Coincidence probability of streamflow in water resources area, water receiving area and impacted area: implications for water supply risk and potential impact of water transfer

Xingchen Wei, Hongbo Zhang, Vijay P. Singh, Chiheng Dang, Shuting Shao and Yanrui Wu

ABSTRACT

Under changing environment, the feasibility and potential impact of an inter-basin water transfer project can be evaluated by employing the coincidence probability of runoff in water sources area (WSA), water receiving area (WRA), and the downstream impacted area (DIA). Using the Han River to Wei River Water Transfer Project (HWWTP) in China as an example, this paper computed the coincidence probability and conditional probability of runoff in WSA, WRA and DIA with the copula-based multivariate joint distribution and quantified their acceptable and unfavorable encounter probabilities for evaluating the water supply risk of the water transfer project and exploring its potential impact on DIA. Results demonstrated that the most adverse encounter probability (dry–dry–dry) was 26.09%, illustrating that this adverse situation could appear about every 4 years. The acceptable and unfavorable probabilities in all encounters were 44.83 and 55.17%, respectively, that is the unfavorable situation would be dominant, implying flood and drought risk management should be paid greater attention in project operation. The conditional coincidence probability (dry WRA & dry DIA if dry WSA) was close to 70%, indicating a requirement for an emergency plan and management to deal with potential drought risk.

Key words | bivariate copula, coincidence probability, conditional probability, Han River to Wei River Water Transfer Project, trivariate copula

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HIGHLIGHTS

- Coincidence probability of annual runoff in all main impacted areas is investigated.
- Copula-based method to capture the encounter situations of water transfer project.
- Acceptable and unfavorable probabilities in all encounters imply water transfer risk.
- Conditional coincidence probability with dry water resources area was computed.
- An emergency water scheduling plan is required to deal with potential drought risk.

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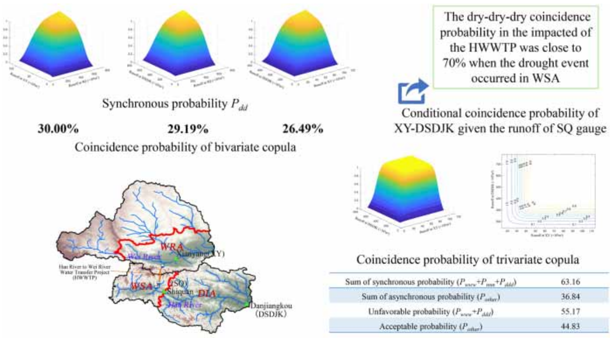
GRAPHICAL ABSTRACT



INTRODUCTION

Inter-basin water transfer (IBT) means building water transfer projects that span two or more basins for transferring water from a basin with abundant water resources to those in shortage and for redistributing water resources among the basins to meet water demand in the water-deficient area (Zhuang 2016). IBTs project, as an important safeguard to join different water systems, has been widely applied in many countries and regions, e.g. Australia, Canada, China, India and the United States, with the purpose of supporting economic and societal development (Manshadi *et al.* 2013; Yan & Chen 2013; Du *et al.* 2019). However, it is being debated that the hydrological cycle has altered in some basins or regions under the combined influence of climate change and human activities (Zou *et al.* 2018), with the result that the feasibility of IBT projects planned or under construction may be questionable. The questions include whether there will be enough water to be diverted and the new potential influence on water use, ecological protection and disaster control (e.g. drought and pollution) in the downstream areas of the water resources area under the changing environment. Thus, the coincidence probability analysis of annual runoff in these areas, including synchronous and asynchronous probabilities between or among the water sources area (WSA), water receiving area (WRA) and the downstream impacted area (DIA), is appealing for evaluating the feasibility and potential influence of IBT projects.

In previous studies, the coincidence probability analysis of IBT projects played an important role in determining project feasibility. Some multivariate approaches as main analysis tools were applied to calculate synchronous–asynchronous probabilities of streamflow, precipitation and drought between water source area and WRA. For instance, He *et al.* (2012) employed a Bayesian network model to investigate the rich–poor rainfall encounter risk between WSA and WRA in the middle route of the South-to-North Water Transfer Project (SNWTP) in China and implemented real-time scenario simulations, reflecting the change in risk in the operation of water transfer projects. Liu *et al.* (2015) investigated the concurrent drought probability between the water source and destination regions of the central route of the SNWTP using Clayton copula and general circulation models (GCMs) and found that the probability of concurrent drought events was highly likely to increase during 2020–2050, representing the WSA probably having insufficient amounts of water for diversion while the WRA urgently needing the diversion of water in concurrent drought years. Du *et al.* (2019) investigated the synchronous and asynchronous exceedance probabilities of wet versus dry conditions of precipitation in WSA and WRA of the Shuhe to Futuan Water Transfer Project (SFWTP) using a bivariate copula joint distribution function, and results indicated that climate change had positive impacts on the exceedance probabilities, demonstrating that the project risk was decreasing. In addition, the coincidence probability analysis of precipitation in WSA, WRA and DIA had been reported by Yan & Chen (2013). This analysis quantified the synchrony and asynchrony of precipitation for the middle route of SNWTP and verified the effectiveness of trivariate Clayton copula in the study area, and obtained the combination frequencies for the middle route of SNWTP, representing that the amount of transferable water was generally assured, but the possibility for water transfer was very small if extreme deficit rainfall events occurred in the WRA.

It is found from the literature that bivariate and trivariate copulas have been widely used in the coincidence probability analysis of hydrological variables in the relevant areas of IBT projects (Yan & Chen 2013; Du *et al.* 2019). Therein, bivariate copulas are generally used to investigate the hydrological combination frequencies between WSA and WRA for determining the feasibility of a water transfer project, and that between WSA and DIA for analyzing the potential influence of the project on the downstream areas (Yan & Chen 2013). Trivariate copulas are employed to calculate the hydrological combination frequencies and conditional frequencies among WSA, WRA and DIA by capturing the spatial dependence structure of hydrological variables influencing the coincidence probabilities of asynchrony and synchrony. Recent years have seen a growing interest in applying copulas to hydrological frequency analysis, which can be attributed to manifold advantages of copulas in modeling joint distributions, representing flexibility in selecting arbitrary margins and dependence structure, the ability to deal with three variables or more, and the separability in analyzing marginal and dependence structure (Salvadori & De Michele 2007; Serinaldi *et al.* 2009; Zhang & Singh 2019).

In this study, trivariate combination frequencies and conditional frequencies of annual runoff series in WSA, WRA and DIA influenced by the Han River to Wei River Water Transfer Project (HWWTP) in China, were investigated through copula-based multivariate probability distribution, with the purpose of estimating water supply risk of water transfer project and exploring its potential impact on the downstream area of the water source areas. Different from the previous relevant studies on the water transfer project, it uses annual runoff data from three gauges located in WSA, WRA and DIA, respectively and provides a reference for the scheduling of inter-basin transfer projects. The bivariate and trivariate copulas were employed to build the joint probability distribution between the annual runoff of three regions (WSA, WRA and DIA) and trivariate coincidence probability and conditional coincidence probability were analyzed to obtain information for flood and drought risk management for the project.

