

## Application of water resource multi-objective allocation service based on digital water network

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### ABSTRACT

The rational allocation of water resources plays an important role in alleviating disparities between supply and demand in areas with water shortages. With the continuous development of modern information technology, the pace of digitization is accelerating. Digital water networks provide a means of technical support, and their application is becoming more extensive. Based on the traditional study of water resource allocation combined with the development of modern information technology, this paper proposes a new operational application model of multi-objective water resource allocation based on a digital water network and applies this model to allocate water resources in the Heihe River basin in Xi'an, Shaanxi Province. First, a topological digital water network is constructed based on the connectivity criterion of water systems, and a cooperative configuration model with social, economic and ecological objectives is established. Second, the model and its solution method are componentized, and the water resource allocation business system is constructed based on the comprehensive integration platform to integrate the digital water network and the water resource multi-objective allocation business. Finally, to verify the scientificity and feasibility of the new model, the new model was applied to allocate water resources in the Heihe River basin of Xi'an city, Shaanxi Province.

**Key words:** business convergence, comprehensive integrated, digital water network, multi-objective cooperative configuration

### HIGHLIGHTS

- A topological digital water network was constructed based on the connectivity criterion of water systems.
- A cooperative configuration model with social, economic and ecological objectives was established.
- The water resources allocation business system is built based on the comprehensive integration platform to realize the integration of digital water network and water resources multi-objective allocation business.

### INTRODUCTION

The rational allocation of water resources can greatly improve the utilization efficiency of regional water resources and alleviate shortages of regional water resources. With the rapid development of modern water control concepts and information technologies (such as the Internet of Things, big data and cloud computing), a series of concepts such as smart Earth, smart basin and smart water conservancy, along with new water control ideas, have been applied in the water conservancy industry. Digital water networks (Kline & Moretti 2014), as the frontier of smart basins and smart water conservancies, can coordinate water resources (Karim *et al.* 2015), water engineering (Jain & Tandon 2010), water ecology (Liu 2020), water environments (Li *et al.* 2003) and other fields. Digital water networks are considered to be an important means of solving water resource problems and have been implemented in many countries.

Digital water networks and their applications have been the object of extensive long-term exploration and research. Israel has completed the 'South-north Water Transfer' large-scale water transmission project, which is controlled by computers and the Internet of Things, and has developed a water resource dispatching system that can realize the real-time allocation and management of water resources and optimize the allocation scheme. By using remote sensing, Global Positioning System and geographic information system (3S) technology (Dreizin *et al.* 2008), multimedia technology and other technical means, the United States developed a visual simulation system for the digital management of the Tennessee River Basin. By using information technology such as 3S and virtual reality (VR), a visual watershed management platform was built for the Danube

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River basin flowing through nine countries. Zhang Yongchuan (Zhang *et al.* 2001) first proposed the concept of a ‘digital basin’ and that the scope of research of digital basins includes basic framework research, model building, platform building and related technology research. This provided a roadmap for future research and facilitated its rapid development. By employing the concept of a ‘digital watershed’, Zhou Xiaofeng (Zhou *et al.* 2003) and Wang Zhijian established a system model of a digital watershed that can manage multidimensional watershed data. Using 3S integration and component technology, Yu Xiang (Yu *et al.* 2020) and others constructed a visual digital water network and an assessment and management system for the Beijing-Tianjin-Hebei Water functional area.

Research on ‘digital water networks’ in China and globally has found that these networks are the product of water conservancy informatization, which plays a decisive role in the modern management of water resources, reflecting the mainstream water conservancy informatization development trend in this field. Although much research currently focuses on ‘intelligent water networks’, this research primarily involves data collection of data information, visual displays, information queries and intelligent controls; there is less research on the integration of digital water networks in water resource allocation businesses.

Therefore, this paper proposes a new concept of water resource allocation, which organically combines digital, component and knowledge visualization technologies. First, the digital water network was topologically constructed to build a visual digital water network. Second, the multi-objective optimal allocation model of water resources was established; the model and solution method were modular. Finally, the integrated application of the digital water network and water resource allocation service was realized based on the comprehensive integration platform. To test the effectiveness of the model, the object of the research was the water supply project of the Heihe River Basin to Xi’an. Reasonable allocation of water resources can effectively alleviate the regional water resources shortage and the prominent contradiction between supply and demand. It is an important non-engineering measure to realize the coordinated development of society, economy and ecology. This research model can meet the demand of social and economic water supply in Heihe River basin and make the problem of water supply no longer restrict the regional social and economic development.

## Study area

The Heihe River is the largest tributary of the Weihe River, a tributary of the Yellow River, in Shaanxi Province, with a basin area of approximately 2,258 square kilometres, annual average runoff of 628.5 million m<sup>3</sup>, and average annual precipitation of 638.3 mm. Present engineering in the basin consists of water storage engineering, water diversion engineering, water-lifting engineering and electromechanical well engineering. The water storage project includes 1 large reservoir (Jinpan reservoir), 1 small (I)-type reservoir (Xiliuyu reservoir) and 4 small (II)-type reservoirs. Ninety-six small water diversion projects have been built in the Heihe River basin. Among them, the Tianyu low dam diversion project is located in the Tianyu River valley involving 25 small water-lifting projects and 5,931 underground water electromechanical wells.

