)	Data Series
Liupanshan	106°07′	35°24′	2841	1971–2020
Pingliang	106°24′	35°20′	1347	1971–2020
Changwu	107°29′	35°07′	1206	1971–2020

2.2. Data Processing and Research Framework

The dataset for this study consisted of meteorological and streamflow data from 1971 to 2020, concentrating around the middle and upper JRB (Figure 1 and Tables 1 and 2). Runoff data were obtained from the Hydrological Yearbook of the People's Republic of China, while meteorological data were obtained from the National Meteorological Centre of the China Meteorological Administration. Both runoff and meteorological data were subjected to rigorous quality control procedures. The procedures included extreme value tests, plausibility checks, and standard normal homogeneity tests. In addition, missing runoff data and meteorological data for individual years were interpolated using the gap-filling method after correlation analyses. Basic information on the hydrological and meteorological stations is presented in Tables 1 and 2.

The Google Earth Engine (GEE, a planetary-scale platform for Earth science data and analysis) was used to collect all available Landsat 5/7/8 images from 1985 to 2020, from which annual maximum NDVI values were calculated. The spatial resolution of the images was 30 m. The average of the annual maximum NDVI values within the middle and upper reaches of the Jinghe River was calculated as the series data of interannual NDVI.

The daily reference evapotranspiration (ET_0) was computed from meteorological data using the Penman–Monteith equation, corrected by the Food and Agriculture Organization (FAO) [36].

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T_{mean}+273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (1)$$

where ET_0 represents the potential evapotranspiration, mm, R_n denotes the full-wave net radiation at the canopy surface, MJ·m^{-2}·d^{-1}, and G indicates the soil heat flux density, MJ·m^{-2}·d^{-1}. Additionally, T_{mean} refers to the daily air temperature, °C, while u_2 signifies the wind speed, m·s^{-1}. The terms e_s and e_a represent the saturated vapor pressure and the actual vapor pressure, kPa, Δ is the slope pressure curve, kPa·°C^{-1}, and γ is a psychrometric constant, kPa·°C^{-1}.

To better illustrate the data processing and analysis steps, the research framework of the study is shown in Figure 2.

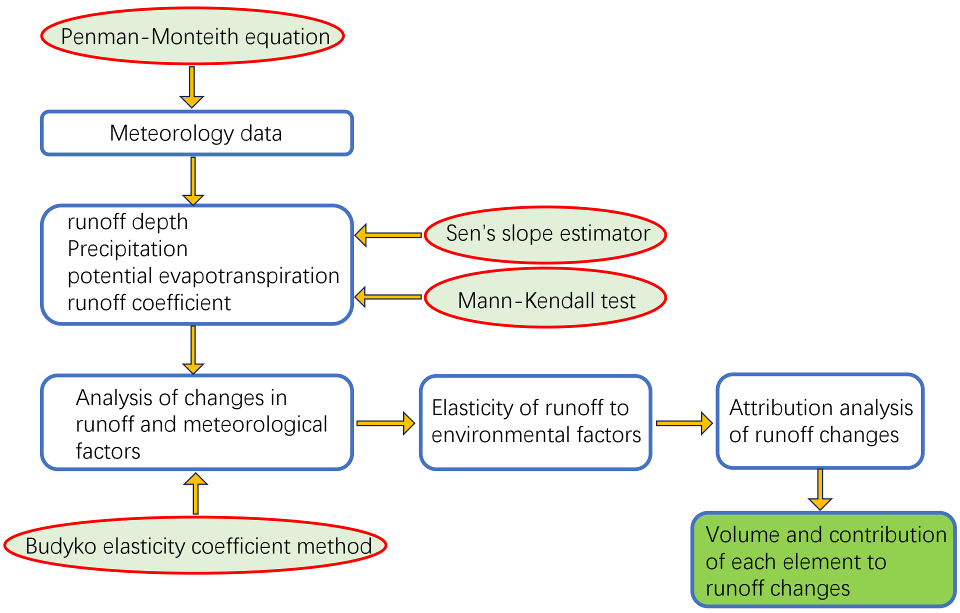

Figure 2. Steps used to process and analyze data, i.e., our research framework.

2.3. Methods

2.3.1. Trends in the Evolution of Hydrological Elements and Tests for Mutations

Non-parametric methods are extensively employed to identify trends and assess significance levels in hydrometeorological series. In this study, the Sen's slope estimator [37] and the Mann–Kendall test (M–K test) [38,39] were utilized to investigate trends in hydrometeorological variables, including precipitation, runoff, and potential evapotranspiration [7,8,40]. Specifically, this study focuses on detecting trends in runoff, precipitation, temperature, and potential evapotranspiration in the middle and upper reaches of the Jinghe River, as well as identifying the timing of changes in runoff patterns.

2.3.2. Budyko Elasticity Coefficient Method

Budyko's hypothesis posits that the multi-year average evapotranspiration of a watershed is influenced by both atmospheric water supply (precipitation) and energy supply conditions at the surface (net radiation and potential evapotranspiration). This hypothesis was implemented as follows. In semi-arid regions, the potential evapotranspiration exceeds precipitation, resulting in all precipitation being converted to evapotranspiration. Conversely, in humid conditions, the potential evapotranspiration is less than the precipitation, with all available energy for evapotranspiration being converted to latent heat [38,39].

The basin water balance equation is as follows:

$$R = P - ET - \Delta S \tag{2}$$

where R is the runoff depth, mm, P is the precipitation, mm, ET is the actual evapotranspiration, m, and ΔS is the amount of change in the basin storage, mm.

Quantification of the contribution of runoff changes.

The contribution of climatic variables and changes in subsurface conditions to changes in runoff was assessed using the Budyko elasticity coefficient method. The climatic elasticity coefficient of runoff is defined as the change in runoff volume due to climate variations within the watershed, while the subsurface elasticity coefficient of runoff refers to the changes in runoff due to changes in the subsurface of the watershed. In this study, changes in the subsurface of the catchment primarily refer to changes caused by human activities:

$$R = f(P, ET_{0,}n) \tag{3}$$

where R is the runoff depth, mm, P is the precipitation, mm, ET_0 is the multi-year mean potential evapotranspiration, mm, and n is a parameter reflecting the subsurface characteristics of the basin.

