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RESEARCH ON RISK AND EARLY WARNING SYSTEM OF INTER-BASIN MULTI-RESERVOIR WATER TRANSFER-SUPPLY OPERATION WITH CONSIDERATION OF UNCERTAIN FACTORS†

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ABSTRACT

According to traditional risk assessment methods it is impossible to have a quantitative analysis of the nonlinear relationship between uncertain factors of inter-basin reservoir regulation. So, fuzzy mathematics and a mixed Copula function are used in this paper to determine existing water supply indexes. The joint probability distribution of runoff forecasting and water demand is simulated and it also makes a quantitative analysis of future flows. The information entropy principle is applied to determine early risk warning index and signals, and emergency water shortage measures are established for an inter-basin water transfer-supply operation. Then the early warning decision system of reservoir optimization water supply dispatching is built up. A practical example computation shows that the information of water supply and water shortage can be described effectively with such an early risk warning system regarding donor and recipient reservoirs. The early risk warning method is applied for the first time, which simultaneously takes into account water inflow, water utilization and water shortage regarding donor and recipient reservoirs. Copyright © 2018 John Wiley & Sons, Ltd.

KEY WORDS: inter-basin; multi-reservoir operation; early risk warning system; mixed Copula function; early warning signals; uncertain factor; emergency water shortage measures

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RÉSUMÉ

Selon la méthode traditionnelle d'évaluation des risques, il est impossible d'avoir une analyse quantitative de la relation non linéaire entre les facteurs incertains de la régulation des réservoirs inter-bassins. Ainsi, les mathématiques floues et la fonction mixte de Copula sont utilisées dans cet article pour déterminer les indices d'approvisionnement en eau existants. La distribution de probabilité conjointe de la prévision des eaux de ruissellement et de la demande en eau est simulée et elle effectue également une analyse quantitative des flux futurs. Le principe de l'entropie de l'information est appliqué pour déclencher une alerte précoce et mettre en œuvre les mesures d'urgence en cas de pénurie en transférant l'eau entre bassins. Ensuite, le système de décision d'alerte précoce lance l'optimisation du réservoir d'approvisionnement en eau. Un exemple pratique de calcul montre que l'information sur l'approvisionnement en eau et la pénurie d'eau concernant le réservoir donneur et le réservoir receveur peut être décrite efficacement avec un tel système d'alerte précoce. La méthode d'alerte précoce est appliquée pour la première fois en tenant compte simultanément de l'afflux d'eau, de l'utilisation de l'eau et de la pénurie d'eau des réservoirs donneur et receveur. Copyright © 2018 John Wiley & Sons, Ltd.

MOTS CLÉS: inter-bassin; système multi-réservoir; système d'alerte précoce des risques; fonction mixte de Copula; signaux d'avertissement précoce; facteur incertain; mesures d'urgence en cas de pénurie d'eau

INTRODUCTION

An inter-basin reservoir multi-reservoir water supply operation is an important element of inter-basin water diversion, but because of the limit of randomness of runoff and forecasting techniques, this increases the uncertainty and risk

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of the multi-reservoir optimal water supply operation. Because of the numerous reservoirs, and complex hydraulic and spatial relations, the risk and early warning system of an inter-basin multi-reservoir operation becomes a key scientific issue.

In recent years, research on optimal reservoir operation has received more and more attention, which provides favourable theoretical technical support for the development of optimized operation schemes. However, research on reservoir operation decision and risk assessment techniques has progressed slowly. Only one or few sector risks have attracted attention, and it is difficult to completely cover the intrinsic connection, interaction and transformation among the various objectives of complicated reservoir operation with consideration of the uncertain hydrological conditions (Mateus and Desiree, 2016; Alvar *et al.,* 2017). Therefore, the risk and early warning system of a water transfer-supply operation is studied and it is significant for improving the manoeuvrability of the reservoir operation scheme.

At present, research has concentrated on the definition and selection of water supply risk indexes by domestic and overseas scholars. Some suggestions of the selection of water supply risk indexes were proposed by Kjeldsen and Rosbjerg (2004); the definition and selection of water risk indexes were established and the weight determination method proposed for a risk index system with a combination of various efficiency indexes of reservoir operation by Wang *et al.* (2014). Generally, the water supply risk index system is built in respect of water supply reliability, recoverability, vulnerability and destruction, but it cannot fully reflect the possibility of water events occurring, nor quantify the consequences of water scarcity (Harding *et al.,* 1995; Fang *et al.,* 2007; Fu *et al.,* 2012). There has been some research on the risk analysis of inter-basin multi-reservoir water supply operations. The risk assessment of an inter-basin reservoir operation was studied by Xi *et al.* (2010) in respect of the rainfall forecast; though the overall risk is determined by the index weight vector used (determined by the decision-makers), it is difficult to describe the water transfer risk and degree of risk.

Considering the complexity, uncertainty, dynamic and comprehensive utilization nature of reservoir operations, the various types and aspects of risk assessment should be involved in the future risk analysis process of optimal reservoir operation. Taking into account the complex relationship between different factors of risk, how to build an early warning system of risk degrees based on existing methods of risk assessment has been investigated little at home and abroad.