Actual water consumption is calculated according to the new scale, which is divided into domestic, production and ecological uses. Production includes primary, secondary and tertiary industries. Based on the actual situation in the basin and relevant data, the connectivity between water sources and users is summarized, as shown in Table 1. The main water sources in the Heihe River Basin are the Jinpan Reservoir, the Xiluoyu Reservoir, the Tianba water diversion project and groundwater. Table 1 shows the water supply regions of each water source project and water supply in this region, which clearly depicts the current annual water system connectivity of the Heihe River Basin.

## MATERIALS AND METHODS

### Topological generalization of digital water networks

Topology refers to the overall property that geometry or space remains unchanged under generalized and abstract conditions (Milad *et al.* 2016). Point, line and plane elements are the main components of topological digital water networks and correspond to node, arc and plane graphical elements, respectively (Riggs *et al.* 2019). The topological relationship of a digital water network refers to the relationship between connecting point-like and linear elements, which actually reflects the process of water movement transformation. Water resources that are hydraulically transmitted by linear elements will be converted into other types of water resources as the paths increase and water quantity decreases continuously. The process of water resource catchment, diversion and transformation takes place in the point element, which is an important element in the conversion, regulation and storage of water resources (Ren 2005). The process of overlapping occurs with respect to the

**Table 1** | Water system connectivity

Water source name	Water supply area	Water supply object
Heihe Jinpen Reservoir	Source to Heiyukou Heiyukou to Weihe	Domestic, production Domestic, production, ecology
Xiluoyu Reservoir	Heiyukou to Weihe	Domestic, agriculture
Tianyu Low Dam Water Diversion Project	Source to Heiyukou Heiyukou to Weihe	Domestic, agriculture Domestic, agriculture
Groundwater	Source to Heiyukou Heiyukou to Weihe	Domestic, production Domestic, production

linear elements and refers to the phenomenon in which several linear elements overlap during the transmission of water resources. The basic topological relationship in digital water networks is shown in Figure 1.

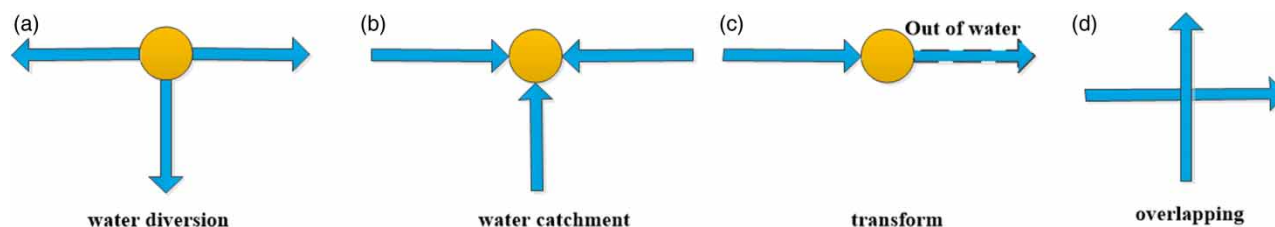
Point and line elements are the basic elements of topological digital water networks, and a description of the relationship between them is necessary to establish hydraulic relationships (Singh & Sinha 2018). From the starting point, each arc passes through one or more water resource transitions (Zakon *et al.* 2005), such as water diversion, transformation, catchment and overlap, before finally reaching the end point. The direction of topological connections between nodes is determined by the direction of water transmission between starting and ending nodes (Zi *et al.* 2018). Therefore, the process of constructing a digital water network is essentially the process of describing the relationship between topological elements.

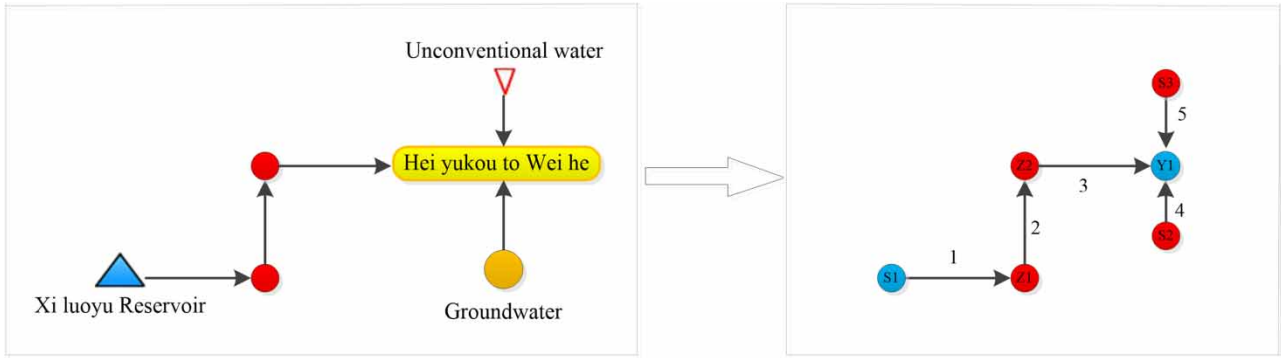
A digital water network is a description of the relationship between the supply and demand networks of water resource allocation (Segurado *et al.* 2013). Through a digital water network, the physical connection in water resource allocation is abstracted into a network topology network formed by nodes and directed edges. Taking Xiluoyu Reservoir as an example (Yang *et al.* 2020), the supply and demand relationship between the water source and its users is generalized into a digital water network and topology, as shown in Figure 2.

