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Research article

A Copula-based interval linear programming model for water resources allocation under uncertainty

Wencong Yue [a,b,1], Shujie Yu [a,1], Meng Xu [c], Qiangqiang Rong [a,b], Chao Xu [a], Meirong Su [a,*]

[a] Research Center for Eco-Environmental Engineering, Dongguan University of Technology, Dongguan, 523808, China
[b] Guangdong Provincial Key Laboratory of Water Quality Improvement and Ecological Restoration for Watersheds, 510006, Guangzhou, China
[c] School of Public Administration, Zhejiang University of Finance & Economics, Hangzhou, 310018, China

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ABSTRACT

Water scarcity tends to be aggravated by increase in water demand with the trend of socio-economic development. Thus, non-stationary characteristics of water demand should be identified in water resources allocation (WRA) to alleviate the potential influences from water shortages. In this study, a Copula-based interval linear programming model was established for regional WRA. Through combining correlation analysis and an interval linear programming model, this model can: 1) identify interactions between water demand and socio-economic development levels based on Copula functions, 2) explore variations in water shortage with consideration of multiple risk tolerance levels of decision-makers based on Copula sampling, and 3) obtain desired strategies for WRA through an interval linear programming model. Also, Dalian City in China was selected as a case study area to verify the effectiveness of the model for WRA to five water users (i.e., agricultural sector, industrial sector, public service sector, domestic residents, and ecological environment). Considering multiple tolerance levels of decision-makers to water shortage risk, three scenarios (i.e., S1 to S3), indicating 20%, 40%, and 60% of their low, medium, and high tolerance levels, were proposed. The results showed that the correlation between the amount of water demand and indicators of socio-economic development can be described by Clayton and Gaussian Copula functions. The total water supply of Dalian in 2030 would increase by 2.06%–2.65%, compared with the one in 2025. The allocation of water resources across districts was influenced by varied water demand, energy consumption, and risk tolerance levels. Compared with the amount of water allocation in 2025, the contribution of transferred water sources would increase by 6.71% and 7.04% under S1 and S2 in 2030, respectively, and decrease by 14.31% under S3. With the increase of risk tolerance levels of decision-makers, the amount of water supply in Dalian City would gradually decrease.

1. Introduction

Water resources are fundamental for maintaining human health, agricultural production, economic activity as well as critical ecosystem functions (Gleick and Palaniappan, 2010). Defined by geographic and temporal mismatch between freshwater demand and availability, water scarcity poses a huge challenge to sustainable development in water-scarce areas (Xu et al., 2019; Wei et al., 2020; Mekonnen and Hoekstra, 2016). Water resources allocation (WRA) supports effective strategies for water utilization to alleviate the risk of water shortages (Wang et al., 2015; Dadmand et al., 2020). Water scarcity tends to be aggravated by increase in water demand with the trend of socio-economic development (Xie et al., 2018b). Thus, non-stationary characteristics of water demand should be identified in WRA management to alleviate the potential influences from water shortages (Yan et al., 2018; Pienaar and Hughes, 2017; Gnawali et al., 2019).

Identifying the tradeoffs between water supply and demand, WRA management supports reasonable strategies for ecological, domestic, agricultural, or industrial sectors (Xu et al., 2019). For example, Liu et al. (2019) revealed physical mechanism of water use in allocating water resources under the background of climate change and social-economic development. Rezaee et al. (2021) studied water allocation strategies for industrial activities to fulfill the objectives in employment and economic development. Energy plays an important

* Corresponding author.
E-mail address: sumr@dgut.edu.cn (M. Su).
[1] Contributed equally to this work.

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role in the processes of WRA management (e.g., extraction, delivery, purification, and allocation of water resources, as well as wastewater treatment) (Moazeni et al., 2020; Zhou et al., 2020; Yu et al., 2022). As indicated by He et al. (2019), the processes in Beijing consumed 55.6 billion kWh of electricity in 2015, accounting for 33% of the total urban energy consumption. Wu et al. (2021) focused on energy consumption in water resources management of the Shiyang River Basin to provide energy-saving schemes. Thus, in order to mitigate greenhouse gas emissions, energy consumption in the WRA system should be paid attention to (Gao et al., 2019).

Regarded as effective tools to deal with tradeoffs between water supply and demand, programming models were widely applied in the WRA management (Ahmad et al., 2014; Daghighi et al., 2017). Among them, linear programming modes were demonstrated as effective tools for obtaining optimal strategies for water allocation to maximize economic benefits or minimize pollution-control costs. For example, Gao et al. (2020) established a linear programming model for the WRA management with the goal of guaranteeing ecological environment and domestic water use in complex river basins and ecological scheduling of reservoir groups. Fu et al. (2018a) developed a simulation-based linear fractional programming model to allocate water resources among agricultural, industrial, residential, and environmental sectors in the Songhua River Basin. He et al. (2016) combined a linear programming model and input-output analysis for realizing sustainable utilization of water resources. Also, programming models were widely applied in decision-making support for reducing energy consumption of the WRA systems (Kermani et al., 2017; Luo et al., 2021; Chini et al., 2016). Ma et al. (2020b) developed an interval programming model to minimize power consumption in the process of water distribution. Due to the real-world WRA management (i.e., planning for the future), deterministic values of parameters in linear programming models were hard to reflect variations in water supply and demand.