Related research of an early risk warning system for reservoir operation starts from the flood disaster risk. The real-time flood early warning model during typhoons was studied by Huang and Hsieh (2010), and a genetic algorithm was applied to solve the flood regulation process, which guided the reservoir real-time operation. The early flood warning system was applied to the Turkey basin system (Ismail, 2015). There is much research on drought early warning; for example, the corn drought early warning in north-west China was studied from the aspect of geography and climatology, and the early risk warning model of drought disaster was established in order to early warning the corn drought degree during drought disaster (Zhang *et al.,* 2014). The drought early warning system was studied in combination with the relation between precipitation and groundwater, which can provide a basis for managing the reaction to drought in irrigated areas (Liu and Huang, 2015). In an early warning about the water supply, the primary effect factors on the water supply in the mainstream of the middle and lower reaches of the Hanjiang River were analysed by identifying the risk source, and the sensitivity of water supply risk to primary effect factors was analysed and computed (Chang *et al.,* 2011). The concept of point early warning and process early warning were proposed, and a quantitative identification measure of middle-sized reservoir early warning was presented by Cao *et al.* (2013); however, it only conducted an early warning system with the reservoir available water supply and obtained early warning results by comparing reservoir storage limit line, which did not fully consider various random and uncertain risk factors of the reservoir water supply operation.

There are many uncertain factors in an inter-basin reservoir group water supply optimized operation; they include not only uncertainty of runoff and water utilization, but consist of a series of uncertainties such as operation time, water diversion quantity and water shortage risk of donor and recipient reservoirs (Chang *et al.,* 2013; Wan *et al.,* 2016). As a highly dimensional and complicated allocation of a water resources system, under the joint action of many uncertainty factors, how to describe and identify the risk process of uncertainty factors, determine the interrelationships among those risk factors, and evade the decision risk of a reservoir group water supply operation is a key scientific problem that needs to be solved in this research field.

In this paper, the risk and early warning decision system is explored and fuzzy mathematics and mixed Copula are adapted to determine the early risk warning index and signals in an inter-basin reservoir group transfer project. The LuanHe River is used as a case study by using 50 years of actual measured runoff series data from 1 January 1962 to 31 December 2011. The result shows that the suggested method can achieve the operational goal effectively.

MODELLING OF RISK AND EARLY WARNING SYSTEM

In an inter-basin reservoir group water supply optimized operation, risk factors include the following: (i) the uncertainty of natural inflow during water diversion and supply; (ii) the occasion and quantity of water diversion and supply; (iii) water shortage during non-flood periods, but surplus water during flood seasons. Therefore, inter-basin reservoir operation risk mainly lies in inflowing runoff, the current pool level of the donor and recipient reservoirs, future water shortage of different water utilization departments and the management level of decision makers. Therefore, the inflowing runoff and water utilization of various departments are treated as a time risk factor, the current impounded level is treated as a space risk factor, and the water diversion quantity, water supply quantity and the occasion of water transfer are treated as energy risk factors respectively. The fuzzy comprehensive assessment and mixed Copula function are adopted to analyse the status and future water regime risk of an inter-basin multi-reservoir operation.

The framework

As everyone knows, the most likely degree of severity of water shortage in the future depends on two important aspects: one is the present hydrological conditions, which were observed and quantified; the other is the prospective condition of future water shortage, which can be evaluated by the proportion of water available and the amount needed in the future (Liu and Huang, 2015). The risk and early warning system was underlain by these two critical foundations, but special attention should be paid to the former as a deterministic assessment presenting the current situation; the latter, however, involves many uncertain factors because of the uncertainty of the future, such as runoff of reservoirs in the following month, water demand of water-recipient areas, different dispatching rules, etc.

The mechanism of the risk and early warning system is shown in Figure 1. Assessment of the current hydrological conditions is a typical multi-factor evaluation. It could include factors such as runoff, water storage in the reservoir, transferable water quantity, etc. As for multi-factor evaluation, a fuzzy comprehensive evaluation matrix is established based on fuzzy theory.

Status risk analysis and assessment of inter-basin reservoir operation

The multi-factor fuzzy evaluation is applied to analyse the status risk. According to fuzzy set theory, it involve multiple

