



OPEN Spatiotemporal patterns of wet–dry encounters between water source and receiving areas in the South-to-North water transfer project

Yuping Han^{2,3}, Jinhang Li¹ & Mengdie Zhao¹✉

As global water scarcity becomes more acute, cross-basin water diversion projects, such as the South-to-North Water Diversion Project in China, need scientific risk assessment methods to ensure sustainable water allocation. This study proposes a coupling analysis framework based on Copula–Bayesian, which fills the gap in the systematic risk research of large-scale water transfer projects. By constructing a joint annual runoff distribution model for the Yangtze River and Yellow River, combined with mutation point detection, periodicity analysis (Morlet wavelet) and frequency statistics of boom–bust encounter, the characteristics of hydrological variability under climate change were systematically evaluated. The risk of water diversion under different scenarios is quantified by using Bayesian network for probabilistic reasoning. The results showed that: (1) During 1959–2023, three abrupt runoff points were detected in both the Yangtze River basin (YTB) and the Yellow River basin (YRB), with periodicism of 27/17/11 years and 12/27/29 years, respectively. The runoff of the lower Yellow River showed a significant downward trend (-1.2% /decade, $p < 0.05$). (2) The occurrence probability of extreme flood and ebb synchronous events is less than 5%, while the overall distribution of asynchronous and synchronous events is balanced (45–55%), indicating that the risk of water transfer is generally controllable; (3) The four-level water diversion risk scenario (optimal to most unfavorable) is identified through probability simulation, showing that the low-risk operation probability of the project under current conditions is 68%. This study innovatively combines statistical hydrological models with risk simulation to provide decision support for inter-basin collaborative water resources management in the context of climate change.

Keywords South-North water transfer, Water diversion risks, Copula models, Wet-dry encounters, Runoff trends

In the face of global challenges in water resource distribution and management, the South-to-North Water Transfer Project, as one of the world's largest and most complex inter-basin water transfer projects, carries the significant mission of alleviating water shortages in northern China and promoting the rational allocation and use of regional water resources. However, due to the impacts of climate change and human activities, the uncertainty in water resource encounters between the water source and receiving areas has increased, presenting unprecedented challenges to effective water management and scheduling^{1–3}. This study aims to explore a new perspective and methodology to reduce water transfer risks, ensure water transfer safety, and promote the sustainable utilization of water resources, providing scientific bases and technical support for water resource management decisions.

Recent research has primarily focused on the characteristics of runoff evolution and studies on floods and droughts, with less attention given to the encounters of wet and dry between two locations and their connection to the risks of the South-to-North Water Transfer Project⁴. Xia et al. (2025) taking the Middle route project of South-to-North Water Diversion Project as an example, the ice prediction model based on the actual

¹North China University of Water Resources and Electric Power, Zhengzhou 450046, China. ²Zhejiang University of Water Resources and Electric Power, Hangzhou 310018, China. ³Zhejiang Key Laboratory of River-Lake Water Network Health Restoration, Hangzhou, China. ✉email: zhaomengdie@ncwu.edu.cn

characteristics of the project is established by using numerical simulation method⁵. Chadwick et al. (2023) introduced a novel method capable of replicating temporal and spatial dependencies from raw data in a multi-site basin context. Previous research on the South-to-North Water Transfer mainly concentrated on extremely high-water transfer efficiencies and the impacts on surrounding ecological environments, with fewer studies on the risks associated with the project⁶. Liu et al. (2023) developed an optimized operational model that, in the context of hydrological changes, reduced energy use in the eastern route of the South-to-North Water Transfer Project by optimizing the scheduling of different pumps⁷. Wang et al. (2025) based on the risk transmission and response between different types of disasters in the process of disaster chain, a complex network structure of disaster chain is established⁸. Existing research on the risks associated with the South-to-North Water Transfer is relatively scarce and lacks systematic and accurate studies of water transfer risk scenarios.

To address this gap, this study proposes four different water transfer risk scenarios: most favorable, more favorable, less favorable, and least favorable water transfers^{9,10}. Based on this, an annual runoff Copula joint distribution model for the water source and receiving areas is constructed to calculate the frequency of encounters between wet and dry in the annual runoff, and Bayesian networks are utilized for a priori inference and simulation of the project's risks. This research has important theoretical and practical value, mainly reflected in the following aspects:

First, the study fills a major gap in risk management of interbasin water transfer projects. Traditional studies mostly focus on the hydrological characteristics of a single basin, but this study innovatively constructs the Copula-Bayesian coupling analysis framework, which for the first time realizes the quantitative assessment of the hydrological joint risk of the water source area and the water receiving area.

Second, the findings significantly improve the climate resilience of water systems. It is found that the occurrence probability of extreme synchronous events is less than 5%, while the overall low-risk operation probability of the project is 68%. This conclusion provides decision support for addressing hydrological non-stationarity under climate change and enables managers to make more forward-looking water resource allocation schemes.

In the aspect of methodology, this study has extensive popularization value. The developed Copula joint distribution model and Bayesian network risk simulation method can be applied to other inter-basin water transfer projects around the world, such as the Indian River Interconnection Project.

This research is innovative in both theoretical methods and practical applications. In terms of methodology, the research constructs the Copula-Bayesian coupling analysis framework for the first time, which breaks through the limitations of traditional single watershed risk assessment and realizes the quantitative analysis of cross-watershed hydrological joint risk. Through the innovative introduction of wavelet periodic analysis method, the periodic characteristics (27–29 long period) and co-evolution law of runoff change in the Yangtze River and Yellow River were systematically revealed. In particular, the important phenomenon that the runoff of the lower Yellow River decreased significantly at a rate of 1.2% per decade ($p < 0.05$) was quantified for the first time. In terms of technical application, a four-level risk scenario system (best to worst) based on probabilistic reasoning has been researched and developed, the first risk simulation platform for the South-to-North Water Transfer project considering climate non-stationarity has been established, and quantitative indicators such as “the probability threshold of abundant and weak encounter” (5% probability of extreme events) and 68% probability of low-risk operation have been proposed, providing a new decision-making basis for project management.

This research has realized the deep cross integration of multiple disciplines, creatively combined hydrology, statistics and decision science, and constructed the whole chain research paradigm of “monitoring - simulation - early-warning - decision”. The evaluation method developed is not only applicable to the South-to-North Water diversion project, but also can be extended to all kinds of inter-basin water transfer projects around the world, providing an innovative solution for water resources management under climate change. These innovative achievements have significantly improved the scientific level of risk management of large-scale water conservancy projects, and promoted the theoretical development and technical progress of water resources.

Materials and methods

Study area overview and data source

In this study, three representative hydrological stations in the upper, middle and lower reaches of the YTB and three representative hydrological stations in the upper, middle and lower reaches of the YRB were selected to analyze the runoff evolution characteristics and the dry-wet encounter scenario from 1959 to 2023. In the YTB, the selected hydrological stations are the Yichang station (111° 16' 59.998" E, 30° 42' 0" N) in the upper reaches, the Hankou station (114° 16' 59.998" E, 30° 45' 0" N) in the middle reaches, and the Datong station (117° 37' 0.0012" E, 30° 45' 36" N) in the lower reaches. The water volume of the Yangtze River is abundant and relatively stable, with small seasonal and interannual fluctuations. The main challenge lies in flood control in summer. Projects such as the Three Gorges have effectively regulated the runoff. The Yellow River, on the other hand, is short of water and highly unstable, with drastic seasonal and interannual variations. Historically, it has frequently dried up. The core issues are water shortage, sediment deposition and ecological fragility, and it relies on special measures such as water and sediment regulation to maintain its course. This paper collates the actual runoff data from three representative sites in the YTB and the YRB from 1960 to 2020 on China Meteorological Data Network (<http://data.cma.cn/>). An overview map of the study area is shown in Fig. 1.

Runoff cycle analysis

In this study, the Morlet wavelet analysis method was used to analyze the runoff cycles within the study area. As a time-frequency analysis method, Morlet wavelet analysis provides an effective means to extract local characteristics from non-stationary signals. By applying the Morlet wavelet to pre-processed data, a continuous wavelet transform is conducted. This process calculates wavelet coefficients at different scales and time shifts, thereby presenting the periodic changes of rainfall data on a time-frequency plane^{6,12}. This paper utilizes Morlet