STUDY AREA AND DATA

Han River to Wei River Water Transfer Project

As an important project to resolve the water conflict in northwest China due to increasing industrial and domestic water consumption, the HWWTP connecting the upper Han River basin (WSA) and Wei River basin (WRA) in China (as shown in Figure 1) is designed to annually transfer an average of 1,000 million m^3 of water in 2025 and 1,500 million m^3 in 2030 from Huangjinxia reservoir and Sanhekou reservoir in the upper Han River basin to large-scale industrial zones and urban areas in the Wei River basin, with the main purpose of alleviating watershed water conflict (Wu *et al.* 2019). Because 70% of water is for industrial development, it requires stable water transfer, implying high requirement in controlling water supply risk, especially in the changing environment.

The WSA and the DIA of HWWTP are located in the upper Han River basin, with a drainage area of 95,200 km^2 and have a mainstream length with approximately 925 km (Figure 1). The basin is influenced by the north subtropic monsoon, representing the annual mean temperature ranging between 12 and 16 °C (Li *et al.* 2009) and average annual precipitation varying from 700 to 1,800 mm, and 80% of annual precipitation falls in the wet period from May to October in which the corresponding runoff is about 4.11×10^{10} m^3, accounting for 70% of the total annual runoff. Also, the runoff of the entire basin demonstrates a large annual and interannual variability (Li *et al.* 2008). Therein, the WSA mainly refers to the watershed above Huangjinxia and Sanhekou reservoirs and the DIA is downstream of them, primarily covering the watershed below Shiquan gauge.

The WRA of HWWTP mainly refers to Guanzhong plain region located in the central part of Shaanxi Province

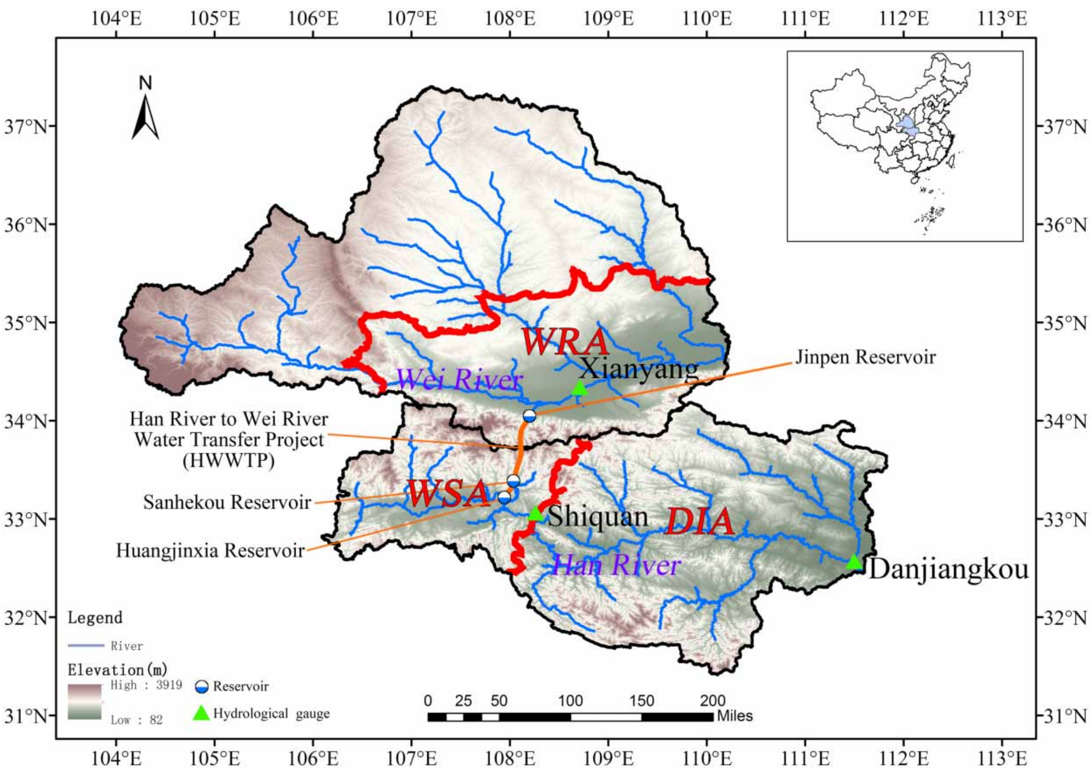


Figure 1 | Study area and locations of three gauges potentially impacted by the Han River to Wei River Water Transfer Project (HWWTP) in China.

and belongs to the Wei River basin. The Guanzhong plain region covers a total area of 55,500 km^2, as the most economically developed area in Shaanxi Province, including five prefecture-level cities, i.e. Xi'an city, Baoji city, Xianyang city, Weinan city, Tongchuan city and one agricultural high-tech industries demonstration zone as Yangling (Tian *et al.* 2020). The Guanzhong plain region has an average elevation of approximately 500 m and belongs to the continental monsoon climate, with the annual mean temperature of 6–13 °C and precipitation of 500–800 mm (Deng *et al.* 2020).

Data

According to the water transfer route of the HWWTP, the data used in this paper included annual runoff data from Shiquan (SQ) gauge on the WSA, Danjiangkou gauge (the watershed above SQ is not covered or the data deducted that from at SQ, DSDJK) on the DIA, and Xianyang (XY) gauge on the WRA (Figure 1) (see Supplementary Material). Therein, the observed runoff data series from SQ and DSDJK gauges were selected during 1956–2000. Considering that measured runoff is greatly affected by human activities in WRA, representing nonstationary feature (Lan *et al.* 2020), the natural runoff data, covering 45 years from 1956 to 2000, were selected from the XY gauge. The runoff data were obtained from hydrological manuals published by the Hydrological Bureaus of the Yellow River Conservancy Commission and Yangtze River Conservancy Commission. Statistical features of the annual data series are shown in Table 1.

Table 1 | Statistical features of annual runoff during 1956–2000

Gauges	Mean (10^8 m^3)	Standard deviation (10^8 m^3)	Coefficient of variation	Coefficient of skewness
Shiquan (SQ)	327.5	143.6	0.4385	0.9964
Xianyang (XY)	49.8	20.6	0.4125	0.7392
Danjiangkou (DSDJK)	368.1	136.4	0.3703	1.0753

Note: Runoff at Danjiangkou does not include the runoff from the area above Shiquan gauge.

METHODOLOGIES

Copula functions

Sklar (1959) introduced the copula theorem to model the stochastic nature of multi-dimensional processes by using univariate marginal distributions to derive multivariate distribution functions. Nowadays, copula models play an active role in the hydrological field (Yan & Chen 2013; Zhang & Singh 2019), such as drought assessment (Chanda *et al.* 2014), flood risk analysis (Favre *et al.* 2004; Serinaldi *et al.* 2009; Chebana *et al.* 2012) and streamflow simulation (Chen *et al.* 2015). According to Sklar's theorem, the copula function C can be used to describe a joint multivariate probability distribution of n correlated variables (X_1, X_2, X_3,…, X_n). If variables (X_1, X_2, X_3,…, X_{n}) have arbitrary marginal distribution functions $F_{X_1}(x_1), F_{X_2}(x_2), \ldots, F_{X_n}(x_n)$, respectively, there will exist a copula function C, which can combine these marginal distribution functions to give the joint distribution function, $F_{X_1,X_2,\ldots,X_n}(x_1, x_2, \ldots, x_n)$, as follows:

$$F_{X_1,X_2,\ldots X_n}(x_1, x_2, \ldots, x_n) = C_\theta[F_{X_1}(x_1), F_{X_2}(x_2), \ldots, F_{X_n}(x_n)] = C_\theta(u_1, u_2, .., u_n) \tag{1}$$

where $u_1, u_2, .., u_n \in [0, 1]$ are uniformly distributed random realizations of the variables, defined as $u_1 = F_{X_1}(x_1), u_2 = F_{X_2}(x_2), \ldots, u_n = F_{X_n}(x_n)$, and the copula parameter is θ. A unique copula function $C(\cdot)$ exists, when these marginal distributions are continuous (Sraj *et al.* 2015).