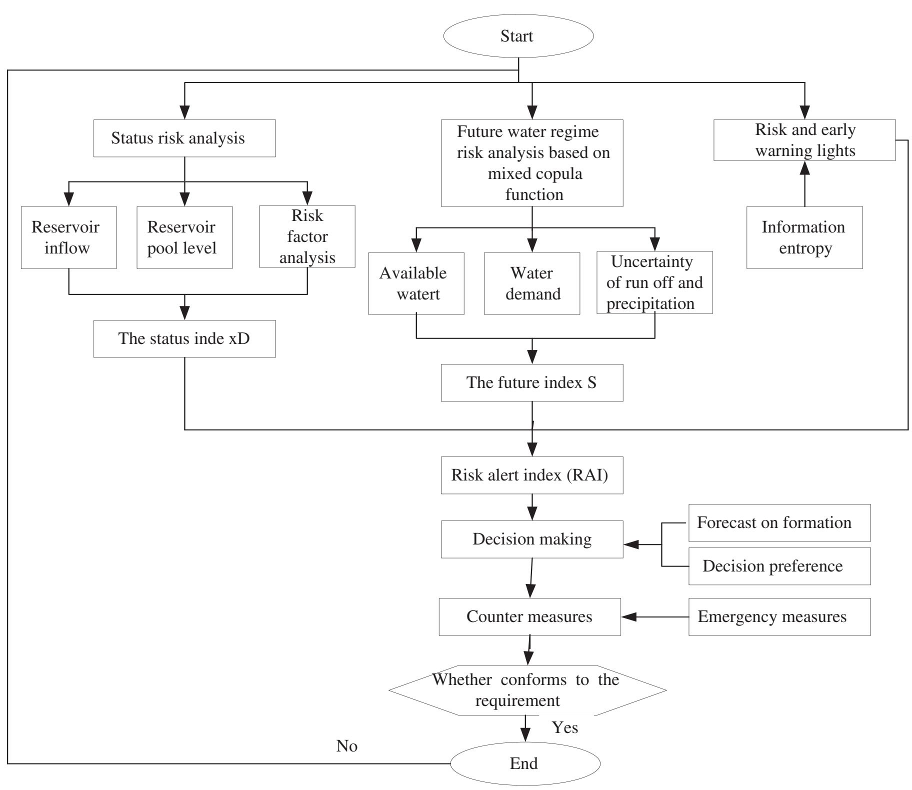

Figure 1. The flow chart for risk and early warning system of an inter-basin reservoir operation.

hydrological factors, all these factors are included in an attribute set U:

$$U = \{\text{reservoir inflow } (u_1), \text{reservoir pool level } (u_2), \text{rainfall precipitation } (u_3), \text{transferable water quantity } (u_4), \text{water demand } (u_5), \text{occasion of water transfer } (u_6)\}$$

The categories to status risk analysis are shown by the evaluation set V:

$$V = \{\text{None } (v_1), \text{slightly severe } (v_2), \text{fairly severe } (v_3), \text{severe } (v_4), \text{very severe } (v_5)\}$$

$R_f(u_i, v_j)$ is treated as a fuzzy relation:

$$R_f(u_i, v_j) = f(u_i)(v_j) = r_{ij} \tag{1}$$

The A is treated as weight $A = (a_1, a_2, \ldots, a_n)$ taking max-min for compositional operation to comprehensive judgment. So B can be acquired:

$$B = A \circ R \tag{2}$$

where R is the fuzzy matrix $R = \begin{Bmatrix} r_{11} & r_{12} & \ldots & r_{1m} \\ r_{21} & r_{22} & \ldots & r_{2m} \\ \ldots & \ldots & \ldots & \ldots \\ r_{n1} & r_{n2} & \ldots & r_{nm} \end{Bmatrix}$ (3)

The expression indicates what status risk the reservoir water shortage degree belongs to, namely the status index D.

Analysis and assessment of future water regime risk based on the copula function

Uncertainty of runoff and precipitation are considered to be the main risk factors for water transfer and supply of the inter-basin reservoir operation. So the study on reservoir future inflow and the distribution of water demand can provide a basis for inter-basin reservoir operation risk assessment and plans for water dispatch. In order to improve the guarantee rate of water supply, water should be diverted as much as possible, but due to the randomness and uncertainty of the natural inflow, if the latter is great at the late stage of the recipient reservoir, surplus water may occur; conversely, if water diversion is less at an early stage and the natural inflow at the late stage is also less, it may increase the destructive degree of the recharge area. How to simultaneously consider the relation between future water regime and water demand factors for joint frequency analysis is the study issue highlighted in this paper.

The future water regime function. Future reservoir water supply potential relates closely to its status of storage capacity and future inflow. As inflowing prediction is greatly affected by uncertain factors, it may affect the correct assessment by decision makers on future water supply potential. Therefore, the potential reservoir inflow in future periods is estimated by reference to the local weather forecast. The future water regime S of reservoir water supply is established according to the difference between the planned water supply and the computer simulation result of reservoir operation:

$$S = s' \cdot \left(1 - \frac{X}{Y}\right) \cdot 100\% \tag{4}$$

The water shortage expected degree of reservoir future water supply represents the expected severity degree of water resources balance of supply and demand is destructed, which can be expressed by Equation (5):

$$E_s = \int_a^b \int_c^d s' \cdot f(x, y) \cdot \left(1 - \frac{X}{Y}\right) dxdy \tag{5}$$

X is the transferable water quantity, Y the water demand, $f(x, y)$ the joint probability density function of stochastic variables X and Y, s' the degree of future water shortage, a and b are respectively for the minima and maxima of transferable water quantity X, c and d are respectively for the minimum and maximum of water demand Y.

Structure of mixed Copula function and relevance analysis. The Copula function can describe the relevant structure between hydrology variables and the joint distribution of hydrology variables with flexible structural boundaries serving as random distribution (Yue *et al.,* 1999; Zhuang and Meng, 2011; Chang *et al.,* 2016; Ren and Zhan, 2016; Qian *et al.,* 2016). The common Copula function includes three types of Archimedes functions, namely Gumbel Copula function, Clayton Copula function and Frank Copula function, but the associative mode among variables is hard to describe comprehensively using a simple Copula function, so the two variables, distribution of future reservoir inflow and water requirement, are established based on a mixed Copula function in this paper.

The $M - Copula$expression of a mixed Copula function is given as follows:

$$\begin{cases} MC_3 = w_{\mathrm{G}} C_{\mathrm{G}} + w_{\mathrm{F}} C_{\mathrm{F}} + w_{\mathrm{Cl}} C_{\mathrm{Cl}} \\ w_{\mathrm{G}} + w_{\mathrm{F}} + w_{\mathrm{Cl}} \geq 0 \\ w_{\mathrm{G}} + w_{\mathrm{F}} + w_{\mathrm{Cl}} = 1 \end{cases} \tag{6}$$

where C_G, C_F, C_{cl} are respectively Gumbel-Copula, Frank-Copula, Clayton-Copula functions; w_G, w_F, w_{cl} are respectively the weight coefficients of the Copula function.

