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Multiple-risk assessment of water supply, hydropower and environment nexus in the water resources system

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Abstract: Hydropower has been one of the effective and reliable renewable sources utilized for electricity generation globally, which forms over 70 % of all the renewable energy measures since 2016. However, this effective energy source can be greatly affected by the uneven spatiotemporal distributions of water resources in the catchment, leading to the potential risks of insufficient water supply, hydropower and ecological water uses. In this study, the multi-dimensional models by coupling water supply, hydropower generation and environment effects were developed to improve the efficiency and sustainability of water resources utilization. To this end, the joint distributions and conditional expectation models were established to analyze the nexus of water supply, hydropower and environment variables, thereby to evaluate multiple risks in the water resources system. For the validation and demonstration of the proposed method, the upper Yangtze River Basin was selected for a case study through multivariate analysis under different conditions. The application results of bivariate analysis indicated that the probability of water supply exceeding a threshold value decreases gradually with the increase of hydropower generation, which means that the risk of insufficient water supply increases with the increasing of the hydropower generation. Specifically, when the frequency of hydropower generation exceeds 90 %, both the expected values of water supply sufficiency and water use sustainability will decrease sharply, causing potential risks of water supply insufficiency and environment damage at upstream of the dam. Furthermore, the application results of trivariate analysis evidenced that different combinations of hydropower generation and ecological water use may be achievable for optimally compromising the water resources supply and utilization. The results and findings of this study may provide useful implications for effective multiple function-based development of water resources, with aims to reduce the water supply risks as well as to improve the water utilization efficiency and environmental sustainability.

Keywords: water resources system, water supply, hydropower, water-energy-environment nexus, multiple-risk assessment

1. Introduction

Freshwater is one of most valuable and crucial natural resources for agricultural, industrial, municipal, and environmental uses. In the early times of human history, the global freshwater is more than enough to fulfill the demands and requirements of different water use purposes , so that the ecosystems and environment conditions on the Earth can be well maintained during that period. However, in the recent and modern times, the rapid progress and development of the human society, including economic and population increases as well as agricultural and industrial activities, have resulted in and subsequently accelerated the water withdrawals over the world. Moreover, it is indicated that by 2050, the world population is projected to reach 9.8 billion, which may result in 55 % more water required to meet the basic demands worldwide (Kaneda et al., 2015). Thus, the competition among various purposes of water use will become more and more intense and critical worldwide in the future. From this perspective, water scarcity has been a crucial problem globally, which may affect every continent and around 2.8 billion people on the Earth with at least one month out of every year. More precisely, water scarcity is the shortage of water resources available to meet the demands of water usage within a region. Currently, more than 1.2 billion people are lacking access to potable water (Onda et al., 2012). As a result, the shortage situation of water will sacrifice partially or fully the household, industrial, agricultural, and environment demands.

On the other hand, with the increasing population and GDP, the global electricity demand will reach around 38,700 terawatt-hours by 2050 from 25,000 terawatt-hours in 2017 (i.e., with about 55 % increase), driving new investment in power generation capacity. Hydropower is one of the promising renewable sources for electrical power generation, accounting for over 70 % of total renewable electricity globally in recently years (Pazheri et al., 2014). With total amount of 1,064 GW installed capacity in 2016, hydropower has contributed to more than 16 % of the global electricity among all energy sources (Ciriminna et al., 2018). Moreover, hydropower has also been found to be a renewable and reliable energy resource with high flexibility and consistency, which can meet both requirements of base-load electricity and unexpected demands (e.g. with pumped storage technology) (Dell et al., 2001; Duan and Gao, 2019). Estimates from the World Energy Council have indicated that the availability of the untapped hydropower potential worldwide attains to approximately 10,000 TW·h/year since 2015, of which the main hydropower generation potential countries include China, USA, Brazil, Canada, India, and Russia (Ahamd, 2019). In this regard, the variabilities in water supply and policies governing water use are important factors for defining the efficiency and capacity of hydropower generation (Macknick et al., 2012). At the same time, these variations in hydropower generation may affect the quantity and quality of basin water supply.

Environment is another key issue in water resources management (Williams, 2011). The Water Security Series has set out key concepts in water management in the context of the global need for environmental sustainability. Rational water resources management could be an improvement of the environment. With the increasing demand of essential resources (food, water and energy) due to the rapid growth of global population, the water resources systems and ecosystems have suffered from severe pressures for maintaining their sustainability. As a result, it has been gradually emphasized in the relevant policy and management worldwide for the importance of the environmental water needs and allocations (e.g. Postel and Richter, 2003). The report from the World's Local Bank has also confirmed that the priority of water allocations for social and environmental purposes has been and will be increasingly recognized in water laws around the world (Dinar et al., 1997).

Consequently, how the allocation, use, and management of water resources are addressed will have dramatic impacts on the environment, economy, and quality of human life. Water, energy and environment can interdependently support and influence the overall economic development and societal progress. In addition, the environmental need for water must be balanced against human water use. On this point, it is important to analyze the water supply, hydropower generation and environment impact in the water resources system together, so as to understand and emphasize the dependences and interactions of all these aspects (Wu and Chen, 2013; Stemberg, 2010).

Recently, many researches have been carried out concerning the water-energy nexus, water-food nexus, and energy-food nexus (Siddiqi and Anadon, 2011; McCornick et al., 2008; Biggs et al., 2015; Zhang et al., 2019). To respond the influence of the global climate change and societal development (e.g., population and economic growth, globalization and urbanization), the water-food-energy (WFE) nexus has been conceptualized and used recently by different researchers in the community (Endo et al., 2015; Leck et al., 2015). In fact, the WPE systems are essentially interconnected within a practical water cycle that is interfered largely by different human activities (Sivapalan et al., 2012, 2014; Feng et al., 2016). In this regard, the WPE systems should be described and investigated as a comprehensive nexus (which is defined as WPE nexus in this study), because of its complex interconnections and interdependences (Feng et al., 2016). Due to the uneven spatiotemporal distributions of water resources, the WPE nexus may be encountered with multiple risks of insufficient water supply, inadequate hydropower generation, deteriorative environmental condition and others. In recent years, few researches have focused on risk analysis associated with water-energy nexus (Gallagher et al., 2016; Cai et al., 2019). Specifically, the water, food and energy policy and management has been prescribed as a crucial risk role for their research directions (Gallagher et al., 2016). Hussien et al. (2018) assessed the risk of water-energy-food nexus by exceeding a threshold. Cai et al. (2019) analyzed integrated risk of water-energy nexus through a comprehensive method of system dynamics, orthogonal design and copula analysis. Zhang et al. (2019) assessed the risk and structure of the dynamics of water-food-energy nexus based on a water footprint method. However, so far there are very few studies on the risk assessment of the WPE nexus.

For river basins, the water supply, hydropower generation and environmental water use are related and linked by water flows in the basin. Usually, the water resources used for water supply in the basin at the upstream of the dam cannot be used for hydropower generation at downstream (Whittington et al., 2005). As a result, there is great of conflicts among these different water uses, which forms a typical benefit-risk problem in water resources system. To this end, a Bayesian approach could be a useful tool to analyze the conflict problem of water resources (Varouchakis et al., 2016, 2019). For example, Varouchakis et al. (2016) used the Bayesian approach to analyze the cost-benefit-risk for water resources management. However, so far in the hydrological community, there is no study focusing on the comprehensive risk assessment for the WPE system under different influential conditions.

Since the water supply, hydropower generation and environment are dependent in a water resources system (Stickler et al., 2013), a joint analysis method, namely copula method, can be a useful method to involve these kinds of dependences, which will also be introduced in this study for the WPE nexus investigation. Meanwhile, multivariate distribution functions are useful tools and have been commonly applied in the hydrological research community for analyzing multiple dependent variables and corresponding dependence structures (Chebana and Ouarda, 2011). Specifically, the multivariate distribution function has been widely used for rainfall frequency analysis, flood frequency analysis, and stochastic simulation (Yin et al., 2018; Tu et al., 2016, 2018).

In this study, three variables were defined for representing the water supply, hydropower and environmental water use, respectively. The WPE nexus was analyzed based on the multivariate distribution functions as follows. First, a joint distribution was established to simulate the dependences among different variables. Second, the conditional distribution was derived for each representative variable. Third, the conditional expectation composition (CEC) method was proposed for the risk analysis. Based on the proposed model. The multiple risks of the WPE nexus were systematically evaluated and discussed through the case study of the upper Yangtze River basin.