Due to the complexity of water resources systems, multiple uncertainties existed in the WRA management (Wang et al., 2020; Ji et al., 2018). For example, variations in water demand of multiple users, random characteristics of water supply, and subjective judgment in future water management may influence the effectiveness of strategies in WRA (Xie and Huang, 2013; Sun et al., 2018; Li and Guo, 2014; Tong and Guo, 2013). Many effective methods were proposed to solve the complexity and uncertainty in water resources management (e.g., stochastic programming, interval programming, and fuzzy programming) (Ma et al., 2020a). Incorporating interval numbers to indicate the uncertainty range of the parameter, interval linear programming models were widely applied in the WRA management (Huang et al., 1995). For example, in view of the complexity of management scheduling in agricultural and industrial activities, interval linear programming models were established to allocate water resources for the activities (Fu et al., 2018b; Gong et al., 2020; Sun et al., 2017). Suo et al. (2022) proposed an interval dynamic programming model for regional water management to identify the dynamic characteristics of WRA management.

Since WRA is affected by the relationship between water supply and demand and the subjective decisions of stakeholders, there are extensive uncertainties and complexities in water resources management (Kong et al., 2018; Li et al., 2020; Xie et al., 2018a; Wang and Huang, 2014). In order to improve the suitability of WRA scheme, it is necessary to consider the above uncertain variables in the programming models. Risk tolerance of policy makers, defined as their ability to bear water shortage risk, significantly influenced the effectiveness of the WRA strategies (Yue et al., 2022; Wang and Guo, 2021). For example, the risk tolerance levels can be described by fuzzy and random sets (Ji et al., 2020). Thus, traditional interval programming models should be incorporated by statistical methods, such as Monte Carlo sampling and Copula functions, to support non-stationariness analysis of water demand and risk tolerance in the WRA management. Identifying interaction and influence between the associated variables, Copula functions were introduced for water resources management (Won et al., 2022; Yan, 2007). For example, joint probabilities of water supply among adjacent regions were explored by Copula functions (Cai et al., 2021). Gumbel Copula was applied to predict water shortage risk in Tianjin influenced by joint distributions of water supply and consumption (Qian et al., 2021). The Copula-based linear programming models have the advantage in dealing with the correlated variables in the WRA management (Li et al., 2021). For example, Yu et al. (2018) proposed a programming model based on Copula functions to reflect the uncertain interactions of energy consumption in adjacent regions.

Although many previous studies focused on WRA, variations of water demand influenced by socio-economic development were seldom considered in traditional optimizing models (Li et al., 2018). Thus, the objective of this study is to identify the variations in water demand of multiple users influenced by socio-economic development, and to transfer the variations into a programming model for desired strategies of water allocation. Also, considering the subjective decision making in WRA, multiple risk-tolerance levels will be taken into account. In particular, variations of water demand will be analyzed based on Copula functions. An interval linear programming model will be established, with the goal of minimizing energy consumption in the WRA system. A typical water-stress city in China (i.e., Dalian) will be selected as a case study area. Allocation strategies for multiple users will be obtained to support decision-making for mitigating water shortage in Dalian.

2. Methodology

In this study, a hybrid approach, incorporating Copula functions and an interval linear programming model, was proposed for the WRA management. The proposed approach included the following aspects: 1) identifying interactions between water demand and socio-economic development levels based on Copula functions, 2) exploring variations in water shortage with consideration of multiple tolerance levels of decision-makers to water shortage risk based on Copula sampling, and 3) obtaining desired strategies for WRA through an interval linear programming model (Fig. 1).

2.1. Correlation analysis based on Copula functions

Correlation analysis focused on the relationship between water demand and socio-economic development based on Copula functions. Proposed by Sklar (1959), Copula functions were regarded as effective methods to construct N-dimensional joint distribution functions with multiple distribution functions. Assuming that F_1 and F_2 are marginal distributions of a two-dimensional distribution function (i.e., f), a two-dimensional Copula function (i.e., C) can be obtained by the following equation:

$$f(x_1, x_2) = C[F_1(x_1), F_2(x_2)] = C(u_1, u_2) \tag{1}$$

where x_1 is the socio-economic indicator, and x_2 is the water consumption of each user. In this study, five Copula functions (i.e., Gaussian, Gumbel, Frank, Clayton, and Student t Copulas) were introduced to verify the fitness of the correlation. The Multivariate Copula Analysis Toolbox (MvCAT) was used to conduct correlation analysis (Sadegh et al., 2017). MvCAT employed a Bayesian framework with a residual-based Gaussian likelihood function for inferring copula parameters and estimating the underlying uncertainties. Indicators of Nash-Sutcliffe efficiency (NSE) and root mean square error ($RMSE$) are used to rank the performance of selected Copulas (Equation (2)) (Sadegh et al., 2017).

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} \left[\widetilde{f}_i - f_i(\theta)\right]^2}{n}} \tag{2a}$$