### Visual construction of a digital water network

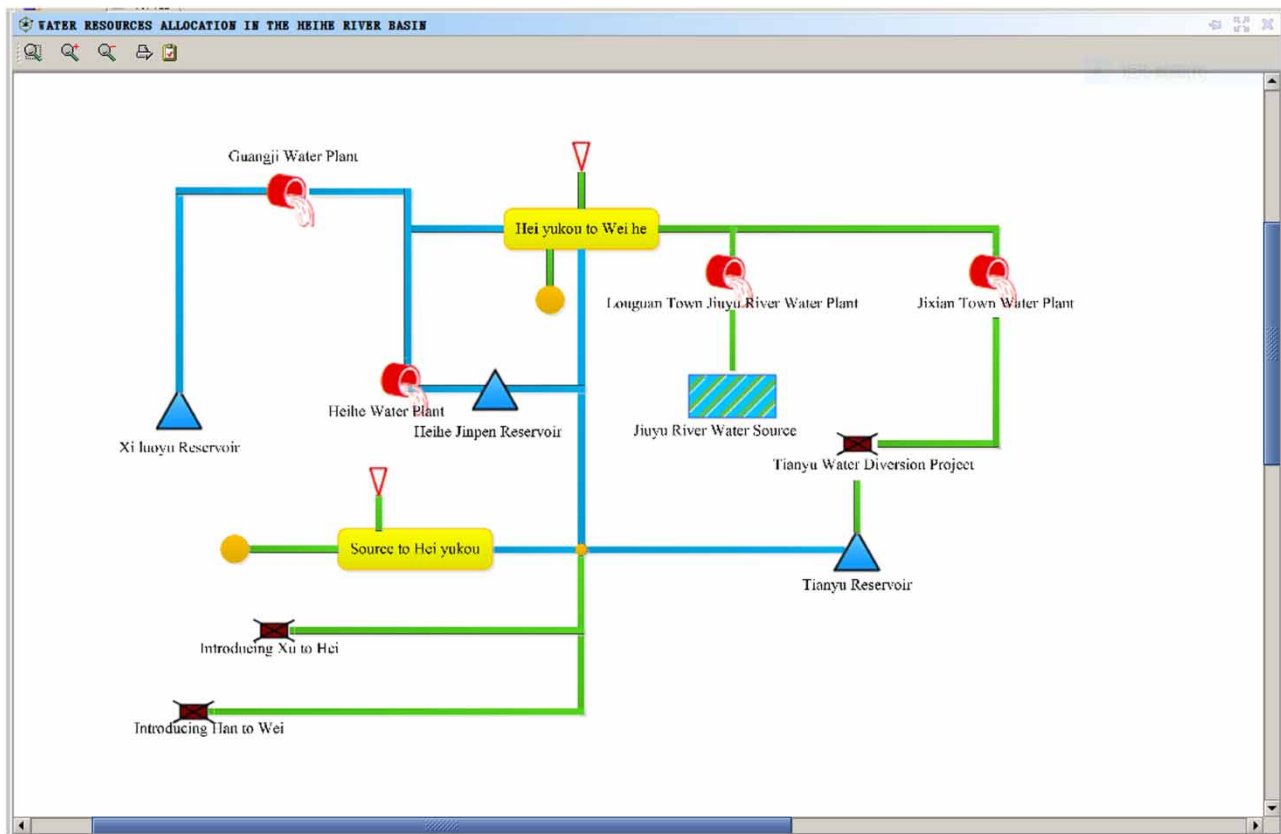
The comprehensive integrated platform independently developed in accordance with the Water Resources Industry Standard of the People's Republic of China 'Technical Provisions for Water Resources Information Processing Platform' (SL538-2011) can enable the visualization and integration of digital water networks into businesses (Stadler *et al.* 2009). Important components include knowledge-graph technology, components and data resource bases. Through the selection and connection of nodes and lines, the integrated platform provides users with a visual means to construct digital water networks for different business needs.

Business components are divided according to knowledge content and are considered knowledge nodes (Xu 2020). Text annotations may be added to knowledge nodes to describe information. The logical relationship of business components between nodes, or the model calculation process, can be described by the method of knowledge link. The business data presented in XML involves a one-way transfer from the previous recognition node to the next knowledge node (Taelman *et al.* 2018). The visualization of the water resources business is realized by drawing a knowledge graph through a knowledge node, knowledge link and knowledge annotation. Figure 3 shows the constructed digital water network of the Heihe River Basin.

**Figure 1** | The basic topological relationship in digital water networks.



**Figure 2 |** Topological network structure of the supply and demand of Xiliuyu reservoir based on a digital water network abstract.



**Figure 3 |** Digital water network of Heihe River Basin.

**Construction of multi-objective collaborative configuration model**

Collaborative allocation of a water resource business mainly considers social, economic and ecological perspectives to determine the comprehensive benefits of the objective function and constraint conditions by establishing a collaborative allocation model of water resources allocation using a supply and demand balance analysis to consider two planning years (2025 and 2030) under a reasonable configuration scheme and realize the sustainable development of water resources.