2. Study area and data material

The Yangtze River, the longest river in the Asia region and the third longest river in the world, has a length of 3,915 miles (6,300 kilometers). From its origin to the Yichang city is usually defined as the upper reach of the Yangtze River. This upper reach of the Yangtze River flows across the Plateau of Tibet and receives confluence discharges from many different tributaries (large and small). The mainstream elevation descends under through deep valleys in the east Plateau mountains and then appears onto the Yunnan-Guizhou Plateau, where summer season is warm and winter season is cold. The area of the upper Yangtze River covers about 0.85 million km^2. In the upper Yangtze River, the water resources can reach 585.33 billion m^3. The average water resources per capita attains to 32,000 m^3. In this study, the upper Yangtze section was selected for the case study, of which the basin mainly involves the Chongqing city, Tibet, Qinghai, Yunnan, Guizhou and Sichuan provinces. The water use data of these provinces were collected for the analysis. For clarity, the skeleton of the research area is given in Figure 1, in which the deep blue area is the upper Yangtze River Basin.

Figure 1 Skeleton of the Yangtze River Basin.

In a water resources system, water use is mainly composed of domestic water use, ecological water use, agricultural water use, and industrial water use. Since the environment and ecology has been emphasized more and more for their importance to daily practice, the ecological water use was taken in this study as a variable for representing the environmental situation in the water resources system. Thus, the water use is divided into two kinds. One kind is named as water supply defined as W in this study, including all the water use for human beings, such as domestic, agricultural and industrial water uses. The other kind is called environmental water use, including the ecological water use in the basin, which was defined as E in this study. In addition to these two variables, the water use for hydropower generation was also considered in this study, defined as P herein, which is quantified by the hydropower generation capacity in this study.

Taking the upper Yangtze River Basin as a virtual reservoir, the relation among water supply, hydropower generation and environmental water use in the basin can be described in Figure 2. The natural flow is the input of the reservoir system. The flow stored in the virtual reservoir can be used for water supply, hydropower generation and preserving the ecosystem. As for the water allocation strategy, the water withdrawn in the upstream of the dam for water supply and/or ecological use will not flow through the dam for electricity generation.

In this study, the water consumption data of the provinces involved in this research area (Figure 1) were collected for the model development and analysis. Specifically, the data of water supply and ecological water use were obtained from the China Water Resources Bulletin, China Hydrological Yearbook and Yangtze & Southwest Rivers Water Resources Bulletin. The duration of the data set covers from 1998 to 2015. In terms of the hydropower generation, with the construction of the reservoirs and the increase of hydropower generation every year, the number of the reservoirs will be fixed at the same level in order to rationally analyze the nexus of the water supply, hydropower generation and environment. For the analysis, the number of the reservoirs was set to 60 at the current level. The hydropower generation data was derived based on the reservoir operation.

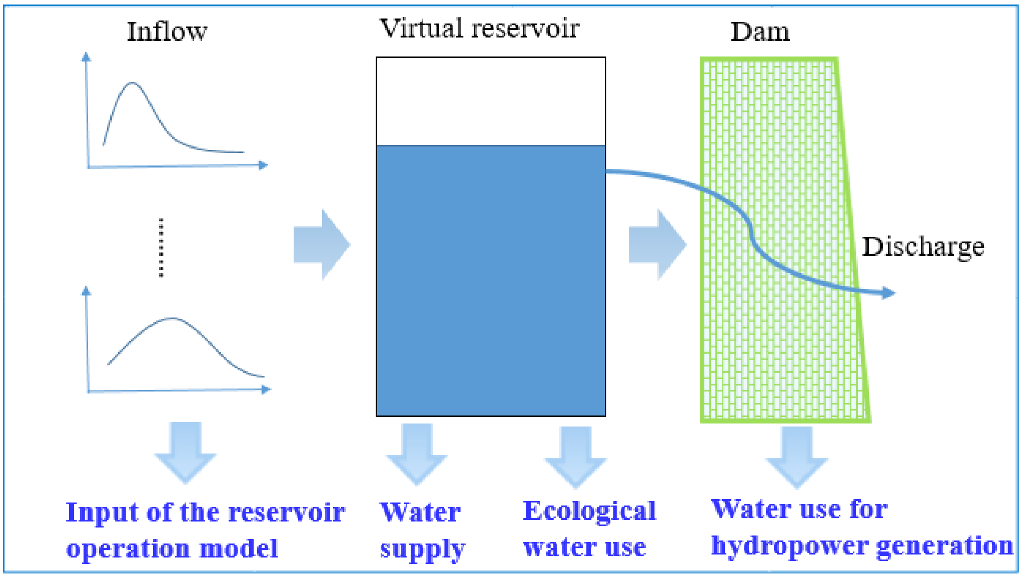


Figure 2 The virtual reservoir of the upper Yangtze River Basin.

3. Establishment of the joint distributions

In order to investigate the water supply, hydropower generation and environment nexus in a water resources system, a joint distribution was established in this section. Three variables were defined as follows. The first variable W represents the water use for human needs, including the domestic water demand, industrial and agricultural water demand. The second variable is related to the water used for hydropower generation. Since the amount of water used for hydropower is not easily quantified, the hydropower generation capacity is taken into account in this study, defined as variable P. In order to analyze the impact of water allocation on environment, the third variable E represents the water use for the basin environment.

3.1 Establishment of the marginal distributions

First the samples of the three variables (*W*, *P*, *E*) are assumed to be independent and identically distributed (IID). The marginal distribution was established based on the univariate hydrological frequency method. Many probability distribution models were developed and applied for hydrological studies, which mainly include the following two types: (a) two-parameter distributions such as Gumbel, Weibull, Gamma and Lognormal distributions (Leigh and Du, 2015; Jiang et al., 2015; Villarini et al., 2009); and (b) three-parameter distributions such as general extreme value (GEV) distribution (Cannon, 2011; El Adlouni et al., 2007) and Pearson type III distribution (Chen et al., 2011, 2015). The commonly used distributions in hydrology are selected to fit variables. In this study, the L-moment analysis method was used to evaluate the coefficients of these marginal distributions. The established marginal distribution is given by

$$u_W = F(W) = \int_0^w f_1(w)\mathrm{d}w \tag{1a}$$

$$u_P = F(P) = \int_0^p f_2(p)\mathrm{d}p \tag{1b}$$

$$u_E = F(E) = \int_0^e f_3(e)\mathrm{d}e \tag{1c}$$

where $f_1(w)$, $f_2(p)$ and $f_3(e)$ are probability density functions of water supply, hydropower and environment, respectively; u_W , u_P, and u_E or $F(W)$, $F(P)$, and $F(E)$ are their corresponding cumulative distribution functions, respectively.

In order to evaluate the performance of the marginal distributions, the empirical probability was needed. For the univariate case, the empirical probabilities were estimated by the Weibull plotting position formula (Makkonen, 2008),

$$F_{emp}(X_i) = \frac{i}{n+1}; i = 1, 2, \ldots, n \tag{2}$$

where X_i is observed data; n is the sample size; and $F_{emp}(X_i)$ is the empirical exceedance probability of the i^{th} observed data X_i.

3.2 Establishment of joint distributions

Bivariate and trivariate joint distributions were established to analyze the WPE nexus. For this purpose, the copula functions were used to establish such joint distributions (Sklar, 1959). The main advantage of copulas is attributed to its flexibility in the arbitrary selection of marginal dependence structures (Nelsen, 2006). The procedures for establishing the joint distribution were detailed as follows.

3.2.1 Establishment of bivariate joint distributions

As mentioned above, the variables W, P and E follow the selected marginal distribution functions $F(W)$, $F(P)$, and $F(E)$ respectively, so that there exist bivariate copulas that combine these marginal distribution functions to joint distributions. Accordingly, the three bivariate joint distributions are obtained for this study as follows.

$$F(W,P) = C(F(W), F(P)) = C(u_W, u_P) \tag{3a}$$

$$F(W,E) = C(F(W), F(E)) = C(u_W, u_E) \tag{3b}$$

$$F(P,E) = C(F(P), F(E)) = C(u_P, u_E) \tag{3c}$$

For bivariate case, Archimedes copulas have been widely used in the hydrology field (Nelson, 2006). Therefore, the Gumbel, Frank, and Clayton copulas of the

Archimedes copulas family were considered in this study.