Parameter estimation, inspection and evaluation of the copula model

(1) Parameter estimation of the Copula model. There are many parameter estimations in the copula functional model; usually the maximum likelihood and moment estimation are adopted, while maximum likelihood estimate is a common estimation method of the copula model. Taking the frank-copula function as an example for presentation, its equation is

$$C(u,v) = -\frac{1}{\theta}\ln\left[1+\frac{\left(e^{-\theta u}-1\right)\left(e^{-\theta v}-1\right)}{e^{-\theta}-1}\right] \quad (7)$$

where θ is the parameter vector of the Copula function, assumed $\{(x_1,y_1),(x_2,y_2),\ldots,(x_N,y_N)\}$ is the sample consisting of N groups of observed values of stochastic variables (X,Y); the density function of the joint distribution function $F(x,y)$ of two-dimension stochastic variable (X,Y) is $f(x,y)$, their marginal distributions are respectively $F_1(x)$, $F_2(y)$.

$$f(x,y) = \frac{\partial F(x,y)}{\partial x \partial y} = c(F_1(x),F_2(y))f_1(x)f_2(y) \quad (8)$$

where $c(\bullet,\bullet)$ is the density function of the Copula function $C(\bullet,\bullet)$; $f_1(x)$, $f_2(y)$ are respectively the density functions of $F_1(x)$, $F_2(y)$. The other parameters meaning are the same as above.

Rank the data X (transferable water quantity) of the sample from small to large, namely$x_1 < x_2 < . \ldots < x_N$, by counting the number of $x_j \le x_i$, $y_j \le y_i$,$(i,j=1,2,\ldots,N)$, the joint empiric frequency of transferable water quantity X and water demand Y is.

$$h(x_i,y_i) = p(X \le x_i, Y \le y_i) = \frac{m_i - 0.44}{N+0.12} \quad (9)$$

Assuming that the estimated parameter vector $\bar{V} = (v_1, v_2, \theta)$ is composed of the estimated parameter v_1, v_2 of marginal distribution and the estimated parameter θ of the Copula function, then the maximum likelihood parameter estimation is described by the following equation:

$$L\left(\bar{V}\right) = \sum_{i=1}^{N}\{\ln c(u_1,u_2;\theta) + \ln f_1(x_i;v_1) + \ln f_2(y_i;v_2)\} \quad (10)$$

where $u_1 = F_1(x_i;v_1)$, $u_2 = F_2(y_i;v_2)$.

(2) Inspection and evaluation of the Copula model. It is not assigned whether the copula distribution function is a well-fitted referential structure and distribution among variables, so inspection of the copula function and fitting priority evaluation need to be established. K-S (Kolmogorov-Smirnov test) is used to prove whether or not the sample conforms to identical distribution, so it is applied to prove the copula distribution function (Mo *et al.,* 2009); the root mean square error (RMSE) least criteria are adopted to calculate the fitting evaluation of the copula function, and its definition is shown as equation (11):

$$\text{RSME} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(p_c(i) - p_0(i)\right)^2} \quad (11)$$

where N is the sample size; i is the sample number; p_c is the theory frequency of model computation; p_0 is the empiric frequency of joint distribution.

The statistics F of K-S are shown as Equation (12):

$$F = \max_{1\le k\le n}\left[\left|C(u_k,v_k) - \frac{u_k}{N}\right|, \left|C(u_k,v_k) - \frac{v_k - 1}{N}\right|\right] \quad (12)$$

where N is the sample size; $C(u_k, v_k)$ is the Copula value of sample x_k, y_k; u_k, v_k is the number of samples meeting the condition $x \le x_k$, $y \le y_k$.

Criteria for the degree of future reservoir water shortage. The difference of water shortage degree can be divided into five grades: 1 (no water shortage); 2 (slightly severe water shortage); 3 (fairly severe water shortage); 4 (severe water shortage); 5 (very severe water shortage). The water shortage rate corresponding to different grades of water shortage is shown in Table I.

METHOD AND SOLUTIONS

Determination of early warning signals

Future reservoir water shortage is a random issue, and entropy is a sort of measurement for a probabilistic system state (Hao, 2010); information theory is a science using probability and mathematical statistics methods to study information processing and transitive, so information entropy is applied to determine the number of early warning signals for water shortage degree.

Assuming random issue x^* has n_0 potential states, emergent probability of each state is $p_i(i=1,2,\ldots,n_0)$, and then the information entropy $H(x^*)$ of undetermined event x^* is expressed as.

$$H(x^*) = -\sum_{i=1}^{n_0} p_i \log_2(p_i) \quad (13)$$

When system probability is equal probability, then taking $p_i = 1/n_0$ into Equation (13) to get $H(x^*)$ as

$$H(x^*) = -\sum_{i=1}^{n_0}\frac{1}{n_0}\log_2\left(\frac{1}{n_0}\right) = \log_2(n_0) \quad (14)$$

As for correlated event x^*, y^*, its uncertainty can be expressed as $H(x^*, y^*)$:

Table I. Determination of the future reservoir water shortage index S.