The elasticity coefficient of the runoff with respect to the climate variable X_i, i.e., ε_{X_i}, can be expressed as follows:

$$\varepsilon_{X_i} = \frac{\partial R}{\partial X_i} \times \frac{X_i}{R} \tag{4}$$

where R is the runoff depth, mm, and X_i is the climate variable P, ET_0, or the subsurface parameter n.

$$\begin{cases} \varepsilon_P = \frac{(1+\theta^n)^{\frac{1}{n+1}} - \theta^{n+1}}{(1+\theta^n)\left[(1+\theta^n)^{\frac{1}{n}} - \theta\right]} \\ \varepsilon_{ET_0} = \frac{1}{(1+\theta^n)\left[1-(1+\theta^{-n})^{\frac{1}{n}}\right]} \\ \varepsilon_n = \frac{\ln(1+\theta^n)+\theta^n \ln\left(1+\theta^{-n}\right)}{n\left[(1+\theta^n)-(1+\theta^n)^{\frac{1}{n+1}}\right]} \end{cases} \tag{5}$$

The effect of each factor on the change in runoff can be calculated using the following differential equation:

$$dR = \frac{\partial R}{\partial P} dP + \frac{\partial R}{\partial ET_0} dET_0 + \frac{\partial R}{\partial n} dn \tag{6}$$

where dP, dET_0, and dn are the differences between the average precipitation, potential evapotranspiration, and subsurface characteristics of the two phases before and after the mutation, respectively.

To estimate changes in runoff due to changes in climate and subsurface conditions, the following equation can be used:

$$dR_{X_i} = \varepsilon_{X_i} \frac{R}{X_i} dX_i \tag{7}$$

The contribution of a single factor to changes in runoff can be calculated as follows:

$$C_{X_i} = \frac{dR_{X_i}}{dR} \times 100\% \quad (8)$$

where C_{X_i} is the proportion of the contribution of the factor X_i to runoff changes.

3. Results

3.1. Analysis of Changes in Runoff and Meteorological Factors

The trends of Q (runoff depth), P (precipitation), ET_0 (potential evapotranspiration), and RC (runoff coefficient) at three hydrological stations in the middle and upper reaches of the Jinghe River and the results of the M–K test are shown in Figure 3 and Table 3. Overall, the Q values at the PL, JC, and YJP stations showed a gradual decrease from 1971 to 2020, with YJP showing a significant decreasing trend and passing the significance level ($p < 0.01$). During the same period, P showed a non-significant fluctuating upward trend, while ET_0 at the PL and JC stations showed a significant downward trend ($p < 0.01$); ET_0 at the YJP station did not pass the significance test, and RC showed a similar trend to Q.

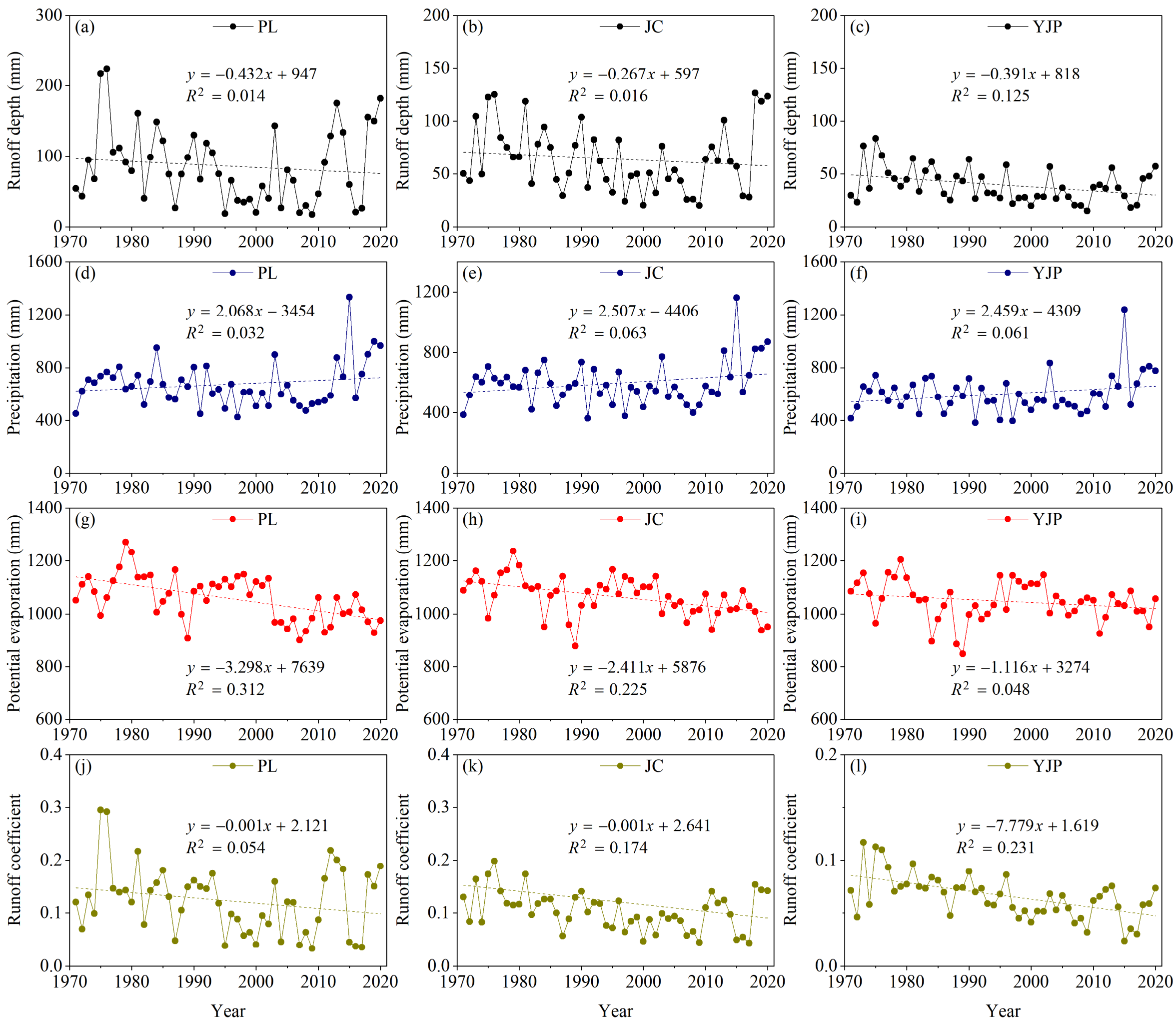

Figure 3. Trends of Q (runoff depth), P (precipitation), ET_0 (potential evapotranspiration), and RC (runoff coefficient) at three hydrological stations in the upper and middle reaches of the Jinghe River. (**a**–**c**) Q (runoff depth), (**d**–**f**) P (precipitation), (**g**–**i**) ET_0 (potential evapotranspiration), and (**j**–**l**) RC (runoff coefficient). PL, JC and YJP denote the Pingliang, Jingchuan, and Yangjiaping hydrological stations, respectively.