3.2.2 Establishment of trivariate joint distribution

The trivariate joint distribution *F* (*W*, *P*, *E*), was established in this section. Since this is for high dimensional joint distributions, the Archimedes copulas can only simulate the *n*-1 dependence structure. For this purpose, the metaelliptical copula was used hereafter to build the trivariate joint distribution. The metaelliptical copula can model arbitrary pairwise dependencies between variables through a correlation matrix (Chen et al., 2013). The expression for trivariate distribution is given by

$$C(W,P,E)=\Phi_3(\Phi_1^{-1}(u_W),\Phi_2^{-1}(u_P),\Phi_3^{-1}(u_E);\boldsymbol{\rho}) \tag{4}$$

where $\Phi_3(\cdot)$ is the three-dimensional standard normal distribution; Φ_i^{-1} is the inverse function of standard normal distribution; and $\boldsymbol{\rho}$ is the correlation matrix.

For a multivariate case, the empirical probability can be expressed by (Zhang and Singh 2007a, b)

$$C'(u_1(i),u_2(i),\ldots,u_d(i))=\frac{\sum_{j=1}^{n}1(U_1(j)\le u_1(i),U_2(j)\le u_2(i),\ldots,U_d(j)\le u_d(i))}{n} \tag{5}$$

3.3 Model performance evaluation

In order to evaluate the performance of the developed marginal and joint distributions, the Root Mean Square Error (RMSE), Akaike Information Criterion (AIC) and K-S test were used together in this study for a comprehensive evaluation. The RMSE can be expressed by

$$RMSE_1 = \sqrt{\frac{\sum_{i=1}^{n}(F(x_i) - F_{emp}(x_i))^2}{n}} \tag{6a}$$

$$RMSE_2 = \sqrt{\frac{\sum_{i=1}^{n}(C(u_{1i}, u_{2i}) - C'(u_1(i), u_2(i)))^2}{n}} \tag{6b}$$

$$RMSE_3 = \sqrt{\frac{\sum_{i=1}^{n}(C(u_{1i}, u_{2i}, u_{3i}) - C'(u_1(i), u_2(i), u_3(i)))^2}{n}} \tag{6c}$$

where *n* is the sample size; $RMSE_1$, $RMSE_2$ and $RMSE_3$ are the RMSE values for marginal distributions, two-dimensional and three-dimensional joint distributions, respectively; $F(x_i)$ and $C(\cdot)$ are the theoretical probabilities of the marginal and joint distributions respectively; and $F_{emp}(x_i)$ and $C'(\cdot)$ are the empirical probabilities of the marginal and joint distributions respectively.

4. WPE nexus analysis

The conditional distribution and conditional expectation model were proposed to analyze the nexus of water supply, hydropower and environment variables.

4.1 Bivariate analysis of WPE nexus

The bivariate analysis model was built for investigating the bivariate nexus of water supply, hydropower, and environment. Accordingly, the nexus of water supply-hydropower, hydropower-environment, and water supply-environment were analyzed respectively based on the model established below.

Based on the bivariate joint distributions in Equation (3a-c), the pairwise conditional distribution function was constructed to analyze the risk or probability of variable $X_1 > x_1$ given $X_2 = x_2$. The variables X_1 and X_2 can be any two of water supply, hydropower, and environment. Two-dimensional conditional probability model can be expressed by

$$\begin{aligned} C(X_1 \mid X_2) &= P(X_1 \geq x_1 \mid X_2 = x_2) \\ &= \int_{x_1}^{+\infty} \frac{f(x_1, x_2)}{f(x_2)} dx_1 \\ &= \int_{x_1}^{+\infty} \frac{c(u_1, u_2) f(x_1) f(x_2)}{f(x_2)} dx_1 \\ &= \int_{u_1}^{1} c(u_1, u_2) du_1 \end{aligned} \tag{7}$$

where $f(x_1, x_2)$ is the joint probability density function (PDF) of variables x_1 and x_2; $f(x_1)$ and $f(x_2)$ are the PDFs of variables x_1 and x_2 respectively; u_1 and u_2 are the cumulative distribution functions (CDFs) of variables x_1 and x_2 respectively; and $c(u_1, u_2)$ is the density function of copula function.

The conditional distribution model can be used to evaluate the risk or probability of WPE nexus in the water resources system. However, in order to assess the expectation values of variable x_1 under the conditional of $X_2 = x_2$, the two-dimensional conditional expectation model was established as follows:

$$\begin{aligned} \bar{E}(x_1 \mid x_2) &= \int_{0}^{+\infty} x_1 \cdot f(x_1 \mid x_2) dx_1 \\ &= \int_{0}^{+\infty} x_1 \cdot f(x_1) \cdot c(u_1, u_2) dx_1 \end{aligned} \tag{8}$$

This model can be used to evaluate the average value of variable X_1 under the condition of $X_2 = x_2$. Taking the water supply W and hydropower generation P for an example, the expected value of water supply W given $P_2 = p_2$ can be calculated by the established two-dimensional conditional distribution. This value indicates the average water supply value given $P_2 = p_2$.

4.2 Trivariate analysis of WPE nexus

In this section, the trivariate model was established to analyze the nexus of water supply, hydropower, and environment in the water resources system. The three-dimensional conditional probability model and conditional expectation model were proposed here to evaluate the probability and expected value of variable X_1 given variables $X_2 = x_2$ and $X_3 = x_3$. The three-dimensional conditional probability model and conditional expectation model are expressed in Equations (9) and (10) respectively as below.

$$
\begin{aligned}
C(X_1 \mid X_2, X_3) &= P(X_1 \geq x_1 \mid X_2 = x_2, X_3 = x_3) \\
&= \int_{x_1}^{+\infty} \frac{c(u_1,u_2,u_3)\,f(x_1)\,f(x_2)\,f(x_3)}{c(u_2,u_3)\,f(x_2)\,f(x_3)}\,dx_1 \\
&= \int_{u_1}^{1} \frac{c(u_1,u_2,u_3)}{c(u_1,u_2)}\,du_1
\end{aligned}
\tag{9}
$$

$$
\begin{aligned}
\bar{E}(x_1 \mid x_2, x_3) &= \int_{0}^{+\infty} x_1 \cdot f(x_1 \mid x_2, x_3)\,dx_1 \\
&= \int_{0}^{+\infty} x_1 \cdot f(x_1) \cdot \frac{c(u_1,u_2,u_3)}{c(u_2,u_3)}\,dx_1
\end{aligned}
\tag{10}
$$

where u_1, u_2 and u_3 are the cumulative distribution functions of variables x_1, x_2 and x_3 respectively; and $c(u_1,u_2,u_3)$ is the density function of three-dimensional copula.

The variables X_1, X_2 and X_3 represent water supply, hydropower generation and environment in the water resources system. This trivariate model can be used to evaluate the average value of variable X_1 under the condition of $X_2 = x_2$ and $X_3 = x_3$. For example, considering the correlations among water supply W, hydropower generation P and environment E, the expected value of water supply W under the condition of hydropower generation $P = p$ and the environment $E = e$, can be calculated by the established three-dimensional conditional distribution. This value indicates the average water supply value given $P= p$ and $E = e$.

These expected values from the trivariate model analysis can provide a reference for rational and efficient water resources allocation, so as to improve the water resources utilization and reduce the potential risks of the water resources system development.

5. Results analysis

The proposed model was applied to the case study. First, the correlations among water supply, power generation and environment were analyzed. Then, the marginal distribution and joint distribution were established. Third, the conditional probability and expectation models were built to analyze the multiple risks in WPE nexus.

5.1 Correlation analysis of WPE nexus

The correlations between water supply and hydropower, water supply and environment, and hydropower generation and environment were calculated based on the Pearson linear correlation coefficient, as shown in Figure 3. On one hand, the results reveal that negative correlations exist between water supply and hydropower generation and between hydropower generation and environment. That is, when the hydropower generation capacity increases, the water uses for human beings (water supply) and environment in the basin with decrease accordingly. On the other hand, there exists a positive correlation between water supply and environment. This is reasonable, since for dry years more water would be withdrawn for human beings and environment in the basin, and vice versa. Thus, the water supply and environment present positive correlation to each other.

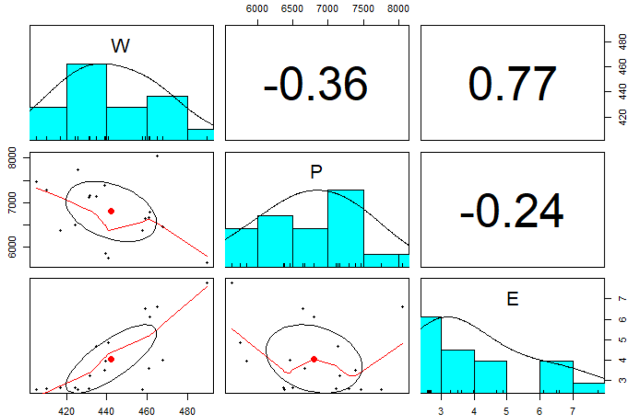


Figure 3 Correlation analysis of WPE nexus in the water resources system.