There are many types of copula functions, such as Plackett copula (Plackett 1965), Archimedean copulas and elliptical copulas (Fang *et al.* 2002). Because the Archimedean copulas can be easily constructed and are capable of capturing a variety of dependence structures with several desirable properties, such as symmetry and associativity, they have become very popular (Nelsen 2006; Hofert 2008).

The widely used Archimedean family copulas include the Frank copula, Clayton copula, Ali–Mikhail–Haq copula (AMH) and Gumbel–Hougaard (G–H) copula, with a parameter θ. For bivariate copula function, Kendall's correlation coefficient τ has a certain relation with parameter θ, as shown in Table 2. The appropriate copulas can be determined by different values of Kendall's τ from observations (Hofert 2011; Xie & Wang 2013).

Moreover, parameters of multi-dimensional copulas can be estimated by the maximum-likelihood estimator (MLE) or inference of functions for margins (IFM) method (Joe 1998, 2005). In view of the well-known optimality properties of the MLE, it would be the preferred option for estimating θ. Nevertheless, it is found from application that the more flexible IFM method is preferable to the MLE. Although the conceptual bases of the two methods are very similar, and the efficiency of these two methods is almost the same in many cases, the IFM method is easier to calculate than the MLE method.

For example, the trivariate copula parameter θ is estimated in two steps in the IFM method. In the first step, the parameters α_k ($k = 1, 2, 3$) of each marginal distribution are estimated separately via X_{ki}, $i = 1,2,\ldots,n$, and this estimator is expressed as $\hat{\alpha}_k$. The second step is that θ is estimated by replacing $\hat{\alpha}_k$ for α_k in the log-likelihood (as shown in Equation (2)) and the IFM estimate of θ is as follows:

$$\hat{\theta} = \arg\max \sum_{i=1}^{n} \log\left[c_\theta\{F_1(X_{1i}, \hat{\alpha}_1), F_2(X_{2i}, \hat{\alpha}_2), F_3(X_{3i}, \hat{\alpha}_3); \theta\}\right] \tag{2}$$

Table 2 | Types of Clayton, Frank and GH copula (Nelsen 2006)

Archimedean copula	C_θ	θ' range	Relation between θ and τ
Frank	$-\frac{1}{\theta}\ln\left[1+\frac{(e^{-\theta u}-1)(e^{-\theta v}-1)}{e^{-\theta}-1}\right]$	$-\infty < \theta < \infty$	$\tau = 1+\frac{4}{\theta}\left[\frac{1}{\theta}\int_0^\theta \frac{t}{e^t-1}dt - 1\right]$
Clayton	$(u^{-\theta}+v^{-\theta}-1)^{-1/\theta}$	$\theta > 0$	$\tau = \frac{\theta}{2+\theta}$
AMH	$uv/[1-\theta(1-u)(1-v)]$	$-1 \le \theta < 1$	$\tau = \left(1-\frac{2}{3\theta}\right)-\frac{2}{3}\left(1-\frac{1}{\theta}\right)^2\ln(1-\theta)$
G–H	$\exp\{-[(-\ln u)^\theta+(-\ln v)^\theta]^{1/\theta}\}$	$\theta \ge 1$	$\tau = 1-\frac{1}{\theta}$

Marginal distribution

The Pearson type III (P-III) distribution, Gumbel distribution and Lognormal distribution were employed in this study for describing the marginal distribution of single annual runoff.

The cumulative distribution function (CDF) of P-III distribution can be defined as

$$F(x) = P(x > x_p) = \frac{\beta^\alpha}{\Gamma(\alpha)} \int_{x_p}^{\infty} (x - \delta)^{\alpha - 1} e^{-\beta(x-\delta)} \quad (3)$$

where α, β and δ are the shape, scale and location parameters of the P-III distribution, respectively.

The CDF of Gumbel distribution can be defined as

$$F(x) = P(x > x_p) = \exp\left[-e^{-\frac{x-k}{\gamma}}\right] \quad (4)$$

where γ and k are the scale and the location parameters of the Gumbel distribution, respectively.

The CDF of Lognormal distribution can be defined as

$$F(x) = P(x > x_p) = \frac{1}{\sigma\sqrt{2\pi}} \int_{x_p}^{\infty} \frac{\exp\left[\frac{-(\ln x - \mu)^2}{2\sigma^2}\right]}{t} dt \quad (5)$$

where μ and σ are the mean and standard deviation formed by the natural logarithm of the variable x, respectively.

The linear moment method (Hosking 1990) was employed to estimate the parameters of the above three distributions, and a fitting test was used to choose the suitable marginal distribution of a single variable.

Fitting test

In this paper, Kolmogorov–Smirnov (K–S) test (D_n, Massey 1951), root mean square error (RMSE, Zhang & Singh 2006, 2019), Akaike's information criterion (AIC, Zhang & Singh 2007, 2019) were employed to measure the goodness of fit of the marginal and joint distributions which can be expressed as follows:

$$D_n = \max |P_{Ei} - P_{Ti}| \; (i = 1, 2, \ldots, n) \quad (6)$$

$$\text{RMSE} = \sqrt{\text{MSE}} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} (P_{Ei} - P_{Ti})}^{2} \quad (7)$$

$$\text{AIC} = N \ln(\sqrt{\text{MSE}}) + 2k \quad (8)$$

where N is the sample size, k is the number of parameters of different distributions, P_{Ei} and P_{Ti} are the empirical frequency and theoretical frequency, respectively. Therein, the empirical joint probability always plays a significant role in the selection of a copula function, which is used as a criterion for judging and selecting the best theoretical distribution from the Archimedean copula functions. Assuming the variables X and Y with the same length, the empirical frequency of bivariate variables (X and Y) was estimated by using the Gringorten formula (Gringorten 1963), as follows.

$$H(x, y) = P(X \le x_i, Y \le y_i) = \frac{NO.\ of(X \le x_i, Y \le y_i) - 0.44}{N + 0.12} \quad (9)$$

where (x_i, y_i) is the combination of the ith values in the X and Y series arranged in increasing order, i is 1: N, and N is the length of the series. For the trivariate copula function also, the above equation was used. The theoretical frequencies can be obtained by the models of marginal and copula distributions.

It is noted that according to RMSE and AIC criteria, the smaller AIC and RMSE are, the better the fitness of the distribution.