Table 3. Mean values and trends of runoff and environmental factors in the middle and upper reaches of the Jinghe River, 1971–2020.

Station	Q/mm yr^{-1}		P/mm yr^{-1}		ET_0/mm yr^{-1}		RC		n	
	Mean Value	Z Value	Mean Value	Z Value	Mean Value	Z Value	Mean Value	Z Value	Mean Value	Z Value
Period (1971–2020)										
PL	85.9	−1.15	659.8	0.23	1058.6	−3.60 **	0.123	−1.34	2.501	3.26 **
JC	64.0	−1.31	585.0	0.38	1064.6	−3.80 **	0.104	−2.31 *	2.276	4.33 **
YJP	39.3	−2.29 *	587.3	0.79	1047.6	−1.89	0.065	−4.23 **	2.923	3.40 **
First subperiod (1971–1986 for PL; 1971–1983 for JC; 1971–1986 for YJP)										
PL	108.4	0.59	684.8	0.41	1112.5	0.32	0.154	0.68	2.071	−0.14
JC	78.8	0.06	587.4	0.43	1122.6	0.43	0.131	−0.18	1.897	0.55
YJP	49.1	−0.05	589.7	0.32	1073.4	−1.94	0.082	−0.32	2.560	1.04
Second subperiod (1987–2020 for PL; 1984–2020 for JC; 1987–2020 for YJP)										
PL	75.3	0.80	648.0	1.48	1033.2	−2.46 **	0.108	0.09	2.704	1.72
JC	58.8	0.77	584.1	1.29	1044.2	−2.05 *	0.095	−0.59	2.410	2.29 *
YJP	34.8	−0.06	586.2	1.63	1035.5	−0.09	0.058	−1.84	3.093	2.14 *

In Table 3, the M–K test for the Q series detected trends at the 95% and 99% significance levels; PL, JC, and YJP denote the Pingliang, Jingchuan, and Yangjiaping hydrological stations, respectively. * $p < 0.05$; ** $p < 0.01$.

In general, changes in precipitation and potential evapotranspiration can affect water vapor dynamics. Precipitation and runoff were positively correlated, with an increase in precipitation resulting in an increase in river runoff, while potential evapotranspiration was negatively correlated with runoff, with an increase in evapotranspiration resulting in a decrease in river runoff. Precipitation is an important factor affecting runoff, and the middle and upper reaches of the Jinghe River are sensitive to changes in runoff in the middle reaches of the Yellow River. The runoff recharge of the middle and upper reaches of the Jinghe River was mainly due to precipitation, which has increased significantly since 2008, with the runoff also slowing down significantly during the same period (Figure 3).

Using the M–K mutation test, the trend of Q was approximately divided into two subperiods (the first subperiod and the second subperiod). The mutation years at the PL, JC, and YJP stations were 1986, 1983, and 1986, respectively. After the mutation period, there was a significant decrease in the Q value compared to the previous period (Figure 3). As it can be seen from Table 4, the runoffs before and after the mutation period at the three hydrological stations in the middle and upper reaches of the Jinghe River showed a significant decrease compared to the pre-mutation period. The largest rate of change was −31% at the PL station, −25% at the JC station, and −29% at the YJP station. Therefore, the effect of changes in the subsurface conditions on the discharge increased, and the factor of changes in the subsurface conditions became the most important factor influencing the discharge. Subsurface factors included topography, soil, etc. Human activities (hydraulic engineering, etc.) and vegetation emerged as the most important factors.

Table 4. Comparison of runoff before and after mutation at three hydrological stations in the middle and upper reaches of the Jinghe River, 1971–2020.

Station	Year of Mutation	First Subperiod/10^8 m^3	Second Subperiod/10^8 m^3	Rate of Change/%
PL	1986	1.4144	0.9824	−31
JC	1983	2.4767	1.8491	−25
YJP	1986	6.9279	4.9086	−29

In Table 4, PL, JC, and YJP denote the Pingliang, Jingchuan, and Yangjiaping hydrological stations, respectively.

3.2. Elasticity of Runoff with Respect to Environmental Factors

The elasticity coefficients of runoff with precipitation, potential evapotranspiration, and characteristic parameters of the surface for the whole study period and the sub-study period in the middle and upper reaches of the Jinghe River are shown in Figure 4 and Table 5. From the whole study period, Q emerged as being positively correlated with P but negatively correlated with ET_0 and n (Figure 4 and Table 5). The elasticity coefficients ranged from 2.556 to 3.725 for P, −1.556 to −2.725 for ET_0, and −1.723 to −2.448 for n. The absolute values of the three elasticity coefficients were largest for P and relatively small for ET_0 and n, reflecting the fact that Q was the most sensitive to P (Table 5). The analysis of the elasticity coefficients showed that a 1% increase in P, ET_0, and n increased runoff by 2.902–3.555%, decreased runoff by 1.902–2.555%, and decreased runoff by 1.904–2.378%, respectively. However, there was a spatio-temporal variation in the coefficient of elasticity. Spatially, the variation in the elasticity coefficient was greatest in the middle reaches of the YJP station and less so in the upper reaches of the PL and JC stations. The coefficients in the second subperiod were larger than those in the first subperiod.