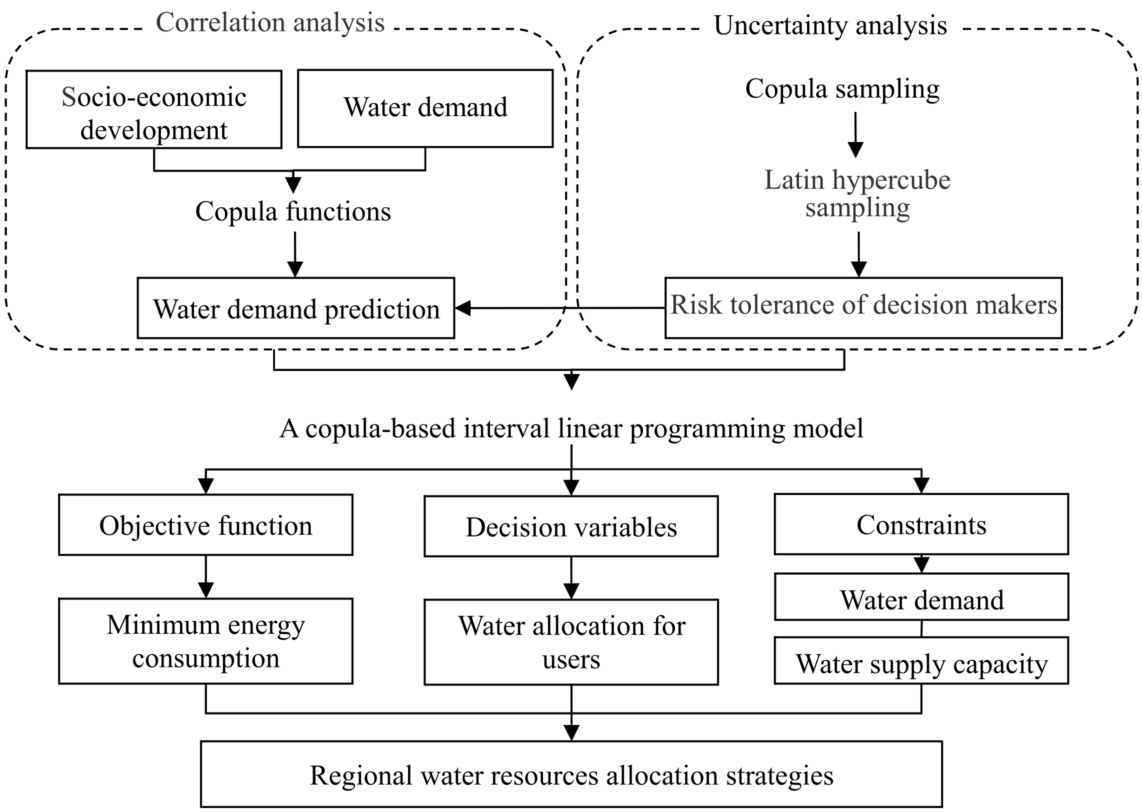

Fig. 1. The framework of methodology for water resources allocation.

$$NSE = 1 - \frac{\sum_{i=1}^{n} [\widetilde{f}_i - f_i(\theta)]^2}{\sum_{i=1}^{n} [\widetilde{f}_i - \overline{\widetilde{f}}_i]^2} \tag{2b}$$

where $\widetilde{f}$ represents the joint probability in observed variables of socio-economic indicator and water consumption of each user, $\overline{\widetilde{f}}$ represents mean value of $\widetilde{f}$, and f is their joint probability predicted by Copula functions. $\frac{\sum_{i=1}^{n}[\widetilde{f}_i - f_i(\theta)]^2}{n}$ is the Gaussian assumption of error residuals. When the value of *RMSE* or *NSE* is close to 0 or 1 respectively, the performance of the selected Copula function fits well.

2.2. Copula sampling

Water demand distributions of multiple users were obtained through experimental design method based on the best fitted Copula functions (i.e., Copula and Latin hypercube sampling). In this study, Copula sampling was used to generate a random sample from the most fitted Copula functions (Gao et al., 2018). In order to effectively obtain non-overlapping sampling intervals, Latin hypercube sampling was used to extract the interval values of decision-makers' different risk tolerance levels (Yan and Minsker, 2011).

2.3. Water resources allocation management

Interval linear programming models can tackle uncertainties expressed as intervals (Ashayerinasab et al., 2018). The objective of the WRA management was to minimize energy consumption. The decision variable was the amount of water allocation to different users. Constraints were established based on the tradeoffs in water demand of multiple users and water supply capacities of the reservoirs. Optimizing model for WRA management can be expressed by Equation (3):

$$\min f_p^{\pm} = \sum_{i=1}^{n} \sum_{l=1}^{k} E_{il} X_{ilp}^{\pm} + \sum_{i=1}^{n} \sum_{r=1}^{s} E_{ir} X_{irp}^{\pm} \tag{3a}$$

s.t.

$$\sum_{l=1}^{k} X_{ilp}^{\pm} + \sum_{r=1}^{s} X_{irp}^{\pm} \geq \sum_{j=1}^{o} Q_{ijp}^{\pm}, \forall i, p \tag{3b}$$

$$\sum_{i=1}^{n} X_{ilp}^{\pm} \leq C_l, \forall l, p \tag{3c}$$

$$\sum_{i=1}^{n} X_{ipr}^{\pm} \leq C_r, \forall r, p \tag{3d}$$

where $f_p^{\pm}$ is the energy consumption of water allocation management under the *p-th* level of risk tolerance of decision makers; E_{il} is the energy consumption of allocating per unit of water resources; $X_{ilp}^{\pm}$ is a control variable of water allocation from water source l to district i; $X_{irp}^{\pm}$ is the control variable of water allocation from transferred water source r to district i; $Q_{ijp}^{\pm}$ is the water demand of the *j-th* industry in the *i-th* district; C_l is the water supply capacity of the *l-th* local water source; C_r is the water supply capacity of the *r-th* transferred water source; and i, l, r, j, and p indicate the districts, the local surface water sources, the transferred water sources, water users, and levels of risk tolerance of decision makers, respectively. Referred to Huang et al. (1992), the solution of the model was composed by solving the upper and lower limits of the sub-models.