Coincidence probability

The coincidence probability is usually defined as the probability of two or more events that happen at the same time. For the IBT project, it is considered that the runoff coincidence is generally defined as the simultaneous occurrence of runoff in two or more basins, which represent the frequency P of wetness, dryness or normal of one basin when the other basin is in a condition of wetness, dryness or normal. It is reported that the 37.5 and 62.5% quantiles are usually used as thresholds to define the condition of wetness or dryness in precipitation coincidence (Liu & Zheng 2002; Yan & Chen 2013), and this paper used them due to high rainfall–runoff relation and simultaneous frequency.

For the annual runoff variable X, X_w and X_d were assigned the values of $P_w = 62.5\%$ and $P_d = 37.5\%$, respectively, as the threshold quantiles of wetness and dryness, respectively. The degree of wet–dry runoff can be described as wetness ($X \geq X_w = X_{62.5\%}$), dryness ($X < X_d = X_{37.5\%}$) and normal ($X_w > X \geq X_d$). In terms of bivariate copula, there were nine encounter situations (X and Y), and the trivariate copula (X, Y and Z) had 27 combinations. Some of all 36 combination functions were as follows.

Wet–wet periods coincidence probability, P_{ww}:

$$P_{ww} = P_{x,w} \wedge P_{y,w} = P(X \geq X_w, Y \geq Y_w) \\ = 1 - u_w - v_w + C_\theta(u_w, v_w) \quad (10)$$

Wet–dry periods coincidence probability, P_{wd}:

$$P_{wd} = P_{x,w} \wedge P_{y,d} = P(X \geq X_w, Y < Y_w) \\ = v_w - C_\theta(u_w, v_d) \quad (11)$$

Normal–wet periods coincidence probability, P_{nw}:

$$P_{nw} = P_{x,n} \wedge P_{y,w} = P(X_d \leq X < X_w, Y \geq Y_w) \\ = u_w - v_d - C_\theta(u_w, v_w) + C_\theta(u_d, v_w) \quad (12)$$

Wet–wet–wet periods coincidence probability, P_{www}:

$$P_{www} = P_{x,w} \wedge P_{y,w} \wedge P_{z,w} = (X \geq X_w, Y \geq Y_w, Z \geq Z_w) \\ = 1 - u_w - v_w - w_w + C_\theta(u_w, v_w) + C_\theta(u_w, \omega_w) \\ + C_\theta(v_w, \omega_w) - C_\theta(u_w, v_w, \omega_w) \quad (13)$$

Wet–normal–dry periods coincidence probability, P_{wnd}:

$$P_{wnd} = P_{x,w} \wedge P_{y,n} \wedge P_{z,d} = (X \geq X_w, Y_d \leq YY_w, ZZ_d) \\ = C_\theta(v_w, \omega_w) - C_\theta(v_d, \omega_d) - C_\theta(u_w, v_w, \omega_w) + C_\theta(u_w, v_w, \omega_d) \quad (14)$$

Dry–dry–dry periods coincidence probability, P_{ddd}:

$$P_{ddd} = P_{x,d} \wedge P_{y,d} \wedge P_{z,d} = (X < X_d, YY_d, ZZ_d) \\ = C_\theta(u_d, v_d, \omega_d) \quad (15)$$

where u, v and ω are the marginal distributions of X, Y and Z, and subscripts w, n and d mean wet, normal and dry conditions. The composite letters note the coincidence condition. For example, ddd presents the dry–dry–dry condition (period), and P_{ddd} is the coincidence probability of this condition. Here, the $\wedge$ product notation is used to express the simultaneous occurrence of events. Other combination probabilities listed in Tables 3 and 4 were calculated in a similar way.

RESULTS AND DISCUSSION

Parameter estimation and fitting test of marginal distributions

The parameters of the P-III, Gumbel, and Lognormal distributions mentioned above were estimated using the linear moment method, and results are shown in Table 5.

Also, the K–S test (D_n), RMSE and AIC were employed to test the feasibility of fitting these three distributions to runoff data, and results are shown in Figure 2.

The statistical results in Figure 2 indicate that the P-III, Gumbel and Lognormal distributions all passed the K–S test

Table 3 | Nine coincidence combinations of bivariate copula

	Y		
X	**Wet**	**Normal**	**Dry**
Wet	$P_{ww} = P_{x,w} \wedge P_{y,w}$	$P_{wn} = P_{x,w} \wedge P_{y,n}$	$P_{wd} = P_{x,w} \wedge P_{y,d}$
Normal	$P_{nw} = P_{x,n} \wedge P_{y,w}$	$P_{nn} = P_{x,n} \wedge P_{y,n}$	$P_{nd} = P_{x,n} \wedge P_{y,d}$
Dry	$P_{dw} = P_{x,d} \wedge P_{y,w}$	$P_{dn} = P_{x,d} \wedge P_{y,n}$	$P_{dd} = P_{x,d} \wedge P_{y,d}$

Table 4 | Twenty-seven coincidence combinations of trivariate copula

		Z		
X	**Y**	**Wet**	**Normal**	**Dry**
Wet	Wet	$P_{www} = P_{x,w} \wedge P_{y,w} \wedge P_{z,w}$	$P_{wwn} = P_{x,w} \wedge P_{y,w} \wedge P_{z,n}$	$P_{wwd} = P_{x,w} \wedge P_{y,w} \wedge P_{z,d}$
	Normal	$P_{wnw} = P_{x,w} \wedge P_{y,n} \wedge P_{z,w}$	$P_{wnw} = P_{x,w} \wedge P_{y,n} \wedge P_{z,n}$	$P_{wnd} = P_{x,w} \wedge P_{y,n} \wedge P_{z,d}$
	Dry	$P_{wdw} = P_{x,w} \wedge P_{y,d} \wedge P_{z,w}$	$P_{wdn} = P_{x,w} \wedge P_{y,d} \wedge P_{z,n}$	$P_{wdd} = P_{x,w} \wedge P_{y,d} \wedge P_{z,d}$
Normal	Wet	$P_{nww} = P_{x,n} \wedge P_{y,w} \wedge P_{z,w}$	$P_{nwn} = P_{x,n} \wedge P_{y,w} \wedge P_{z,n}$	$P_{nwd} = P_{x,n} \wedge P_{y,w} \wedge P_{z,d}$
	Normal	$P_{nnw} = P_{x,n} \wedge P_{y,n} \wedge P_{z,w}$	$P_{nnn} = P_{x,n} \wedge P_{y,n} \wedge P_{z,n}$	$P_{nnd} = P_{x,n} \wedge P_{y,n} \wedge P_{z,d}$
	Dry	$P_{ndw} = P_{x,n} \wedge P_{y,d} \wedge P_{z,w}$	$P_{ndn} = P_{x,n} \wedge P_{y,d} \wedge P_{z,n}$	$P_{ndd} = P_{x,n} \wedge P_{y,d} \wedge P_{z,d}$
Dry	Wet	$P_{dww} = P_{x,d} \wedge P_{y,w} \wedge P_{z,w}$	$P_{dwn} = P_{x,d} \wedge P_{y,w} \wedge P_{z,n}$	$P_{dwd} = P_{x,d} \wedge P_{y,w} \wedge P_{z,d}$
	Normal	$P_{dnw} = P_{x,d} \wedge P_{y,n} \wedge P_{z,w}$	$P_{dnn} = P_{x,d} \wedge P_{y,n} \wedge P_{z,n}$	$P_{dnd} = P_{x,d} \wedge P_{y,n} \wedge P_{z,d}$
	Dry	$P_{ddw} = P_{x,d} \wedge P_{y,d} \wedge P_{z,w}$	$P_{ddn} = P_{x,d} \wedge P_{y,d} \wedge P_{z,n}$	$P_{ddd} = P_{x,d} \wedge P_{y,d} \wedge P_{z,d}$