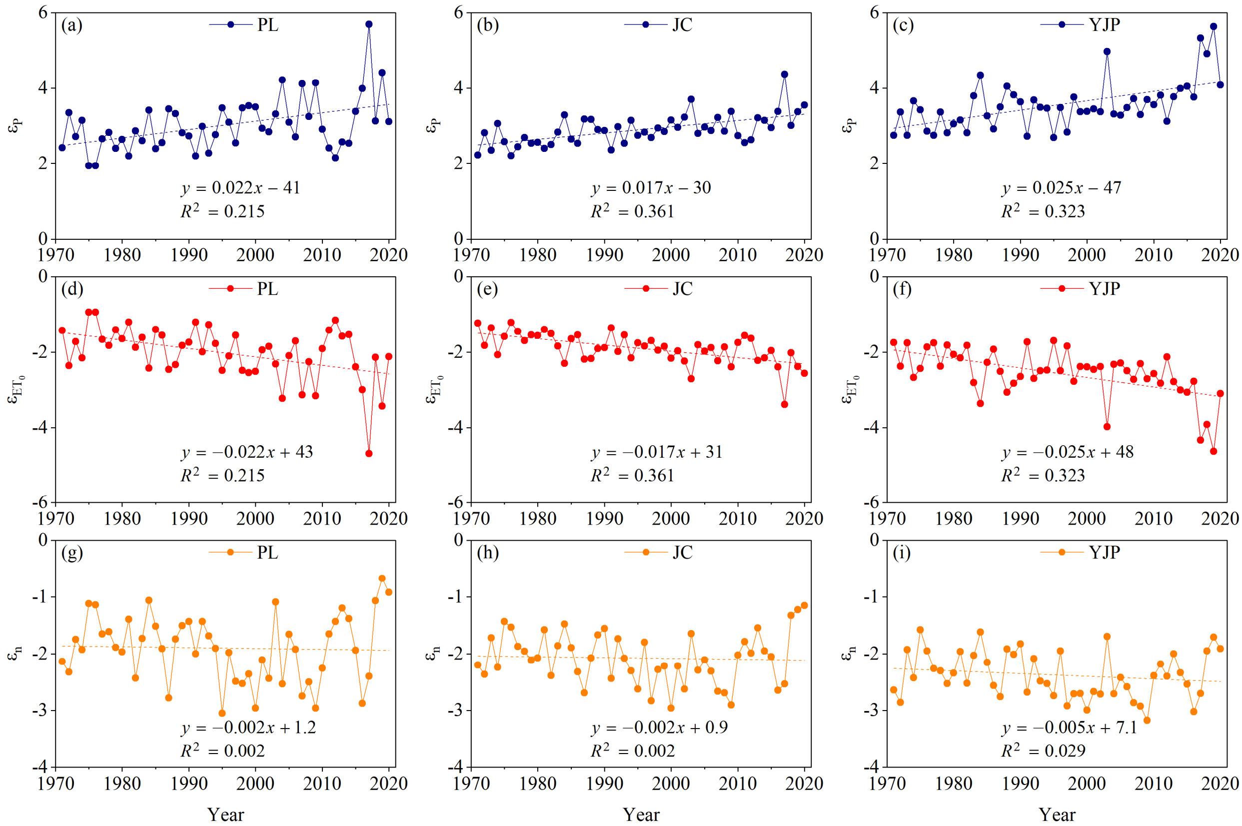

Figure 4. Trends in the interannual variability of the elasticity coefficients of (**a**–**c**) precipitation ε_P, (**d**–**f**) potential evapotranspiration ε_{ET_0}, and (**g**–**i**) surface condition ε_n. PL, JC, and YJP denote the Pingliang, Jingchuan, and Yangjiaping hydrological stations, respectively.

By comparing the elasticity coefficients of the elements in the first and second subperiods at the YJP station, it was possible to observe that the elasticity coefficient of the precipitation increased from 3.195 to 3.725, with a relative rate of change of 16.5%. The elasticity coefficient of the potential evapotranspiration decreased from −2.195 to −2.725, with a relative rate of change of 24.1%. The elasticity coefficient of the characteristic parameter of the subsurface decreased from −2.230 to −2.448, with a relative rate of change of 9.8%, indicating that human activities were more intense during the period of 1987–2020, having a profound impact on the change in runoff. The above analyses indicate that the runoff depth in the middle and upper reaches of the Jinghe River changed significantly in response to changes in precipitation, potential evapotranspiration, and subsurface characteristics. The runoff was more sensitive to both climate change and changes in subsurface conditions.

Table 5. Elasticity coefficients of runoff to changes in climatic elements and surface conditions in the middle and upper reaches of the Jinghe River.

Station	ε_P	ε_{ET_0}	ε_n
Period (1971–2020)			
PL	3.025	−2.025	−1.904
JC	2.902	−1.902	−2.080
YJP	3.555	−2.555	−2.378
First subperiod (1971–1986 for PL; 1971–1983 for JC; 1971–1986 for YJP)			
PL	2.631	−1.631	−1.723
JC	2.556	−1.556	−1.951
YJP	3.195	−2.195	−2.230
Second subperiod (1987–2020 for PL; 1984–2020 for JC; 1987–2020 for YJP)			
PL	3.211	−2.211	−1.989
JC	3.024	−2.024	−2.126
YJP	3.725	−2.725	−2.448

PL, JC, and YJP denote the Pingliang, Jingchuan, and Yangjiaping hydrological stations, respectively.

3.3. Attribution Analysis of Runoff Changes

As shown in Table 6, the changes in runoff depth due to changes in precipitation, potential evapotranspiration, and subsurface conditions, respectively, at the three hydrological stations in the middle and upper reaches of the Jinghe River during the period 1971–2020 were −6.594 mm, 13.015 mm, and −41.366 mm for PL, 3.873 mm, 8.957 mm, and −29.986 mm for JC, and 3.444 mm, 3.640 mm, and −17.076 mm for YJP. In other words, climatic factors and changes in subsurface conditions during the abrupt change period jointly caused the reduction in runoff depth in the middle and upper reaches of the Jinghe River. From the analysis of the YJP hydrological station, it can be seen that the contribution of climate change to the change in runoff depth was 29.4%, with precipitation accounting for −14.3% and potential evapotranspiration accounting for 15.1%, while the change in subsurface conditions accounted for 70.6% (Figure 5). In summary, human activities and climate change, together, are responsible for the significant reduction in runoff volume in the middle and upper reaches of the Jinghe River, with human activities exerting the greatest influence, potential evapotranspiration exerting the second-greatest influence, and precipitation exerting the least amount of influence.

Table 6. Results of the quantitative attribution analysis of the runoff depth changes in the middle and upper reaches of the Jinghe River, 1971–2020.