**The objective function**

(1) Social benefit target

Social benefits mainly include ensuring the safety of the water supply and meeting the needs of the population and for economic development. According to water users' different water requirements, corresponding weight should be given to domestic, agriculture, industry, tertiary industries, construction and ecology to maximize the security of the water supply.  $F_1$  is used as the objective function of the total water supply, and  $f_c$ ,  $f_A$ ,  $f_I$ ,  $f_T$  and  $f_E$  are used to represent the water supply for domestic, agricultural, industrial, tertiary industrial, construction and ecological uses, respectively.

$$F_1 = \max (f_c + f_A + f_I + f_T + f_E) \quad (1)$$

Among them, the domestic water supply is the sum of surface water, groundwater and external water transferred into the basin. The agricultural, industrial, tertiary production, construction and ecological water supplies are the sum of surface water, groundwater, water diversion engineering and unconventional water.

## (2) Economic efficiency target

By assigning a certain weight coefficient to water shortages of different industries, the minimum water shortage can achieve the optimal economic benefit, which not only fulfills the needs of each water user but also drives the coordinated development of the whole region.  $F_2$  is the target function of total water shortage with the formula as follows:

$$F_2 = \min \sum_{j=1}^n (\beta_j^C \cdot XZMC_j + \beta_j^A \cdot XZMA_j + \beta_j^I \cdot XZMI_j + \beta_j^T \cdot XZMT_j + \beta_j^E \cdot XZME_j) \quad (2)$$

In the formula,  $\beta_j^{C(A,I,T,E)}$  represents the weight coefficient of water shortages in households, agriculture, industry, tertiary industry, construction and ecology of the  $j$ -th calculation unit;  $XZMC(A, I, T, E)_j$  represents the lack of water for domestic, agricultural, industrial, tertiary industrial, construction and ecological uses.

## (3) Goals for ecological and environmental benefits

By maximizing the reuse of water and minimizing shortages in the natural environment, the ecological environment benefits outside of the rivers reach their maximum values.  $F_3$  is the objective function of ecological benefit, and the expression is as follows:

$$F_3 = \max \sum_{j=1}^n (\gamma_j^{ec} \cdot XZTR_j - \gamma_j^E \cdot XZME_j) \quad (3)$$

where  $\gamma_j^{ec}$  and  $\gamma_j^E$  represent the weight coefficient of the reused water and ecological water shortage in the  $j$ -th calculation unit; denotes the amount of reclaimed water for sewage treatment and the lack of water for the ecological environment.

## Constraint condition

### (1) Water balance equation

$$PZWC_{tm}^j = XCSC_{tm}^j + XCDC_{tm}^j + XZGC_{tm}^j + XZMC_{tm}^j \quad (4)$$

$$PZWA_{tm}^j = XC SA_{tm}^j + XCDA_{tm}^j + XZTA_{tm}^j + XZGA_{tm}^j + XZMA_{tm}^j \quad (5)$$

Among them, the calculation of industrial, tertiary industrial, construction and ecological water requirements is the same as for agriculture.

In the formula,  $PZWC(A)$  represents domestic and agricultural water demand;  $XCSC(A)$  represents the amount of surface water for domestic and agricultural use;  $XCDC(A)$  represents the amount of water transferred for domestic and agricultural use;  $XZTA$  refers to the amount of reclaimed water for agriculture;  $XZGC(A)$  represents the amount of groundwater for domestic and agricultural use;  $XZMC(A)$  represents the lack of water for domestic and agricultural purposes.

## (2) Economic benefit constraint

$$\begin{cases} \sum_{j=1}^n I^j \geq I_s \\ \sum_{j=1}^n T^j \geq T_s \\ \sum_{j=1}^n G^j \geq G_s \end{cases} \quad (6)$$

In the formula,  $I^j$ ,  $T^j$  and  $G^j$  denotes the unilateral water benefit value of industry, tertiary industry, construction and GDP in the  $j$ -th calculation unit;  $I_s$ ,  $T_s$  and  $G_s$  represent the unilateral water efficiency targets realized by industry, tertiary industry, construction and GDP planning.

## (3) Ecological benefit constraint

$$\sum_{j=1}^n XZTR_{tm}^j \geq \lambda^j \cdot XQTS_{tm}^j \quad (7)$$

where  $XZTR$  represents wastewater treatment water reuse;  $XQTS$  represents the wastewater treatment volume of the  $j$ -th computing unit; and represents the planned reclaimed water reuse rate of the  $j$ -th computing unit.

**Multi-objective cooperative configuration model solving**

On the premise of obtaining a clear objective function, balance equation, constraint conditions and water supply priorities, the Java language is used to realize the solution of the model in Eclipse software and finally generate the water resource configuration component. In the model calculation process, it is necessary to ensure the coordinated development of social, economic and ecological benefits. Iterative calculations are carried out by taking control of the total amount of conventional water available for supply, the total amount of water required, the amount of groundwater available for exploitation and the total amount of reclaimed water as the discriminant conditions to generate the collaborative allocation scheme of water resources. The specific calculation process is shown in Figure 4.