5.2 Results of joint distributions

For the case study, the marginal distributions of water supply, hydropower generation and environment were first obtained, followed by their joint distributions by different copula functions.

5.2.1 Marginal distributions

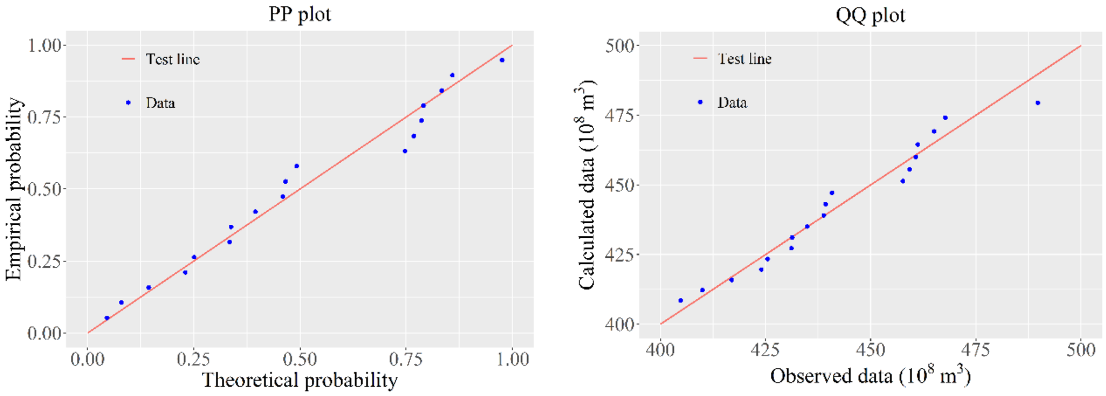
The commonly used marginal distributions were employed to fit the water supply, hydropower generation and environment series, respectively. The RMSE and K-S test indictors were used to evaluate the performance of the marginal distributions, and the goodness-of-fit results are given in Table 1. Based on these results, the GPA, GEV and GPA distributions are selected as the marginal distributions of water supply, hydropower generation and environment variables respectively, and the parameters of these distributions are listed in Table 2. The empirical probabilities of the marginal distributions were calculated by Equation (2). In order to better compare the fitting, the Q-Q plot (Quantile-Quantile plot) and P-P plot (Probability-Probability plot) were used for the observed and calculated data. The fitting curves of the marginal distributions are plotted in Figure 4. The comparison of results from these figures confirms that the marginal distributions can fit well with the empirical distributions.

Table 1 Goodness-of-fit results of marginal distributions.

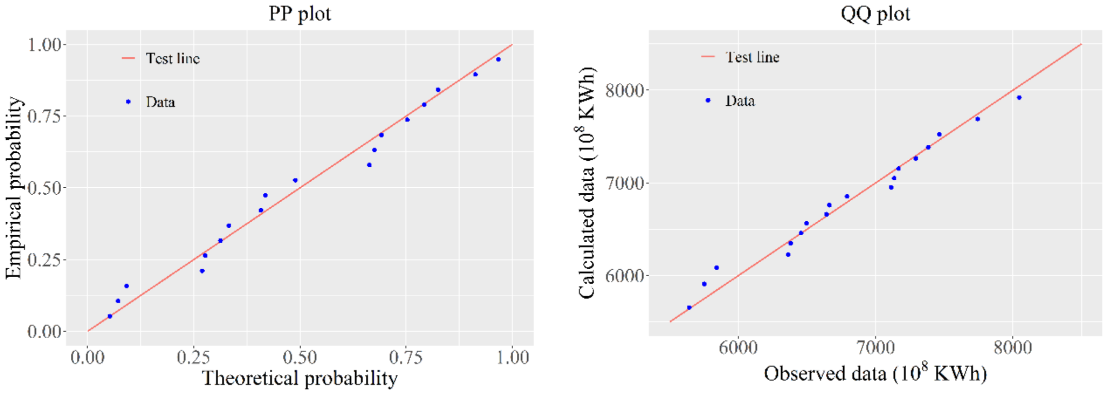
Distributions	Water supply			Hydropower			Environment		
	RMSE	AIC	K-S (P-value)	RMSE	AIC	K-S (P-value)	RMSE	AIC	K-S (P-value)
Exponential	0.0855	-33.73	0.7658	0.1033	-27.31	0.7658	0.0633	-40.25	0.9639
Gamma	0.0505	-48.80	0.9715	0.0415	-56.77	0.9999	0.0765	-33.72	0.7658
Normal	0.0518	-47.96	0.9715	0.0393	-58.51	0.9999	0.0971	-26.67	0.7658
Gumbel	0.0548	-48.60	0.9715	0.0645	-43.50	0.9715	0.0744	-34.89	0.7658
Weibull	0.0471	-50.73	0.9715	0.0375	-59.40	0.9999	0.0629	-40.31	0.9639
GEV	0.0476	-50.66	0.9715	**0.0374**	**-59.48**	**0.9999**	0.0746	-36.34	0.7658
GLO	0.0572	-45.71	0.9715	0.0453	-55.40	0.9715	0.0784	-35.16	0.7658
GPA	**0.0468**	**-50.31**	**0.9999**	0.0454	-51.42	0.9999	**0.0625**	**-40.47**	**0.9639**
GNO	0.0493	-49.67	0.9715	0.0388	-58.90	0.9999	0.0705	-37.61	0.7658
P-III	0.0492	-49.72	0.9715	0.0388	-58.90	0.9999	0.0631	-40.31	0.9639

Table 2 Estimated parameters for the marginal distributions.

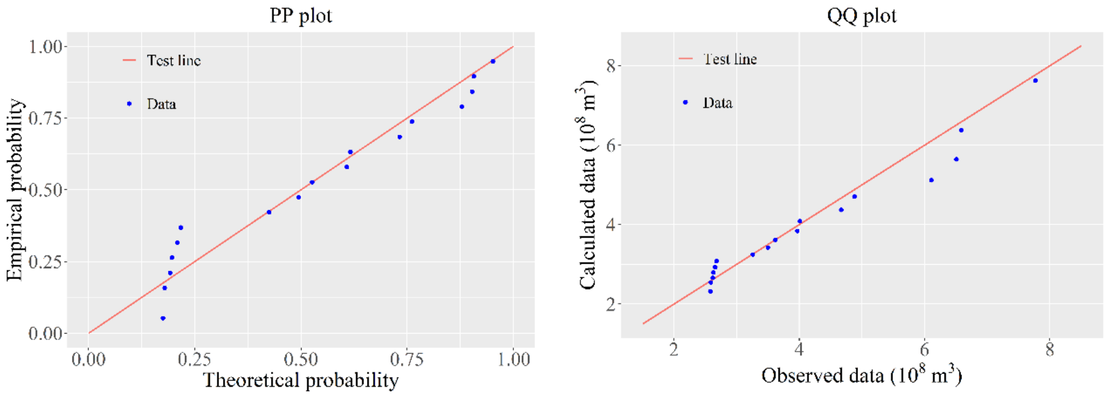
Indicators	Distributions	Estimated parameters		
		k	σ	μ
Water supply	GPA	-0.85015	69.051	404.84
Hydropower	GEV	-0.30922	707.21	6,561.2
Environment	GPA	-0.01966	1.8897	2.2157



(a) Water supply



(b) Hydropower



(c) Environment

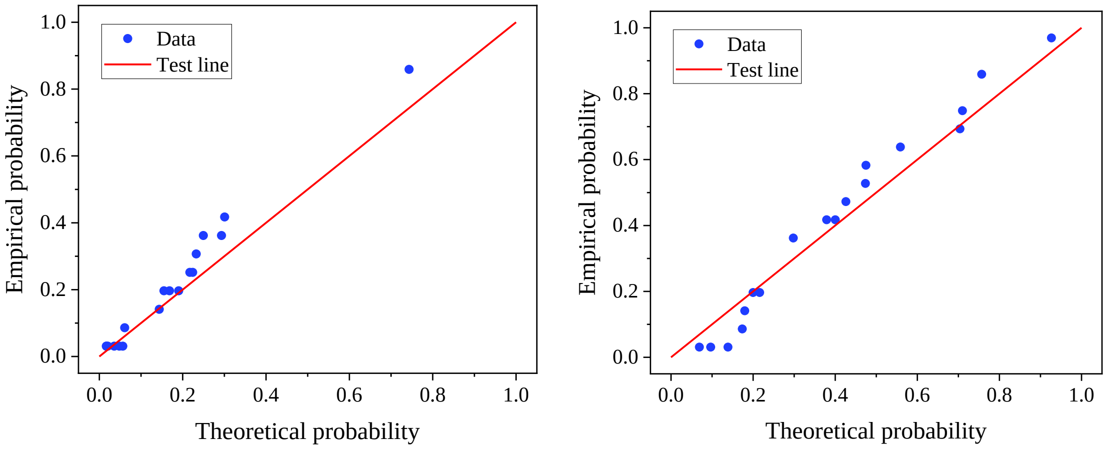
Figure 4 P-P and Q-Q plots for the variables of water supply, hydropower and environment.