Table 5 | Estimated parameters of P-III, Gumbel and Lognormal distributions

	P-III			Gumbel		Lognormal	
Gauges	α	β	δ	γ	k	μ	σ
SQ	4.0371	71.4811	38.9582	110.7327	263.6216	327.5376	142.0196
XY	8.1332	7.2092	−8.7950	15.8512	40.6888	49.8382	20.3298
DSDJK	3.4689	73.1856	114.2435	105.0921	307.4579	368.1180	134.7853

with the critical value $D_{0.05} = \frac{1.36}{\sqrt{45}} = 0.2027$. At SQ gauge, it was seen that the AIC of the Gumbel distribution was the smallest of the three models, while the P-III distribution had the smallest RMSE. After consideration, the P-III distribution was finally selected to fit the annual runoff data from the SQ gauge. For XY and DSDJK gauges, the Gumbel distribution had both the smallest AIC and RMSE, thus the Gumbel distribution was employed to fit at the two gauges. The curves in Figure 2 represent the performances of three models in fitting annual runoff data from the three gauges visually.

Parameter estimation and fitting test of joint distribution

Various forms of the copula function have different requirements for the correlation of variables. For example, the G–H copula and Clayton copula functions are suitable for random variables with positive correlation, the Frank copula function applicable to random variables with positive and negative correlations, and the AMH function is often applied to random variables with weak correlations. For this, Pearson's correlation coefficient (R) and Kendall's tau (τ) are first calculated to describe the dependence (concordance) of annual runoff for any two of the three gauges, and the values of R and τ are shown in Table 6.

In Table 6, it is seen that runoff series from any two of the three gauges had positive correlation, thus the G–H copula and Clyton cupola functions were considered suitable for the data series analysis.

Then, Kendall's correlation coefficient τ was counted between annual runoff data from any two of the three gauges, and the corresponding copula parameters θ can be computed in terms of the equations of the G–H and Clyton copulas listed in Table 2. The values of τ and θ are shown in Table 7.

Furthermore, the bivariable joint distributions from the Clayton copula and G–H copula were constructed by using the estimated parameters and the equations in Table 2, respectively, while the parameters of trivariate Clayton and G–H copula functions need to be estimated through Equation (2) for the construction of trivariate distributions, which is different from the bivariable joint distribution. So, the fitness results of all joint distributions, representing D_n, RMSE and AIC, are shown in Tables 8 and 9.

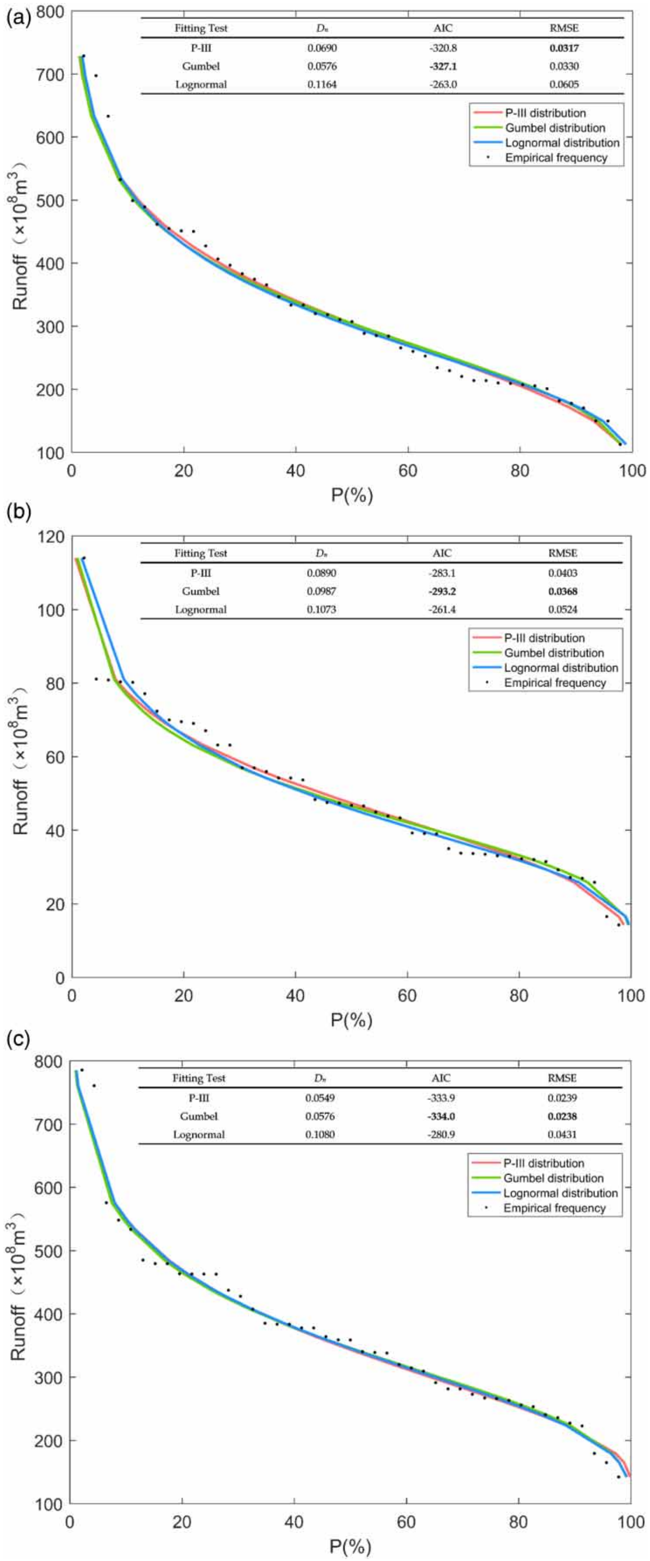


Figure 2 | Marginal distributions fitted with empirical frequency and models.

Table 6 | Pearson's correlation coefficient (R) and Kendall' tau (τ) between runoff series from three gauges

Gauges	R	τ
SQ–XY	0.7983	0.5993
SQ–DSDJK	0.8542	0.6721
XY–DSDJK	0.7355	0.4611

Table 7 | Parameter values of bivariate copula functions

		Θ	
Gauges	τ	**G—H**	**Clayton**
SQ–XY	0.5993	2.494	2.988
SQ–DSDJK	0.6721	3.049	4.098
XY–DSDJK	0.4611	1.855	1.711

Tables 8 and 9 show that bivariate and trivariate copulas, based on the G–H and Clayton copula, both passed the K–S test (D_n less than 0.207). The smallest values of RMSE and AIC (0.0811, −224.12) in Table 8 demonstrate that Clayton copula was the best-fitted bivariable joint distribution between runoff series from SQ and XY gauges and was also suitable for that between XY and DSDJK gauges, with RMSE and AIC of 0.0995 and −205.71. Differently, the best-fitted bivariable joint distribution between SQ and DSDJK gauges was the G–H copula, and the smallest values of RMSE and AIC were 0.0700 and −237.33. Additionally, it can be seen from Table 9 that the smallest values of RMSE and AIC are 0.1646 and −212.66, respectively, implying the G–H copula was the best suitable function among trivariate copula functions and can describe the joint distribution among three gauges.