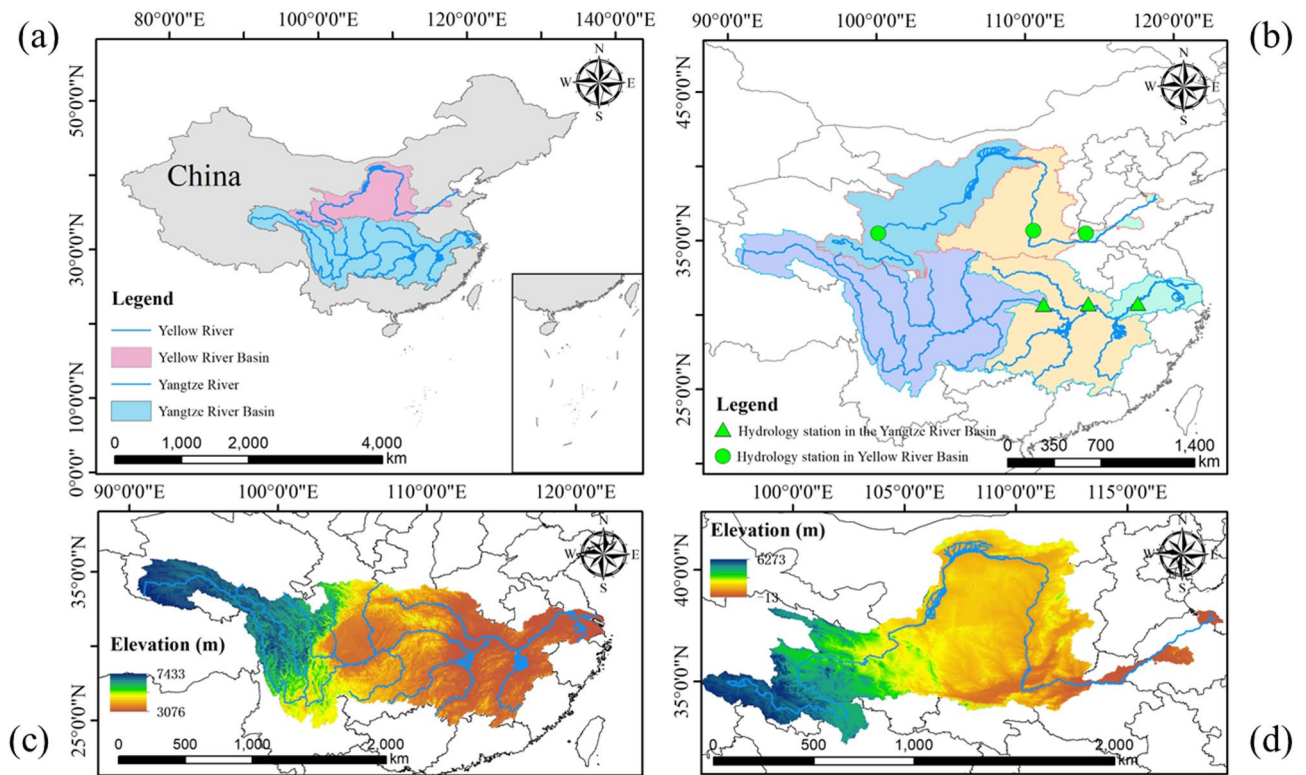


Fig. 1. Overview of the study area This map is created by the authors with ArcGIS software (version 10.7 ESRI, Redlands, CA, USA, <http://www.esri.com/software/arcgis/arcgis-for-desktop>).

wavelet analysis to explore the periodic variations in the runoff of the water source and receiving areas of the South-to-North Water Transfer Project. The standard form of the Morlet wavelet is as follows:

$$\psi(t) = \pi^{-\frac{1}{4}} e^{j\omega_0 t} e^{-\frac{t^2}{2}} \quad (1)$$

For A continuous signal $f(t)$, the continuous wavelet transform can be defined as:

$$W_f(a, b) = \int_{-\infty}^{\infty} f(t) \frac{1}{\sqrt{|a|}} \psi\left(\frac{t-b}{a}\right) dt \quad (2)$$

Where, a and b represent the scale and time displacement of the wavelet respectively, and the larger the scale of the wavelet, the lower the corresponding frequency.

The runoff trend analysis

In this study, M-K trend test was used to test the change of runoff trend in the study area. M-K trend test is less affected by abnormal data and is often used for trend test in hydrology¹². The tested sample sequence does not need to follow a specific distribution^{8,13}. Test the hydrologic series $H(h_i, i = 1, 2, \dots, n)$, define the statistic T as:

$$T = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sgn}(h_j - h_i) \quad (3)$$

$$\text{sgn}(h_j - h_i) = \begin{cases} 1, & h_j - h_i > 0 \\ 0, & h_j - h_i = 0 \\ -1, & h_j - h_i < 0 \end{cases} \quad (4)$$

In the formula, h_j and h_i are the corresponding values of variables in j and i respectively, and n is the sequence length. If $n \geq 10$, then the variance of the statistic S can be expressed as:

$$\text{Var}(T) = [n(n-1)(2n+5)]/18 \quad (5)$$

Construct the test statistic Z to judge the trend of the sequence, which is defined as:

$$Z = \begin{cases} \frac{(T-1)}{\sqrt{\text{Var}(T)}}, & T > 0 \\ 0 & T = 0 \\ \frac{(T+1)}{\sqrt{\text{Var}(T)}}, & T < 0 \end{cases} \quad (6)$$

In the formula, $Z > 0$ indicates that the sequence has an upward trend, and $Z < 0$ indicates that the sequence has a downward trend. In this study, it is assumed that the sample sequence has no trend change at the significant level of 0.05. When the Z value is between $Z_\alpha = 1.96$, it satisfies the original hypothesis, indicating that there is no significant trend change^{12,13}. Otherwise, the null hypothesis is rejected, indicating that the sequence has changed significantly.

Runoff abrupt change point diagnosis

In this study, the Pettitt test is employed to diagnose abrupt change points in the annual runoff within the study area. The Pettitt test is characterized by its clear physical interpretation and straightforward computational steps. It can accurately determine the number and location of abrupt change points and statistically verify their significance¹⁴. To ensure the accuracy of the diagnosis of abrupt change points, this study utilizes the Mann-Kendall (M-K) trend test as a comparative method in addition to the Pettitt test.

The mutation test statistic $U_{t,n}$ defined by Pettitt's method is:

$$U_{t,n} = \sum_{i=1}^t \sum_{j=t+1}^n \text{sgn}(x_j - x_i) \quad 1 \leq t \leq n \quad (7)$$

$$K_\tau = |U_{\tau,n}| = \max |U_{t,n}| \quad (8)$$

$$p = 2 \exp \left(\frac{-6K_\tau^2}{T^2 + T^3} \right) \quad (9)$$

If τ is satisfied and p is less than or equal to 0.05, it indicates that the detected mutation point τ is significant.

Runoff wet and dry encounter analysis

In this study, a quintile method is used to categorize the levels of wet and dry in the runoff of the YTB and YRB. Based on this categorization, the frequency of encounters between the wet and dry conditions in the water source and receiving areas is calculated using the Copula joint distribution function of runoff.

Standards for categorizing wet and dry levels

The study employs the quintile method to divide the annual runoff frequencies of the upper, middle, and lower reaches of the YTB and YRB into five levels: abundant period ($P < 12.5\%$), slightly abundant period ($12.5\% \leq P < 37.5\%$), normal period ($37.5\% \leq P < 62.5\%$), slightly dry period ($62.5\% \leq P < 87.5\%$), and dry period ($P > 87.5\%$)^{14,15}. The specific categorization results are shown in Table 1.

Optimal fitting of copula joint distribution functions

This study employs the Kolmogorov-Smirnov test (abbreviated as “K-S test”) and Anderson-Darling test (abbreviated as “A-D test”) to select the best fitting marginal distribution among five types: P-III distribution, log-normal distribution (LOGN), exponential distribution (EXP), generalized extreme value distribution (GEV), and Gumbel distribution for the runoff in the upper, middle, and lower reaches of the YTB and YRB¹⁵. Parameters for these marginal distributions are estimated using the method of moments, and the goodness-of-fit between the theoretical and empirical distributions is assessed. Evaluation metrics such as Root Mean Square Error, Mean Absolute Error, Akaike information criterion, and Bayesian Information Criterion are utilized to determine the optimal marginal distribution, thereby enhancing the accuracy and reliability of the joint distribution model for basin runoff.

Classification criteria	YTB			YRB		
	Upstream	Midstream	Downstream	Upstream	Midstream	Downstream
Wet ($P < 12.5\%$)	> 86,723,395	> 107,940,384	> 117,411,552	> 3,066,365	> 2,196,570	> 5,597,210
Slightly wet ($12.5\% \leq P < 37.5\%$)	(45177177, 86723395)	(75401280, 107940384)	(96618268, 117411552)	(2251627, 3066365)	(99440, 2196570)	(3833900, 5597210)
Normal ($37.5\% \leq P < 62.5\%$)	(41035161, 45177177)	(67555296, 75401280)	(84222720, 96618268)	(1862447, 2251627)	(49520, 99440)	(2921500, 3833900)
Slightly dry ($62.5\% \leq P < 87.5\%$)	(21245932, 41035161)	(48102681, 67555296)	(60197472, 84222720)	(1543950, 1862447)	(26866, 49520)	(2295485, 2921500)
Dry ($P > 87.5\%$)	< 21,245,932	< 48,102,681	< 60,197,472	< 1,543,950	< 26,866	< 2,295,485

Table 1. Standard table for grading wet and decline /Volume of runoff (m³/s).

The study introduces five types of Copula functions: Gaussian Copula, Frank Copula, Clayton Copula, Gumbel Copula, and t Copula, aiming to establish a joint distribution model for the annual runoff in the upper, middle, and lower reaches of the YTB and YRB. The parameters of the Copula models are estimated using non-parametric methods. Additionally, to verify the suitability and accuracy of the selected Copula models, the K-S test, OLS, and RMSE are used as statistical criteria for goodness-of-fit assessments, thus identifying the optimal Copula function¹⁶. The general mathematical definition of the Copula function is as follows:

$$F(x_1, x_2, \dots, x_n) = C(F_1(x_1), F_2(x_2), \dots, F_n(x_n)) \quad (10)$$

Water transfer risk analysis

Bayesian networks are notable for their flexibility and scalability in handling data uncertainties and integrating multi-source prior knowledge. By updating observed data, Bayesian networks can be used for prediction, inference, decision support, and learning the probability distribution of unknown parameters¹⁷. In this study, water transfers are categorized into four scenarios: most favorable, more favorable, less favorable, and least favorable. Based on this, Bayesian networks are employed in combination with the encounters of wet and dry between the water source and receiving areas to perform a priori reasoning and simulation of water transfer scenarios.

Results

Period analysis results

Based on the Morlet wavelet analysis, this study analyzed the periodic changes in runoff sequences from 1959 to 2023 in the upper, middle, and lower reaches of the Yangtze and Yellow Rivers. The results are displayed in the Figs. 2 and 3.

YTB runoff period analysis results

As shown in Fig. 2, over the 65-year study period, the upper, middle, and lower reaches of the Yangtze River exhibited periodic changes with cycles of 27 years, 17 years, and 11 years, respectively. Specifically, the upper Yangtze River showed eight distinct alternating periods of wet and dry, the middle Yangtze River had five such periods, and the lower Yangtze River experienced three clear alternating periods of wet and dry.