5.2.2 Multivariate Joint distributions

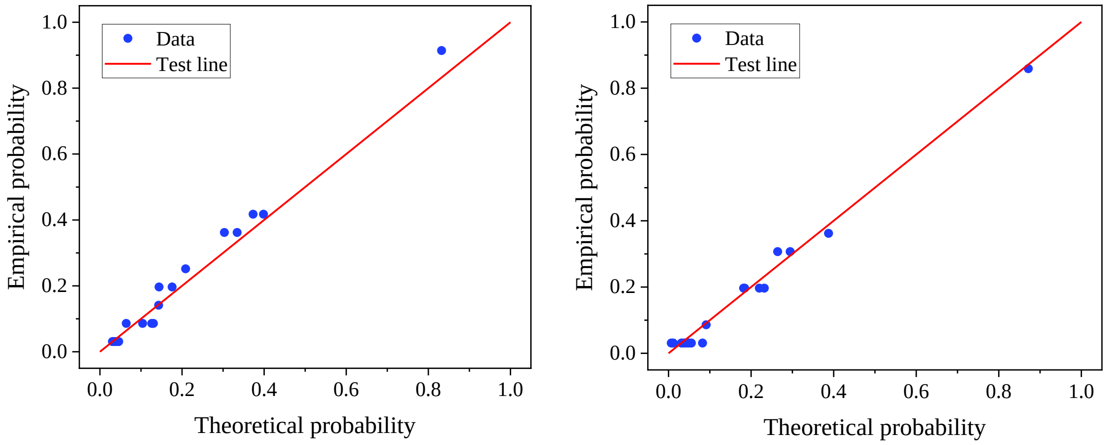
In this study, the Gumbel, Frank, and Clayton copulas were used to construct the two-dimensional joint distributions in the water resources system. Similarly, the performance and capability of the two-dimensional joint distributions were assessed through the analysis results of RMSE index and K-S test. The results are obtained and shown in Table 3, indicating that it is preferable to select the Frank copula to build the two-dimensional joint distributions in the water resources system. While for three-dimensional case, Gaussian copula was more suitable to construct the three-dimensional joint distribution. The parameters and fitting curves of these joint distributions are shown in Table 3 and Figure 5, respectively. It can be found from Figure 5 that the selected copula function fits very well with the empirical frequencies. The RMSE values and K-S test results in in Table 3 can testify again the suitability and validity of the used copula functions for this case study. Specifically, the RMSE values are relatively small for all the four joint distribution and the results of the K-S test (P-value) also demonstrate that the selection of the copula functions is acceptable to construct the joint distributions.

Table 3 Estimated parameters, RMSE and P-value of the K-S test for the joint distributions.

Indicators	(W, P)	(W, E)	(P, E)	(W, P, E)
Selected	Frank	Frank	Frank	Gaussian
Parameters	-3.1491	8.3879	-2.2240	Figure 3
RMSE	0.056	0.062	0.0357	0.0234
K-S (P-value)	0.7088	0.9448	0.7088	0.982



(a) Joint distribution of W and P (b) Joint distribution of W and E



(c) Joint distribution of P and E (d) Three-dimensional joint distribution

Figure 5 Fitting curves of joint distributions.

5.3 Multiple-risk analysis of WPE nexus

Based on the established conditional probability and expectation models, the potential risks in the water resources system under different threshold conditions were evaluated in this section.

5.3.1 Results of bivariate risk analysis

The conditional distributions and conditional expectation models were used to assess the potential risks related to the water supply, hydropower and environment in the water resources system.

First, according to Equation (7), the two-dimensional conditional distribution model was established to calculate the probabilities of $X_1>x_1$ given $X_2=x_2$, and the results of water supply and hydropower, water supply and environment, and hydropower and environment are given in Tables 4, 5 and 6, respectively.

Table 4 Results of conditional probability analysis for water supply and hydropower nexus

$C(W\|P)$			$C(P\|W)$		
P (10^8 kW·h) $F(P)$	W (10^8 m^3) $F(W)$	$C(W \geqslant w \| P=p)$	W (10^8 m^3) $F(W)$	P (10^8 kW·h) $F(P)$	$C(P \geqslant p \| W=w)$
7,185 (70 %)	456.88 (70 %)	0.1631	456.88 (70 %)	7,185 (70 %)	0.1631
	465.39 (80 %)	0.0952		7,410 (80 %)	0.0952
	474.59 (90 %)	0.0416		7,708 (90 %)	0.0416
7,410 (80 %)	456.88 (70 %)	0.1246	465.39 (80 %)	7,185 (70 %)	0.1246
	465.39 (80 %)	0.0713		7,410 (80 %)	0.0713
	474.59 (90 %)	0.0307		7,708 (90 %)	0.0307
7,708 (90 %)	456.88 (70 %)	0.0941	474.59 (90 %)	7,185 (70 %)	0.0941
	465.39 (80 %)	0.0531		7,410 (80 %)	0.0531
	474.59 (90 %)	0.0226		7,708 (90 %)	0.0226

The two-dimensional conditional distribution was used to calculate the probability of water supply exceeding a threshold value ($W > w$) given hydropower generation $P=p$, or the probability of hydropower generation exceeding a threshold value ($P>p$) given water supply $W=w$. The results in Table 4 show that, under the condition of hydropower generation being 7,185×10^8 kW·h with an occurrence frequency of 70 %, the probability of water supply exceeding 456.88×10^8 m^3 (with frequency of 70 %) is 16.31 %, and that of water supply exceeding 465.39×10^8 m^3 (with frequency of 80 %) or 474.59×10^8 m^3 (with frequency of 90 %) reduces to only 9.52 % or 4.48 %, respectively. Moreover, the results also indicate that the probability of water supply exceeding a threshold value, for example 456.88×10^8 m^3, decreases gradually with an increase of hydropower generation capacity. Therefore, in order to improve the water use efficiency, it is expected to achieve a balance of the water resources allocation between water supply and hydropower generation.

Table 5 Results of conditional probability analysis for water supply and environment nexus.

$C(W\|E)$			$C(E\|W)$		
E (10^8 m^3) $F(E)$	W (10^8 m^3) $F(W)$	$F(W \geqslant w \| E=e)$	W (10^8 m^3) $F(W)$	E (10^8 m^3) $F(E)$	$F(E \geqslant e \| W=w)$
4.4641 (70 %)	456.88 (70 %)	0.4797	456.88 (70 %)	4.4641 (70 %)	0.4797
	465.39 (80 %)	0.2603		5.2094 (80 %)	0.2603
	474.59 (90 %)	0.0959		6.4699 (90 %)	0.0959
5.2094 (80 %)	456.88 (70 %)	0.6808	465.39 (80 %)	4.4641 (70 %)	0.6808
	465.39 (80 %)	0.4488		5.2094 (80 %)	0.4488
	474.59 (90 %)	0.1971		6.4699 (90 %)	0.1971
6.4699 (90 %)	456.88 (70 %)	0.8315	474.59 (90 %)	4.4641 (70 %)	0.8315
	465.39 (80 %)	0.6532		5.2094 (80 %)	0.6532
	474.59 (90 %)	0.3623		6.4699 (90 %)	0.3623

According to the former correlation analysis, there is a positive correlation between water supply and environmental water use. When the water supply increases, the ecological water use will inevitably increase, as shown in Table 5. It is also found from Table 5 that under the condition of ecological water use being 5.0294×10^8 m^3 (with frequency of 80 %), the probability of water supply exceeding 465.39 ×10^8 m^3 (with frequency of 80 %) is 44.88 %. With the increase of ecological water use to 6.4699×10^8 m^3 (with frequency of 90 %), the probability of water supply exceeding 465.39×10^8 m^3 increases to 65.32 %.

