https://doi.org/10.17221/76/2026-SWR

Segmented characteristics of precipitation-runoff response structure relationship in the Yellow River Basin over the past 20 years

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Citation: Huang X., Wei C.W., Qiu L. (2026): Segmented characteristics of precipitation-runoff response structure relationship in the Yellow River Basin over the past 20 years. Soil & Water Res., 21: 133–146.

Abstract: Under a changing environment, the characteristics of precipitation-runoff hydrological response relationship and the analysis of synchronous and asynchronous encounter frequency in large river basins play a crucial role in the water resources planning and management. Under the precipitation and runoff bivariate hydrological framework, segmented joint distribution models for precipitation and runoff of the Yellow River Basin (YRB) are constructed using the copula function. The wet and dry synchronous-asynchronous encounter frequency of precipitation and runoff is quantitatively analysed, and the driving factors underlying the variations in the precipitation-runoff relationship are discussed. The results show that from 2005 to 2024, precipitation and runoff for Lanzhou (upper reaches), Longmen (middle reaches), and Lijin (lower reaches) hydrological station of the YRB exhibited an upward trend. The wet and dry synchronous frequencies between precipitation and runoff at these three stations were 55.24%, 58.26% and 57.67%, respectively, all higher than the asynchronous frequencies, indicating that the whole basin is likely to experience synchronous wet or dry hydrological regimes. Furthermore, in the YRB, the explanatory power of precipitation on natural runoff gradually decreases from upstream to downstream. Land use and land cover change induced by grain-for-green projects and urbanisation are likely the main causes of natural runoff variation and the alteration of the hydrological response mechanism in the YRB.

Keywords: copula; runoff; precipitation; wet and dry encounter frequency; YRB

The global climate has undergone dramatic changes (Krajewski et al. 2021; Grant et al. 2025; Tan et al. 2025). Meanwhile, regional hydrological cycle processes have also been profoundly affected by human activities (Shi et al. 2024; Zhang et al. 2025). Precipitation (Tabari 2020; Wang et al. 2025), runoff (Moragoda & Cohen 2020; Gao et al. 2025; Kaiwen et al. 2025) and the precipitation-runoff relationship (Saft et al. 2015; Yin et al. 2018; Lan et al. 2025; Liu et al. 2025) – one of the critical correlations in the hydrological cycle – have all changed significantly, driven by both climate change and anthropogenic activities. Investigating variations in the structural linkage of precipitation-runoff stands of great significance for rationally formulating water resources development and utilisation planning, implementing watershed flood control, and maintaining the healthy evolution of rivers (Chen et al. 2020; Zhang et al. 2023).

Hydrological processes are highly complex natural phenomena driven by multiple influencing factors, with numerous internal factors exhibiting both correlation and randomness. Univariate analysis of hydrological variables is difficult to accurately reflect their characteristic attributes and inherent laws (Hao

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& AghaKouchak 2013; Han et al. 2021). Multivariable hydrological analysis links and comprehensively analyses two or more hydrologically relevant factors, providing a more specific and accurate description of the characteristics of hydrological phenomena. With the advantages of being able to flexibly select marginal distribution functions and superior accuracy of analysis results, the copula function method has been increasingly favoured by researchers in recent years. It has gradually become a mainstream approach in the field of multivariate analysis of hydrology and water resources (Jiang et al. 2019; Qian et al. 2022; Wei et al. 2023; Khajehali et al. 2025) and has been widely applied in precipitation-runoff related research. Lu et al. (2024) established a copula joint distribution model based on standardised precipitation index-standardised runoff index (SPI-SRI) indicators and studied the drought-wetness encounter frequencies for the Yangtze and Yellow River basins. Zhang and Singh (2012) combined copula theory with entropy theory for developing a joint rainfall runoff distribution, and validated it using watershed data from Texas and Ohio. Abdollahi et al. (2019) structured two rainfall runoff models (bivariate copula-based rainfall-runoff model (BCRR) and fully-nested copula-based rainfall-runoff model (FCRR)) in an Iranian watershed and evaluated their performance. Nazeri Tahroudi et al. (2023) used Random Forest and copula-based simulation models to evaluate the accuracy and efficiency of the identification of unit hydrographs and component flows from rainfall, evapotranspiration and streamflow (IHACRES) rainfall-runoff model in simulating the discharge of the Siminehroud River in Iran. The results indicated that the model performed well. Moradzadeh Rahmatabadi et al. (2023) established a copula joint probability distribution for different descriptive characteristics of rainfall and runoff , such as peak discharge and rainfall depth, and calculated the return period.

Although copula functions have been widely applied in the fields of precipitation-runoff multivariate joint distribution and frequency analysis (Golian et al. 2012; Dodangeh et al. 2019; Ju et al. 2023; Yang et al. 2025), existing research still exhibits the following obvious deficiencies: (1) Single spatial scale. Most studies focus on single-station or whole-basin analysis, making it difficult to reveal the spatial heterogeneity of precipitation-runoff dependence for larger basins. Consequently, the established general models suffer from insufficient regional adaptability and a lack of basin segmentation comparison; (2) Shallow research on wet and dry encounters. Most studies merely calculate various synchronous and asynchronous frequencies. The targeted interpretation of the probabilistic characteristics of various wet and dry combinations for basin-specific demands, such as water resources application, water regulation, flood control and drought resistance, is inadequate.

The non-stationary and nonlinear characteristics in the precipitation-runoff dependence relationship in the Yellow River Basin (YRB) are becoming increasingly apparent (Deb & Kiem 2020). Traditional univariate frequency analysis is incapable of characterising the joint probability characteristics and the patterns of wet and dry encounters between the two variables. There is an urgent need to construct a copula-based precipitation-runoff joint distribution model to quantify the probabilities of different wet and dry combinations, providing a scientific basis for basin water resource management (Huang et al. 2022). Meanwhile, the YRB features a large area and significant geographical spans. There are notable differences in geographical and hydrological characteristics, runoff generation and concentration mechanisms, intensity of human activities, and water-related goals across its three major reaches. The precipitation-runoff dependence relationship and wet and dry encounter characteristics exhibit obvious spatial variations. A single basin-wide study cannot reflect this heterogeneity pattern, making it difficult to support precise policy implementation in different regions and unified river management. Therefore, conducting research on the joint distribution of rainfall-runoff, investigating the wet and dry encounter probability in the YRB, and analysing them across upper, middle and lower reaches, is of important theoretical value and practical significance.