Coincidence probability of bivariate copula

According to the chosen and established bivariate copula functions, the bivariate joint runoff distribution between any two gauges was obtained, and the joint coincidence probability was calculated under certain conditions. The joint cumulative probability distribution and contours at any two of the three coupled gauges are shown in Figure 3. From the contours in Figure 3, one can obtain the probabilities that annual runoff of any two gauges was less than a certain value at the same time, and that possible combinations of annual runoff from different gauges under a

Table 8 | K–S test (D_n), RMSE and AIC of bivariate copulas

	D_n		RMSE		AIC	
Gauges	G–H	Clayton	G–H	Clayton	G–H	Clayton
SQ–XY	0.1600	0.1280	0.0854	0.0811	−219.47	−224.12
SQ–DSDJK	0.1279	0.1086	0.0700	0.0701	−237.33	−237.16
XY–DSDJK	0.1840	0.1472	0.1016	0.0995	−203.82	−205.71

Table 9 | K–S test (D_n), RMSE and AIC of trivariate copulas

Trivariate copula functions	Θ	D_n	RMSE	AIC
G–H copula	3.49	0.0921	0.1646	−212.66
Clayton copula	3.27	0.1160	0.1648	−191.85

certain probability, such as the combination of annual runoff from the SQ gauge with a 30% probability and corresponding annual runoff from the XY gauge, or the combination of annual runoff from the XY gauge with a 30% probability and annual runoff from the SQ gauge. At this time, the joint cumulative probability in Figure 3 was able to analyze the worst situation of simultaneous dry periods occurring from any two gauges. For instance, it can be calculated that the joint probability was 10%, that the annual runoff was less than 2×10^{10} m^3 at SQ gauge and less than 0.27×10^{10} m^3 at XY gauge; that the joint probability was 90%, that the annual runoff was less than 0.86×10^{10} m^3 at XY gauge and less than 7×10^{10} m^3 at DSDJK gauge. For other examples, the possible combination of annual runoff at SQ and DSDJK gauges with a joint probability less than 50% was that the annual runoff was less than 5×10^{10} m^3 at SQ gauge and less than 3.5×10^{10} m^3 at DSDJK gauge, or that the annual runoff was less than 3.05×10^{10} m^3 at SQ gauge and less than 6×10^{10} m^3 at DSDJK gauge.

Through the constructed bivariate joint distributions, the nine coincidence probabilities of annual runoff data mentioned in Table 3 were computed at any two gauges. In the IBT project, the most adverse encounter situation was considered as dry–dry periods, which means that a shortage of water resources appeared both in the WSA and the WRA. The statistical results showed that P_{dd} was not too high, 30, 29.19 and 26.49% in SQ–XY, XY–DSDJK and SQ–DSDJK, respectively. The synchronous coincidence probabilities generally pointed to wet–wet periods coincidence probability, normal–normal periods coincidence probability and dry–dry coincidence probability, while other probabilities were regarded as asynchronous coincidence probabilities. The synchronous and asynchronous coincidence probabilities at any two gauges were computed, as shown in Table 10. Obviously, it is seen from the table that the synchronous coincidence probability was generally higher than asynchronous coincidence probability. It can be explained well due to the close geographical position among three gauges and similar climatic conditions. The larger synchronous coincidence probabilities indicated when there was enough water to be diverted in WSA, WRA or DIA was also likely to be wet, implying water demand in WRA for transferring water was small or the potential influence caused by the water transfer in DIA was low. Contrarily, when WSA was dry and cannot provide abundant water for diversion, water demand in WRA for transferring water was very high or the potential influence in DIA was greatly strong due to WRA or DIA being probably dry at that time. This was not expected in the IBT project, because it took on the project with a big risk, threatening the water security in WSA, WRA and DIA. Of course, when there was enough water to be diverted in WSA, WRA just happened to be dry and DIA was wet, and transferring water in the inter-basin provided the benefit at this time and caused the low impact in the downstream river basin. Thus, it was clear that coincidence probability of bivariate copula failed to provide a valuable reference when considering WSA, WRA and DIA of the IBT project

Coincidence probability of trivariate copula

The coincidence probability of trivariate copula certainly provided an effective tool to comprehensively analyze the