Index S	1 (No water shortage)	2 (Slightly severe water shortage)	3 (Fairly severe water shortage)	4 (Severe water shortage)	5 (Very severe water shortage)
Water shortage rate	0	0–15%	15–25%	25–35%	>35%

$$H(x^*, y^*) = -\sum_{i,j}^{n_1 n_2} p_{ij} \log_2(p_{ij}) \tag{15}$$

where p_{ij} is the probability of correlated event x^*, y^*under the joint action; n_1, n_2 are respectively for likelihood states of x^*, y^*. In this paper, it refers to the probability of different water shortage levels under the joint impact of status index D and future index S. $H(x^*, y^*)$ is namely the approximate number of early warning signals.

Assuming p_{ij} is equal probability, then $p_{ij} = 1/n_1 n_2$:

$$\begin{aligned} H(x^*, y^*) &= -\sum_{i,j}^{n_1 n_2} \frac{1}{n_1 n_2} \log_2\left(\frac{1}{n_1 n_2}\right) \\ &= \log_2(n_1 n_2) \end{aligned} \tag{16}$$

Assuming, D,S each has n_D, n_S kinds of likelihood state, of which indexes D and S are respectively used to quantify reservoir status and future water shortage ($D = (1, 2, \ldots, 5)$, $S = (1, 2, \ldots, 5)$), so n_D, n_S are both equal to 5. $H(x, y) = \log_2(n_D n_s) = \log_2(25) \approx 5$, so set as five early warning levels; as per routine custom, lights (m_0) are respectively expressed as: green light ('G' no water shortage); blue light ('B' slightly severe water shortage); yellow light ('Y' fairly severe water shortage); orange light ('O' severe water shortage); and red light ('R' very severe water shortage).

Computation of Risk Alert Index (RAI)

RAI is the fineness degree of the future reservoir scheduling strategy reflected through combined reservoir status water supply index D and future water shortage index S; the interaction relationship between D and S can be expressed by a direct nonlinearity expression, namely DS^k, so RAI can be expressed by logarithms as.

$$\mathrm{RAI} = \log_{n_D}(D) + k \log_{n_s}(\mathrm{S}) \tag{17}$$

where $n_D = n_s = 5$;$D = (1, 2, \ldots, 5)$;$\mathrm{S} = (1, 2, \ldots, 5)$, so $0 \le RAI \le k + 1$, k is for non-negative integer ($k \neq 1$). RAI in different intervals is for different light levels,setting the estimated upper limit (ul) of RAI as.

$$ul = k\frac{i-1}{m_0 - 1} + 1 \quad (i = 1, 2, \ldots, m_0; \ m_0 = 5) \tag{18}$$

When$k = 2$, take it into Equation (17) to get.

$$\mathrm{RAI} = \log_5(DS^2) \quad D = 1, 2, \ldots 5; S = 1, 2, \ldots, 5 \tag{19}$$

Computing by Equation (18), $ul = (1, 1.5, 2, 2.5, 3)$ can be obtained. Early warning index range of the RAI and the corresponding water supply early warning degree are shown in Table II.

Take different groups combining D and S into Equation (19), calculation the value of RAI, the classification of early warning level can be obtained in Table III.

When $k > 2$, Equation (17) cannot be fully indicative of early warning level, so it is determined as $k = 2$ in Equation (17). Namely Equation (19) is the computing equation of RAI.

Emergency treatment measures of inter-basin operation risk

An inter-basin multi-reservoir water transfer-supply operation, as the non-structural measure of water resource shortage, plays an important role in solving uneven distribution of water resources in time and space. It combines with the status and future water regime of donor and recipient reservoirs, and the early risk warning signals are respectively computed. According to the different combination lights between reservoirs, water supply emergency measures are set for inter-basin reservoir operation. The water transfer and supply emergency measures of donor and recipient reservoirs have different early warning lights, as shown in Table IV.

According to the different combination of lights of donor and recipient reservoirs, water supply emergency measures are set for inter-basin reservoir operation. And according

Table II. The index range of the early warning system.

Early warning level early	Green light (G)	Blue light (B)	Yellow light (Y)	Orange light (O)	Red light (R)
Warning index range alert degree	$0 \le \mathrm{RAI} \le 1$ Normal	$1 \le \mathrm{RAI} \le 1.5$ Alert	$1.5 < \mathrm{RAI} \le 2$ Improving alert	$2 < \mathrm{RAI} \le 2.5$ High alert	$2.5 < \mathrm{RAI} \le 3$ Severe alert

Table III. The value of RAI and classification of the early warning level

Analysis of status water supply index D	Analysis of future water shortage index S				
	1 (None)	2 (Slightly severe)	3 (Fairly severe)	4 (Severe)	5 (Very severe)
1(None)	0 (G)	0.86 (G)	1.36 (B)	1.72 (Y)	2.00 (Y)
2(Slightly severe)	0.43 (G)	1.29 (B)	1.80 (Y)	2.15 (O)	2.43 (O)
3(Fairly severe)	0.68 (G)	1.54 (Y)	2.05 (O)	2.41 (O)	2.68 (R)
4(Severe)	0.86 (G)	1.72 (Y)	2.23 (O)	2.58 (R)	2.86 (R)
5(Very severe)	1 (G)	1.86 (Y)	2.37 (O)	2.72 (R)	3.00 (R)

Table IV. Emergency measures of early warning lights under different combinations for inter-basin reservoir operation.