This research employs the copula function to study the variation characteristics of the precipitation-runoff response structure relationship within the YRB, calculates the wet and dry encounter probabilities of precipitation-runoff series, and discusses the main reasons for the changes in hydrological response relationships. Based on the determined joint distribution models of rainfall-runoff in the YRB, runoff can be predicted and estimated according to real-time rainfall conditions and future precipitation forecasts, flexibly adjust basin-scale water resources allocation, and it bears profound implications for the planning and regulation of basin water systems, which helps to improve the level of basin engineering planning and comprehensive management. The calculation of precipitation-runoff wet and dry encounter frequency in the basin provides a theoretical basis for the rational utilisation of water

https://doi.org/10.17221/76/2026-SWR

resources within the basin. It also offers decision support for decision-makers to carry out flood control and drainage work, reduce losses caused by extreme hydrological events, and realise the unified allocation of basin water resources. The segmented research approach is adopted to ensure better adaptability and accuracy of the research results.

MATERIAL AND METHODS

Study area and data. The YRB (95°53'–119°05'E, 32°10'–41°50'N) is an important river basin in Northern China. Spanning nine provincial-level administrative regions and multiple climatic zones, this basin exhibits remarkable disparities in the spatial and temporal distribution of rainfall and runoff, and is characterised by a vast geographical span, climatic variability, and strong ecological fragility. In this study, the selection of hydrological stations followed the principles of representativeness, data integrity, and hydrological response consistency. Lanzhou Station, Longmen Station, and Lijin Station were selected as research sites in the upper, middle, and lower reaches of the YRB, respectively. Figure 1 illustrates the study area and station distribution.

The precipitation data adopted in this study were derived from the Hydrological Bureau of the Yellow River Conservancy Commission. Natural runoff series were collected from the "Yellow River Water Resources Bulletin".

Marginal distribution. Select seven widely used distribution functions (Maeng et al. 2017): Normal distribution (NOR), Gamma distribution (GAM), Pearson type III distribution(P-III), Exponential distribution (EXP), Weibull distribution (WBL), Generalised extreme value distribution (GEV), Lognormal distribution (LOGN) as candidate marginal distributions. The Kolmogorov-Smirnov (K-S) test is first applied to assess the fit of the marginal functions. Subsequently, the ordinary least squares (OLS) principle and Akaike information criterion (AIC) criterion method (Akaike 1974) are adopted to assess the optimal marginal distributions.

Copula function. Sklar's theorem (Sklar 1959) states, that the joint distribution function $F(x, y)$ of random variables X and Y can be decomposed into the marginal distribution functions $F(x)$ and $F(y)$ of X and Y, respectively, and a copula function $C(F(x), F(y))$, that is:

$$F(x, y) = C(F_a(x), F_b(y)) \tag{1}$$

Copula functions can be classified into multiple categories. Considering the physical mechanism of hydrological processes, the adaptability to data characteristics, and model robustness, three widely used bivariate copula functions – Gumbel copula, Clayton copula and Frank copula – are chosen as the candidate joint distribution functions for the precipitation and runoff series in the YRB. Subsequently, OLS, AIC and Bayesian information criterion (BIC) (Chen et al. 2022) indicators are employed to conduct goodness-of-fit tests for copula functions and screen out the optimal copula.

Precipitation-runoff encounter frequencies analysis. When using the hydrological probability method to classify precipitation and runoff into wet

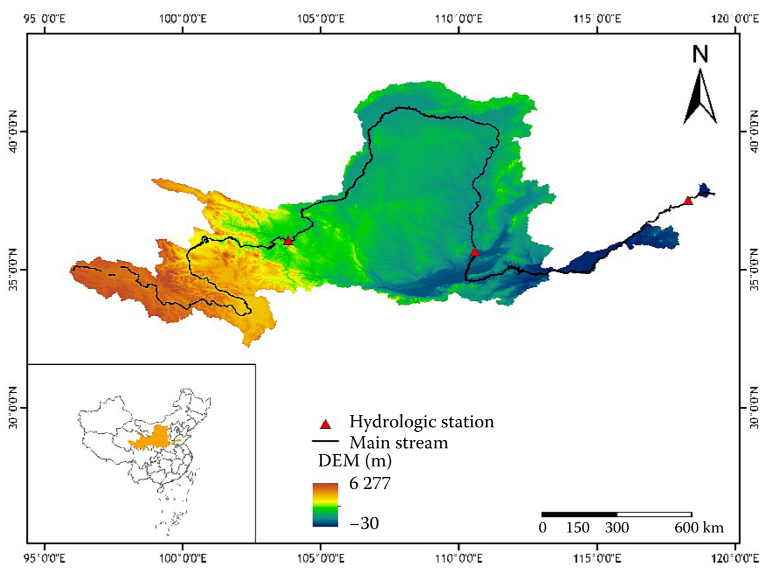

Figure 1. Study area location in Yellow River Basin (YRB)

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Table 1. Calculation formulas for the encounter frequency of precipitation and runoff

Type	Formula
W–W	$P(X > x_w, Y > y_w) = 1 - F_a(x_w) - F_b(y_w) + F(x_w, y_w)$
N–N	$P(x_d < X \leq x_w, y_d < Y \leq y_w) = F(x_w, y_w) - F(x_w, y_d) - F(x_d, y_w) + F(x_d, y_d)$
D–D	$P(X \leq x_d, Y \leq y_d) = F(x_d, y_d)$
W–N	$P(X > x_w, y_d < Y \leq y_w) = F_a(x_w) - F_b(y_d) + F(x_w, y_d) - F(x_w, y_w)$
N–D	$P(x_d < X \leq x_w, Y \leq y_d) = F(x_w, y_d) - F(x_d, y_d)$
W–D	$P(X > x_w, Y \leq y_d) = F_b(y_d) + F(x_w, y_d)$

W – wet; N – normal; D –dry; $P(X, Y)$ – the joint distribution probability function of runoff X and precipitation Y under given conditions; x_w (y_w) – abundant precipitation (runoff) classified at a probability of 37.5%; x_d (y_d) – deficient precipitation (runoff) classified at a probability of 62.5%

and dry conditions, frequency thresholds of 37.5% and 62.5% are used to delineate the wet and dry states of precipitation and runoff. Based on this, the nine combinations of wet and dry encounter conditions can be determined. The probability calculation formulas for wet and dry encounters under different scenarios are presented in Table 1. In Table 1, $P(X, Y)$ represents the joint distribution probability function of runoff X and precipitation Y under given conditions. x_w (y_w) denotes abundant precipitation (runoff) classified at a probability of 37.5%; x_d (y_d) denotes deficient precipitation (runoff) classified at a probability of 62.5%.