YRB runoff period analysis results

As indicated in Fig. 3, over the 65-year study period, the upper, middle, and lower reaches of the Yellow River exhibited periodic changes with cycles of 12 years, 27 years, and 29 years, respectively. Specifically, the upper Yellow River demonstrated 17 distinct alternating periods of wet and dry, the middle Yellow River experienced 3 such periods, and the lower Yellow River showed 12 clear alternating periods of wet and dry.

Trend analysis results

YTB runoff trend analysis

This study conducted the Mann-Kendall (M-K) test at a significance level of $\alpha = 0.05$ to analyze the trend of runoff in the upper, middle, and lower reaches of the Yangtze River from 1959 to 2023. According to the M-K test results, the Z-value for the annual runoff in the upper Yangtze River is negative, while the Z-values for the middle and lower reaches are positive. However, the absolute values of the Z-values for all three regions are less than $Z_{\alpha/2} = 1.96$. Therefore, there is no significant trend in the runoff in the upper, middle, and lower reaches of the Yangtze River. The results of the M-K test are presented in Table 2.

YRB runoff trend analysis

Under the same conditions, the trend analysis of the runoff in the upper, middle, and lower reaches of the Yellow River from 1959 to 2023 was conducted. The test results show that the Z-value for the annual runoff in the upper Yellow River is positive, while the Z-values for both the middle and lower reaches are negative. Notably, the absolute value of the Z-value in the lower reaches is 2.7231, which is greater than $Z_{\alpha/2} = 1.96$. Therefore, there is a clear decreasing trend in the runoff in the lower reaches of the Yellow River, whereas the trends in the upper and middle reaches are not significant. The results of the M-K test are presented in Table 3.

Abrupt change point diagnosis results

YTB runoff abrupt change point diagnosis

This study used the Pettitt test to analyze the characteristics of abrupt change points in the runoff of the upper, middle, and lower reaches of the Yangtze River. The test results indicate that at a 0.05 significance level, there is one abrupt change point each in the upper, middle, and lower reaches of the Yangtze River occurring in 2011, 2006, and 2017, respectively. In the upper Yangtze River, the average annual runoff from 1959 to 2011 was approximately 50,581,418.01 million cubic meters, which increased to 74,037,355.2 million cubic meters from 2011 to 2023. In the middle reaches, the average annual runoff from 1959 to 2006 was 86,833,962 million cubic meters, increasing to 96,648,417.32 million cubic meters from 2006 to 2023. In the lower reaches, the average annual runoff from 1959 to 2017 was 97,299,130.11 million cubic meters, which increased to 123,929,208 million cubic meters from 2017 to 2023. The results of the Pettitt test are shown in Fig. 4, and the Mann-Kendall test results are included in the Supplementary Information Figure S1.

YRB runoff abrupt change point diagnosis

The test results reveal that at a 0.05 significance level, there is one abrupt change point each in the upper, middle, and lower reaches of the Yellow River occurring in 2018, 2019, and 1986, respectively. In the upper Yellow River,

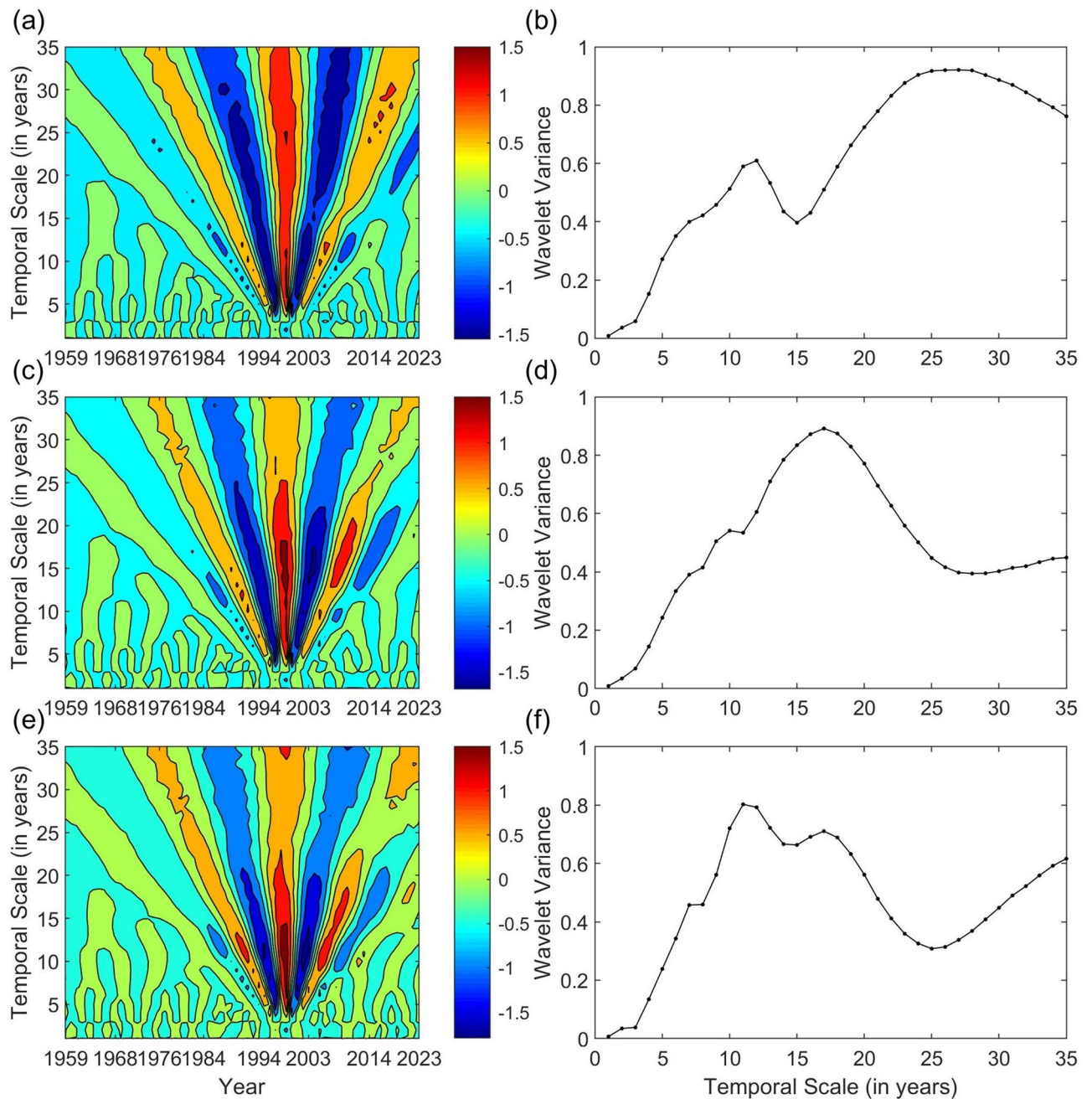


Fig. 2. Annual runoff cycle analysis in the YRB.

the average annual runoff from 1959 to 2018 was approximately 2,073,934.893 million cubic meters, which increased to 3,436,256 million cubic meters from 2018 to 2023. In the middle reaches, the average annual runoff from 1959 to 2019 was 246,367.0612 million cubic meters, increasing to 3,786,656 million cubic meters from 2019 to 2023. In the lower reaches, the average annual runoff from 1959 to 1986 was 4,419,026.786 million cubic meters, which decreased to 3,187,383.239 million cubic meters from 1986 to 2023. The results of the Pettitt test are shown in Fig. 5, and the results of the Mann-Kendall test are included in the Supplementary Information Figure S2.

Runoff wet and dry encounter analysis between water source and receiving areas

This study utilized the fitting of five two-dimensional Copula functions, including the Clayton Copula, to construct a joint distribution model for the runoff between the water source and receiving areas. By integrating scientifically determined wet and dry grading standards, the frequency of encounters between wet and dry conditions in the water source and receiving areas was calculated.