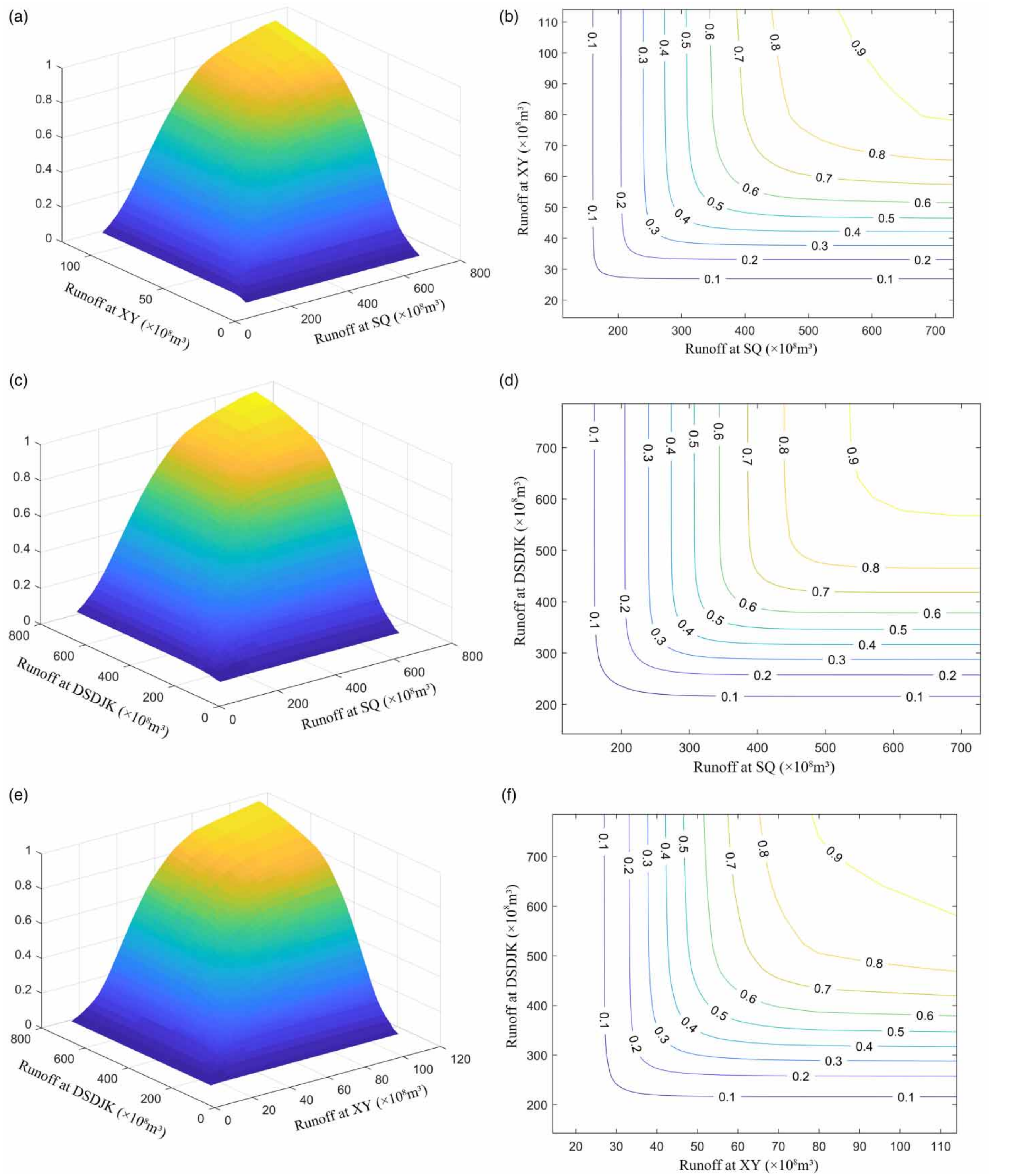


Figure 3 | Contours and joint cumulative probability distribution: (a) joint cumulative probability distribution of annual runoff from the SQ and XY gauges; (b) contours of the joint cumulative probability distribution of annual runoff from the SQ and XY gauges; (c) joint cumulative probability distribution of annual runoff from the SQ and DSDJK gauges; (d) contours of the joint cumulative probability distribution of annual runoff from the SQ and DSDJK gauges; (e) joint cumulative probability distribution of annual runoff from the XY and DSDJK gauges; (f) contours of the joint cumulative probability distribution of annual runoff from the XY and DSDJK gauges.

Table 10 | Coincidence probability of bivariate copula (%)

Probability	Periods	SQ–XY	XY–DSDJK	SQ–DSDJK
Synchronous probability	Wet–wet	26.78	30.43	23.33
	Normal–normal	10.50	12.06	8.38
	Dry–dry	30.00	29.19	26.49
	Total	67.29	71.68	58.19
Asynchronous Probability	Wet–normal	8.86	5.85	9.89
	Wet–dry	1.86	1.22	4.28
	Normal–wet	8.86	5.85	9.89
	Normal–dry	5.64	7.09	6.73
	Dry–wet	1.86	1.22	4.28
	Dry–normal	5.64	7.09	6.73
	Total	32.72	28.32	41.8

influence of the IBT project. Based on the G–H copula, this study constructed trivariate joint distributions, by which 27 coincidence probabilities from the trivariate copula, corresponding to the combinations shown in Table 4, were computed. Similarly, the wet–wet–wet coincidence probability P_{www}, normal–normal–normal coincidence probability P_{nnn}, and dry–dry–dry coincidence probability P_{ddd} were considered as synchronous coincidence probabilities of trivariate copula, while other probabilities were asynchronous coincidence probabilities. Furthermore, synchronous coincidence probabilities and asynchronous coincidence probabilities at three gauges (SQ–XY–DSDJK) can be obtained, as shown in Table 11.

As is known, the purpose of HWWTP was to balance the non-uniform temporal and spatial distributions of water resources in WSA and WRA and increase water supply for guaranteeing industrial and domestic water safety in Guanzhong plain, China. Considering this, the wet–wet–wet and dry–dry–dry encounter situations were determined as unfavorable circumstances, in which the wet–wet–wet situation implying flood risk and the dry–dry–dry situation implying drought risk in this study. Other encounter situations were also regarded as acceptable conditions. These results are shown in Table 11 where the values of synchronous coincidence probabilities P_{www}, P_{nnn} and P_{ddd} were 29.08, 7.99 and 26.09%, respectively. Therein, the most adverse encounter situation was in dry–dry–dry periods, with the coincidence probability (P_{ddd}) of 26.09%. Through the probability, the recurrence interval was obtained in the worst encounter situation, and the value was 3.8 years, which means the most adverse situation (dry–dry–dry) could appear once every 3.8 years on average. Also, it can be seen from the table that unfavorable probability ($P_{www} + P_{ddd}$) reached 55.17%, greater than the acceptable probability, implying the hydrological condition was very unfavorable to water transfer in more than half of the whole operation period. It undoubtedly posed a big challenge to the scheduling of inter-basin projects, threatening the safety of water delivery.

Furthermore, in order to implement the optimal scheduling of the transfer project, it was necessary to identify the possible runoff in WRA and DIA when different runoff rhythms happened in WSA. Fortunately, the joint distribution model established by the copula function provided an effective tool for solving this problem. So three equations were constructed to calculate dry–dry coincidence probabilities of annual runoff from the XY and DSDJK gauges with the condition that SQ gauge was in wet, normal and dry periods.

Table 11 | Coincidence probability of trivariate copula (%)

	Wet (SQ)			Normal (SQ)			Dry (SQ)		
Periods	Wet (XY)	Normal (XY)	Dry (XY)	Wet (XY)	Normal (XY)	Dry (XY)	Wet (XY)	Normal (XY)	Dry (XY)
Wet (DSDJK)	29.08	2.23	0.05	2.23	2.78	0.34	0.05	0.34	0.39
Normal (DSDJK)	2.23	2.78	0.34	2.78	7.99	2.40	0.34	2.40	3.75
Dry (DSDJK)	0.05	0.34	0.39	0.34	2.40	3.75	0.39	3.75	26.09
Sum of synchronous probability ($P_{www} + P_{nnn} + P_{ddd}$)						63.16			
Sum of asynchronous probability (P_{other})						36.84			
Unfavorable probability ($P_{www} + P_{ddd}$)						55.17			
Acceptable probability (P_{other})						44.83			

The conditional dry–dry coincidence probabilities were obtained as follows, where X notes runoff from the SQ gauge, Y is that from the XY gauge and Z refers to the runoff from the DSDJK gauge.

Wet SQ, dry XY and dry DSDJK,

$$F(y, z|x) = P(Y < Y_d, Z < Z_d|X \geq X_w) = \frac{C_\theta(v_d, \omega_d) - C_\theta(u_w, v_d, \omega_d)}{1 - u_w} = 0.0104 \quad (16)$$

Normal SQ, dry XY and dry DSDJK,

$$F(y, z|x) = P(Y < Y_d, Z < Z_d|X_d \leq X < X_w) = \frac{C_\theta(u_n, v_d, \omega_d) - C_\theta(u_d, v_d, \omega_d)}{u_n - u_d} = 0.4483 \quad (17)$$

Dry SQ, dry XY and dry DSDJK,

$$F(y, z|x) = P(Y < Y_d, Z < Z_d|X < X_d) = \frac{C_\theta(u_d, v_d, \omega_d)}{u_d} = 0.6957 \quad (18)$$

where u, v and ω are the marginal distributions of X, Y and Z, and subscript w, n and d mean the wet, normal and dry conditions, respectively.

The above calculation showed that the coincidence probability of wet SQ, dry XY and dry DSDJK was 1.04%; that of normal SQ, dry XY and dry DSDJK was 44.83%; that of dry SQ, dry XY and dry DSDJK was 69.57%. Therein, the probability that dry XY and dry DSDJK happened at the same time reached 69.57%, in the case that dry SQ was occurring, and that of dry XY and dry DSDJK arrived at 44.83% even though normal runoff occurred at SQ gauge. They implied that water supply deficit in WRA due to the insufficient transfer of water caused by low watershed yield in WSA, and water supply deficit in DIA due to low flow from the upstream watershed caused by normal water transfer, could disturb the operation of the HWWTP, when there was not abundant water yield in WSA.