RESULTS

Precipitation and runoff characteristics. Precipitation and runoff are crucial hydrological data for ensuring river ecological security. To explore the variation characteristics and correlation between precipitation and runoff across the YRB, a time series chart of annual rainfall and runoff at Lanzhou, Longmen and Lijin hydrological Station spanning 2005–2024 is plotted, as shown in Figure 2. From the figure, it can be observed that both rainfall and runoff of the three Stations exhibit an upward trend. Annual runoff at the upstream Lanzhou Station consistently exceeds that of the midstream Longmen Station for each year, and except for 2021, Lanzhou's annual runoff remains greater than that of the downstream Lijin Station. In terms of precipitation, the annual precipitation at Lanzhou Station exceeds Longmen Station for each year, and exceeds that at Lijin Station in all years except 2013 and 2021. Precipitation and runoff at each station share generally consistent interannual trends.

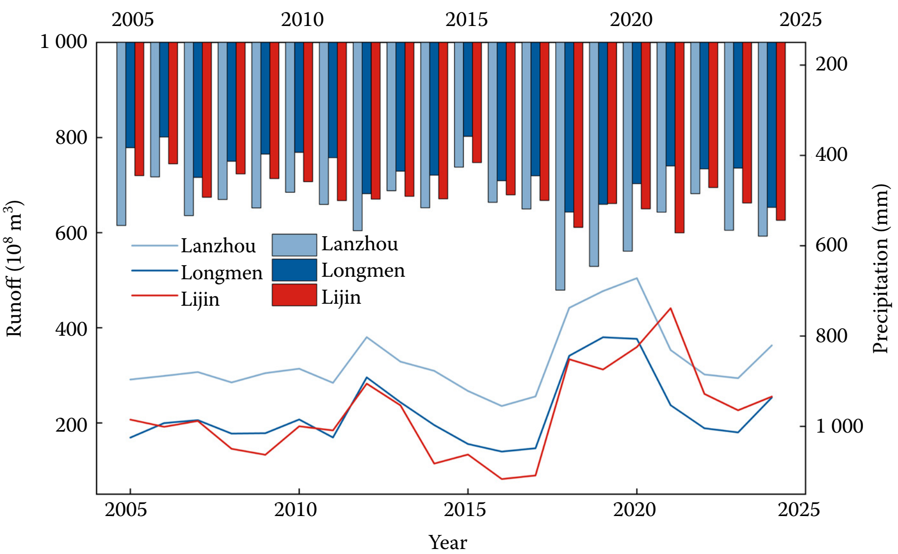

Figure 2. Interannual variations in precipitation and runoff

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Table 2. Statistical characteristics of precipitation and runoff

Station	Characteristic variable	Mean	Extreme value ratio	Standard deviation	*CV*	SK
Lanzhou	runoff ($10^8 m^3$)	329.857	2.141	69.912	0.212	1.305
	precipitation (mm)	533.06	1.639	63.787	0.12	0.889
Longmen	runoff ($10^8 m^3$)	222.035	2.722	71.092	0.32	1.188
	precipitation (mm)	435.751	1.468	46.441	0.107	0.277
Lijin	runoff ($10^8 m^3$)	219.318	5.387	91.667	0.418	0.608
	precipitation (mm)	488.47	1.374	41.084	0.084	0.111

CV – coefficient of variation; SK – skewness coefficient

The main statistical characteristic values of precipitation and runoff of three stations during 2005–2024 are listed in Table 2. It can be observed from Table 2 that the average runoff values for three hydrological stations is 329.86, 222.04, and 219.32 billion m^3, respectively, with the overall order being Lanzhou Station > Longmen Station > Lijin Station. The average annual precipitation is 533.06, 435.75, and 488.47 mm, respectively, ranking as Lanzhou Station > Lijin Station > Longmen Station, consistent with the trend shown in Figure 2. The extreme value ratio reflects the extreme differences between wet and dry conditions, with a higher ratio indicating a more extreme hydrological regime. The extreme value ratio of runoff at the three hydrological stations shows an increasing trend, with the ratio at Lijin Station (downstream) significantly higher than that at Lanzhou Station and Longmen Station, indicating strong interannual fluctuations in runoff and a prominent disparity between wet and dry runoff years at Lijin Station. The extreme value ratio of precipitation at the three hydrological stations shows no obvious significant changes, and generally exhibits a slight decreasing trend. The coefficient of variation (*CV*) characterises the dispersion of data. Overall, runoff displays a larger dispersion relative to precipitation at each station. The dispersion of runoff increases gradually from upstream to downstream, while the dispersion of precipitation changes slightly and shows a weak decreasing trend along the river course, suggesting that the stability of runoff decreases from upstream to downstream. The skewness coefficient (SK) quan-

Table 3. Marginal distribution evaluation

Margin	Test	Station					
		Lanzhou		Longmen		Lijin	
		runoff	precipitation	runoff	precipitation	runoff	precipitation
Normal	OLS	0.1143	0.0735	0.1093	0.0472	0.0523	0.0611
	AIC	−82.7518	−100.4063	−84.5495	−118.1309	−114.0633	−107.7977
Gamma	OLS	0.1015	0.0647	0.0916	0.0414	0.0370	0.0606
	AIC	−87.5143	−105.5088	−91.5947	−123.4161	−127.8663	−108.1610
P-III	OLS	0.0729	0.0477	0.0682	0.0400	0.0379	0.0605
	AIC	−100.7556	−117.7027	−103.3947	−124.7582	−126.9235	−108.1981
Weibull	OLS	0.1194	0.0919	0.1052	0.0681	0.0437	0.0736
	AIC	−81.0013	−91.5034	−86.0586	−103.4781	−121.2226	−100.3709
Generalised extreme value	OLS	0.0602	0.0452	<u>0.0403</u>	0.0400	0.0376	0.0614
	AIC	−108.3851	−119.8934	<u>−124.4855</u>	−124.7955	−127.2407	−107.6421
Lognormal	OLS	0.0942	0.0610	0.0807	0.0389	0.0395	0.0606
	AIC	−90.4989	−107.8687	−96.6692	−125.8586	−125.2128	−108.1331

OLS – ordinary least squares; AIC – Akaike information criterion; the underlined items represent the optimal marginal distributions

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tifies the asymmetry of a probability distribution. The skewness coefficient of both runoff and precipitation at the three hydrological stations shows a decreasing trend.