Emergency measures		Light level of recipient reservoir				
		Green (G)	Blue (B)	Yellow (Y)	Orange (O)	Red (R)
Light level of donor reservoir	Green (G)	No water transfer	Moderate water transfer	Enhancing water transfer	When increasing water transfer, reduce agricultural water by 5% or so	Further increase water transfer, reduce industrial water by 5% or so, agricultural water by 10% or so to ensure domestic water consumption
	Blue (B)	No water transfer	Moderate water transfer	When increasing water transfer, reduce agricultural water by 5% or so	When increasing water transfer, reduce agricultural water by 10% or so	Further increase water transfer, reduce industrial water by 10% or so, agricultural water by 10–20% or so to ensure domestic water consumption
	Yellow (Y)	No water transfer	No water transfer	Mild water transfer	Further increase water transfer, reduce industrial water by 10–20% or so, agricultural water by 20–30% or so to ensure domestic water consumption	Further increase water transfer, reduce industrial water by 20–30% or so, agricultural water by 30–50% or so. And stop subordinate domestic water consumption
	Orange (O)	No water transfer	No water transfer	No water transfer	No water transfer	Moderate water transfer to relieve the loss of water shortage in recharge area. Dominated by domestic water consumption, stop agricultural and industrial water consumption
	Red (R)	No water transfer	No water transfer	No water transfer	No water transfer	No water transfer

to the statistical information, it includes water resources, water usage, runoff, and the importance of different water-use sectors/areas/provinces. These are the empirical data, also the reduced percentage of industrial/agricultural water within limits. The definite percentage needs concrete analysis for specific areas.

As for the decision about water transfer, the launch conditions for donor reservoirs are water transfer or no water transfer. The condition for water transfer can be described as: adequate water of the donor reservoir but the recipient reservoir is in water shortage. Judgement of the donor reservoir not transferring water to the recipient reservoir: the donor reservoir has no surplus water, no matter whether or not the recipient reservoir is in water shortage; or the water of the donor reservoir is adequate, while the recipient reservoir is not in water shortage.

CASE STUDIES

The inter-basin transfer-supply project H in China is located between two reservoirs of different basins (Figure 2). Reservoir B is a large-sized reservoir of city Z, with a capacity of 0.385 billion m^3. With social and economic development,

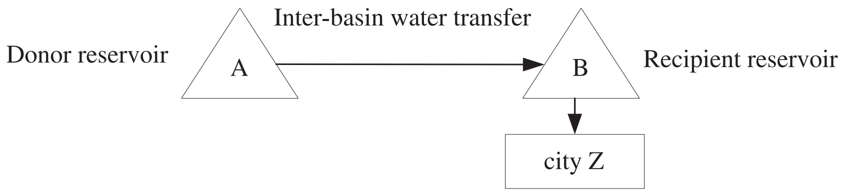

Figure 2. The inter-basin water transfer project H.

the water resources supply and demand contradiction has become increasingly obvious, and has greatly affected local development. Reservoir A, located in the middle and lower reaches of another basin and where the water is abundant, without direct water users and a capacity of 1.95 billion m^3, can transfer water to reservoir B. The long series inflow is computed month by month, treating the inflowing runoff from 1962 to 2011 (50 years) as the basic data.

RESULTS AND DISCUSSION

Taking 2011 as an example, it has a computation of status water supply index *D* of donor reservoir A, future water shortage index *S* and risk alert index RAI, and the results are shown in Tables V–VIII.

As for donor reservoir 'A', the related parameters and inspection assessment value are computed by the Gumbel-Copula, Clayton-Copula, Frank-Copula and M-Copula functions. The computation, inspection and assessment results are shown in Table VI (K-S proven is obvious at 0.05 level).

The results of Table VI reveal that the Gumbel-Copula, Clayton-Copula, Frank-Copula and M-Copula functions all passed through K-S proven, and can fit the marginal distribution of reservoir future water regime well. According to RMSE least criteria, the M-Copula function as the contiguous function is selected to fit the reservoir future water supply regime. The future water regime of the donor reservoir in 2012 is shown in Figure 3 and Table VII.

The computation aimed at the donor reservoir which is identical in principle with the recipient reservoir, which will be no longer listed due to limited space. Treating the runoff

Table VI. Computations, proven and assessment results of the Copula model.

Function name	Parameter	Parameter value	K-S statistics	RMSE
Gumbel-Copula	α	2.58	0.126	2.16
Clayton-Copula	λ	3.35	0.137	2.28
Frank-Copula	θ	7.85	0.143	2.64
M-Copula	$\alpha = 2.59$; $\lambda = 2.95$; $\theta = 7.80$ / $w_G = 0.153$; $w_{Cl} = 0.326$; $w_F = 0.521$		0.130	2.03

Note: α, λ, θ are respectively the corresponding parametric variables of the Copula function, describing correlative degree among variables.

Table VII. Computation of early warning light level of donor reservoir'A'.

Month	1	2	3	4	5	6	7	8	9	10	11	12
Water deficient ratio (%)	15	10	25	30	18	10	5	0	13	34	40	20
Grade of future water regime[a]	2	2	3	4	3	2	2	1	2	4	5	3
Grade of status water regime[b]	3	3	2	2	2	1	1	1	1	2	2	3
Early warning light level [c]	Y	Y	Y	O	Y	G	G	G	G	O	O	O

[a]Grade of future water regime is obtained from the data of Figure1 and standard of Table I.
[b]Grade of status water regime is obtained from the results of Table V.
[c]Early warning light level is obtained from the integrative results of grade of future water regime and grade of status water regime, referred to the classification of early warning level in Table III.

Table V. Analysis of status reservoir water supply of 'A' in 2011.