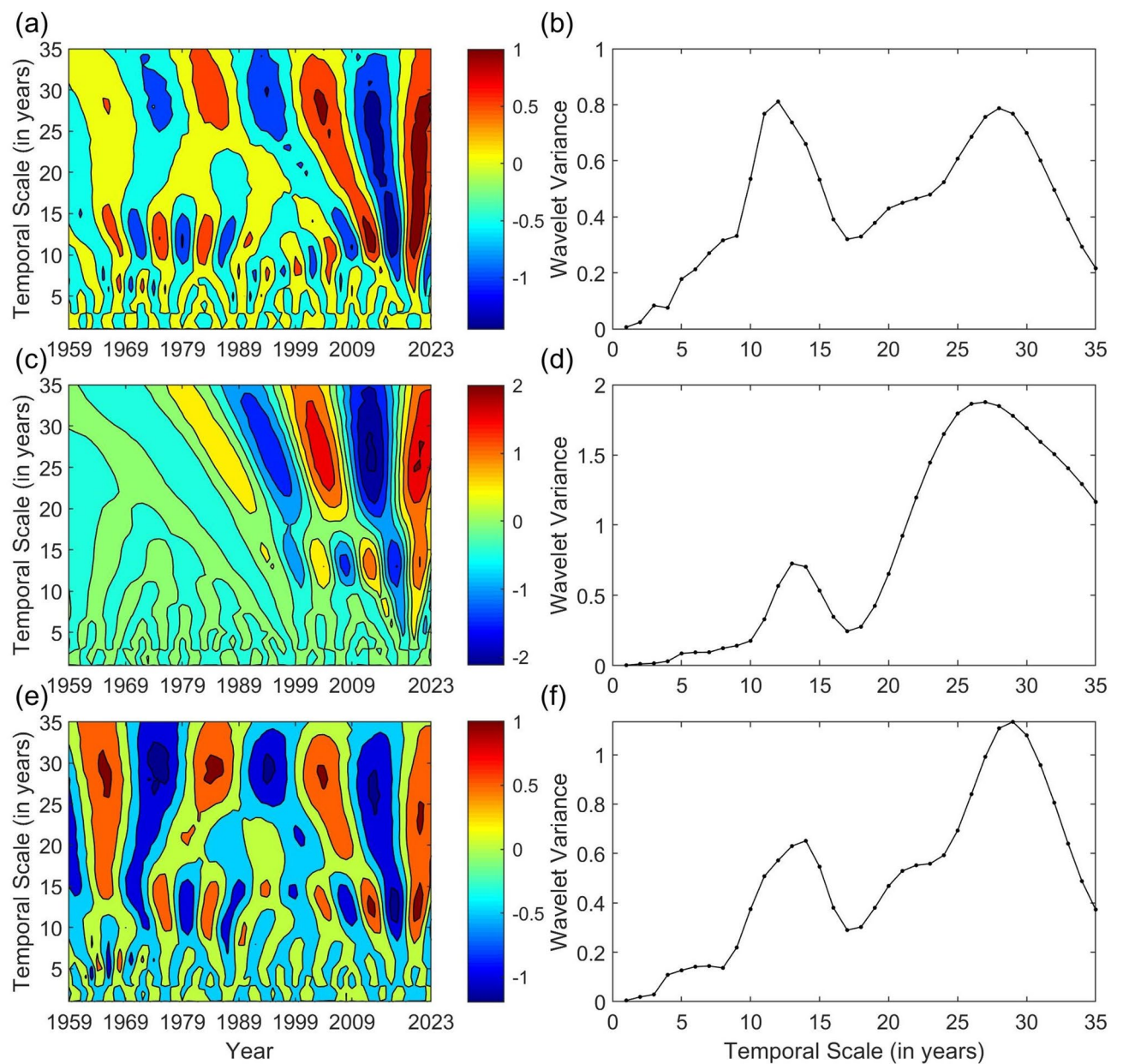


Fig. 3. Annual runoff cycle analysis in the YTB.

YTB	Z	Trend	Significant or not
Upstream	-0.11889	↓	Not significant
Midstream	1.7154	↑	
Downstream	1.6588	↑	

Table 2. M-K trend test results in the YTB.

YRB	Z	Trend	Significant or not
Upstream	0.80958	↑	Not significant
Midstream	-0.48122	↓	
Downstream	-2.7231	↓	Significant

Table 3. M-K trend test results in the YRB.

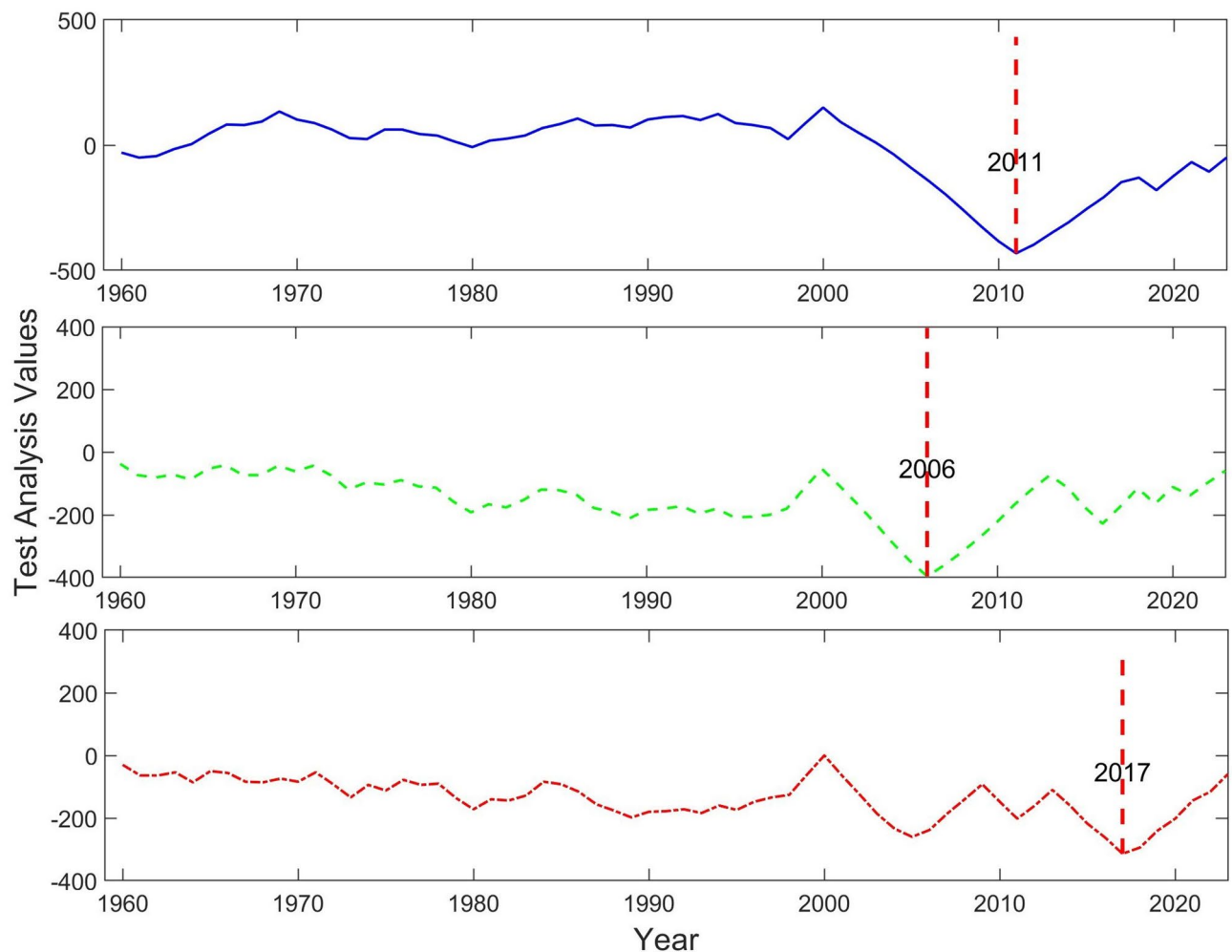


Fig. 4. Test results of abrupt annual runoff points in the YTB.

Optimal marginal distribution fitting results

Based on the principles of minimizing RMSE, MAE, AIC, and BIC, the optimal marginal distribution functions were determined using the Kolmogorov-Smirnov (K-S) test and Anderson-Darling (A-D) test. The numerical results of the tests for the optimal marginal distribution functions and the curve fittings between empirical and theoretical frequencies for the upper, middle, and lower reaches of the Yangtze and Yellow Rivers are included in the Supplementary Information Table S1 and S2. The results of the tests for the five distribution functions indicate that the Generalized Extreme Value (GEV) distribution is the optimal marginal distribution for the upper, middle, and lower reaches of both the Yangtze and Yellow Rivers. The GEV parameter values for the upper, middle, and lower reaches of the Yangtze River are respectively 0.11999, 0.70897, and 0.06797. For the Yellow River, the GEV parameter values are 0.46705, $k=0.47054$, and $k=0.3179$.

Using the optimal marginal distribution function results, the study constructed Copula joint distribution models for the runoff in the upper, middle, and lower reaches of both the water source and receiving areas and conducted a goodness-of-fit test on the selected Copula joint distribution models. Based on the test results, the optimal Copula function model was chosen.

In this study, the generalized extreme value distribution (GEV) analysis reveals the distinct extreme hydrological characteristics of the two major rivers in China: There is significant spatial heterogeneity in the YTB, in which the abnormally high k value (0.70897) indicates that this reach has a prominent extreme flood risk, which is mainly due to its special hydrometeorological conditions as a confluence area of several tributaries and limited flood discharge capacity. However, the YRB showed a relatively uniform but consistently high k value (0.3179–0.47054), reflecting the typical characteristics of significant monsoon impact, strong human intervention and “small water disaster”. These findings have important management implications: the Yangtze River needs to focus on strengthening the flood control system in the middle reaches, and the Yellow River needs to coordinate drought and flood risk management in the whole basin. In terms of research methods, the strategies of multi-index optimization and composite testing are used to effectively capture the statistical characteristics of extreme events. In particular, K-S test is used to ensure the goodness of fit of the overall distribution, while the tail sensitivity of A-D test is used to accurately depict the extreme value behavior. This combination of methods provides A reliable paradigm for extreme value analysis. These statistical parameters