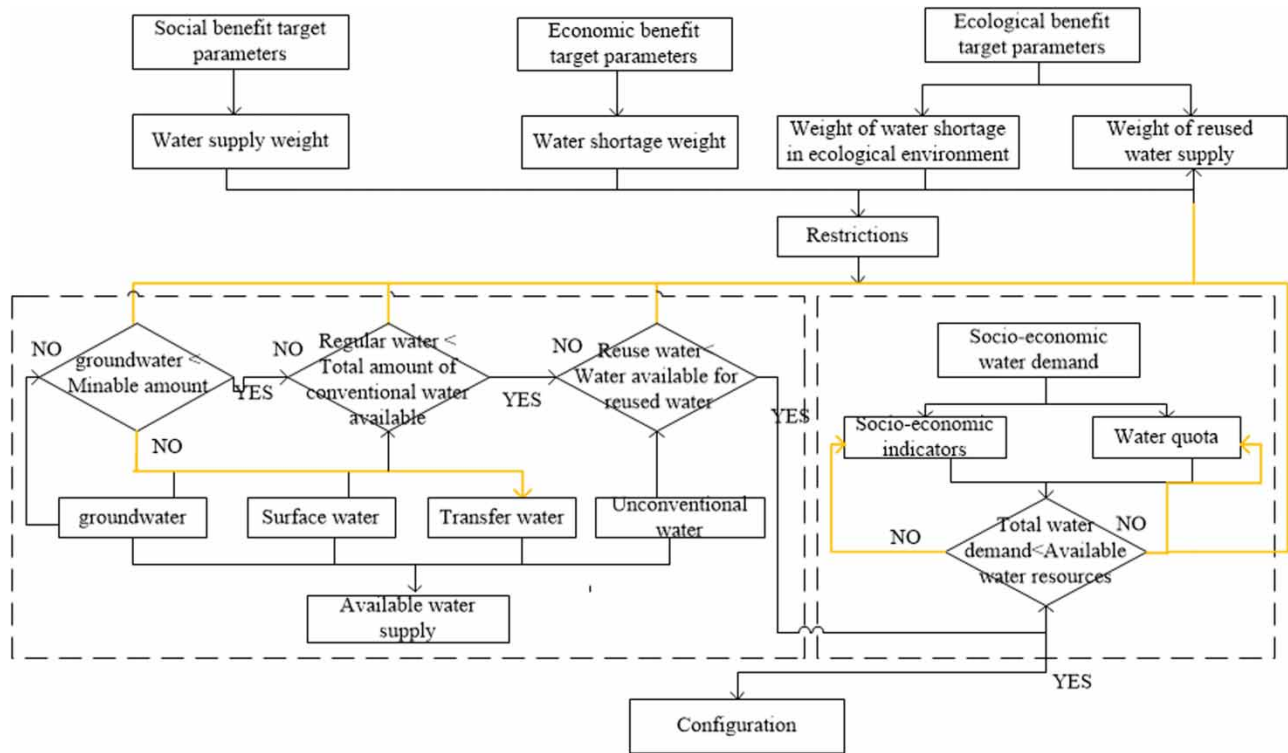
As shown in Figure 4, multiple iterations are used to solve the water resource allocation model. In terms of the available water supply, the supply of conventional water resources and the total supply of reused water are obtained through the coordinated water supply configuration of multiple water sources and the iterative calculation of the total water supply. In terms of water demand, by controlling the water resource availability in the study area, multi-user water demand is calculated iteratively. The specific steps are as follows:

Step 1: Define the target of the configuration model, establish the objective function, balance equation, constraint conditions etc.

Step 2: Multi-source water supply analysis. (1) Is the total amount of groundwater less than or equal to the recoverable amount of groundwater? If so, then the next step involves judging the total conventional water consumption amount. If not, to reduce the groundwater supply, it is necessary to increase the weight of unconventional water supply or the weight of external water transfer. (2) Is the total amount of conventional water supply less than or equal to the total amount of the water consumption control index? If so, the next step of unconventional water supply is to be judged. If not, increase the unconventional water supply weight. (3) Determine whether the quantity of recycled water meets the reuse water utilization rate value in 'Water Ten Rules'. If so, conduct the multiuser water demand analysis. If not, increase the reuse water supply weight.

Step 3: Multi-user water demand analysis. Determine whether the total amount of water needed by water users is less than or equal to the total amount of water resources available. If so, generate a water resource allocation plan. If not, increase the weight of unconventional water supply or the weight of external water supply, or adjust socioeconomic indicators and water quota to reduce the demand of domestic, production and ecological water users.