2011	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Storage level (m)	180	195	198	203	212	196	245	224	210	218	189	190
Water storage (%)	22.1	31.2	38.1	43.6	71.5	39.6	87.2	92.5	93.6	58.2	40.1	30.2
Inflow (0.1 b m^3)	0.17	0.24	0.34	0.46	0.62	1.95	1.90	1.72	1.58	1.00	0.60	0.31
Transferable water(0.1 b m^3)	0.87	0.79	1.51	1.43	1.39	1.61	1.38	1.44	1.27	0.92	0.05	1.06
Water supply index *D*	3	3	2	2	2	1	1	1	1	2	2	3

b m^3: billion cubic metres.

Table VIII. Combinatorial proportion of early risk warning light of donor and recipient reservoirs (%).

Proportion(100%)		Recipient reservoir				
		Green (G)	Blue (B)	Yellow (Y)	Orange (O)	Red (R)
Donor reservoir	Green (G)	3.8	8.2	6.4	9.6	6.4
	Blue (B)	1.6	6.2	8.6	7.8	6.4
	Yellow (Y)	1.8	5.0	5.2	5.8	3.0
	Orange (O)	0	3.6	0	1.8	3.6
	Red (R)	0	1.6	2.2	0	1.4

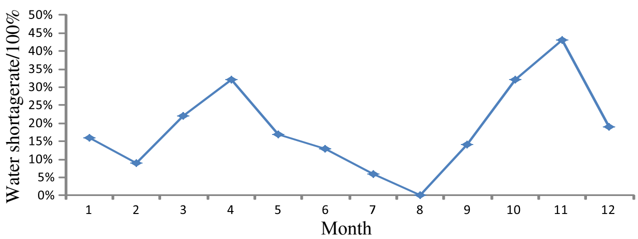

Figure 3. Future water regime of donor reservoir 'A' in 2012. [Colour figure can be viewed at wileyonlinelibrary.com]

of the reservoir over the past 50 years as the statistic, the combinatorial proportion of different early risk warning light levels of the donor and recipient reservoirs can be computed, as shown in Table VIII.

The underlining in Table VIII is for no water transfer, and accounted for 22.8%; the rest is for water transfer from donor to recipient reservoir, accounting for 77.2%, compared with the actual situation (Qiu *et al.,* 2010). The actual percentage of water transfer is 83. This actual percentage outweighs the theory percentage of 77.2 because of the conservative calculation in this paper. This shows that the inter-basin transfer can be achieved in area H; the combinations in which both donor and recipient reservoirs come into identical early warning level include 3.8% (G), 6.2% (B), 5.2% (Y), 1.8% (O), 1.4% (R), when the reservoirs come into green, orange or red lights simultaneously, both donor reservoir and recipient reservoir are in a state of abundant or lack water, so no water transfer is allowed; when the reservoirs both go off to blue or orange lights, although both are in a state of slight or fairly severe water shortage, there is still transferable water since there is no direct water user of the donor reservoir, while the recipient reservoir is in water shortage. In order to improve the water supply guarantee rate in the recharge area, water transfer can be made to some extent, and its water supply limit can be referred to emergency measures as shown in Table IV. At the same time, it is necessary to consider water inflow, water supply and water shortage of the recipient reservoir, which is conducive to preparing in advance the water-supply scheme and starting up the emergency scheme when in water shortage.

An inter-basin reservoir water transfer-supply operation is a significant part of solving uneven spatiotemporal distribution of water resources and the contradiction between supply and demand; as a highly dimensional and complicated allocation of a water resources system, it is constrained by many extrinsic and intrinsic factors and uncertainty factors. The early risk warning mechanism is applied in the reservoir group water supply optimized operation, operation strategy and risk level are established under different water regimes, and corresponding emergency measures taken according to the early warning lights. The following aspects need to be discussed and enhanced: (i) what the paper provided is the general expression for inter-basin reservoir water transfer early risk warning; if donor reservoir 'A', recipient reservoir 'B' and recharge area 'Z' all can be multiplied, 'A', 'B' and 'Z' can be respectively polymerized, then follow decomposition according to certain rules; (ii) owing to the randomness and uncertainty of natural inflow, if much diversion is made from a water transfer area, proper account of a 'water returning programme' can be made: rationally and feasibly return the 'surplus 'water resources to the original waterway through natural flow and other means; (iii) learning from object lessons of built-up and on-building water transfer projects, it is necessary to value water transfer management, reduce water transfer risk and reduce man-made sabotage as best as we can.

CONCLUSIONS

Considering the complexity, uncertainty and dynamic nature of the transfer-supply project, it involves donor reservoirs, recipient reservoirs and recharge areas. There are various risk factors during water transfer and supply, and how to provide an early warning of the risk level based on existing risk assessment is the key issue in this paper. There are many risk factors in the process of water transfer of a large-scale inter-basin reservoir operation. The risk factors and risk process are identified and described firstly, and the inner links of the water supply operation risk factors analysed. At the same time, the fuzzy comprehensive assessment principles of fuzzy mathematics and a mixed Copula function are applied to determine reservoir status and future water regime, and the information entropy principle is adopted to analyse the early warning index and the light of the reservoir water supply; finally emergency measures are set when donor and recipient reservoirs are in different combinations with early warning levels, and an early warning risk system of inter-basin reservoir group operation is established. Those theories in interest area 'H', the results show that: (i) a fuzzy comprehensive assessment can preferably evaluate the reservoir status index; (ii) a mixed Copula function can simulate the joint probability distribution of reservoir future water inflow and water requirement, and have a quantitative analysis of the complex relationship between transferable water and water demand in the rechargeable area, thus obtaining the water shortage degree of the future reservoir water regime; (iii) taking reservoir inflowing runoff over the past 50 years as statistics, the computation finds the proportion of different early risk warning light levels of donor and recipient reservoirs; the result proved that the donor reservoir not transferring water to the recipient reservoir accounted for 22.8%, and the transferable water amount accounted for 77.2%. It conformed to the policy and practical situation of H area's inter-basin transfer of water. In the future, it will be necessary to further study the coupling between inter-basin reservoir operation rules and early risk warning systems, to have an analogue simulation and risk assessment of the water-supply scheme of the reservoir group.