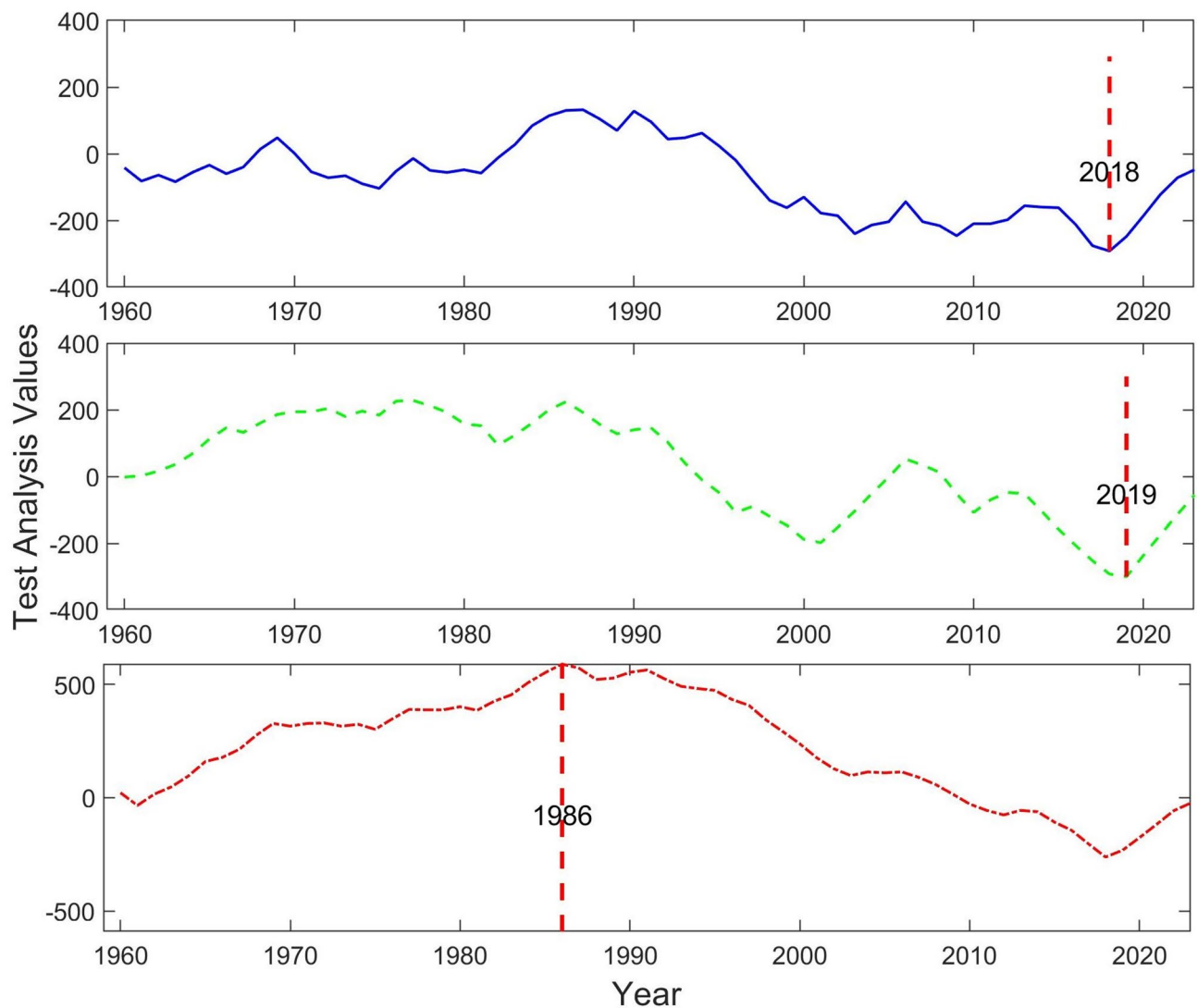


Fig. 5. Test results of abrupt annual runoff points in the YRB.

YTB - YRB	Upstream-upstream	Upstream-midstream	Midstream-downstream	Downstream-downstream
Kendall τ	0.1836	0.6746	0.0259	0.1942
Gaussian	0.2844	0.1058	0.0407	0.3003
Frank	1.1048	1.0353	1.0132	1.1118
Clayton	0.4499	0.1447	0.0533	0.4821
Gumbel	1.2249	1.0723	1.0266	1.2410
T	0.2722	0.1948	0.0129	0.2993

Table 4. Parameter values of copula function.

not only quantified the extreme hydrological behavior of the basin, but also revealed the natural and human compound driving mechanism behind it, providing a scientific basis for differentiated basin management. In the future, dynamic studies can be further carried out combining the impact of climate change and human activities.

Optimal copula function fitting results

This study calculated the Copula joint distribution model parameters using the Kendall τ correlation coefficient method. Based on the principles of minimizing K-S, OLS, and RMSE, the optimal Copula joint distribution function was selected from among the Gaussian, Frank, Clayton, Gumbel, and t two-dimensional Copula functions. The parameter values of the chosen Copula joint distribution function are shown in Table 4. The results table for the optimal Copula function fitting is included in the Supplementary Information Table S3.

Based on the test results, the joint distribution function for runoff between the upper reaches of the Yangtze River and the upper reaches of the Yellow River is the Gaussian Copula, with a parameter value of 0.2844. For the runoff between the upper reaches of the Yangtze River and the middle reaches of the Yellow River, the middle reaches of the Yangtze River and the lower reaches of the Yellow River, and the lower reaches of both the Yangtze River and the Yellow River, the joint distribution functions are all Gumbel Copula, with parameter values of 1.0723, 1.0266, and 1.241 respectively. The joint probability density function graphs for these analyses are presented in Fig. 6.

Runoff wet and dry encounter results between water source and receiving areas

In this research, based on the optimally selected Copula functions, a joint distribution model for runoff between the water source and receiving areas of the South-to-North Water Transfer Project was established. This model provided the joint distribution frequency of runoff between these areas. By integrating scientifically based wet and dry grading standards, the frequency of encounters between wet and dry conditions in the water source and receiving areas was subsequently calculated. The results of these wet and dry encounters are displayed in Fig. 7.

According to Fig. 7a–d, the statistical analysis of the frequency of boom-bust encounters in different reaches of the Yangtze River and the Yellow River shows that there are obvious differences in the combination characteristics of each reach. Figure 7a shows that the synchronous probability of extreme abundance and drought in the upper reaches of the Yangtze River and the Yellow River is extremely low (3.125% with high water and 1.562% with low water), and the combination of partial abundance/partial drought and normal water years is the main (10.937% and 7.812%). Figure 7b reveals that the synchronization rate between the upper reaches of the Yangtze River and

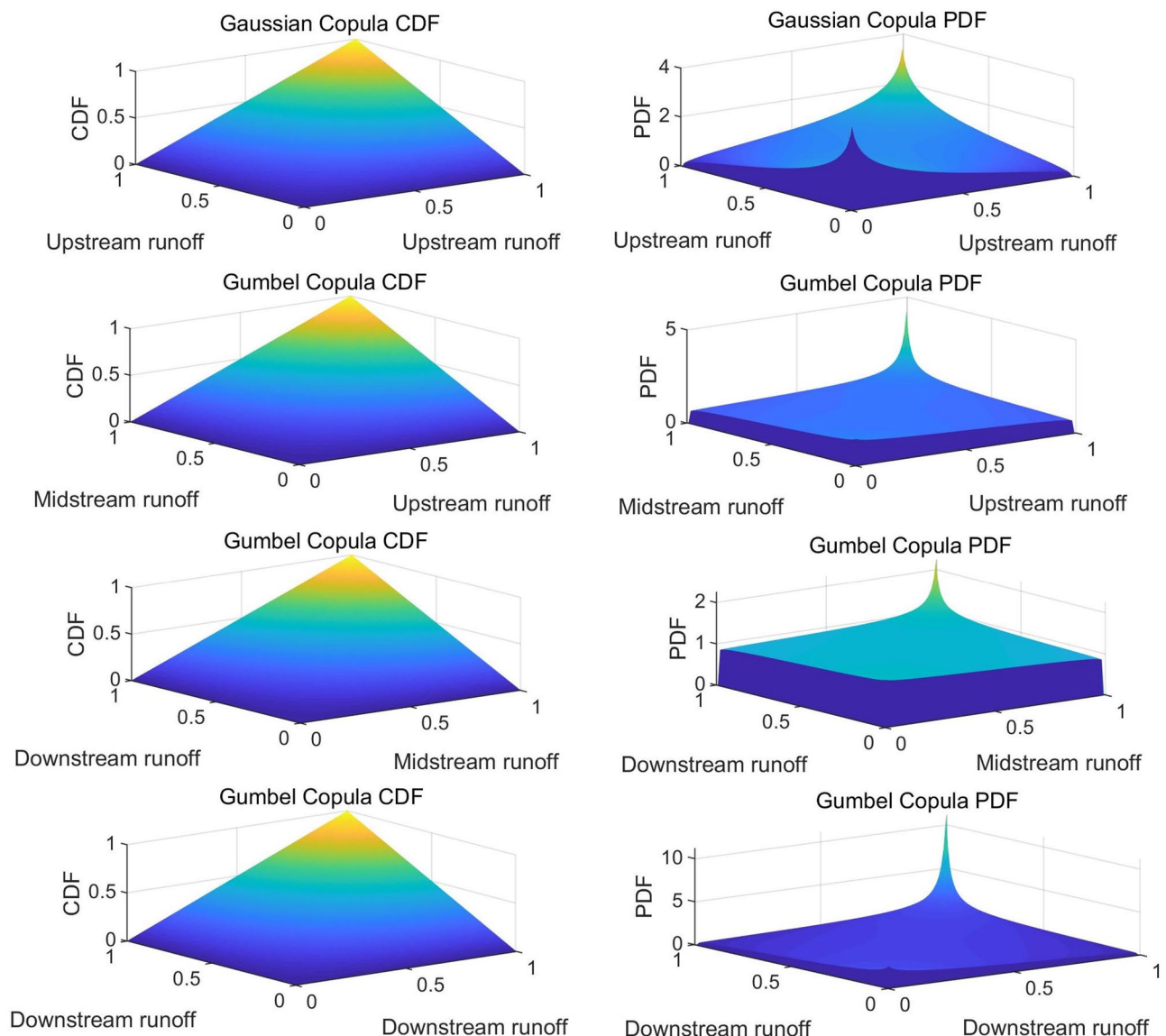


Fig. 6. Joint probability diagram of annual runoff distribution and joint probability density function diagram of water source area and water receiving area.