Optimal marginal distributions. Seven widely adopted theoretical distribution (NOR, GAM, P-III, EXP, WBL, GEV, LOGN) functions are initially selected to fit the annual runoff and annual precipitation series of three stations selected in the YRB. First, the K-S test was applied to evaluate the fit of the seven initially selected distributions. A K-S statistic of 0 represents passing the fitting test and is consistent with the distribution, whereas value 1 corresponds to test failure and inconsistent distributions. The test revealed that neither the annual runoff nor the precipitation series at the three hydrological stations obey the exponential distribution. The remaining six theoretical distributions are all applicable to describe the annual runoff and precipitation series of the three stations.

The maximum likelihood method is employed for parameter estimation, and the optimal marginal distribution is determined using the OLS and AIC statistics. Smaller values of OLS and AIC indicate a better fitting performance. Table 3 presents the selection of the optimal marginal distributions. It is evident from Table 3 that the optimal marginal distributions for runoff and precipitation at the upstream Lanzhou station are both GEV distributions; the runoff at the midstream Longmen station follows a GEV distribution, while the precipitation follows a LOGN distribution; the runoff at the downstream Lijin station follows a GAM distribution, and the precipitation follows a P-III distribution.

The marginal distribution function fitting curves for precipitation and runoff at the three selected hydrological stations are plotted in Figure 3. Figure 3 reflects the final fitting effect by the similarity between the theoretical and empirical distributions. The selected marginal distributions all exhibit good fitting performance, and the results of the optimal distribution are consistent with those in Table 3. The final optimal marginal distributions for precipitation and runoff are shown in Figure 4A, B.

Application of bivariate copulas. For the candidate copula functions, OLS, AIC, and BIC statistics are used to determine the fitting of the copula functions to ultimately identify the optimal copula function. The smaller OLS, AIC and BIC, the better the fit. Table 4 presents the results of the goodness-of-fit testing for the copula functions. As shown in the table, the optimal

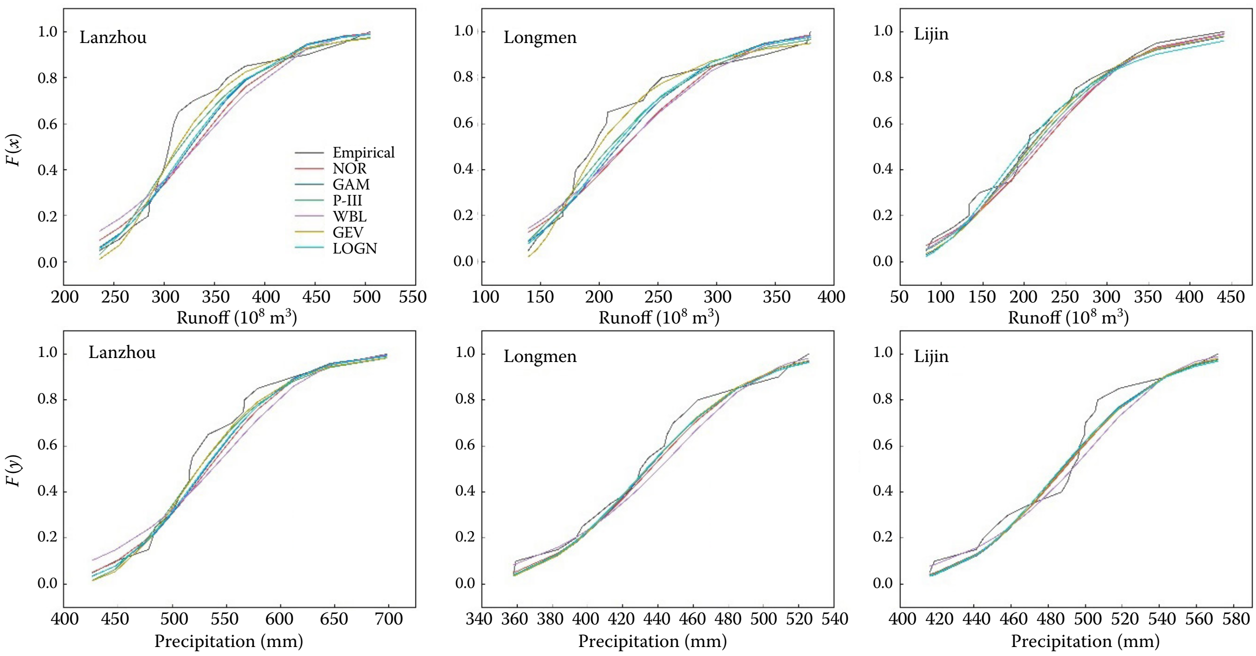

Figure 3. Alternative marginal distributions and empirical distribution function plots for runoff and precipitation in the Yellow River Basin (YRB)

NOR – Normal distribution; GAM – Gamma distribution; P-III – Pearson type III distribution; WBL – Weibull distribution; GEV – generalised extreme value distribution; LOGN – Lognormal distribution

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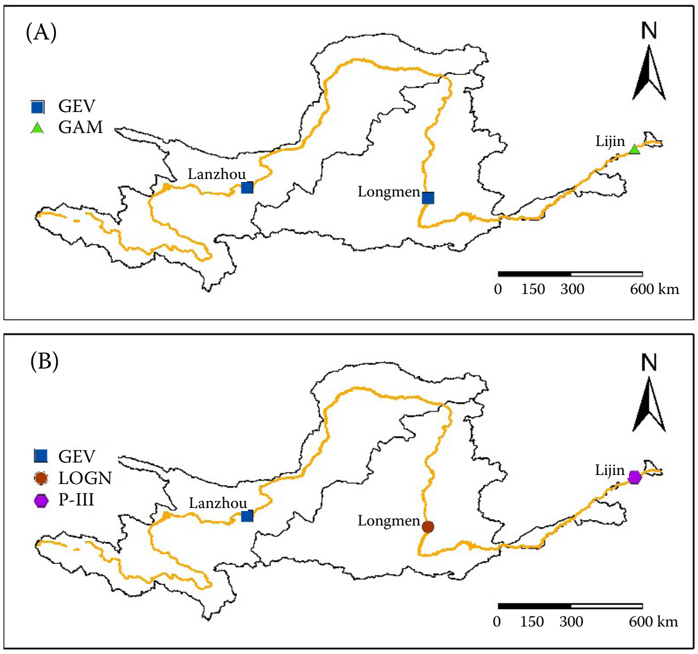

Figure 4. Selected the best-fitted marginal distributions of runoff and precipitation for each hydrological station: runoff (A), precipitation (B)

GEV – generalised extreme value distribution; GAM – Gamma distribution; LOGN – Lognormal distribution; P-III – Pearson type III distribution

copula function for precipitation and runoff at both Lanzhou and Lijin Station is Gumbel, while the Frank copula is the optimal one for the Longmen Station.