**Figure 4** | Flow chart of the multiple iteration algorithm for the multi-objective collaborative configuration model.

## RESULTS AND DISCUSSION

### Business integration of digital water networks and water resource allocation

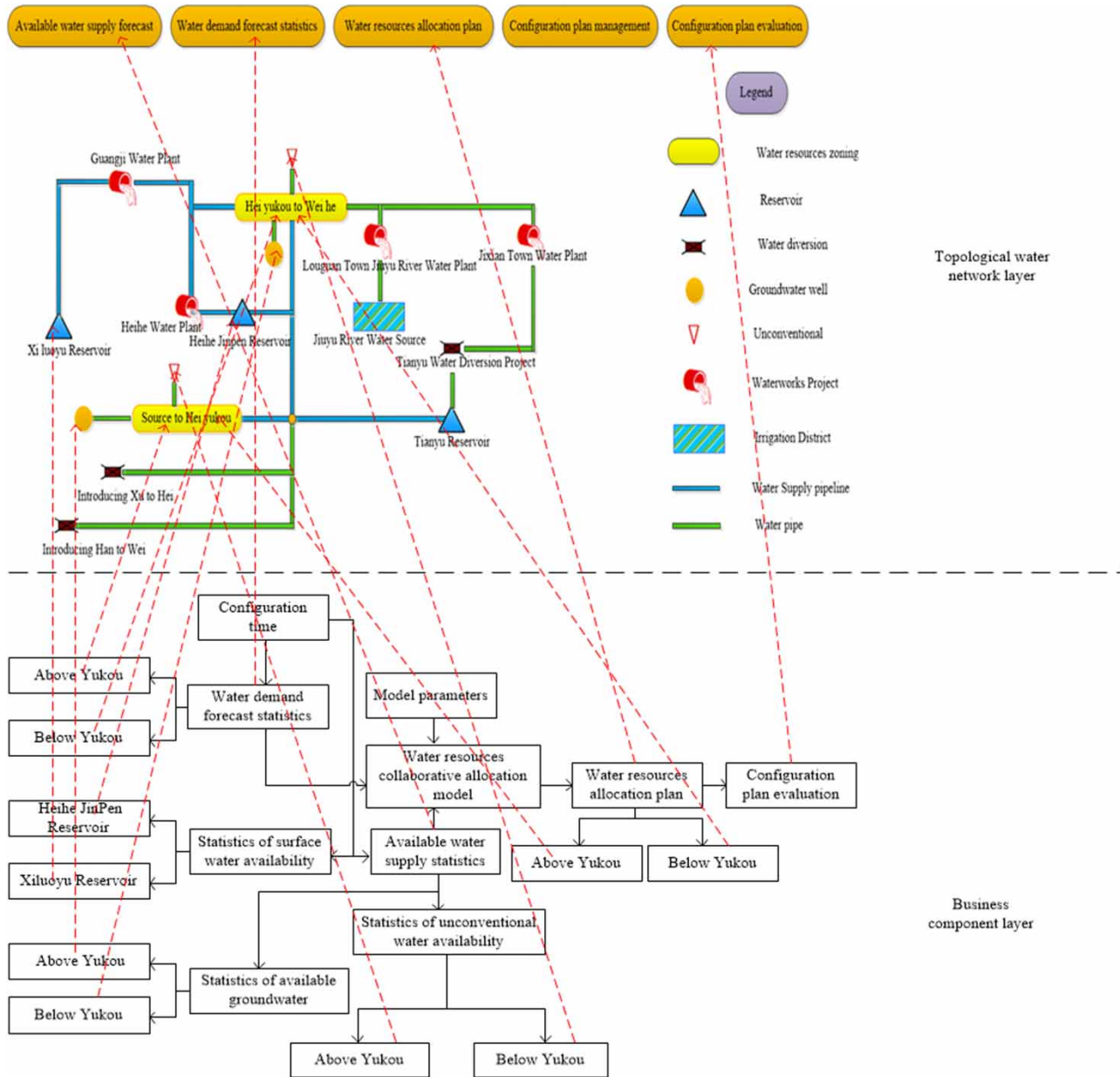
The aim of business componentization is to clarify business logic according to different business themes by dividing components according to business logic; develop, encapsulate and publish components; and customize corresponding business components on the integrated application platform. In this paper, according to the calculation process of multi-objective collaborative allocation, the components are divided into multi-objective collaborative allocation model components, model parameter components, water resource allocation schemes, water demand prediction statistics, available water supply statistical components etc. Business components are added to the corresponding nodes under the graph element of the digital water network to realize the integration of the digital water network and water resource collaborative allocation business. The mapping relationship between the digital water network and the water resource allocation component business network is shown in Figure 5.

A water resource allocation platform based on a digital water network can be customized by adding, deleting, modifying and combining business components and quickly adapts to the changing business content. To a certain extent, this departs from the traditional water resource system development mode and greatly improves the efficiency of water resource businesses. Figure 6 shows the application interface of multi-objective cooperative configuration of water resources.

### Business application

On the basis of the componentization of multi-objective collaborative allocation service and the integration of a digital water network and multi-objective collaborative allocation service, the weight coefficients of water supply and water shortage were determined based on social, economic and ecological benefits. After the objective function and constraint conditions were determined, the collaborative configuration model was iteratively calculated.

- (1) Water resource allocation under a 50% guarantee rate



**Figure 5** | Mapping diagram of the multi-objective collaborative configuration of the digital water network and business components.

Under the water resource configuration topic, click the time button, set the guarantee rate to 50%, and click the Water Resource Cooperative Configuration Model to obtain the water resource configuration plan in 2025 and 2030, as shown in Figure 7.

For the convenience of review and discussion, Table 2 lists the water resource allocation plan of 50% of the representative year in 2025. Similarly, Table 3 lists the 50% representative annual water resource allocation plan in 2030.

The 2025 configuration plan is as follows: The water demand of the Heihe River Basin is 17,451.84 Wm<sup>3</sup>, the domestic water supply is 1,162.07 Wm<sup>3</sup>, agricultural water supply is 7,669.26 Wm<sup>3</sup>, industrial water supply is 2,292.77 Wm<sup>3</sup>, tertiary industry and construction water supply is 229.24 Wm<sup>3</sup>, the ecological water supply was 5,631 Wm<sup>3</sup>, and the total water supply is 16,984.3 Wm<sup>3</sup>, and the water shortage is 467.496 Wm<sup>3</sup>.