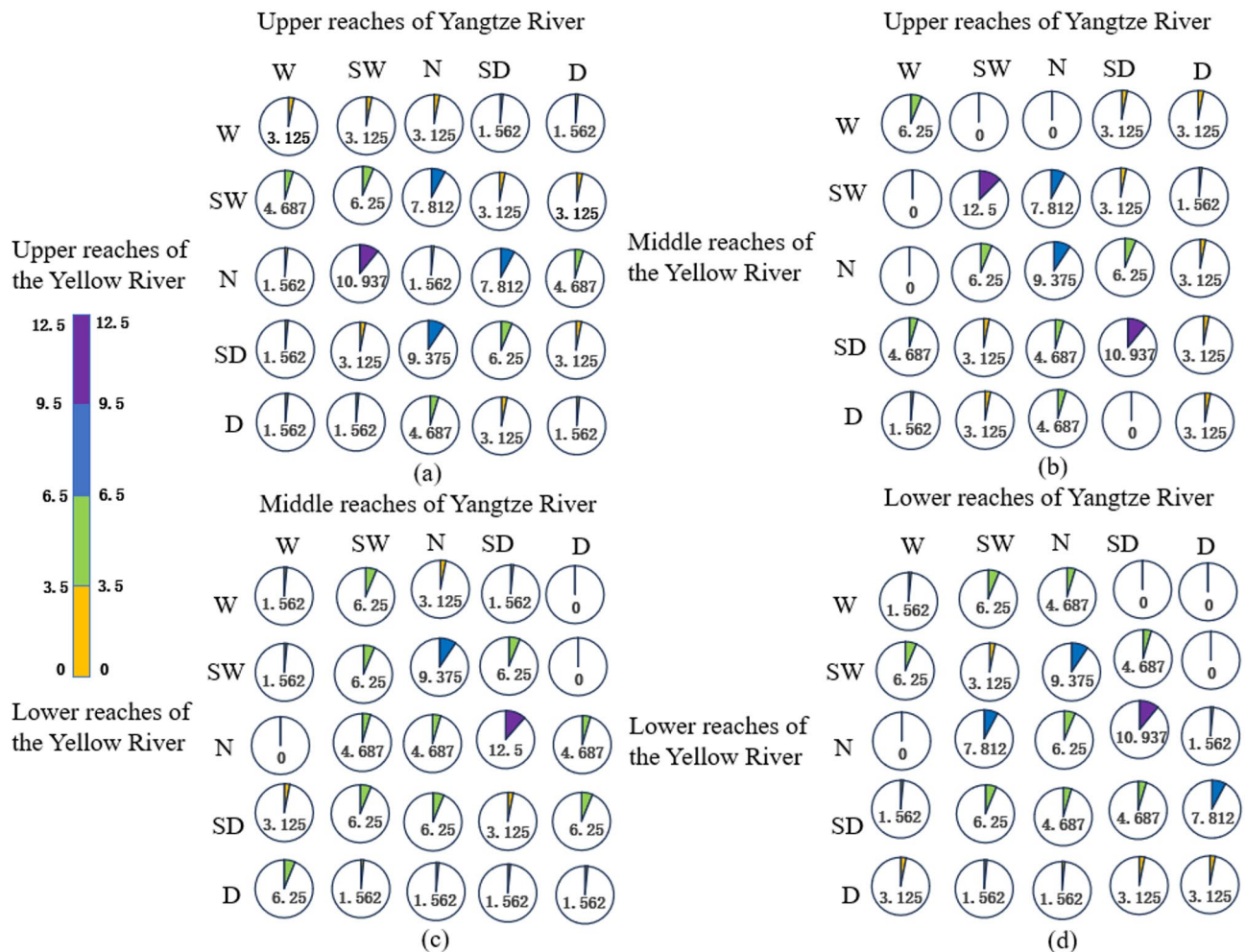


Fig. 7. Probability diagram of wet and decline in water source area and water receiving area. In the figure, the arrows 'W', 'SW', 'N', 'SD', 'D' represent five directions corresponding to the states of wetness, slightly wetness, normal, slightly dryness, and dryness, respectively, in the context of rainfall.

the middle reaches of the Yellow River is the highest (12.50%), and the extreme combination only accounts for 1.562%. Figure 7c shows that the combination of withered and flat water in the middle reaches of the Yangtze River and the lower reaches of the Yellow River is the most prominent (12.50%), and the combination of withered and abundant is 6.250%. Figure 7d further shows that the region is dominated by dry + flat water (10.937%) and abundant + flat water (7.812%), and the extreme combination is as low as 1.562%. The comprehensive analysis shows that the near-normal combination is the main hydrological situation in the two basins, and the probability of extreme events is generally lower than 6.25%, in which the upstream extreme events are the least, and the middle and downstream dry combination is more significant, which has important guiding significance for the collaborative management of water resources in the basin.

Water transfer risk analysis based on runoff wet and dry encounters between water source and receiving areas

This study categorized slightly abundant and slightly dry years as abundant and dry years, respectively, dividing the South-to-North Water Transfer Project into four scenarios: most favorable, more favorable, less favorable, and least favorable water transfers (Fig. 8). Using the Copula function and Bayesian network theories, a risk analysis model for the runoff wet and dry encounters between the water source and receiving areas of the project was established. This model studied the probability of encounter risks under the four water transfer scenarios and conducted simulation analyses of water transfer risks under different scenarios.

Water transfer risk a priori inference

According to the Bayesian network (Fig. 9), when transferring water from the upper reaches of the Yangtze River to the upper reaches of the Yellow River, the probabilities of the four water transfer scenarios are relatively close. The probability for a more favorable water transfer is the highest at 29%, and the combined probabilities for favorable and more favorable water transfers equal those for less favorable and least favorable transfers, each totaling 50%. Therefore, the water transfer risk is relatively low.

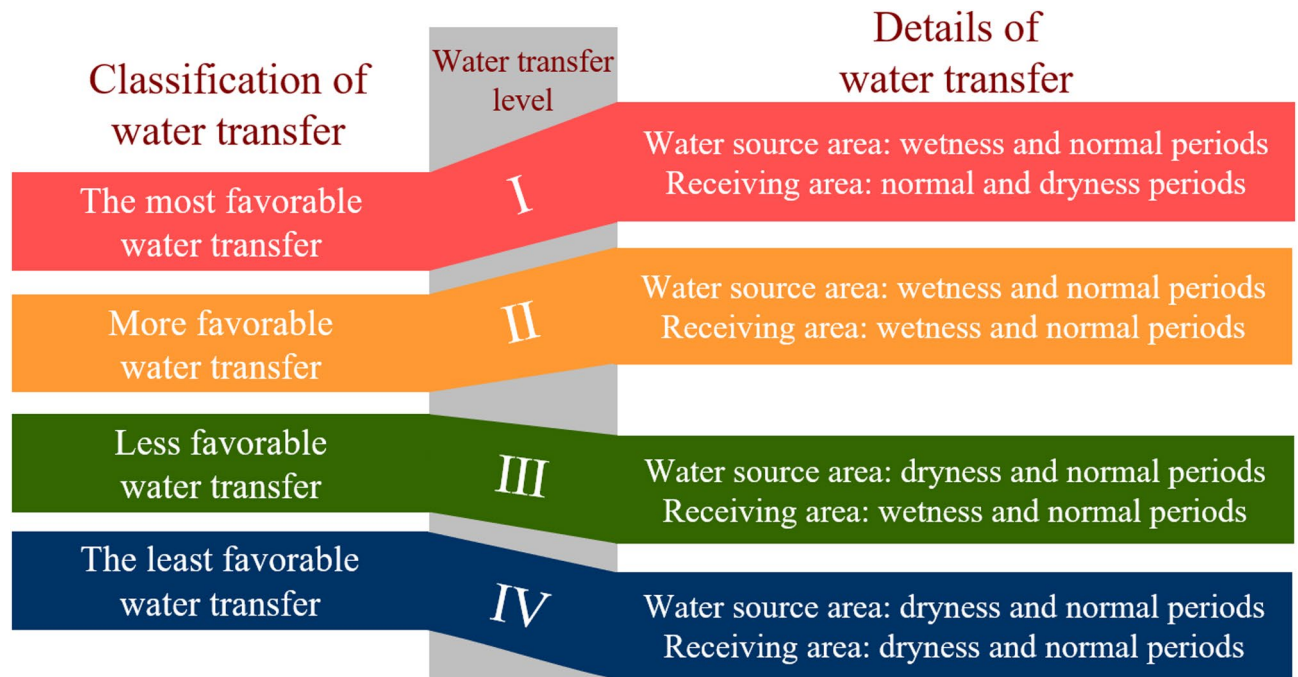


Fig. 8. Risk classification diagram of water diversion project.

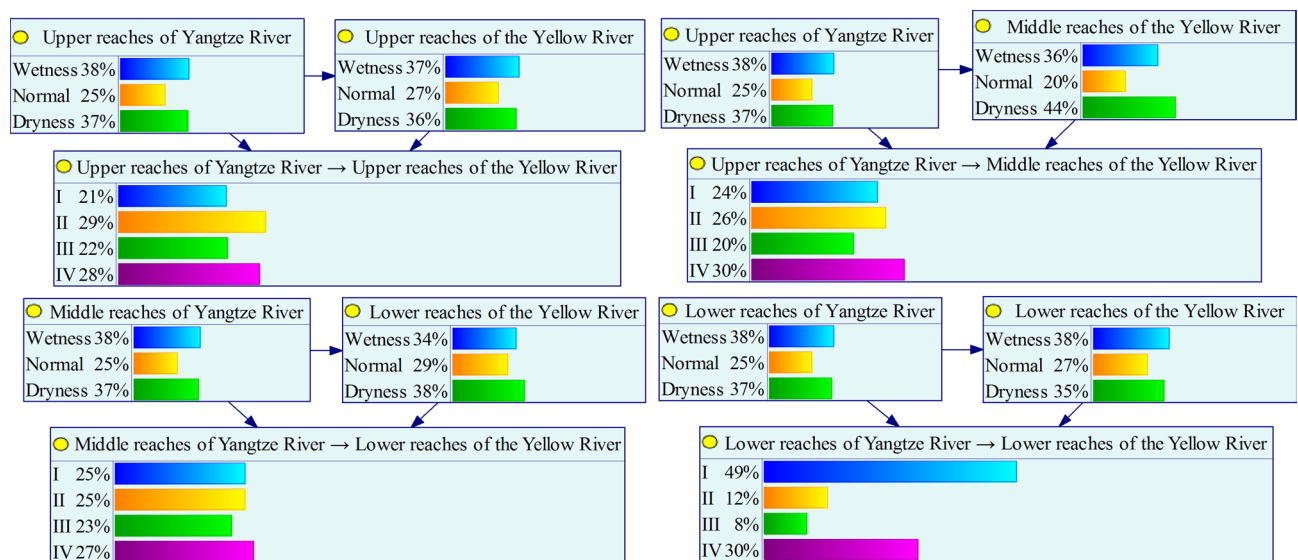


Fig. 9. Bayesian grid prior inference diagram of water transfer risk.