Station	Volume of Change in Runoff per Element			Contribution of Each Element to Runoff		
	$d\varepsilon_P$/mm	$d\varepsilon_{ET_0}$/mm	$d\varepsilon_n$/mm	$C\varepsilon_P$/%	$C\varepsilon_{ET_0}$/%	$C\varepsilon_n$/%
	Period (1971–2020)					
PL	−6.594	13.015	−41.366	10.8	−21.3	67.9
JC	3.873	8.957	−29.986	−9.1	−20.9	70.0
YJP	3.444	3.640	−17.076	−14.3	−15.1	70.6

PL, JC, and YJP denote the Pingliang, Jingchuan, and Yangjiaping hydrological stations, respectively.

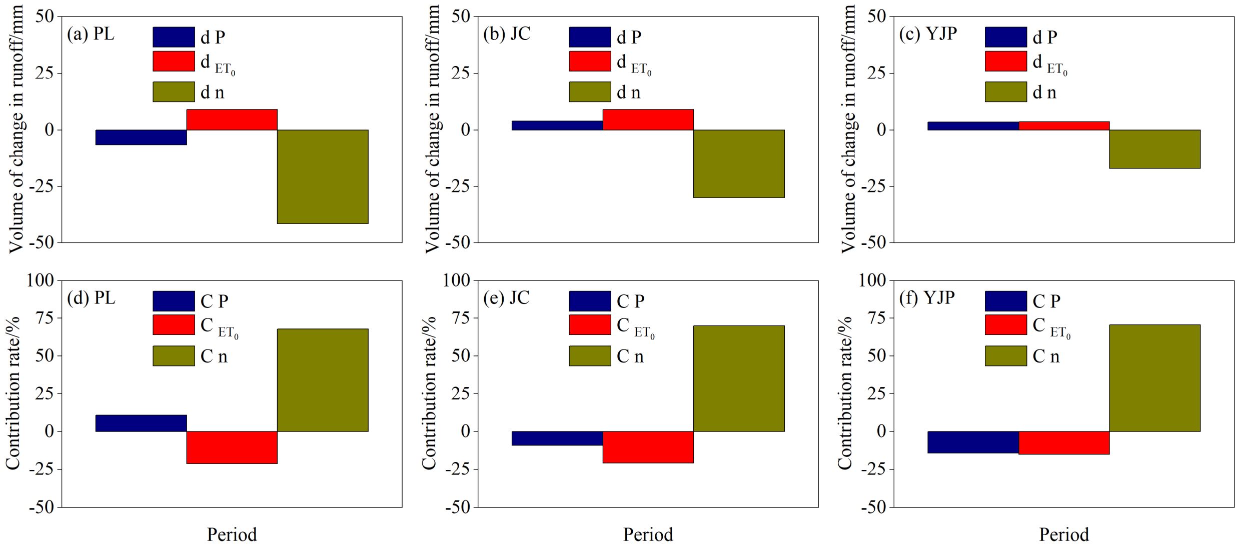

Figure 5. Volume and contribution of each element to runoff changes at three hydrological stations in the middle (**b**,**c**,**e**,**f**) and upper (**a**,**d**) reaches of the Jinghe River, 1971–2020. PL, JC, and YJP denote the Pingliang, Jingchuan, and Yangjiaping hydrological stations, respectively.

The analysis of the contribution of the elasticity coefficient to changes in runoff showed that climate change and human activities, together, have a greater impact on changes in runoff, with changes in surface conditions having the greatest impact on runoff. The middle and upper reaches of the Jinghe River are located on the Loess Plateau and consist mainly of forest, grassland, and farmland. Human activities, through the construction of hydraulic projects and the implementation of soil and water conservation measures (e.g., changes in the area of forested land and grassland), were found to have changed the subsurface conditions and, therefore, the water storage function and water holding capacity of the catchment. As a result of the changes in surface conditions, the timing of runoff in the catchments and the hydrological processes also changed, ultimately leading to changes in runoff.

4. Discussion

The results of the study show that runoff, precipitation, potential evapotranspiration, and anthropogenic surface features in the middle and upper reaches of the Jinghe River changed significantly during the period of 1971–2020. According to the linear trend of the hydrological element series and the elasticity coefficients, the runoff was positively correlated with the precipitation, while it was negatively correlated with the potential evapotranspiration and the surface feature parameter n (Figure 2, Figure 3, and Figure 4 and Table 3, Table 4, Table 5, and Table 6, respectively). In order to assess the sensitivity of the temporal changes in runoff to climate factors (P and ET_0) and surface sensitivity, the annual elasticity coefficients of Q with respect to P, ET_0, and n were estimated by neglecting ΔS. Neglecting ΔS is appropriate for long-term analyses [7,8,30,41].

The impact of human activities on hydrological processes in watersheds can be attributed to changes in the subsurface. Anthropogenic impacts on runoff changes are significant and are beginning to play an important role [42,43]. Changes in the subsurface, which can be a reflection of changes in land use, are the main causes behind the impact of human activities on runoff. Land use change gradually alters hydrological elements such as infiltration, evapotranspiration, and runoff, thus affecting runoff and the water cycle process in the watershed. According to Figure 6, n fluctuated and increased over the whole period, with a clear and sustained upward phase after 1995, followed by a gradual decrease in the 2000s, and finally a clear upward trend around 2010. The overall upward trend of n was most likely related to an increase in hydraulic engineering (water conservation measures, etc.). Soil and water protection measures, the expansion of facilities, and the construction of water protection projects have made the hydrological cycle process of converting precipitation into runoff more complicated, and the amount of water brought by precipitation has been retained for a longer period of time in the watershed, with an increase in potential evapotranspiration leading to a downward trend in runoff in the watershed over a period of time and manifesting itself as a significant increase in n [44]. The construction of protective forests in the middle reaches of the Yellow River began in 1995, when the first pilot projects were carried out in Gansu, Ningxia, and Shaanxi [45]. Around 2008, when the JRB Comprehensive Management Project (e.g., forest ecosystem protection and restoration project, etc.) started to be implemented, the n value increased again, but this state may not last for a long time and is more likely to remain stable in the future.