The 2030 allocation plan is as follows: The water demand of the Heihe River Basin is 18,255.26 Wm<sup>3</sup>, the water supply for domestic use is 1,315.01 Wm<sup>3</sup>, the water supply for agriculture is 8,899.5 Wm<sup>3</sup>, the water supply for industry is 1,887.58 Wm<sup>3</sup>,



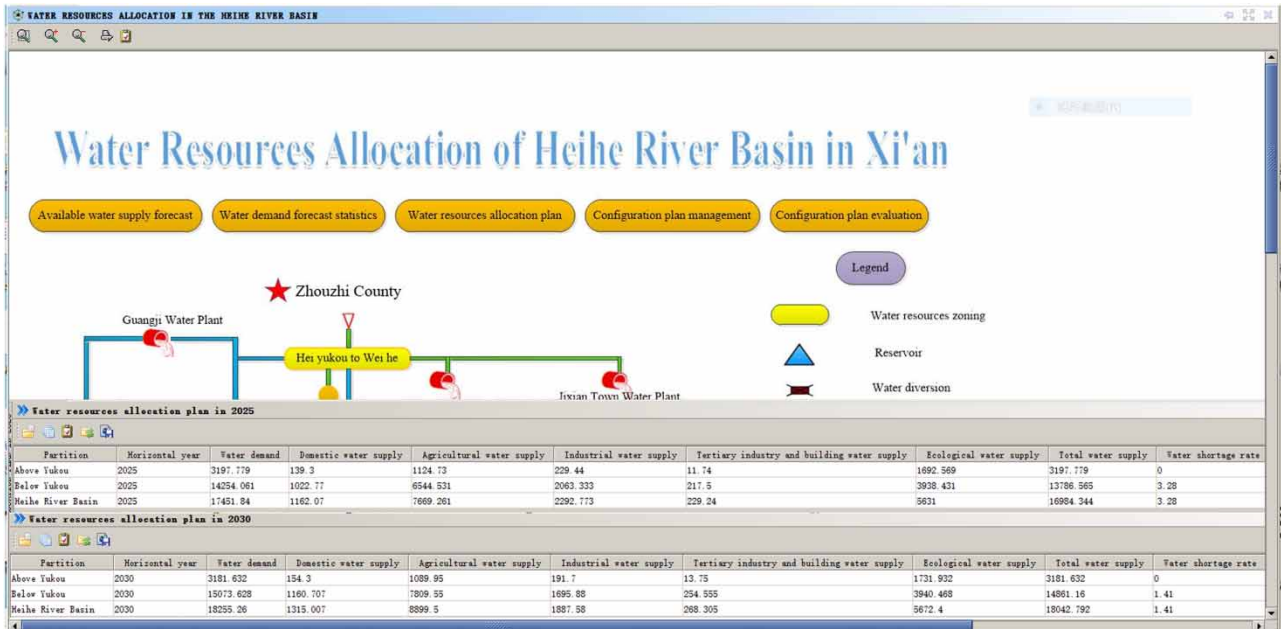
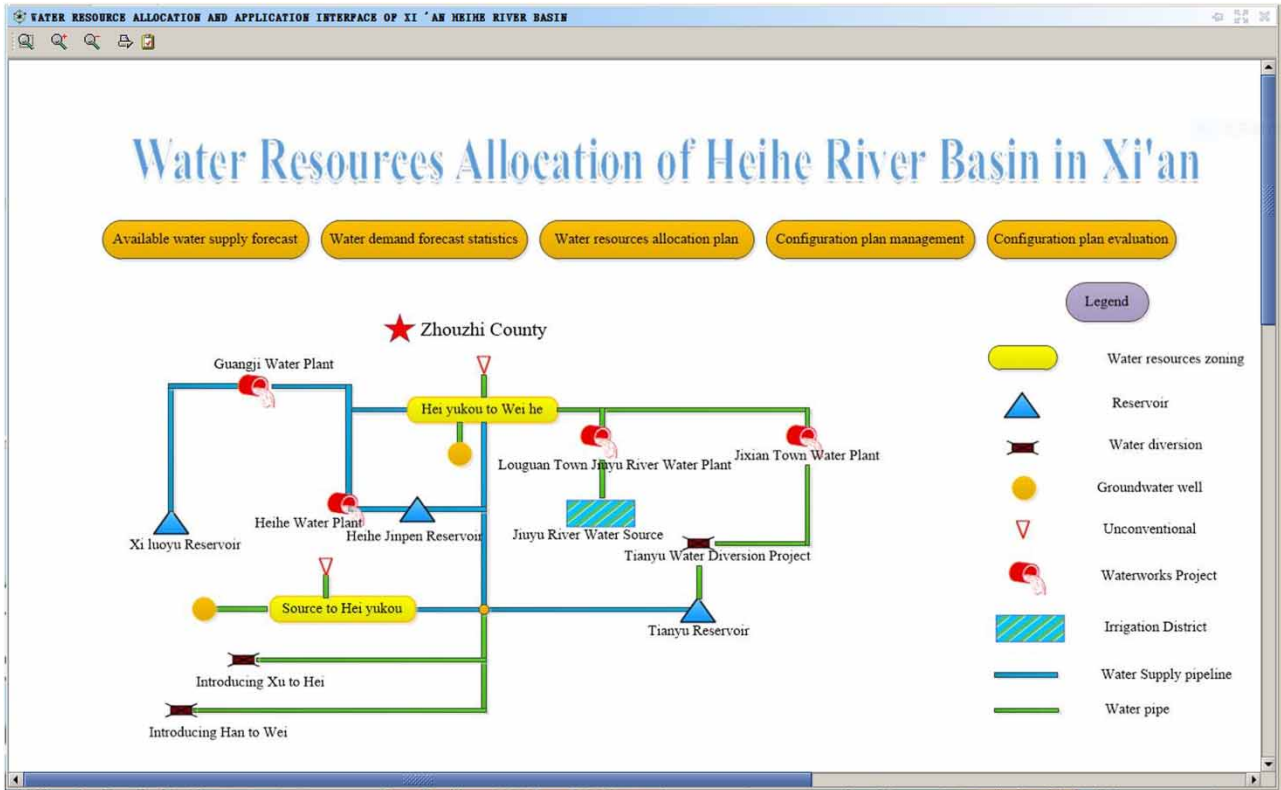