For transfers from the middle reaches of the Yangtze River to the middle reaches and lower reaches of the Yellow River, although the probability for less favorable water transfers is highest at 30% and 27% respectively, the combined probabilities for favorable and more favorable water transfers are equal to those for less favorable and least favorable transfers, each also totaling 50%. Thus, the water transfer risks are relatively low in these scenarios as well.

When transferring water from the lower reaches of the Yangtze River to the lower reaches of the Yellow River, the probability for favorable water transfers is the highest at 49%, and the combined probabilities for favorable and more favorable water transfers total 61%, significantly higher than the combined probabilities for less favorable and least favorable transfers. Therefore, the water transfer risk is minimal when transferring from the lower reaches of the Yangtze to the lower reaches of the Yellow River.

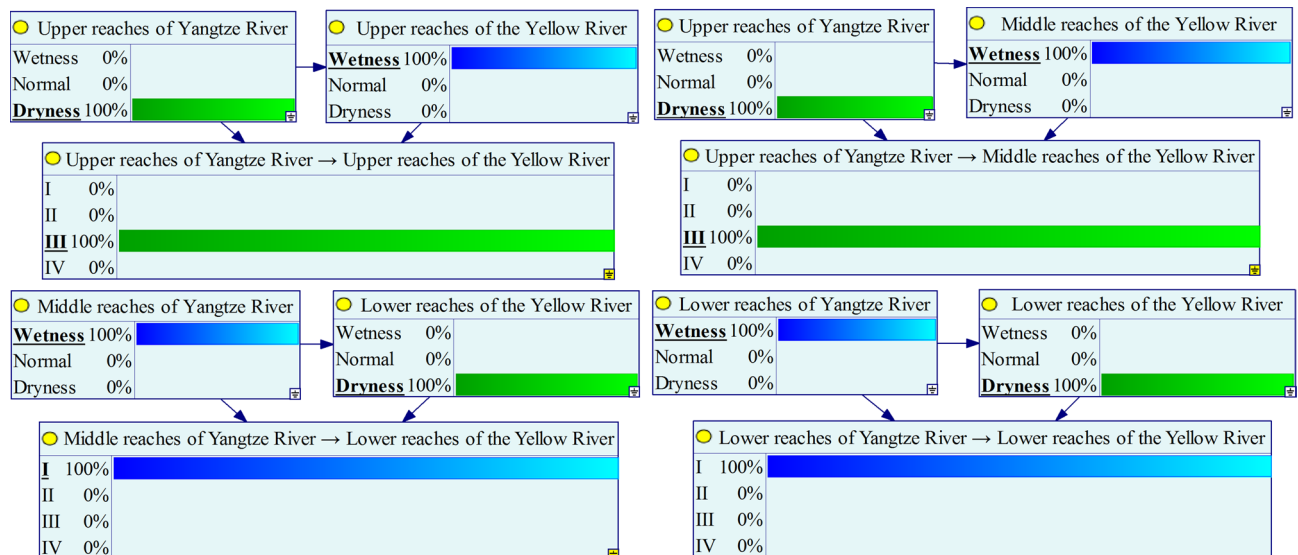


Fig. 10. Results of Bayesian grid simulation of water transfer risk.

Water transfer risk simulation

Incorporating the results of the periodicity and trend analysis, it is projected that the upper reaches of the Yangtze River and the lower reaches of the Yellow River will enter a dry period, while the middle and lower reaches of the Yangtze River and the upper and middle reaches of the Yellow River will experience abundant water periods. Accordingly, the study simulates the runoff from the upper, middle, and lower reaches of the Yangtze River as dry, abundant, and abundant periods, respectively, and for the Yellow River, the upper, middle, and lower reaches as abundant, abundant, and dry periods, respectively.

According to the Bayesian network (Fig. 10), when the upper reaches of the Yangtze River are in a dry period and the upper and middle reaches of the Yellow River are in an abundant period, the water transfer scenarios are predominantly less favorable. Conversely, when the middle and lower reaches of the Yangtze River are in an abundant period and the lower reaches of the Yellow River are in a dry period, the water transfer scenarios are favorable, indicating good conditions for water transfer.

This simulation analysis helps to highlight how the synchronization of water wet or scarcity between different sections of these rivers can significantly influence the feasibility and risks associated with inter-basin water transfers, guiding optimal operational and strategic planning.

Discussion

Analysis of runoff evolution characteristics

The analysis of runoff evolution in the YTB and YRB reveals that while the upper reaches of the Yangtze exhibit a declining runoff trend, the middle and lower reaches show an increasing trend. Conversely, the Yellow River's upper reaches demonstrate an upward trend, with the middle and lower reaches experiencing a significant decline. Huang et al. (2024) and Ni et al. (2022) indicated that annual extreme flow in the middle and lower reaches of the Yangtze River is increasing, whereas it is decreasing in the upper reaches, and climatic changes have led to increased runoff in the upper Yellow River but decreased runoff in the middle and lower reaches^{18,19}.

The analysis of these trends further explores their impact on the risks associated with water transfer projects. The declining runoff trend in the upper Yangtze, combined with the increasing trend in the upper Yellow River, presents potential risks to the safe operation of water transfer projects, particularly under extreme climatic conditions. The increase in the upper Yellow River and the decrease in the upper Yangtze may necessitate adjustments in water transfer strategies to adapt to new hydrological scenarios. Additionally, the variations in runoff in the middle and lower Yangtze, as well as the upper Yellow River, imply that water transfer projects need to consider inter-regional water resource allocation. The increasing runoff trends in the middle and lower Yangtze could help alleviate water shortages in the lower Yellow River, but the significant decline in the middle and lower Yellow River's runoff could increase the impact of water transfer projects on water resource security in the YRB. To address these challenges, it is recommended that water transfer planning and management adopt more flexible and dynamic strategies, including adjusting water transfer volumes based on real-time hydrological conditions, enhancing the adaptability and resilience of water transfer systems, and developing new water supply and storage strategies to cope with potential future changes in water resources. Strengthening inter-basin water resource management and cooperation is also essential to ensure that water transfer projects can effectively improve water resource utilization efficiency and alleviate pressures on water resource systems under varying climate change scenarios.

Runoff evolution in the YTB and the YRB presents significant spatial differentiation, and its driving mechanism is complex and multiple. The runoff pattern of "upper decreasing and lower increasing" in the YTB is mainly due to the comprehensive effect of glacier retreat in the upper reaches, precipitation pattern change and reservoir

regulation, while the increase of runoff in the middle and lower reaches is closely related to the strengthening of monsoon and the frequent occurrence of extreme precipitation events. The trend of “upward increase and downward decrease” in the YRB reflects the increase of runoff in the upper reaches caused by warming and humidification of the Tibetan Plateau, and the sharp decrease of runoff caused by strong intervention of human activities in the middle and lower reaches. This pattern of runoff evolution poses a severe challenge to inter-basin water transfer projects, especially major projects such as South-to-North water diversion, which face risks such as difficulty in matching water quantity between water source area and water receiving area, and increasing impact of extreme climatic events. To address these challenges, it is necessary to build intelligent dynamic water transfer mechanisms, integrate satellite remote sensing and artificial intelligence technologies to achieve accurate scheduling, and enhance system resilience through resilient engineering design and policy tool innovation. Future research should focus on climate change scenario simulation, quantification of human activities impact and coupling analysis of society and hydrology, so as to promote the transformation of water resources management from single project regulation to multi-objective collaborative governance, and finally achieve the goal of sustainable development of the basin. This systematic understanding not only has important guiding value for current water resources management, but also provides a scientific basis for coping with the uncertainty of water resources under future climate change.

Analysis of water transfer risk results

Current research has primarily focused on runoff prediction and simulation and studies on floods and droughts, with less attention to encounters between different regions' runoff. Research on the South-to-North Water Transfer has mainly concentrated on water quality and ecological impacts, with a lack of systematic studies on water transfer risks. Existing studies, such as Zha et al. (2023), have categorized water transfer risks into favorable and unfavorable scenarios during the water diversion process at the Danjiangkou Reservoir, particularly for the South-to-North Transfer Project²⁰.

Based on the runoff encounter results between the water source and receiving areas, Bayesian networks were used to calculate the riskiness of the water transfer project. The results indicate that extreme runoff encounters between the water source and receiving areas are infrequent, with more common occurrences of slightly abundant or slightly dry years encountering normal years, leading to a generally balanced distribution of wet and dry encounters and thus a lower overall risk for the water transfer project.

To further analyze the riskiness of the water transfer project, this study employed both quantitative and qualitative assessment methods, using Bayesian networks combined with runoff trend analysis to calculate water transfer risks. The analysis shows that transfers from the middle and lower Yangtze to the lower Yellow River present lower risks, predominantly in a favorable state, while transfers from the upper Yangtze to the upper and middle Yellow River are at higher risk, generally in a less favorable state.

This research further explores risk management and optimization strategies for water transfer projects under different scenarios. Considering the multidimensional nature of water transfer risks, the study integrates a comprehensive assessment of water resource sustainability and socio-economic factors to construct a more holistic water transfer risk management framework. By analyzing the distribution and utilization efficiency of water resources in the YTB and YRB, as well as potential future trends, the study proposes a series of optimized water transfer strategies to maximize benefits while minimizing risks. Specific measures include optimizing current water transfer plans and technologies, enhancing coordination between the two major river basins, introducing new water supply sources, and improving water use efficiency to reduce dependency on water transfers and mitigate associated risks. For favorable water transfer scenarios from the middle and lower Yangtze to the lower Yellow River, the study suggests continuing to strengthen and optimize water transfer strategies while considering the needs for ecological protection and sustainable development. This includes regularly assessing the impact of water transfers on downstream ecosystems, ensuring the equitable distribution of water resources, and enhancing water use efficiency and management in the receiving areas.