To further verify the fitting accuracy of the copula function, a comparison chart of the consistency between the empirical cumulative frequency and theoretical cumulative frequency for three Archimedean-type copula functions at three hydrological stations is plotted, as shown in Figure 5. By calculating the coefficient of determination R^2 and based on the principle of maximising R^2, it can also be determined the optimal copula functions. From Figure 5, the points of empirical frequency and theoretical frequency corresponding to the three copula functions at each hydrological station basically distribute closely around the 45° diagonal line, with relatively high correlation coefficients (all greater than 0.9551), indicating a good fitting effect between the estimated cumulative probability and empirical cumulative probability. Among them, the Gumbel copula exhibits the highest fitting degree for Lanzhou Station and Lijin Station, while the Frank copula performs best at Longmen Station, which coincide with the conclusions shown in Table 4. The final determined bivariate precipitation–runoff copula functions corresponding to the representative hydrological stations are presented in Figure 6.

Using the copula-based precipitation-runoff model for the YRB determined above, runoff can be estimated from real-time rainfall conditions. This facilitates timely disaster prevention and personnel deployment. At the same time, it allows for flexible adjustment of water resource allocation within the watershed, providing crucial support for the planning and management of the water resource system. Based on the theoretical foundation of the correlation between rainfall and runoff, runoff stochastic

Table 4. Evaluation of fitting performance for marginal distribution functions

Station	Copula								
	Gumbel			Clayton			Frank		
	OLS	AIC	BIC	OLS	AIC	BIC	OLS	AIC	BIC
Lanzhou	0.0539	−112.8082	<u>−110.8167</u>	0.0666	−104.3642	−102.3728	0.0573	−110.3454	−108.3539
Longmen	0.0314	−134.4688	−132.4773	0.0371	−127.8110	−125.8195	0.0293	−137.1646	<u>−135.1732</u>
Lijin	0.0484	−117.1171	<u>−115.1256</u>	0.0591	−109.1441	−107.1527	0.0525	−113.8984	−111.9069

OLS – ordinary least squares; AIC – Akaike information criterion; BIC – Bayesian information criterion; the underlined items represent the optimal copula

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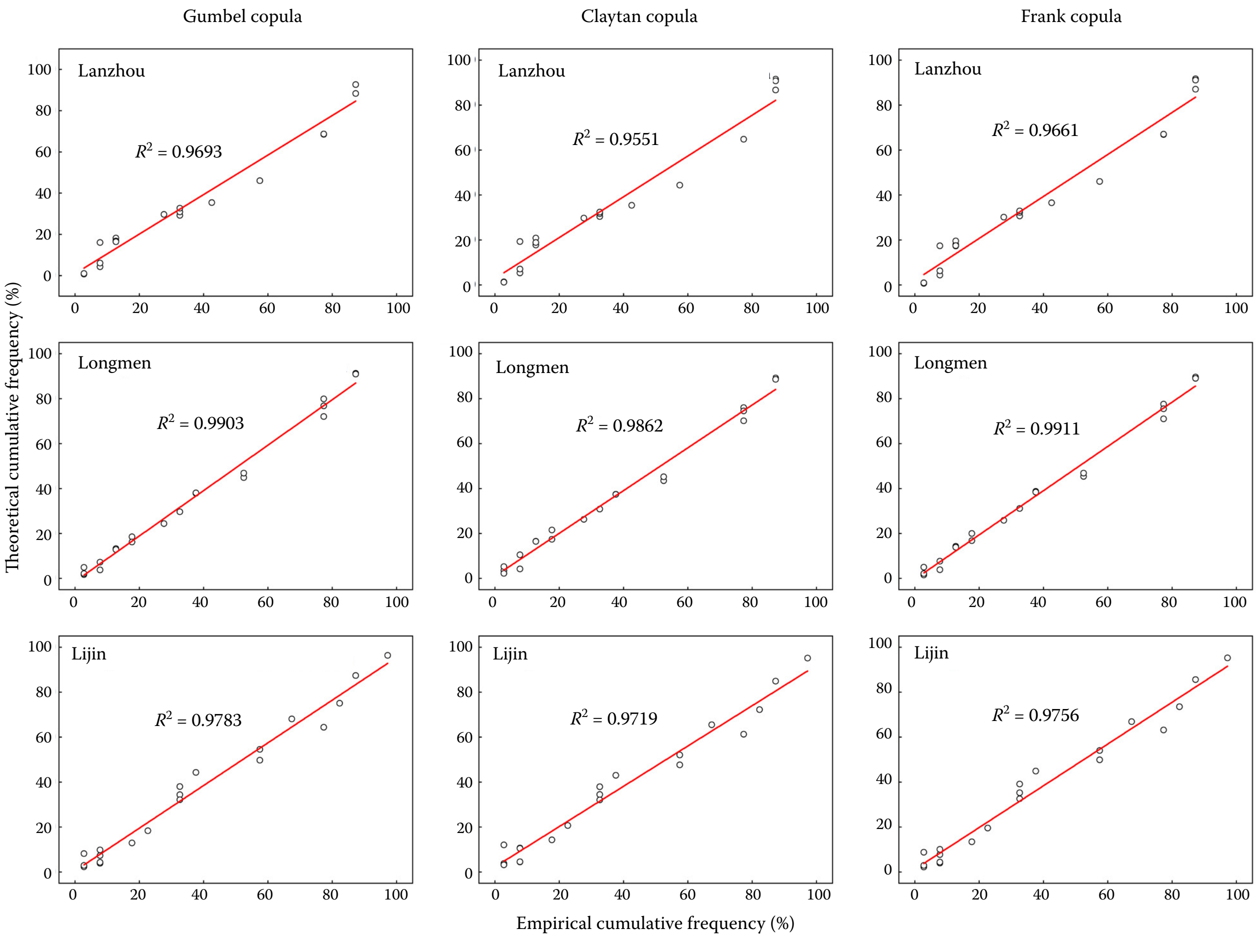

Figure 5. Joint distribution probability-probability (PP) plot

simulation can be conducted using the copula function. It provides a theoretical basis for hydrological analysis and calculation of the basin, and helps improve the level of watershed engineering planning and comprehensive management.