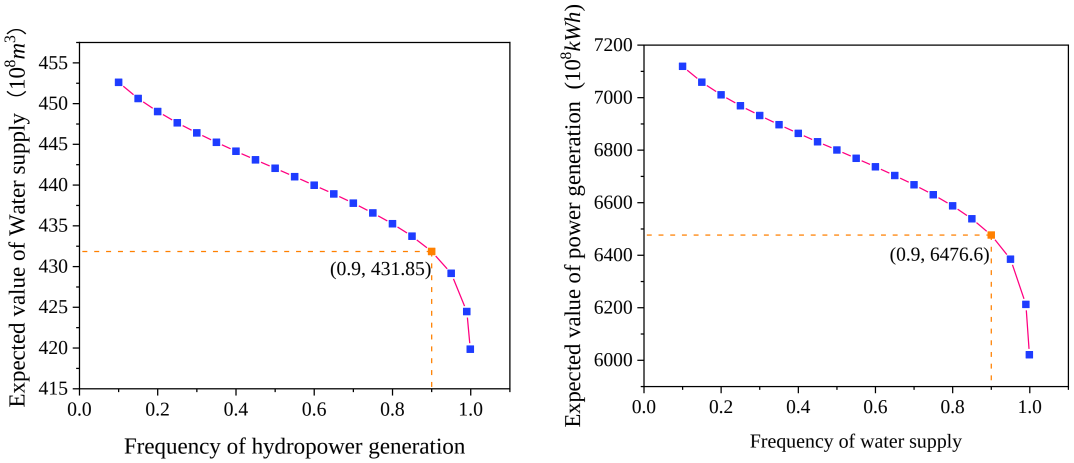
Table 6 Results of conditional probability analysis for hydropower and environment nexus.

$C(P\|E)$			$C(E\|P)$		
E (10^8 m^3) $F(E)$	P(10^8 kW·h) $F(P)$	$F(P \geqslant p \|E=e)$	P (10^8 kW·h) $F(P)$	E (10^8 m^3) $F(E)$	$F(E \geqslant e \|P=p)$
4.4641 (70 %)	7,185 (70 %)	0.2022	7,185 (70 %)	4.4641 (70 %)	0.2022
	7,410 (80 %)	0.1244		5.2094 (80 %)	0.1244
	7,708 (90 %)	0.0572		6.4699 (90 %)	0.0572
5.2094 (80 %)	7,185 (70 %)	0.1687	7,410 (80 %)	4.4641 (70 %)	0.1687
	7,410 (80 %)	0.1021		5.2094 (80 %)	0.1021
	7,708 (90 %)	0.0464		6.4699 (90 %)	0.0464
6.4699 (90 %)	7,185 (70 %)	0.1397	7,708 (90 %)	4.4641 (70 %)	0.1397
	7,410 (80 %)	0.0835		5.2094 (80 %)	0.0835
	7,708 (90 %)	0.0375		6.4699 (90 %)	0.0375

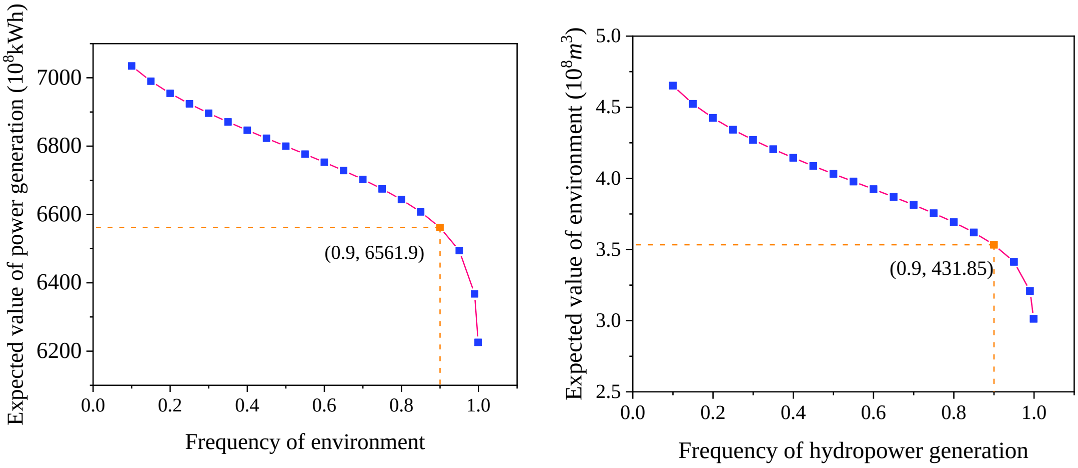
For the hydropower and environmental water consumption subsystem, since there is a competition relationship between them (i.e., negative correlation in Figure 3), the ecological water consumption decreases with the increase of hydropower generation capacity in the basin, with results shown in Table 6. The probability of ecological water consumption exceeding 4.4641×10^8 m^3 (corresponding to a frequency of 70 %) is 20.22 %

under the condition of hydropower generation being 7,185×10^8 kW·h (corresponding to a frequency of 70 %). However, under the condition of hydropower generation being 7,708×10^8 kW·h (with corresponding frequency of 90 %), the probability of ecological water consumption exceeding 6.4699×10^8 m^3 (with same frequency of 90 %) reduces to 3.75 % only. Therefore, in order to reduce the risks of water supply insufficiency, the allocation of water resources for hydropower and ecological water consumption in the basin should not be too high.

In order to further analyze the expected level of each variable under different conditions, the two-dimensional conditional expectation model was used to calculate these expected levels. The results are obtained and plotted in Figure 6. It is indicated from Figure 6(a) that the expected value of water supply decreases with the increase of hydropower generation. Particularly, when the frequency of hydropower generation exceeds 90 %, the expected value of water supply decreases sharply. Thus, the frequency of hydropower generation exceeding this point may lead to an obvious reduction of water resources utilization efficiency in the water resources system, which means that the water supply in the basin will be seriously insufficient. Furthermore, Figure 6(b) shows that the expected value of hydropower generation will decrease sharply when the frequency of water supply exceeds 90 %, indicating the water supply in the basin should not exceed this threshold value so as to maintain the overall sustainability and efficiency of the water resources system. Similarly, results in Figures 6(c) and (d) demonstrate that a threshold value is also existent between the environmental water consumption and hydropower generation. When the environmental water consumption and hydropower generation exceeds this threshold value, the utilization efficiency of water resources in the subsystems will decrease, and thereby the hydropower generation or ecological water consumption in the basin will be seriously insufficient.



(a) $E(W|P)$ (b) $E(P|W)$



(c) $E(P|E)$ (d) $E(E|P)$

Figure 6 Expected level for two-dimensional water resources system.

A synergistic relationship is expected for the water supply and environmental water consumption subsystems. However, when the water supply and environmental consumption increase, the expected value of hydropower generation will decrease accordingly. Therefore, it is necessary to perform a more comprehensive analysis the water resources system by simultaneously considering the water supply, hydropower generation and environmental water variables, which is elaborated in the following study.

5.3.2 Results of trivariate risk analysis

For the studied case in Figure 1, concerning the multiple uses of water supply, hydropower generation and environmental water, the results of three-dimensional conditional probability model are obtained and shown in Table 7.

Table 7 Results of the three-dimensional conditional probabilities

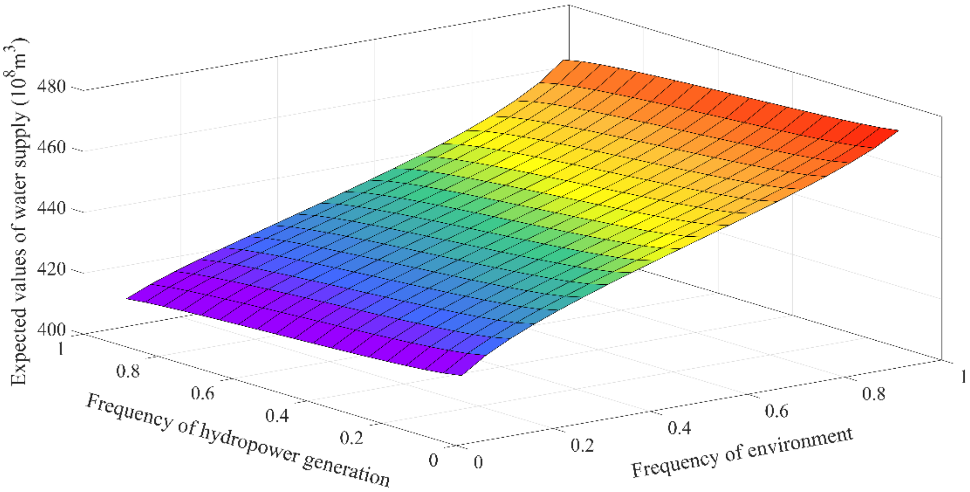
H	*F*(*H*)	*E*	*F*(*E*)	*W*	*F*(*W*)	*C* (*W*|*P*, *E*)
7,410	80 %	5.2094	80 %	465.39	80 %	27.61 %
7,410	80 %	5.2094	80 %	474.59	90 %	9.31 %
W	*F*(*W*)	*E*	*F*(*E*)	*H*	*F*(*H*)	*C* (*H*|*W*, *E*)
465.39	80 %	5.2094	80 %	7,410	80 %	11.15 %
465.39	80 %	5.2094	80 %	7,708	90 %	4.55 %
W	*F*(*W*)	*H*	*F*(*H*)	*E*	*F*(*E*)	*C* (*E*|*W*, *H*)
465.39	80 %	7,410	80 %	5.2094	80 %	39.64 %
465.39	80 %	7,410	80 %	6.4699	90 %	16.69 %