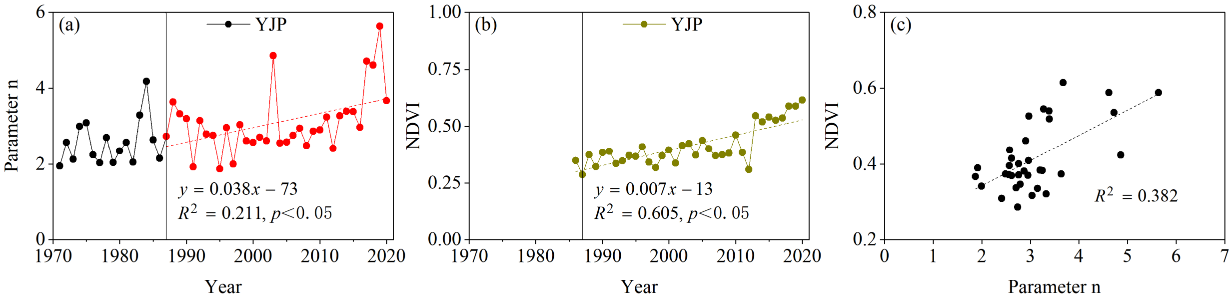

Figure 6. Relationship between the parameter n and the vegetation cover NDVI at the YJP hydrological station in the middle and upper reaches of the Jinghe River from 1986 to 2020. (**a**) Trend plot of surface parameter n; (**b**) Trend plot of NDVI; (**c**) Scatter plot of surface parameter n fitted to NDVI.

In order to further explore the relationship between vegetation changes and runoff changes, the spatial characteristics of NDVI changes in the middle and upper reaches of the Jinghe River from 1985 to 2020 were analyzed by combining the magnitude of NDVI changes and the significance level of the trend test. As Figure 6 shows, the vegetation cover condition of the middle and upper reaches of the Jinghe River has significantly improved since 1990. This time interval is also characterized by a greater decline in runoff, with the attribution analysis showing that the change in the subsurface was the dominant factor behin the decline in runoff in this area. It can be concluded that the increase in vegetation cover due to soil and water conservation was mainly responsible for the decrease in runoff in the middle and upper reaches of the Jinghe River. In the Budyko equation, the properties of the surface parameter (n) are related to soil properties [46,47], topography [14,48], and vegetation [49,50]. Soil properties and topography experience very little change over short periods of time, and vegetation cover and hydraulic engineering measures are considered to be the main factors influencing the surface parameter n [43,51]. In the JRB, an increase in vegetation cover, especially forests and grasslands, has been found to significantly change surface conditions [7,52]. During the period of 1985–2020, the trends of n and NDVI in the middle and upper reaches of the JRB showed similar interannual variations, and the trends of n and NDVI increased significantly after the abrupt change in runoff (Figure 6). The above analyses revealed that vegetation changes had a positive effect on n values. Thus, runoff decreased with increasing n values (Table 3 and Figures 4 and 6).

According to the attribution results with respect to the runoff changes in the middle and upper reaches of the Jinghe River, the main reason for the reduction in runoff was the change in precipitation and subsurface conditions. From Figure 6, it can be seen that the subsurface parameter n of the watershed has increased significantly after 1990. The study shows that a series of soil and water conservation measures have been implemented in the JRB since the 1970s [35]. These include both biological conservation measures, such as planting trees and improving terraces, and hydraulic engineering measures, such as constructing reservoirs and a barrage of silt dams. As the project progressed, the area of the control zone increased. By 2012, the total area of the control zone had reached 7759 km^2 [35]. The topography and soil conditions of the upper and middle reaches of the Jinghe River are relatively stable, so the increase in the subsurface parameter n was mainly due to the increase in vegetation, which, in turn, was the direct effect of soil and water conservation. In terms of the annual water balance of the upper and middle reaches of the Jinghe River, the effect of soil and water conservation on the annual runoff of the watershed mainly showed an increase in the evapotranspiration of the watershed.

The results obtained in this study (higher n being the main reason for the steep reduction in Q) are consistent with previous research [7,35], but the contribution of P to the change in Q is slightly different from previous studies. Ning et al. [7] concluded that the contribution of climate change (P, ET_0, and n) to the reduction in runoff from the YJP hydrological station in the JRB was 7%, 86%, and 7%, respectively. Yang et al. [53] concluded that the combination of climate change and human activities had led to a significant reduction in runoff in the JRB. The differences in these conclusions are likely to be related to the different study periods, the former of which may have been in the dry phase of the hydrological cycle when the reduction in precipitation led to a significant reduction in runoff.

5. Conclusions

In this study, the evolution of hydrometeorological factors in the middle and upper reaches of the Jinghe River is analyzed, and the contribution of precipitation, potential evapotranspiration, and subsurface characteristics to the change in runoff depth is quantified.

1. During the study period from 1971 to 2020, there was a significant decreasing trend in precipitation at the PL and JC stations, and a significant decreasing trend in runoff depth at the YJP station in the middle and upper reaches of the Jinghe River, with no significant changes in the remaining elements. Runoff at the PL, JC, and YJP stations changed abruptly around 1986, with the second subperiod at the three hydrological stations showing a 31%, 25%, and 29% decrease in multi-year average annual runoff depth, respectively, compared to the first subperiod.
2. The contribution of the elasticity coefficients of runoff depth to precipitation at three hydrological stations, PL, JC, and YJP, in the upper and middle reaches of the Jinghe River was the largest and showed an increasing trend, while potential evapotranspiration and subsurface changes showed a decreasing trend. Spatially, the changes in elasticity coefficients were largest at the YJP station, with smaller changes upstream of the PL and JC stations. A comparison between the elasticity coefficients of the elements in the first and second subperiods showed that the runoff depth in the second subperiod was more sensitive to both climate change and changes in subsurface conditions.
3. An analysis of the elasticity coefficient method based on the Budyko hypothesis framework showed that the combination of human activities and climate change has led to a significant reduction in the volume of runoff in the middle and upper reaches of the Jinghe River, with the contribution of human activities amounting to about 70%.

The present study is based on only three hydrological stations and related meteorological stations in the middle and upper reaches of the Jinghe River mainstem,. Although the latter is typical and representative, the study is still limited by the small number of stations in the whole basin if more accurate observations are not obtained. In the future, our study may target a greater number of stations with a more even distribution to conduct more accurate quantitative analyses of the modelled changes in runoff caused by climatic elements and subsurface conditions. The results of such studies could provide a scientific basis for water resource management in the region as well as recommendations for decision-making in the context of climate change adaptation.