Figure 7 presents the joint probability distribution charts for Lanzhou Station, Longmen Station, and Lijin Station. When both precipitation and runoff variables increase simultaneously at the three hydrological stations, the joint distribution probability also increases, and vice versa. The joint distribution probability can be obtained when precipitation and runoff take specific characteristic values. Alternatively, given a certain amount of precipitation, one can deduce the runoff values corresponding to different probabilities.

Precipitation-runoff encounter probability. Adopting the frequency method with division fre-

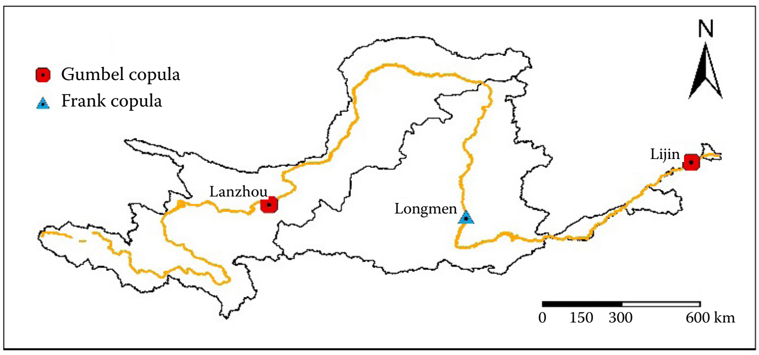

Figure 6. Best fitted bivariate copula for each hydrological station

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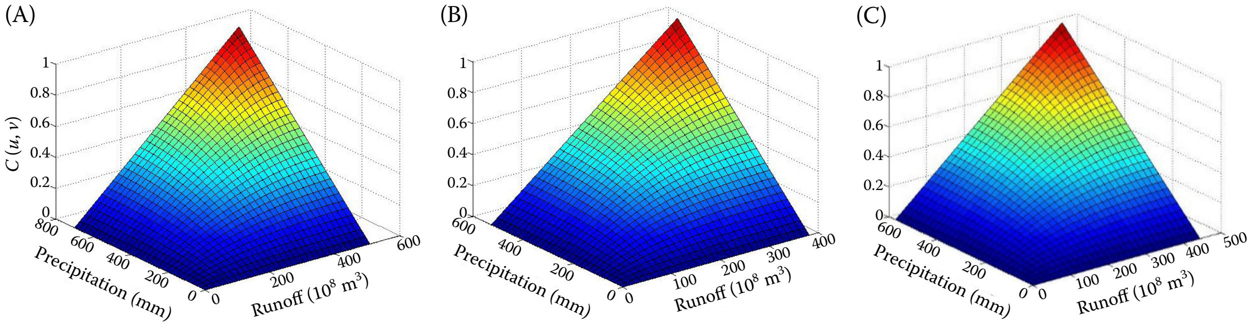

Figure 7. Joint distribution diagram of precipitation-runoff: Lanzhou – Gumbel copula (A), Longmen – Frank copula (B), Lijin – Gumbel copula (C)

quencies of *pw* =37.5% and *pd* =62.5%, the precipitation and runoff are classified into three categories: wet, normal and dry, forming a total of nine combined scenarios. The wet and dry encounter probabilities under each scenario are calculated and presented in Figure 8. As shown in Figure 8: (1) In the combination frequencies of precipitation and runoff at Lanzhou, Longmen and Lijin Station in the YRB, the total wet and dry synchronous frequencies (wet-wet, normal-normal and dry-dry) are 55.24%, 58.26%, and 57.67%, respectively. The wet–dry synchronous frequencies of precipitation and runoff are higher than the asynchronous frequencies, indicating a close correlation between precipitation and runoff, high consistency in wet and dry conditions, and a prominent and stable response of runoff to precipitation. Among the synchronous frequencies of the three stations, the wet–wet frequency is the highest, at 24.3%, 24.95%, and 25.31%, respectively, while the normal–normal frequency is the lowest, at 8.08%, 8.36%, and 8.48%, respectively. For Lanzhou and Lijin Stations, the wet and dry synchronous frequencies follow the order: wet–wet > dry–dry > normal–normal. At Longmen Station, the synchronous frequencies present wet–wet = dry–dry > normal–normal, which implies that the driving effect of precipitation on runoff is more stable in the wet season. (2) In the analysis of wet and dry asynchronous encounter frequencies between precipitation and runoff at each hydrological station, by virtue of the symmetric characteristics of the copula functions adopted, the encounter frequencies for wet precipitation paired with normal runoff are identical to those for normal precipitation paired with wet runoff. Similarly, wet precipitation and dry runoff are equal to that of dry precipitation and wet runoff, and normal precipitation and dry runoff are equal to that of dry precipitation and normal runoff. Among them, normal–dry exhibits the highest probability at Lanzhou and Lijin Stations, reaching 9.18% and 8.99%, respectively. At Longmen Station, both the wet–normal and normal–dry asynchronous frequencies are 8.32%. Among the six asynchronous frequencies, the encounter probabilities of the combinations of wet-dry type at the three hydrological stations are the smallest, at 5.46%, 4.23%, and 4.46%, respectively, indicating that precipitation and runoff

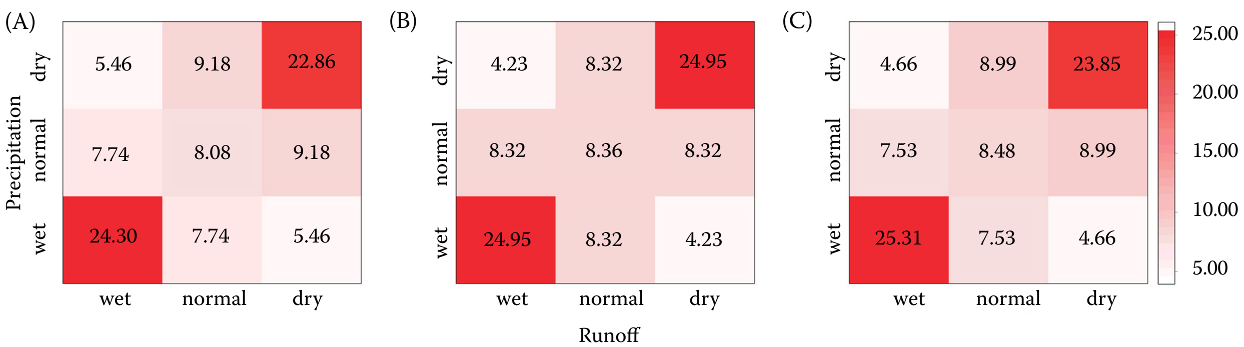

Figure 8. Precipitation-runoff encounter probability (in %): Lanzhou (A), Longmen (B), Lijin (C)