3. Case study

3.1. Study area

Located at the southern tip of the Liaodong Peninsula, Dalian City is one of important port, tour, and trading cities of China. Dalian is an inherently water-stressed city (Xu et al., 2018). Conflicts between water demand and supply in Dalian have become increasingly evident (Yue et al., 2022). The per-capita water resources usage in Dalian was 284.98 m^3 in 2019, less than one-fourth of the national per capita water resources (NBS, 2020). Surface water and groundwater sources supported 1.148 and 0.271 billion m^3 water supply, respectively, accounting for 69.87% and 16.49% of the total supply (LNDWR, 2001–2019). Surface water sources of Dalian are composed of local and transferred water sources. Local surface-water sources (e.g., Biliu, Yingna, and Dasha Rivers) supported about 50% of total water supply in Dalian. Local reservoirs played an important role for the water supply in Dalian. The water supply capacity of the Biliuhe, Yingnahe, Dongfeng, Songshu, Liuda, and Zhuwei Reservoirs were 450, 241, 67, 47, 49, and 81 Mt, respectively (Cai et al., 2016). In the process of urbanization, the local water sources in Dalian will not be able to meet the increasing water demand. Transferred water sources (e.g., Hun River of Fushun city) will support more than 39% of Dalian's water demand by 2030.

In consideration of the complexity in surface water allocation, WRA in Dalian mainly focused on strategies related to surface water. According to the administrative division of Dalian, the following eight districts were considered in this study: the Municipal zone, Jinzhou, Pulandian, Wafangdian, Changxingdao, Zhuanghe, Huayuankou, and Changhai (Fig. 2). The main water users of Dalian included agricultural and industrial sectors, public service sector, domestic residents, and ecological environment. As indicated by Table S2 in Supplementary Material, agricultural and industrial sectors, consuming more than 35% and 24% of water resources in 2019, were main water users in Dalian. The water supply for ecological environment increased by 23.75 times in 2019, compared with the one in 2005.

3.2. Water supply

To support water resources management for future-oriented decision-making, some important indicators (i.e., water demand and supply) were referred to plans of social, economic, and water resources in Dalian (Bureau of Water Resources, 2014). Two planning horizons (i.e., 2025 and 2030) were chosen in this study. The maximum amount of transferred water supply to Dalian from Hun River and other transferred water sources would be 0.288 and 0.7 billion m^3, respectively (Bureau of Water Resources, 2014). Energy consumption in the process of water transportation was regarded as the main input in Dalian's WRA system (Cai et al., 2016). The amount of energy consumption of the WRA system in Dalian is described in Table S3 of Supplementary Material. Energy consumption in WRA for Changhai was the biggest, compared with the one for other districts. Conversely, supported by Zhuwei Reservoir, energy consumption from local and transferred water sources was smallest in Zhuanghe and Wafangdian, respectively.

3.3. Water demand analysis

In this study, seven indicators [i.e., added value, gross output value, disposable income, consumption expenditure, Gross Domestic Product (GDP), urban garden green area, and urban green coverage area] were chosen to indicate the levels of socio-economic development. The correlation between the socio-economic indicators and water consumption was analyzed based on Copula functions. The most suitable Copula functions were selected according to the scores of RMSE and NSE. Distributions of water demand for multiple users in 2025 and 2030 were obtained by Copula sampling. Interval values of water demand for different districts were obtained based on Latin hypercube sampling. The results of co-relationship between water demand and socio-economic development are presented in Table 1 and Figure S1.

The historical data of population, GDP, and water demand were obtained from NBS and DBS (2010–2020), NBS (2010–2020), LNDWR (2001–2019), and WABD (2018). Other related indicators are presented in Table S4 of Supplementary Material. As indicated by the results in correlation analysis, the Clayton and Gaussian Copula functions can describe the relationship between water demand and socio-economic development. Considering multiple tolerance levels of decision-makers to water shortage risk, three scenarios (i.e., S1 to S3), indicating 20%,