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References

1. Intergovernmental Panel on Climate Change (IPCC). *Climate Change 2021: Impacts, Adaptation, and Vulnerability*; Cambridge University Press: Cambridge, UK, 2021.
2. Yan, Z.; Ding, Y.; Zhai, P.; Song, L.C.; Cao, L.; Li, Z. Re-assessing climatic warming in China since the last century. *Acta Meteorol. Sin.* **2020**, *78*, 370–378.
3. Wang, S.W.; Gong, D.Y. Enhancement of the warming trend in China. *Geophys. Res. Lett.* **2000**, *27*, 2581–2584. [CrossRef]
4. Hu, Z.Z.; Yang, S.; Wu, R.G. Long-term climate variations in China and global warming signals. *J. Geophys. Res.-Atmos.* **2003**, *108*, 4614. [CrossRef]
5. 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.
6. Li, D.L.; Wang, W.S.; Hu, S.X.; Li, Y.Q. Characteristics of annual runoff variation in major rivers of China. *Hydrol. Process.* **2012**, *26*, 2866–2877. [CrossRef]
7. Ning, T.T.; Li, Z.; Liu, W.Z. Separating the impacts of climate change and land surface alteration on runoff reduction in the Jing River catchment of China. *Catena* **2016**, *147*, 80–86. [CrossRef]
8. Xu, J.J.; Gao, X.C.; Yang, Z.Y.; Xu, T.Y. Trend and Attribution Analysis of Runoff Changes in the Weihe River Basin in the Last 50 Years. *Water* **2022**, *14*, 47. [CrossRef]
9. Wu, X.; Li, J.S.; Shen, X.J. Quantitative analysis for the response of streamflow variation to driving factors in seven major basins across China. *Ecol. Indic.* **2023**, *148*, 110081. [CrossRef]
10. Zhong, D.Y.; Dong, Z.C.; Fu, G.B.; Bian, J.Q.; Kong, F.H.; Wang, W.Z.; Zhao, Y. Trend and change points of streamflow in the Yellow River and their attributions. *J. Water Clim. Chang.* **2021**, *12*, 136–151. [CrossRef]
11. Mikaeili, O.; Shourian, M. Assessment of the Analytic and Hydrologic Methods in Separation of Watershed Response to Climate and Land Use Changes. *Water Resour. Manage* **2023**, *37*, 2575–2591. [CrossRef]
12. Jehanzaib, M.; Shah, S.A.; Yoo, J.; Kim, T.W. Investigating the impacts of climate change and human activities on hydrological drought using non-stationary approaches. *J. Hydrol.* **2020**, *588*, 125052. [CrossRef]

13. Dey, P.; Mishra, A. Separating the impacts of climate change and human activities on streamflow: A review of methodologies and critical assumptions. *J. Hydrol.* **2017**, *548*, 278–290. [CrossRef]
14. Yokoo, Y.; Sivapalan, M.; Oki, T. Investigating the roles of climate seasonality and landscape characteristics on mean annual and monthly water balances. *J. Hydrol.* **2008**, *357*, 255–269. [CrossRef]
15. Aragaw, H.M.; Goel, M.K.; Mishra, S.K. Hydrological responses to human-induced land use/land cover changes in the Gidabo River basin, Ethiopia. *Hydrol. Sci. J.-J. Sci. Hydrol.* **2021**, *66*, 640–655. [CrossRef]
16. Song, X.M.; Zhang, J.Y.; Zhan, C.S.; Xuan, Y.Q.; Ye, M.; Xu, C.G. Global sensitivity analysis in hydrological modeling: Review of concepts, methods, theoretical framework, and applications. *J. Hydrol.* **2015**, *523*, 739–757. [CrossRef]
17. Haddeland, I.; Heinke, J.; Biemans, H.; Eisner, S.; Flörke, M.; Hanasaki, N.; Konzmann, M.; Ludwig, F.; Masaki, Y.; Schewe, J.; et al. Global water resources affected by human interventions and climate change. *Proc. Natl. Acad. Sci. USA* **2014**, *111*, 3251–3256. [CrossRef]
18. Collignan, J.; Polcher, J.; Bastin, S.; Quintana-Segui, P. Budyko Framework Based Analysis of the Effect of Climate Change on Watershed Evaporation Efficiency and Its Impact on Discharge Over Europe. *Water Resour. Res.* **2023**, *59*, e2023WR034509. [CrossRef]
19. Zhang, S.L.; Yang, Y.T.; McVicar, T.R.; Yang, D.W. An Analytical Solution for the Impact of Vegetation Changes on Hydrological Partitioning Within the Budyko Framework. *Water Resour. Res.* **2018**, *54*, 519–537. [CrossRef]
20. Choudhury, B.J. Evaluation of an empirical equation for annual evaporation using field observations and results from a biophysical model. *J. Hydrol.* **1999**, *216*, 99–110. [CrossRef]
21. Zhang, S.L.; Yang, H.B.; Yang, D.W.; Jayawardena, A.W. Quantifying the effect of vegetation change on the regional water balance within the Budyko framework. *Geophys. Res. Lett.* **2016**, *43*, 1140–1148. [CrossRef]
22. Li, Z.; Liu, W.Z.; Zhang, X.C.; Zheng, F.L. Impacts of land use change and climate variability on hydrology in an agricultural catchment on the Loess Plateau of China. *J. Hydrol.* **2009**, *377*, 35–42. [CrossRef]
23. Huang, M.B.; Zhang, L.; Gallichand, J. Runoff responses to afforestation in a watershed of the Loess Plateau, China. *Hydrol. Process.* **2003**, *17*, 2599–2609. [CrossRef]
24. Jothityangkoon, C.; Sivapalan, M.; Farmer, D.L. Process controls of water balance variability in a large semi-arid catchment: Downward approach to hydrological model development. *J. Hydrol.* **2001**, *254*, 174–198. [CrossRef]
25. McVicar, T.R.; Li, L.; Van Niel, T.G.; Zhang, L.; Li, R.; Yang, Q.; Zhang, X.; Mu, X.; Wen, Z.; Liu, W.; et al. Developing a decision support tool for China's re-vegetation program: Simulating regional impacts of afforestation on average annual streamflow in the Loess Plateau. *For. Ecol. Manage.* **2007**, *251*, 65–81. [CrossRef]
26. Budyko, M.I. *Climate and Life*; Academic Press: New York, NY, USA, 1974.
27. Tang, Y.; Tang, Q.H.; Zhang, L. Derivation of Interannual Climate Elasticity of Streamflow. *Water Resour. Res.* **2020**, *56*, e2020WR027703. [CrossRef]
28. Sankarasubramanian, A.; Vogel, R.M.; Limbrunner, J.F. Climate elasticity of streamflow in the United States. *Water Resour. Res.* **2001**, *37*, 1771–1781. [CrossRef]
29. Roderick, M.L.; Farquhar, G.D. A simple framework for relating variations in runoff to variations in climatic conditions and catchment properties. *Water Resour. Res.* **2011**, *47*, W00G07. [CrossRef]
30. Yang, H.B.; Yang, D.W. Derivation of climate elasticity of runoff to assess the effects of climate change on annual runoff. *Water Resour. Res.* **2011**, *47*, W07526. [CrossRef]
31. Zhang, X.P.; Zhang, L.; Zhao, J.; Rustomji, P.; Hairsine, P. Responses of streamflow to changes in climate and land use/cover in the Loess Plateau, China. *Water Resour. Res.* **2008**, *44*, W00A07. [CrossRef]
32. Zhao, G.J.; Tian, P.; Mu, X.M.; Jiao, J.Y.; Wang, F.; Gao, P. Quantifying the impact of climate variability and human activities on streamflow in the middle reaches of the Yellow River basin, China. *J. Hydrol.* **2014**, *519*, 387–398. [CrossRef]
33. Yan, R.; Cai, Y.P.; Li, C.H.; Wang, X.; Liu, Q. Hydrological Responses to Climate and Land Use Changes in a Watershed of the Loess Plateau, China. *Sustainability* **2019**, *11*, 1443. [CrossRef]
34. Kang, Y.C.; Gao, J.N.; Shao, H.; Zhang, Y.Y. Quantitative Analysis of Hydrological Responses to Climate Variability and Land-Use Change in the Hilly-Gully Region of the Loess Plateau, China. *Water* **2020**, *12*, 82. [CrossRef]
35. Liu, Y.; Gu, Y.; Liu, Y.; Ma, X. Hydrometeorological evolution and its change attribution in Jinghe River Basin. *Water Resour. Hydropower Eng.* **2023**, *54*, 34–48.
36. Allen, R.G.; Pereira, L.S.; Raes, D.; Smith, M. *Crop Evapotranspiration Guidelines for Computing Crop Water Requirements—FAO Irrigation and Drainage Paper 56*; United Nations Food and Agriculture Organization: Rome, Italy, 1998.
37. Sen, P.K. Estimates of the regression coefficient based on Kendall's tau. *J. Am. Stat. Assoc.* **1968**, *63*, 1379–1389. [CrossRef]
38. Mann, H.B. Nonparametric tests against trend. *Econometrica* **1945**, *13*, 245–259. [CrossRef]
39. Kendall, M.G. Rank Correlation Methods. *Br. J. Psychol.* **1975**, *25*, 86–91. [CrossRef]
40. He, Y.; Song, J.X.; Hu, Y.Y.; Tu, X.; Zhao, Y. Impacts of different weather conditions and landuse change on runoff variations in the Beiluo River Watershed, China. *Sustain. Cities Soc.* **2019**, *50*, 101674. [CrossRef]