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have a strong correlation, and the probability of occurring completely opposite scenarios is relatively small(Huang & Qiu 2023). (3) Overall, the three selected hydrological stations are distributed in the upper, middle and lower reaches of the YRB. At all three stations, the synchronous frequencies are all higher than asynchronous frequencies, suggesting a possible hydrological regime of basin-wide synchronous wetness and dryness. From Figure 8, it can also be clearly seen that the wet–wet and dry–dry frequencies rank the highest among the nine combination types. Such synchronous characteristics are conducive to the unified regulation of the entire river basin; meanwhile, they also imply potential risks of basin-wide concurrent floods under wet conditions and concurrent droughts under dry conditions. The calculation of wet and dry encounter frequencies between precipitation and runoff within a basin provides a data basis and practical guidance for unified allocation of water resources, flood control, drought relief and reservoir operation.

DISCUSSION

Climate change and human interventions are the two significant aspects of watershed runoff variation. Precipitation serves as the primary meteorological factor affecting the runoff variation. Human activities primarily affect runoff by altering the basin underlying surface, artificial water intake, and water conservancy project scheduling, manifesting specifically in variations of land use and land cover change (LUCC).

Explanatory analysis of precipitation on natural runoff variation. The main relational characteristic values of precipitation and runoff in the YRB from 2005 to 2024 are listed in Table 5. Analyse the correlation between precipitation and runoff using the Pearson linear correlation coefficient γ and the Spearman rank correlation coefficient ρ. A value of the absolute coefficient closer to 1 indicates a stronger correlation between two variables.

According to the calculation results in Table 5, precipitation and runoff at the three hydrological stations all exhibit a strong correlation. The Pearson linear correlation coefficients all exceed 0.637, and the Spearman rank correlation coefficients all exceed 0.565, which satisfy basic variable requirements for constructing copula functions. The runoff coefficient is the runoff depth divided by precipitation depth within a specified period, describing the ability and proportion of precipitation to be converted into runoff. The average runoff coefficients at Lanzhou, Longmen and Lijin stations are 0.277, 0.101, and 0.059, respectively. gradually decreasing from upstream to downstream, indicating a decrease in the efficiency of precipitation conversion into surface runoff and a weakening of runoff generation capacity. The main reasons are as follows: the upper Yellow River have significant topographic relief, abundant snowmelt and precipitation recharge, relatively good vegetation coverage, and strong soil infiltration capacity. Meanwhile, the overall evaporation is low and numerous tributaries converge into the main stream, enabling precipitation to be efficiently converted into runoff and resulting in a high runoff coefficient. The middle reaches traverse the Loess Plateau, where soil erosion is severe. Substantial sediment entering the river channel alters the runoff generation mechanism to some extent. Part of the precipitation is absorbed or evaporated by the soil on the slope, resulting in a decrease in the effective runoff proportion per unit of precipitation, consequently lowering the runoff coefficient. The lower reaches form a typical "suspended river", where the riverbed is higher than the surrounding ground, and basically no tributaries flow into it. Moreover, it passes through the North China Plain, a densely populated region with highly industrialised and agriculture, where human activities such as agricultural irrigation, urban domestic supply and industrial production are extremely intensive. At the same time, the river channel is wide and shallow with low flow velocity, leading to increased evaporation and seepage losses. Consequently, even with upstream inflow, a high runoff generation efficiency cannot be maintained, and the runoff coefficient decreases further.

The relationship plots between precipitation and runoff for the basins controlled by Lanzhou, Longmen and Lijin Station from 2005 to 2024 are presented in Figure 9. It is observed in Figure 9 that the coef-

Table 5. Characteristic parameters of the bivariate relationship between precipitation and runoff

Characteristic parameters of the relationship	Lanzhou	Longmen	Lijin
γ	0.844	0.674	0.637
ρ	0.85	0.565	0.602
runoff coefficient	0.277	0.101	0.059

γ – Pearson linear dependent coefficient; ρ – Spearman rank correlation coefficient

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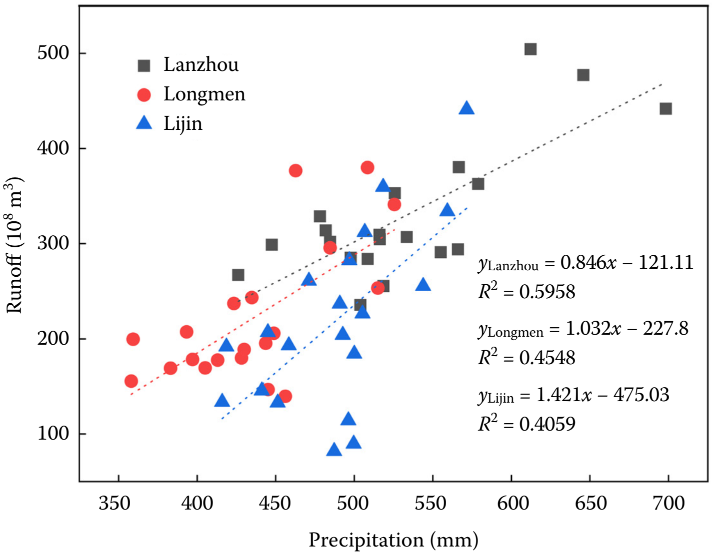

Figure 9. Fitting of precipitation-runoff relationship

ficients of determination for linear regression decrease from upstream to downstream, and are 0.5958, 0.4548, and 0.4059, respectively. The data shows that the precipitation-runoff scatter points gradually disperse from the upper to the lower reaches, indicating a weakening correlation between precipitation and runoff. Consequently, less runoff is generated under the same precipitation conditions, which is consistent with the conclusions obtained in Table 5.

Combining the above analysis, the explanatory ability of precipitation to runoff gradually decreases from upstream to downstream, indicating that the influence of precipitation on runoff variation weakens progressively. Runoff generation gradually declines under the same rainfall conditions, especially in the middle and lower reaches, human activities exerts a stronger influence on runoff than climate change.