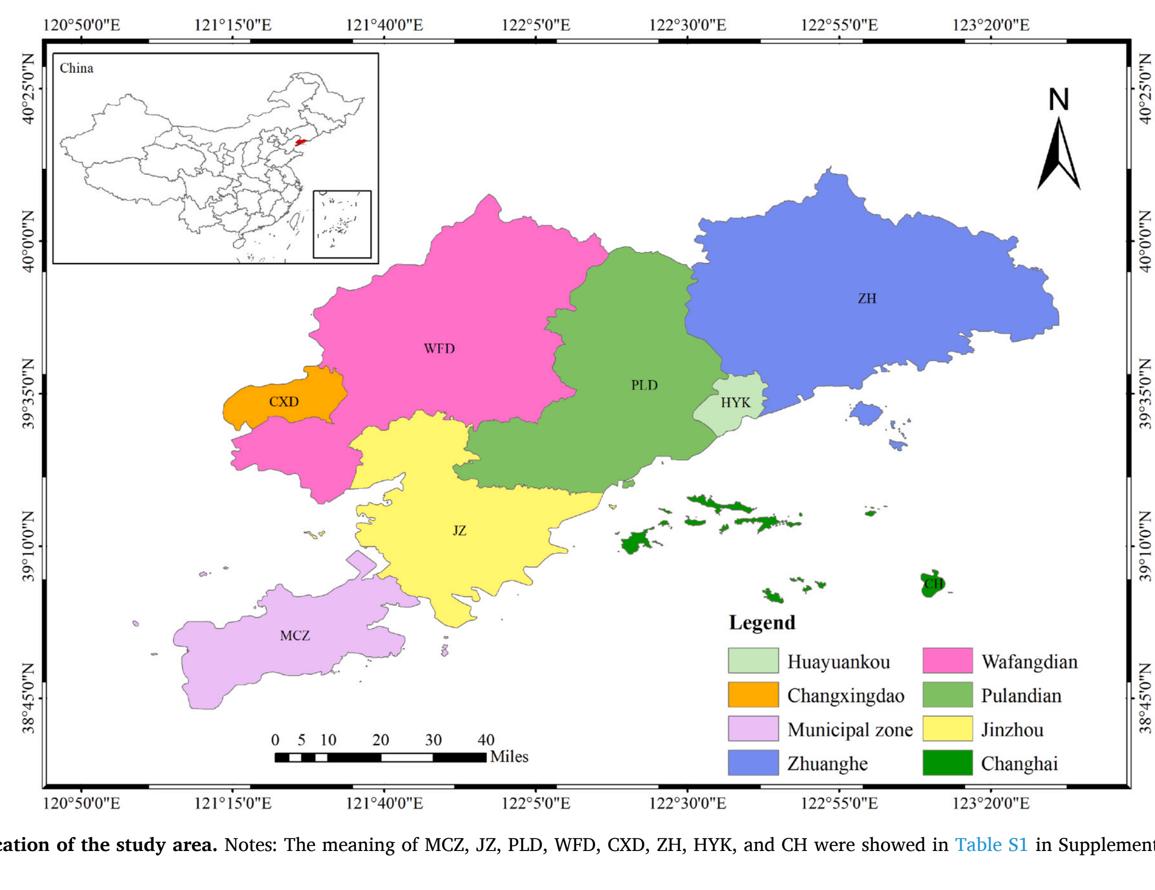

Fig. 2. Location of the study area. Notes: The meaning of MCZ, JZ, PLD, WFD, CXD, ZH, HYK, and CH were showed in Table S1 in Supplementary Material.

Table 1
Parameter estimations of the co-relationship between water demand and socio-economic development in Dalian City.

Water users	x_1[a]	x_2	Copula function	RMSE	NSE	Mean values of association parameters (θ)	Confidence intervals (95%) of θ
Agricultural sector	Added value of primary industry	Agricultural water consumption	Gaussian	0.4497	0.5602	0.1036	[-0.4726, 0.7117]
			Student t	0.4492	0.5613	0.1266	[-0.4038, 0.7348]
			Clayton	0.4368	0.5850	0.4624	[0.0228, 27.5501]
			Frank	0.4488	0.562	0.7289	[-4.6591, 24.9023]
			Gumbel	0.4513	0.5570	1.0001	[1.0001, 34.2755]
	Gross output value of primary industry	Agricultural water consumption	Gaussian	0.4711	0.5274	−0.0447	[-0.5786, 0.2741]
			Student t	0.4714	0.5268	−0.0495	[-0.6508, 0.6301]
			Clayton	0.4628	0.5440	0.3496	[0.0553, 30.4938]
			Frank	0.4714	0.5268	−0.0598	[-12.6500, 21.1529]
			Gumbel	0.4714	0.5268	1.0001	[1.0001, 33.0253]
	Added value from agriculture, forestry, animal husbandry,and fishery	***Agricultural water consumption***	Gaussian	0.3904	0.7493	0.5596	[0.0203, 0.9302]
			Student t	0.3746	0.7692	0.8487	[0.0119, 0.9127]
			Clayton	***0.3745***	***0.7693***	***1.3454***	***[0.5438, 32.4685]***
			Frank	0.3902	0.7496	3.8711	[1.0788, 32.3854]
			Gumbel	0.4026	0.7333	1.6050	[1.0474, 34.7798]
Industrial sector	Industrial added value	Industrial water consumption	Gaussian	0.3884	0.8953	0.9107	[0.5259, 0.9913]
			Student t	0.2782	0.9463	0.9785	[0.4971, 0.9923]
			Clayton	0.3366	0.9213	3.8732	[2.0822, 31.9754]
			Frank	0.3803	0.8996	12.5030	[6.5495, 34.0896]
			Gumbel	0.3942	0.8921	35.0000	[3.8525, 34.6541]
	Gross industrial output value	Industrial water consumption	Gaussian	0.3224	0.9386	0.7466	[0.3855, 0.9353]
			Student t	0.3224	0.9386	0.7447	[0.4223, 0.9355]
			Clayton	0.3069	0.9443	2.2773	[1.2064, 32.4773]
			Frank	0.3307	0.9354	6.1690	[3.4539, 32.9861]
			Gumbel	0.3364	0.9331	2.1473	[1.7500, 34.4319]
	Industrial added value above designated scale	***Industrial water consumption***	Gaussian	0.2903	0.9497	0.8234	[0.5595, 0.9624]
			Student t	0.2904	0.9497	0.8243	[0.5025, 0.9640]
			Clayton	***0.2730***	***0.9555***	***2.9322***	***[1.5882, 32.6669]***
			Frank	0.2946	0.9482	8.3462	[5.3479, 33.6373]
			Gumbel	0.3042	0.9448	2.8286	[2.2293, 34.8781]
Domestic residents	GDP	Domestic water consumption	Gaussian	0.1870	0.9692	0.8629	[0.6520, 0.9708]
			Student t	0.1873	0.9691	0.8646	[0.6467, 0.9818]
			Clayton	0.1765	0.9725	3.8520	[2.3067, 32.8434]
			Frank	0.1699	0.9746	9.4894	[5.9725, 31.7352]
			Gumbel	0.1912	0.9678	3.4653	[2.5447, 34.3976]
	Disposable income	Domestic water consumption	Gaussian	0.2558	0.8292	0.9999	[-0.0821, 0.9887]
			Student t	0.2558	0.292	0.9999	[-0.1677, 0.9943]
			Clayton	0.2421	0.8471	5.4778	[2.3468, 34.7165]
			Frank	0.2580	0.9263	35.0000	[4.9382, 34.5254]
			Gumbel	0.2559	0.8292	35.0000	[3.6492, 34.7418]
	Consumption expenditure	***Domestic water consumption***	Gaussian	0.1787	0.9719	0.8720	[0.6121, 0.9796]
			Student t	0.1789	0.9718	0.8750	[0.6328, 0.9853]
			Clayton	***0.1634***	***0.9765***	***3.8787***	***[2.3535, 33.0312]***
			Frank	0.1641	0.9763	9.9516	[6.4343, 31.5240]
			Gumbel	0.1848	0.9699	3.7032	[2.8929, 34.7257]
Public service sector	***Added value of tertiary industry and construction industry***	***Public service sector water consumption***	Gaussian	0.1521	0.9780	0.7554	[0.5665, 0.9075]
			Student t	0.1526	0.9779	0.7560	[0.5252, 0.8980]
			Clayton	***0.1420***	***0.9808***	***2.5645***	***[1.6343, 20.5217]***
			Frank	0.1468	0.9795	6.6342	[4.5075, 16.2128]
			Gumbel	0.1671	0.9735	2.2599	[1.7561, 34.0707]
Ecological environment	Urban garden green area	Eco-environmental water consumption	Gaussian	0.3558	0.8962	−0.1966	[-0.9292, 0.4951]
			Student t	0.3359	0.9075	−0.3685	[-0.9198, 0.4707]
			Clayton	0.3525	0.8982	0.3618	[0.0338, 3.9904]
			Frank	0.3531	0.8978	−1.4019	[-33.3462, 1.7182]
			Gumbel	0.3593	0.8942	1.0001	[1.0089, 28.9239]
	Urban green coverage area	***Eco-environmental water consumption***	***Gaussian***	***0.2974***	***0.9140***	***0.2061***	***[-0.3531, 0.6355]***
			Student t	0.2948	0.9155	0.1851	[-0.3414, 0.6381]
			Clayton	0.297	0.9138	0.3601	[0.0372, 13.8917]
			Frank	0.2987	0.9132	1.0250	[-2.5201, 4.9172]
			Gumbel	0.2965	0.9145	1.1419	[1.0194, 2.2337]