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REFERENCES

Alvar EB, Manuel PV, David PV. 2017. Economic value of climate change adaptation strategies for water management in Spain's Jucar Basin. *Journal of Water Resources Planning and Management* **145**(5): 040170051-13.

Cao SL, Guo XN, Zheng CS, Zheng CQ, Song SW, Zhuang HB, Chen GQ. 2013. Research on the procedural warning method of reservoir water supply. *China Rural Water and Hydropower* **12**(9): 56–59.

Chang FX, Chen J, Zhang ZY. 2011. Sensitivity analysis of water supply risk in middle and lower reaches of Hanjiang River. *Journal of Yangtze Scientific Research Institute* **12**: 98–102 + 117.

Chang JX, Bai T, Huang Q, Yang DW. 2013. Optimization of water resources utilization by PSO-GA. *Water Resources Management* **27**(10): 3525–3540.

Chang JX, Li YY, Wang YM, Yuan M. 2016. Copula-based drought risk assessment combined with an integrated index in the Wei River Basin, China. *Journal of Hydrology* **540**: 824–834.

Fang HY, Gan SW, Hua JX. 2007. Multi-objective planning method for reservoir water-supply risk analysis during drought periods. *Journal of Hydroelectric Engineering* **26**(2): 14–18 26.

Fu X, Liu QH, Wu SD. 2012. Risk assessment approach for reservoir operation performance. *Journal of Hydraulic Engineering* **8**: 987–990 + 998.

Hao GR. 2010. Study on multi-level fuzzy integrative evaluation based on entropy weight and AHP's combined weight coefficient on library service quality evaluation. *Journal of Modern Information* **30**(2): 133–137.

Harding BJ, Sangoyomi TB, Payton EA. 1995. Impacts of a severe drought on Colorado River water resources. *Water Resources Bulletin* **31**(5): 815–824.

Huang WC, Hsieh CL. 2010. Real-time reservoir flood operation during typhoon attacks. *Water Resources Research* **46**(10): 1–11.

Ismail KT. 2015. Transboundary river basin flood forecasting and early warning system experience in Maritza River basin between Bulgaria and Turkey. *Natural Hazards* **75**: 191–214.

Kjeldsen TR, Rosbjerg D. 2004. Choice of reliability,resilience and vulnerability estimators for risk assessments of water resources systems. *Hydrological Sciences Journal* **49**(5): 755–767.

Liu Z, Huang WC. 2015. Drought early warning in irrigation area by integrating surface water and groundwater. *Paddy Water Environment* **13**(2): 145–157.

Mateus MC, Desiree T. 2016. Reliability, sensitivity, and vulnerability of reservoir operations under climate change. *Journal of Water Resources Planning and Management*. **143**(4): 040160851-14.

Mo SH, Shen B, Zhang XW, Li ZB. 2009. Synchronous–asynchronous encounter probability of rich–poor runoff based on Copula function. *Journal of Northwest A&F University (Nat. Sci. Ed.)* **37**(6): 131–136.

Qian LX, Zhang R, Wang HR, Mei H. 2016. Risk loss model of water supply and water demand based on Copula function and its application. *Systems Engineering-Theory & Practice* **36**(2): 517–527.

Qiu L, Chen XN, Wang WC, Xu DM. 2010. Joint dispatching of reservoir group and three-dimensional simulation on the LuanHe River Basin. *China Water Power Press.*

Ren L, Zhan XH. 2016. Copula-based analysis of hydrologic drought frequency in the upper reaches of Fenhe River. *Water Power* **42**(2): 11–16.

Wan F, Zhou J, Yuan WL. 2016. The scheduling rules of multi-reservoir optimal operation in large-scale inter-basin water supply reservoirs. *Water Resources Management* **27**(3): 448–457.

Wang LP, Huang HT, Zhang YK, Shi J, Zhou X. 2014. Research on risk decision technology for multi-objective operation of reservoir. *Water Power* **3**: 63–66.

Xi SF, Wang BD, Liang GH, Li XS, Lou LL. 2010. Inter-basin water transfer-supply model and risk analysis with consideration of rainfall forecast information. *Science China Technological Sciences* **53**: 3316–3323.

Yue S, Ouarda TB, Bobee B, Legendre P, Bruneau P. 1999. The Gumbel mixed model for flood frequency analysis. *Journal of Hydrology* **226**(1–2): 88–100.

Zhang Q, Zhang JQ, Wang CY, Cui L, Yan D. 2014. Risk early warning of maize drought disaster in northwestern Liaoning Province, China. *Natural Hazards* **72**(2): 701–710.

Zhuang DQ, Meng F. 2011. On Bayesian method of constructing mixed copulas. *Journal of Anhui University of Technology (Natural Science)* **28**(2): 188–191.