Given the hydropower generation of 7,410×10^8 kW·h and the ecological water use of 5.2094×10^8 m^3, the probabilities of the water supply exceeding 465.39×10^8 m^3 and 474.59×10^8 m^3 are 27.61 % and 9.31 % respectively. Clearly, the probability of water supply exceeding 465.39×10^8 m^3 calculated by the three-dimensional model is greater than that calculated by the two-dimensional model, namely

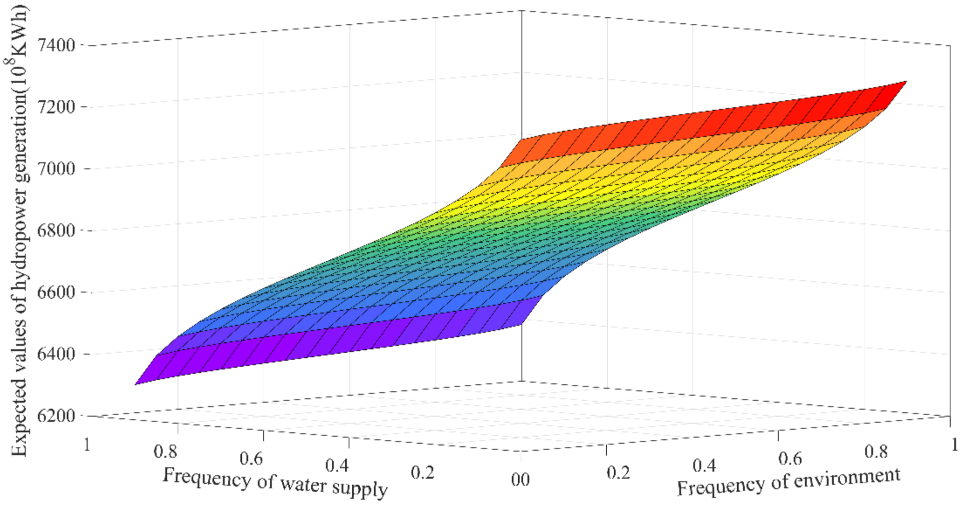
$$\begin{aligned} &C(W \geq 465.39 \mid H = 7,410, E = 5.2094) = 27.61\,\% \\ &> C(W \geq 465.39 \mid H = 7,410) = 11.01\,\% \end{aligned} \tag{10}$$

This difference may be explained as follows. For two-dimensional model, the competitive relation exits in the water supply and hydropower generation sub-systems. While for the three-dimensional model, in addition to the competitive relation between the water supply and hydropower generation, the positive relationship between upstream ecological water consumption and water supply is also considered in the analysis. In other words, the increase of ecological water consumption indicates abundant precipitation and water resources in that year, and therefore the probability of water supply exceeding a certain threshold also becomes relatively high in the water resources system.

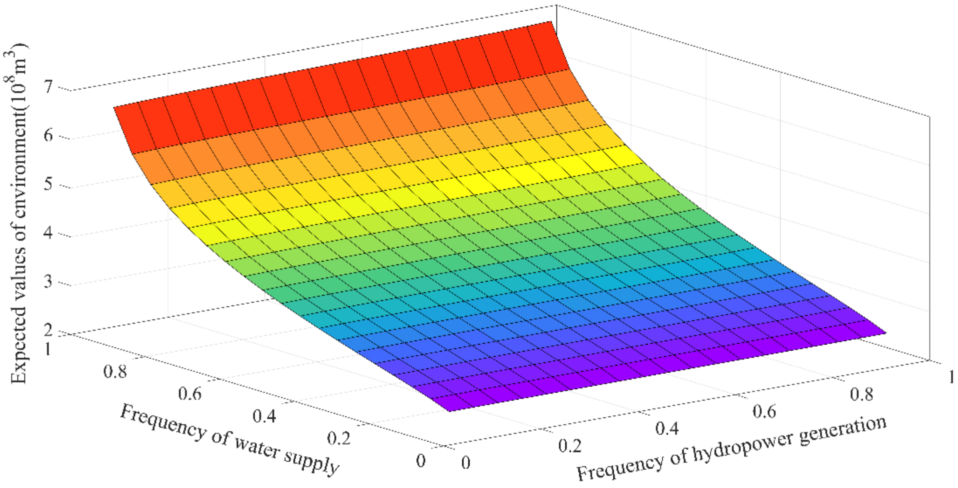
For clarity, the variation of the expected level of a specific variable with the frequencies of the other two variables is calculated by the three-dimensional conditional expectation model, and the results are plotted in Figure 7. It is shown from Figure 7(a) that the expected values of water supply decreases with the increase of both the hydropower generation capacity and the ecological water consumption. For the expected value of water supply being 465.39×10^8 m^3 (with corresponding frequency of 80 %), many different combinations of hydropower generation and ecological water consumption could be retrieved, with some of which shown in Table 8. For example, when the ecological water consumption is 5.64×10^8 m^3 (i.e., $F(E)$=84.2 %) and the hydropower generation is $5{,}892\times10^8$ kW·h (i.e., $F(P)$=10.1 %), the expected level of water supply may attain to 465.39×10^8 m^3. However, under this situation, the potential risk of low hydropower generation capacity appears in the water resource system.



(a) Expected values of water supply



(b) Expected values of hydropower generation



(c) Expected values of environment

Figure 7 Expected levels for three-dimensional water resources system.

Table 8 Expected water supply value for specific hydropower generation ($P=p$) and environmental water consumption ($E=e$)

Expected water supply value ($F(W)$)	$F(P)$	Hydropower generation ($\times 10^8$ kW·h)	$F(E)$	Ecological water consumption ($\times 10^8$ m^3)
465.39×10^8 m^3 (80 %)	**10.1 %**	**5,892**	**84.2 %**	**5.64**
	20.4 %	6,209	86.5 %	5.93
	50 %	6,806	90.1 %	6.49
	70.1 %	7,188	92 %	6.87
	95 %	7,935	95.1 %	7.75

Table 9 Expected hydropower generation for specific water supply $W=w$ and environmental water consumption $E = e$.

Expected hydropower generation value ($F(P)$)	$F(W)$	Water supply ($\times 10^8$ m^3)	$F(E)$	Ecological water consumption ($\times 10^8$ m^3)
$7{,}186\times 10^8$ kW·h （70 %）	6 %	409	11.1 %	2.44
	7.4 %	409.98	43.3 %	3.28
	8 %	410.40	59.3 %	3.90
	8.3 %	410.61	66.6 %	4.27
	9.5 %	**411.45**	**87.6 %**	**6.08**

In Figure 7(b), the expected hydropower generation value decreases with the increase of water supply, while slowly increases with the ecological water consumption. Similarly, the expected hydropower generation values were calculated by the proposed model, and the results are listed in Table 9. For the expected value of hydropower generation being $7{,}186\times 10^8$ kW·h, different combinations of water supply and ecological water consumption can also be retrieved, as shown in Table 9. For instance, if the ecological water consumption is 6.08×10^8 m^3 (i.e., $F(E)$=87.6 %), the water supply becomes only 411.45×10^8 m^3 and its corresponding frequency is less than 10 %, indicating the potential risk of water supply insufficiency in the water resources system. Therefore, under this condition, it is difficult to maximize the overall efficiency of water resources utilization in this system.