[a] Note: The indicators of x_1 and x_2 are described in Equation (1). The bold and italic numbers indicate the best-fit copula functions.

40%, and 60% of their low, medium, and high tolerance levels, were proposed in this study. The water demand was thus obtained based on the above three scenarios. The water demand of Dalian in 2025 and 2030 under the three scenarios are shown in Fig. 3.

Along with socio-economic development, the water demand in Dalian would increase from 2025 to 2030. Also, the higher the risk tolerance level of decision-makers, the narrower the range of water demand. For example, compared with other scenarios, the range of water demand under S1 would be largest; conversely, range of water demand under S3 would be smallest. Compared with water demand of other water users, the water demand of the agricultural and industrial sectors would be the greatest. In detail, the water demand of industrial sector would be largest under S1 and S2, while agricultural sector's water demand would be biggest under S3. The water demand in the two sectors (i.e., 636 to 1655 Mt) would account for 59.4%–61.1% of the total water demand. Conversely, water demand of the public service

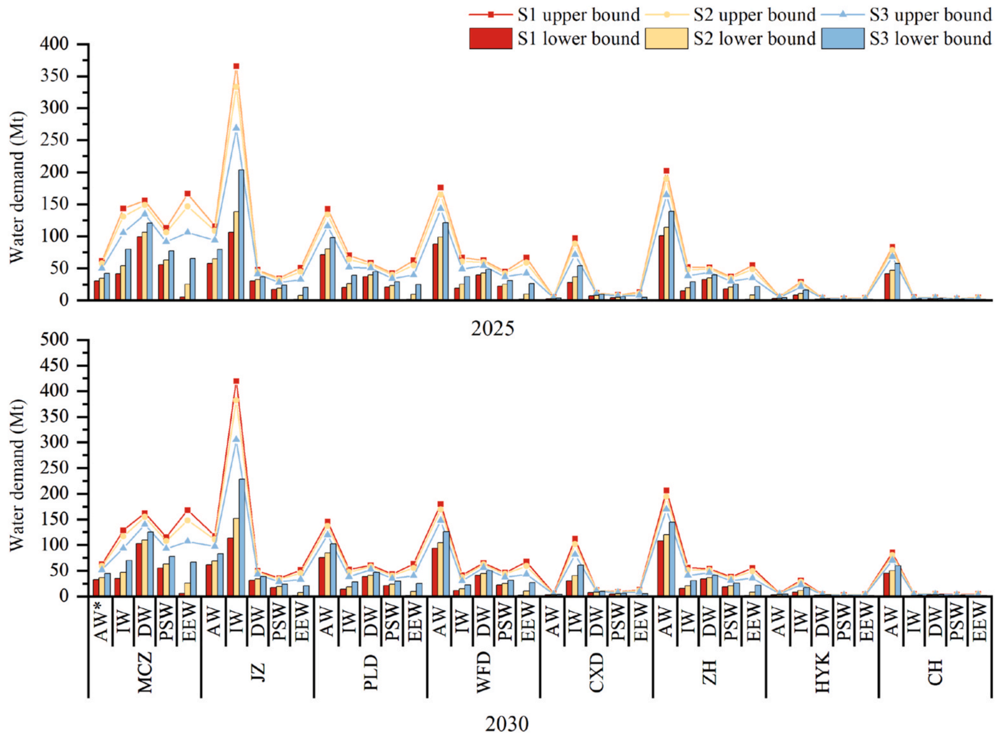

Fig. 3. Water demand of each district in Dalian in 2025 and 2030 under the three scenarios. *Notes: The meanings of the abbreviations in the figure are described in Table S1 of Supplementary Material.

sector would be the smallest, accounting for about 10.52%–13.54% of the total water demand. Compared with other districts in Dalian, districts of the Municipal zone and Jinzhou would consume the largest amount of water resources (i.e., 232.16 to 640.92 Mt, and 225.11 to 674.34 Mt, respectively). The variations in water demand of the two districts would be mainly influenced by industrial activities, contributing 15%–17% and 44%–50% of total water demand, respectively. Conversely, Huayuankou would consume the smallest amount of water resources (i.e., 15.58 to 48.07 Mt).