To visualize the conditional coincidence probability among three gauges mentioned above, the distribution and contours of different magnitudes of runoff from XY and DSDJK gauges in the case that SQ gauge was in dry period were drawn, as shown in Figure 4. From the figure, the conditional coincidence probability of a certain magnitude was obtained directly from the contours. For example, when SQ gauge was dry, the conditional coincidence probability of dry XY and dry DSDJK was 20%, in which dry XY illustrated the annual runoff at XY gauge was less than 0.5×10^{10} m^3 and dry DSDJK demonstrated that it was less than 2.2×10^{10} m^3.

Also, the conditional coincidence probability of the most adverse encounter situation (dry A and dry B if dry C) for the IBT project was 69.57%, representing the encounter probability of dry XY and dry DSDJK in the case that SQ was in the dry period. Compared with the coincidence probability (dry SQ and dry XY and dry DSDJK) of trivariate copula in Table 11, the conditional coincidence probability (dry XY and dry DSDJK if dry SQ) better showed the importance of drought risk, indicating the dry–dry–dry coincidence probability in the study area was close to 70% when the drought event occurred in WSA. Thus, it should be emphasized again that the implementation effect of designed water transfer could not be guaranteed to a large extent, once WSA was in a dry period during the operation of HWWTP.

CONCLUSIONS

The Han River to Wei River Water Transfer Project (HWWTP) is a strategic project serving the water resources allocation in northwest China, aiming to mitigate water shortage in the Guanzhong Plain. It is important for HWWTP to estimate the water supply risk of the water transfer project and explore its potential impact on the downstream of the water sources areas. To discuss this issue, this study analyzed the coincidence probability of annual runoff series between or among the water source area (WSA), WRA and the DIA. In this analysis, the Archimedean copula-based method was used to capture the encounter situations of various water yields in different areas by constructing bivariate and trivariate joint distributions and calculated various combination frequencies, implying the water supply risk of the HWWTP in China. The main conclusions of the study can be summarized as follows.

The coincidence probability of annual runoff series from WSA (SQ gauge), WRA (XY gauge) and DIA (DSDJK gauge) was obtained for different encounter situations by using

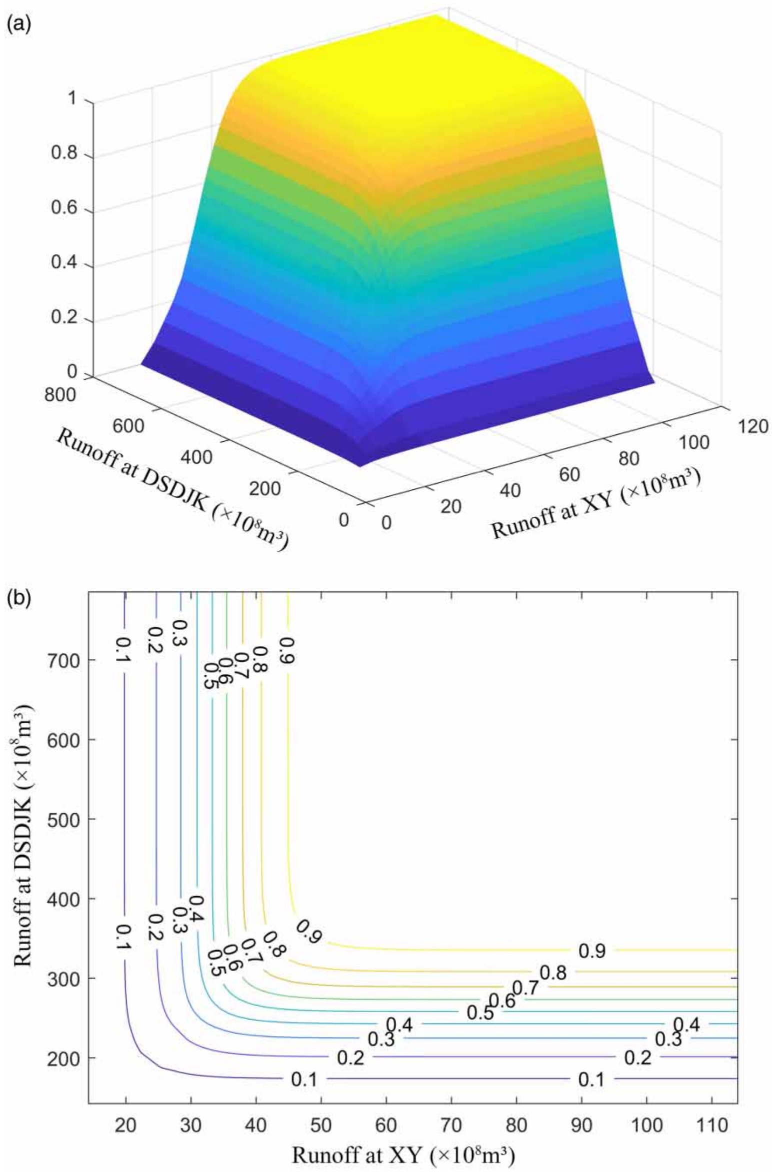


Figure 4 | Conditional coincidence probability of XY–DSDJK given the runoff of SQ gauge.

multivariate copula functions, which provided a valuable reference for water resources scheduling of the IBT project because they covered all primary areas impacted by the project.

The most adverse encounter in all situations was the case that three hydrological gauges (WSA, WRA and DIA) were in the dry period at the same time, i.e. dry–dry–dry, and the coincidence probability was 26.09% obtained by the trivariate copula. Accordingly, the recurrence interval was calculated with a value of 3.8 years, illustrating that this adverse situation would appear about every 4 years. According to the coincidence probability of annual runoff series from the three gauges, it was found that the acceptable and unfavorable probabilities were 44.83 and 55.17%, respectively. Obviously, the unfavorable probability was greater than the acceptable probability and should be paid greater attention to flood and drought risk management during the operation of the project.

Considering the most adverse encounter situation in WRA (XY gauge) and DIA (DSDJK gauge) under the condition that WSA (SQ gauge) was in the dry period, i.e. dry

XY and dry DSDJK if dry SQ, the conditional coincidence probability was computed with a value of 69.57%. Different from the coincidence probability (dry–dry–dry) of trivariate copula, it better emphasized the risk of drought for the water transfer project, representing the probability of drought event simultaneously occurring in WRA and DIA was close to 70% when a drought event occurred in WSA. Therefore, it was inferred that the volume of designed transferable water could not be guaranteed to a large extent once WSA was in a dry period during the operation of HWWTP, which could lead to water shortages caused by drought in WRA and DIA could not be alleviated effectively and could further threaten regional water security. Thus, it is suggested that an emergency water resources scheduling plan and management programs should be drawn up, with the purpose of dealing with potential flood and drought risk of the IBT project.

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AUTHOR CONTRIBUTIONS

All authors contributed to this study. H.Z. provided the writing idea; X.W. carried out data analyses and wrote the first manuscript draft; C. D. and S. S. contributed to the analysis of results; Y.W. drew the figures; H.Z. and V.S. revised the manuscript. All authors read and approved the final manuscript.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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