Table 10 Expected environmental water use for specific water supply (W=w) and hydropower generation (P=p)

Expected environmental water use ($F(E)$)	$F(W)$	Water supply (×10^8 m^3)	$F(P)$	Hydropower generation (×10^8 kW·h)
5.2094×10^8 m^3 (80 %)	81.5 %	466.71	97.9 %	8,153
	82.5 %	467.61	64.4 %	7,074
	83.5 %	468.51	8.7 %	5,834
	84 %	468.96	1.2 %	5,226

Figure 7(c) shows the expected environmental water use increases with the water supply, and the results are listed in Table 10. Meanwhile, the expected environmental water use slowly increases with the increase of hydropower generation capacity. In order to achieve the expected ecological water consumption of 5.2094×10^8 m^3, with the water supply of 466.71×10^8 m^3 (i.e., $F(w)$=81.5 %), the frequency of hydropower generation can reach relatively high level at 97.9 %. However, the frequency of hydropower generation declines sharply with the increase of the water supply. For instance, when the frequency of water supply increases from 81.5 % to 84.0 %, the frequency of hydropower generation decreases from 97.9 % to 1.2 % only. In order words, when the frequencies of water supply and hydropower generation are 81.5 % and 97.9 % respectively, the expected ecological water consumption can attain to

5.2094×10^8 m^3. From this perspective, it is feasible to maximize the overall efficiency of water resources utilization and at the same time, to minimize the potential multiple risks in the water resources system.

Table 11 Comparisons of expected values calculated by the bivariate and trivariate models (10^8m^3)

$F(E)$	$\bar{E}(W\vert E)$	$\bar{E}(W\vert H, E)$; $F(H) = 0.8$	$\bar{E}(W\vert H, E)$; $F(H) = 0.9$
0.1	418.93	417.39	416.27
0.2	425.57	423.30	421.86
0.3	431.20	428.37	426.74
0.4	436.45	433.16	431.39
0.5	441.59	437.92	436.05
0.6	446.81	442.84	440.92
0.7	452.36	448.17	446.25
0.8	458.58	454.30	452.43
0.9	466.32	462.22	460.54

For further inspection, the results of the two-dimensional and three-dimensional conditional expectation models are compared and shown in Table 11. In the table, $\bar{E}(W|E)$ represents the expected value of water supply when the upstream ecological water use is given; and $\bar{E}(W|H, E)$ represents the expected value of water supply, when the hydropower generation and the upstream ecological water use are given. It can be seen from Table 11 that when considering the impact of hydropower generation, the expected value of water supply will decrease due to the competitive relationship between the hydropower generation and water supply, namely $\bar{E}(W|E) > \bar{E}(W|H, E)|_{F(H) = 0.8} > \bar{E}(W|H, E)|_{F(H) = 0.9}$.

5.3.3 Comparative analysis with the observed data

In order to testify the rationality of the proposed model, the observed hydropower and ecological water consumption data were substituted into the model to calculate the expected value of water supply with fixing hydropower generation and environmental water use. First, the probabilities $F(W)$, $F(P)$ and $F(E)$ were calculated by the marginal distribution based on the observed data. Then, two variables, namely the hydropower generation and environmental water use were set as conditional constraints, and the expected water supply values were calculated by the proposed model. Finally, the calculated expected values were compared with the observed data, as shown in Figure 8. The overall results of Figure 8 imply that the expected water supply values from the proposed model may represent the average level of the data. Specifically, the calculated expected values are not far from the observed data, in which 9 years' data exceeding the expected values and other 9 years' data below the expected values. Consequently, the comparison of Figure 8 demonstrates the rationality and accuracy of the proposed method in this study.

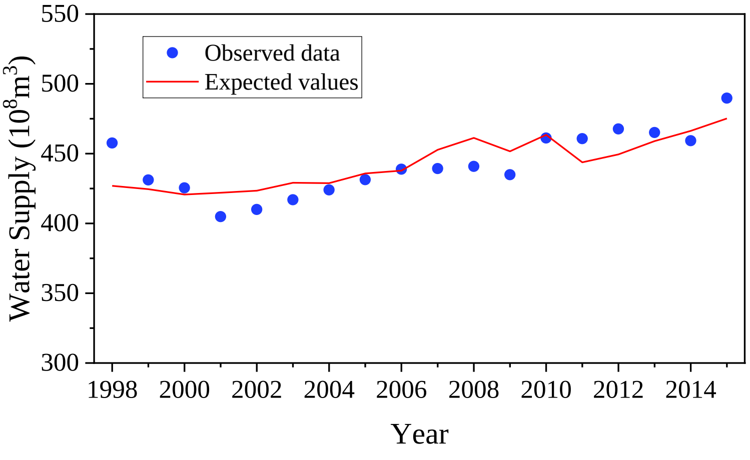


Figure 8 Comparison between the observed data and expected values by the proposed model.

6. Discussions

Global climate change brings great challenge in hydrological predictions and increases the uncertainties in water resources system management. Thus, the impacts caused by climate change on the water resources system should be further studied and analyzed.

Climate change affects the intensity and distribution of the rainfall in the basin. which also influences the soil erosion. The sediment deposition from the upstream catchment may lead to the gradual decrease of the effective reservoir volume, so as to affect the operations and functions of the reservoir system (Chaudhry et al., 2014; Chen, 2018). The hydropower generation of the reservoir also reduces with the decrease of the reservoir storage volume (Chen, 2018). Therefore, the change in sediment yield can affect the reservoir storage volume and hydropower production.

In addition, the uncertainties in the runoff prediction also impose an influence on the hydropower generation. Because of the uncertainties in hydrological model, there are errors in runoff predictions. The predicted runoff is usually used as the inputs of the reservoir operation model. When the predicted runoff in the flood season is larger, the reservoir will increase the discharge for flood control. However, increasing the discharge of the reservoir can affect the efficiency of hydropower generation. Therefore, the uncertainty of runoff forecast leads to the uncertainty of reservoir operation process. To summarize, identifying the major sources of uncertainties of the water resources system and reducing it can improve the accuracy of quantitative evaluation of the water resources system.

Finally, it is worthy of noting that there are also some limitations for using the proposed models in this study for multiple-risk analysis in the water resources system. First, variables in the proposed models must be relevant. Second, the proposed model is not applicable when the correlation between variables is too small.

7. Conclusions

This paper investigated the multiple-risk assessment for the water resources system under a comprehensive nexus of water supply, hydropower, and environment (termed as WPE nexus in this study). A joint analysis method, namely copula method, was introduced to address the dependences of the three variables (water supply, hydropower and environment) in the WPE nexus. The marginal distributions of these three variables were first built based on the hydrological distributions, followed by the bivariate and trivariate joint distributions established using the copulas. The nexus analysis of the three variables of water supply, hydropower generation and environment was performed for their influences and contributions to the risk of the water resources system. To this end, the conditional probabilities and the expected values were calculated for the multiple-risk evaluation. For demonstration of the developed method framework, the upper Yangtze River Basin was selected for the case study. Based on the application results and analysis, the main findings and conclusions are summarized as follows.

(1) Based on the correlation analysis, the results revealed the negative correlations between water supply and hydropower generation as well as between the

hydropower generation and environmental water consumption, indicating the competitive relations within these variables. Meanwhile, a positive correlation was found between water supply and environment, which implies the synergistic relationship between these two variables;

(2) Relatively small RMSE values were observed between the empirical and theoretical probabilities. The results of both RMSE and P-values (for K-S test) confirmed the suitability of the selection of copula functions to construct the joint distributions for the studied case in this study;

(3) Bivariate nexus analysis demonstrated that the probability of water supply exceeding a threshold value decreases gradually with the increase of hydropower generation, while increases with the growing of the ecological water consumption; and that of the ecological water consumption decreases with the increase of hydropower generation. In particular, when the frequency of hydropower generation exceeds 90 %, the expected values of both water supply and environment will present sharply decreasing trends.

(4) Through the trivariate nexus analysis, many different combinations of hydropower generation and ecological water consumption could be retrieved to achieve the expected water supply values in the water resources system. However, potential risks were also observed for some specific combinations for practical use. Based on the trivariate nexus analysis method, an overall balanced situation is expected to be achieved for the WPE nexus of the water

resources system.

The contributions and novelty of this study may include following aspects: (i) the WPE nexus in the water resources system was first investigated using the bivariate and trivariate distribution methods; (ii) the expectation model was proposed to analyze the complex dependence relationships of WPE nexus in the water resources system; (iii) the proposed models and methods were testified through the observation data from the Water Resources Bulletin of China. The results and findings of this study may provide useful framework and basis for the water resources system management, in the context of multi-function system development for water supply and demand, hydropower and environment.

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