4. Results and discussions

4.1. Water resources allocation strategies

In this paper, an interval linear programming model was established to optimize allocation strategies of water resources in Dalian. With consideration of complication in surface water supply of Dalian, WRA management mainly focused on the allocation of surface water. Water supply from other sources (i.e., groundwater and desalinated water) was deducted proportionally according to Bureau of Water Resources (2014). The surface water demand of the multiple users in Dalian are shown in Table S5 of Supplementary Material. Previously, agricultural sector, industrial sector, and residents were chosen as typical water users. For example, Liu et al. (2017) conducted a dry-year analysis of water supply target optimization and shortages for different inflow levels in domestic, agricultural and industrial sectors. In this study, water supply to ecological environment and public service water sector were also incorporated in the WRA management. Compared with the related study for Dalian [e.g., Cai et al. (2016)], desired strategies for WRA were obtained based on the multiple tolerance levels of decision-makers to water shortage risk.

The strategies for WRA in Dalian in 2025 and 2030 are shown in Fig. 4. The total water supply of Dalian in 2030 would increase by 2.06%–2.65%, compared with the one in 2025. The allocation of water resources across districts was influenced by varied water demand, energy consumption, and risk tolerance levels. Compared with 2025, the contribution of transferred water sources would increase by 6.71% and 7.04% under S1 and S2 in 2030, respectively, and decrease by 14.31% under S3 in 2030. More than 85% of water supply in Jinzhou, Huayuankou and Changhai would be supported by local reservoirs. Conversely, less than 42% water supply in Municipal zone would be supported by transferred water sources.

From the perspective of water supply, the amount of WRA varied according to multiple risk tolerance levels of decision makers. First, with the increase of risk tolerance levels of decision-makers, the water allocation amount in Dalian would gradually decrease. The total water supply under S1 would be larger than that under S2 and S3. Second, with the increase of risk tolerance levels of decision-makers, water supply from transferred water sources would decrease. For example, water demand of most districts in Dalian under S1, would be supported by the local reservoirs and transferred water sources. The local reservoirs and Dahuofang Reservoir could meet the water supply needs of Dalian city under S3.

From the perspective of multiple users, the distribution trend of total WRA would not vary with the risk tolerance levels of decision-makers (Table S6). Under all scenarios, the amount of water resources allocated to industrial sector would be greater than that of other industries. In 2025 and 2030, the WRA amount of industrial sector would account for 24%–33% of the total WRA amount under the all scenarios. Compare with other industries, the amount of water resources allocated to the public service sector would be the smallest, accounting for only 11%–15% of the total amount for WRA. With the increase of decision makers' risk tolerance, the proportion of WRA to industrial sector and ecological environment would increase, while that to agricultural sector and domestic residents would decrease. Conversely, the amount of WRA to public service sector would not vary with the risk tolerance levels of decision makers.

4.2. Energy consumption in the process of WRA

According to strategies for water allocation, energy consumption in water allocation in Dalian is shown in Table 2. Influenced by the amount