Current research mainly focuses on runoff prediction and simulation and flood and drought disaster analysis, and systematic research on cross-regional runoff encounters is relatively insufficient. As for the South-to-North Water diversion project, most of the existing studies focus on water quality and ecological impact assessment, but the comprehensive analysis of the risk of water diversion is still weak. This study innovatively combined Bayesian network and runoff trend analysis to explore the risk characteristics of different water transfer routes, and found that the risk status of water transfer from the middle and lower reaches of the Yangtze River to the lower reaches of the Yellow River is more favorable, while the risk level of water transfer from the upper reaches of the Yangtze River to the upper and middle reaches of the Yellow River is relatively higher. Based on the research results, this paper proposes a multi-dimensional risk management and control framework, covering multiple levels such as technological innovation, management optimization and strategic planning. At the technical level, the intelligent dynamic scheduling system is suggested. At the management level, the coordination mechanism combining water rights trading and ecological compensation should be implemented; At the strategic level, build an integrated monitoring network and integrate climate scenario analysis to optimize long-term water transfer plans. In particular, it should be pointed out that although the probability of extreme runoff encounter event is low, its potential impact cannot be ignored. Therefore, the elastic scheduling strategy proposed focuses on improving the system coping ability. This study not only provides a new analytical framework for risk management of inter-basin water transfer projects, but also has important reference value for similar projects around the world, and lays a foundation for future research on water resources adaptive management in the context of climate change.

The spatial heterogeneity of runoff evolution observed in the YTB and YRB reflects a global pattern under climate change and human interventions, with clear parallels to other major river systems worldwide. The Bayesian network and runoff trend analysis methodology developed in this study could be particularly valuable

for risk assessment in developing regions with proposed mega-projects like Africa's Transaqua, while China's experiences could significantly contribute to achieving UN SDG 6.5 on transboundary water cooperation. This global perspective not only validates the study's findings but also positions them within an international framework for climate-adaptive water management, suggesting that the proposed dynamic allocation models and resilient engineering solutions have broad applicability across diverse hydrological and institutional contexts worldwide.

Conclusions

This study constructed a joint distribution model for runoff between the water source and receiving areas of the South-to-North Water Transfer Project by optimally fitting five Copula functions, including the Frank Copula. The study arrived at the following conclusions:

1. In the YTB, the runoff cycles are 27 years in the upper reaches, 17 years in the middle reaches, and 11 years in the lower reaches, showing no significant overall trend. The abrupt change points occurred in 2011 (upper reaches), 2006 (middle reaches), and 2017 (lower reaches). In contrast, the YRB displays runoff cycles of 12 years (upper reaches), 27 years (middle reaches), and 29 years (lower reaches), with a significant decreasing trend observed in the lower reaches. The abrupt change points were detected in 2018 (upper reaches), 2019 (middle reaches), and 1986 (lower reaches).
2. Encounter Analysis: Generally, extreme runoff encounters between the water source and receiving areas were infrequent. The upper Yangtze and upper Yellow River experienced low-frequency encounters of extreme abundant and dry years, while deviations from average conditions were more common. The upper Yangtze and middle Yellow River generally maintained a moderate or near-average hydrological state with rare occurrences of simultaneous extreme abundant or dry years. The middle Yangtze and lower Yellow River frequently encountered slightly dry years with normal years, and encounters between slightly abundant and slightly dry years showed a balanced distribution.
3. Water Transfer Risk Scenarios: The study proposed four new water transfer risk scenarios: most favorable, more favorable, less favorable, and least favorable. A priori inference of water transfer risks indicated that the overall risk of the South-to-North Water Transfer Project is relatively low, with a 49% probability of favorable water transfers from the lower Yangtze to the lower Yellow River. Simulation results showed that water transfers from the upper Yangtze to the upper and middle Yellow River were generally in a less favorable state, while transfers from the middle and lower Yangtze to the lower Yellow River were in a favorable state.

It is suggested to expand multi-basin collaboration and complex process coupling: The current model is limited to the runoff coupling of the YTB and YRB. In the future, it is necessary to integrate and construct a multi-basin joint hydrological network model to more comprehensively assess the water balance constraints and the potential chain risks of long-term water diversion to the regional water cycle and ecology. The current risk quantification mainly relies on historical statistical laws, and insufficient consideration is given to the adaptability to future extreme climate mutations and season-scale risks.

Data availability

The datasets generated and/or analysed during the current study are not publicly available due [REASON WHY DATA ARE NOT PUBLIC] but are available from the corresponding author on reasonable request.

Received: 23 December 2024; Accepted: 20 June 2025

Published online: 01 July 2025

References

1. Lianzhou, W., Xiaoling, S. & Te, Z. Challenges of typical inter-basin water transfer projects in China: Anticipated impacts of climate change on streamflow and hydrological dry under CMIP6. *J. Hydrol.* **627**, 1 (2023).
2. Liu, Y. et al. A holistic approach to projecting streamflow and analyzing changes in ecologically relevant hydrological indicators under climate and land use/cover change. *J. Hydrol.* **632**, 130863 (2024).
3. Wang, T. et al. Risk assessment based on Bayesian network for the typhoon-storm surge-flood-dike burst disaster chain: A case study of Guangdong, China. *J. Hydrol. Reg. Stud.* **1**, 102251. <https://doi.org/10.1016/J.EJRH.2025.102251> (2025).
4. Meng, D. & Yongping, W. A conceptual framework for quantitatively understanding the impacts of floods/droughts and their management on the catchment's social-ecological system (C-SES). *Sci. Total Environ.* **828**, 154041 (2022).
5. Xianneng, Z. et al. Coupling Bayesian Network and copula theory for water shortage assessment: A case study in source area of the South-to-North Water Division Project (SNWDP). *J. Hydrol.* **620**, 434. <https://doi.org/10.1016/J.JHYDROL.2023.129434> (2023).
6. Chadwick, C. et al. Synthetic simulation of spatially-correlated streamflows: Weighted-modified fractional Gaussian noise. *Water Resour. Res.* **60** (2), 371. <https://doi.org/10.1016/10.1029/2023WR035371> (2024).
7. Yueyi, L. et al. Optimal operation toward energy efficiency of the long-distance water transfer project. *J. Hydrol.* **618**, 152. <https://doi.org/10.1016/J.JHYDROL.2023.129152> (2023).
8. Sun, R. et al. The dynamic changes in phytoplankton and environmental factors within Dongping Lake (China) before and after the South-to-North Water Diversion Project. *Environ. Res.* **246**, 118138. <https://doi.org/10.1016/J.ENVRES.2024.118138> (2024).
9. Yue, W. et al. Determinants of land use conflicts with the method of cross-wavelet analysis: Role of natural resources and human activities in spatial-temporal evolution. *J. Clean. Prod.* **429**, 1 (2023).
10. Yun, L. et al. Development of multivariate standardized dry index for large lake basins based on the copula function: A case study of Hongze Lake Basin, China. *J. Hydrol. Reg. Stud.* **50**, 1 (2023).
11. Anan, G. et al. Reshuffling of the sediment suspension regime in the "starving" middle Yangtze River downstream from cascade mega-reservoirs. *J. Hydrol.* **622**, 1 (2023).
12. Xu, W. et al. Coupling deep learning and physically based hydrological models for monthly streamflow predictions. *Water Resour. Res.* **60** (2), 1 (2024).

13. Cheng, W. et al. Modeling and assessing the impacts of climate change on groundwater recharge in endorheic basins of Northwest China. *Sci. Total Environ.* **918**, 170829 (2024).
14. Huang, A. et al. Spatiotemporal variations of inter- and intra-annual extreme streamflow in the YTB. *J. Hydrol.* **629**, 130634. <https://doi.org/10.1016/j.jhydrol.2024.130634> (2024).
15. Jinhang, L. et al. Assessment on water cycle health in the Central Plains Urban cluster based on the DSWU NWU SWS NWS A—WCHI model. *Ecol. Ind.* **157**, 36. <https://doi.org/10.1016/j.ecolind.2023.111236> (2023).
16. Sumit, D. Recent decline in streamflow and sediment discharge in the Godavari basin, India (1965–2015). *Catena* **206**, 1 (2021).
17. Yang, G. et al. Understanding dry propagation through coupling spatiotemporal features using vine copulas: A compound dry perspective. *Sci. Total Environ.* **1**, 171080 (2024).
18. Yongxin, N. et al. Spatial difference analysis of the runoff evolution attribution in the YRB. *J. Hydrol.* **612**, 149. <https://doi.org/10.1016/j.jhydrol.2022.128149> (2022).
19. Zhang, Q. et al. Bayesian analysis of variance for quantifying multi-factor effects on dry propagation. *J. Hydrol.* **632**, 130911 (2024).
20. Zubeizu, S. et al. Coupling machine learning and physical modelling for predicting runoff at catchment scale. *J. Environ. Manag.* **354**, 120404. <https://doi.org/10.1016/j.jenvman.2024.120404> (2024).

Acknowledgements

This study was supported by the National Natural Science Foundation of China (52009045), Postdoctoral funding in Henan Province (202102086), Henan innovative talent support program (24HASTIT017).

Author contributions

Yuping Han and Jinhang Li: Conceptualization, Methodology, Formal analysis, Writing – original draft. Mengdie Zhao: Conceptualization, Methodology, Writing – review & editing, Supervision. Jinhang Li: Conceptualization, Methodology, Writing – review & editing. Yuping Han: Conceptualization, Methodology, Writing – review & editing.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1038/s41598-025-08429-w>.

Correspondence and requests for materials should be addressed to M.Z.

Reprints and permissions information is available at www.nature.com/reprints.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by-nc-nd/4.0/>.

© The Author(s) 2025