41. Potter, N.J.; Zhang, L. Interannual variability of catchment water balance in Australia. *J. Hydrol.* **2009**, *369*, 120–129. [CrossRef]
42. Zhou, Y.Y.; Shi, C.X.; Fan, X.L.; Shao, W.W. The influence of climate change and anthropogenic activities on annual runoff of Huangfuchuan basin in northwest China. *Theor. Appl. Climatol.* **2015**, *120*, 137–146. [CrossRef]
43. Shi, G.S.; Gao, B. Attribution Analysis of Runoff Change in the Upper Reaches of the Kaidu River Basin Based on a Modified Budyko Framework. *Atmosphere* **2022**, *13*, 1385. [CrossRef]
44. Ma, Y.L.; Sun, D.Y.; Niu, Z.R.; Wang, X.F. Contribution of Climate Change and Human Activities to Runoff and Sediment Discharge Changes Based on Budyko Theory and Water-Sediment Relationships during 1960–2019 in the Taohe River Basin, China. *Atmosphere* **2023**, *14*, 1144. [CrossRef]
45. 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.
46. Potter, N.J.; Zhang, L.; Milly, P.C.D.; McMahon, T.A.; Jakeman, A.J. Effects of rainfall seasonality and soil moisture capacity on mean annual water balance for Australian catchments. *Water Resour. Res.* **2005**, *41*, W06007. [CrossRef]
47. Zhang, L.; Potter, N.; Hickel, K.; Zhang, Y.Q.; Shao, Q.X. Water balance modeling over variable time scales based on the Budyko framework—Model development and testing. *J. Hydrol.* **2008**, *360*, 117–131. [CrossRef]
48. Yang, H.B.; Qi, J.; Xu, X.Y.; Yang, D.W.; Lv, H.F. The regional variation in climate elasticity and climate contribution to runoff across China. *J. Hydrol.* **2014**, *517*, 607–616. [CrossRef]
49. Huang, T.T.; Liu, Y.; Wu, Z.Y.; Xiao, P.Q.; Wang, J.S.; Sun, P.C. 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]
50. Gao, G.Y.; Fu, B.J.; Wang, S.; Liang, W.; Jiang, X.H. 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]
51. Xu, X.Y.; Yang, D.W.; Yang, H.B.; Lei, H.M. Attribution analysis based on the Budyko hypothesis for detecting the dominant cause of runoff decline in Haihe basin. *J. Hydrol.* **2014**, *510*, 530–540. [CrossRef]
52. Wang, S.A.; Fu, B.J.; Piao, S.L.; Lu, Y.H.; Ciais, P.; Feng, X.M.; Wang, Y.F. Reduced sediment transport in the Yellow River due to anthropogenic changes. *Nat. Geosci.* **2016**, *9*, 38–41. [CrossRef]
53. Yang, H.B.; Yang, D.W.; Hu, Q.F. An error analysis of the Budyko hypothesis for assessing the contribution of climate change to runoff. *Water Resour. Res.* **2014**, *50*, 9620–9629. [CrossRef]