Effects of LUCC. Variations in land use types and quantities correspond to changes in the runoff generation and concentration mechanisms, thereby affecting surface runoff. Following the National Standard for Current Land Use Classification (GB/T21010-2007), land resources can be classified into cropland, forest land, grassland, water bodies, urban land, and barren land. Three land use/cover maps in the YRB from different years are presented in Figure 10. It is evident from Figure 10 that YRB is mainly covered by grassland and cultivated land, with grassland occupying the highest percentage. Forest land concentrates in the southeastern part of the basin, and barren land dominates the northwestern region.

The evolutionary analysis of land use types in the YRB is illustrated in Figure 11. From 2000 to 2020, grassland was the most dominant land use type across the YRB, covering 48.22–48.58% of the entire basin. Cropland ranked the second, with a proportion of 24.99–26.29%; forest land ranked third at 12.96–13.31%; barren land ranked fourth at 7.96–8.31%; urban land was fifth,

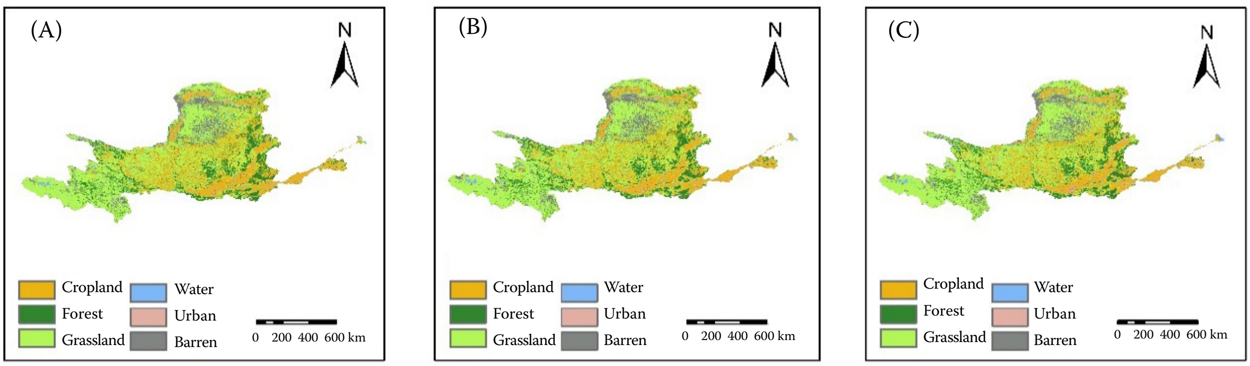

Figure 10. Land use type maps: 2000 (A), 2008 (B), 2020 (C)

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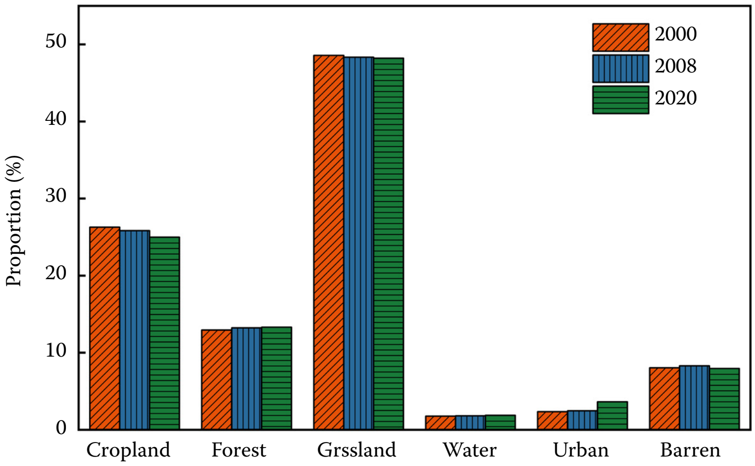

Figure 11. Percentage change of land use types

accounting for 2.37–3.63%; and water bodies occupied the smallest area, with a proportion of 1.77–1.89%. During 2000–2020, the main variations of land use types within the YRB were as follows: the area and proportion of cultivated and grassland decreased, while those of water bodies, forest land, and urban land increased. The area and proportion of barren land first increased and then decreased, with an overall insignificant change. The large-scale Grain for Green program has played a role in soil and water conservation to some extent. Furthermore, the accelerating urbanisation process and the significant expansion of urban construction land have altered vegetation types, disrupted ecological balance, modified the runoff generation characteristics and hydrological response relationship of the basin. These changes affect the watershed runoff generation capacity and constitute an important driving factor for runoff evolution in this watershed.

CONCLUSION

This article selects Lanzhou, Longmen and Lijin hydrological stations as representative stations of the YRB. Utilising copula theory, the joint distribution models of precipitation and runoff at each hydrological station are established, the wet and dry encounter frequencies of precipitation-runoff are calculated, and the main causes of changes in hydrological response relationships are explored. Conclusions are summarised as follows:

(1) From 2005 to 2024, both precipitation and runoff of Lanzhou, Longmen, and Lijin Stations in the YRB exhibited an upward trend. From a multi-year average perspective, the runoff in the YRB gradually decreases from upstream to downstream, following the order: Lanzhou Station > Longmen Station > Lijin Station; in terms of precipitation, the order is: Lanzhou Station > Lijin Station>Longmen Station.

(2) At Lanzhou Station, both precipitation and runoff follow the GEV distribution, and the optimal joint distribution function is the Gumbel copula. At Longmen Station, runoff follows the GEV distribution while precipitation obeys the LOGN distribution, and the optimal copula function is Frank. At Lijin Station, runoff conforms to the GAM distribution and precipitation follows the P-III distribution, with the Gumbel copula chosen as the optimal joint distribution function. On this basis, the precipitation-runoff correlation relationships are established for representative hydrological stations.

(3) The wet-dry synchronous frequencies at the three stations are 55.24%, 58.26% and 57.67%, respectively, all of which are higher than the asynchronous frequencies. This indicates that the basin may present a hydrological regime characterised by synchronous wet and dry conditions across the entire basin. Such synchronism is conducive to the unified water resources regulation of the whole basin, but it also implies the potential risk of disasters such as simultaneous flooding and drought.

(4) The explanatory ability of precipitation on natural runoff gradually decreases from upstream to downstream across the YRB. LUCC, such as the Grain for Green Program and urbanisation, may be the reasons for the variation of natural runoff and the evolution of hydrological response relationships in the Yellow River.

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Received: June 11, 2026
Accepted: August 3, 2026
Published online: August 31, 2026