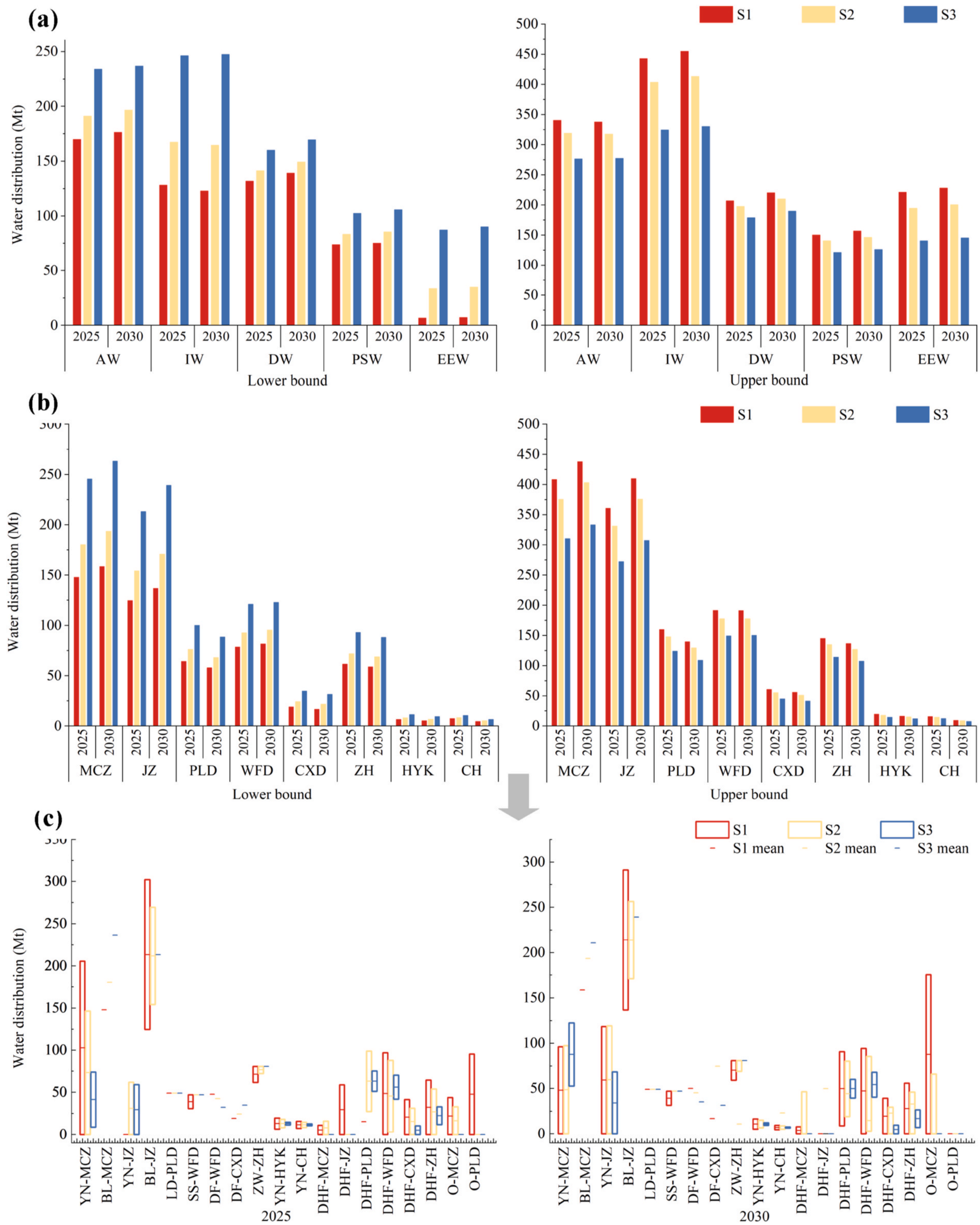

Fig. 4. The strategies of water resources allocation of Dalian in 2025 and 2030. (Fig. 4a is the results of water resources allocation by different users, Fig. 4b is the results of water resources allocation by different districts, and Fig. 4c is the total water resources allocation results). Notes: The meanings of the abbreviations in the figure are described in Table S1 of Supplementary Material.

of transferred water allocation, energy consumption under S1 would be greater than that under S2 and S3. Similarly, energy consumption in 2030 would be greater than that in 2025. In terms of the districts in Dalian, the energy consumption in the WRA to Pulandian and Wafangdian would be higher than that to other districts, accounting for 36–93% of the total energy consumption. Conversely, the energy consumption in the WRA to Huanyuankou would be lower. Although the energy consumption would vary with the districts of Dalian, energy consumption for the WRA would gradually decrease with the increase of decision makers' risk tolerance levels. The supply from other transferred water sources tend to decrease with the decrease of decision makers' risk tolerance levels.

Table 2
Energy consumption of water resources allocation in Dalian.

Area	S1		S2		S3	
	2025	2030	2025	2030	2025	2030
Municipal zone	[87, 9505]	[94, 30990]	[106, 8453]	[114, 19029]	[149, 217]	[180, 253]
Jinzhou	[74, 9990]	[81, 296]	[91, 224]	[101, 277]	[126, 188]	[141, 213]
Pulandian	[2654, 19177]	[1546, 15607]	[4707, 17028]	[3304, 13849]	[8814, 12921]	[6819, 10334]
Wafangdian	[13, 14075]	[479, 12777]	[479, 12777]	[471, 12418]	[6082, 10182]	[5875, 9857]
Changxingdao	[10, 8813]	[9, 8333]	[12, 6615]	[11, 6254]	[18, 2218]	[16, 2097]
Zhuanghe	[9, 13782]	[9, 11953]	[11, 11542]	[10, 9872]	[2583, 7063]	[1552, 5712]
Huayuankou	[4, 12]	[3, 10]	[5, 11]	[4, 9]	[7, 9]	[6, 8]
Changhai	[35, 74]	[22, 45]	[40, 69]	[25, 42]	[50, 59]	[31, 36]
Total	[2886, 75429]	[1777, 80832]	[5452, 56719]	[4041, 61751]	[17828, 32857]	[14620, 28511]

Unit: MKWh.

5. Conclusions

A hybrid approach, incorporating Copula functions and an interval linear programming model, was proposed in this study in order to identify non-stationary influence of water demand to WRA management. The approach was proven to be effective in 1) reflecting variation in water demand influenced by socio-economic development, 2) consideration of the risk-tolerance levels of decision makers, and 3) providing decision-making support for WRA. To verify the effectiveness of the approach, Dalian City of China was selected as a case study area. Considering multiple tolerance levels of decision-makers to water shortage risk, three scenarios (i.e., S1 to S3), indicating 20%, 40%, and 60% of their low, medium, and high tolerance levels, were proposed in this study. The results showed that the amount of WRA to the industrial sector would be bigger than the one to other users, while the WRA to the public service sector would be smaller. The districts of Municipal zone and Jinzhou would consume the biggest amount of water resources, compare with the other districts. With the increase of risk tolerance levels of decision-makers, the amount of water supply in Dalian city would gradually decrease. In view of the remarkable increase in energy consumption for allocating transferred water sources, policy makers should consider the improvement of supply capacity in local water sources.

This study had some limitations. First, allocation strategies were focused on surface water sources. Other water sources (e.g., groundwater, seawater, and reclaimed water), which would play an important role in WRA management, should be further considered. Second, improvement of water use efficiency in the future may influence the effectiveness of the WRA strategies. Despite these limitations, the Copula-based interval linear programming model proposed in this study, is valuable in terms of its applications in mitigating water-shortage risk and energy consumption in the process of WRA. This approach can be applied to other water-stress cities.

Credit author statement

All authors contributed to and collaborated in this research. YUE W. C., YU S.J. and SU M.R. developed the methods. XU M. provided the case study for application of the methods. RONG Q.Q. and XU C. collected and analyzed the data. All authors have contributed to paper preparation, have seen and approved the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2022.115318.

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