Figure 7 | 50% represents annual water resource allocation plan.

**Table 2** | 50% Represents the annual water resource allocation plan in 2025 W m<sup>3</sup>

Partition	Year	Water demand	Water supply					Total	Water shortage rate (%)
			Domestic	Agricultural	Industrial	Third industry	Ecological		
Above Yukou	2025	3,197.78	139.3	1,124.73	229.44	11.74	1,692.57	3,197.8	0
Below Yukou	2025	14,254.06	1,022.77	6,544.53	2,063.33	217.5	3,938.43	13,786.6	3.28
Heihe River Basin	2025	17,451.84	1,162.07	7,669.26	2,292.77	229.24	5,631	16,984.3	3.28

**Table 3** | 50% Represents the annual water resource allocation plan in 2030 W m<sup>3</sup>

Partition	Year	Water demand	Water supply					Total	Water shortage rate (%)
			Domestic	Agricultural	Industrial	Third industry	Ecological		
Above Yukou	2030	3,181.63	154.3	1,089.95	191.7	13.75	1,731.93	3,181.63	0
Below Yukou	2030	15,073.63	1,160.71	7,809.55	1,695.88	254.56	3,940.47	14,861.2	1.41
Heihe River Basin	2030	18,255.26	1,315.01	8,899.5	1,887.58	268.31	5,672.4	18,042.8	1.41

the water supply for tertiary production and construction is 268.31 million m<sup>3</sup>, and the water supply for ecology is 5,672.4 Wm<sup>3</sup>. The total water supply is 18,042.8 Wm<sup>3</sup>, and the water shortage was 212.47 Wm<sup>3</sup>.

## (2) Water resource allocation under 75% guarantee rate

When the guarantee rate is selected as 75%, the water resource allocation plan for 2025 and 2030 can be obtained. [Table 4](#) lists the water resource allocation plan of 75% of the representative year in 2025. Similarly, [Table 5](#) lists the 75% representative annual water resource allocation plan in 2030.

The 2025 configuration plan is as follows: In the Heihe River Basin, the water demand is 18,298.64 Wm<sup>3</sup>, the water supply for domestic use is 957.52 Wm<sup>3</sup>, the water supply for agriculture is 7,636.68 Wm<sup>3</sup>, the water supply for industry is 2,145.90 Wm<sup>3</sup>, the water supply for tertiary production and construction is 185.74 Wm<sup>3</sup>, and the water supply for ecology is 5,630.9 Wm<sup>3</sup>. The total water supply is 16,556.7 Wm<sup>3</sup>, and the water shortage is 1,741.901 Wm<sup>3</sup>.

The 2030 allocation plan is as follows: In the Heihe River Basin, the water demand is 18,255.26 Wm<sup>3</sup>, the water supply for domestic use is 1,093.40 Wm<sup>3</sup>, the water supply for agriculture is 8,300.16 Wm<sup>3</sup>, the water supply for industry is

**Table 4** | 75% Represents the annual water resource allocation plan in 2025 W m<sup>3</sup>

Partition	Year	Water demand	Water supply					Total	Water shortage rate (%)
			Domestic	Agricultural	Industrial	Third industry	Ecological		
Above Yukou	2025	3,316.38	139.3	1,243.33	229.44	11.74	1,692.57	3,316.38	0
Below Yukou	2025	14,982.26	818.22	6,393.35	1,916.46	174	3,938.33	13,240.4	1.16
Heihe River Basin	2025	18,298.64	957.52	7,636.68	2,145.90	185.74	5,630.9	16,556.7	1.16

**Table 5** | 75% Represents the annual water resource allocation plan in 2030 W m<sup>3</sup>

Partition	Year	Water demand	Water supply					Total	Water shortage rate (%)
			Domestic	Agricultural	Industrial	Third industry	Ecological		
Above Yukou	2030	3,300.23	154.3	1,208.55	191.7	13.75	1,731.93	3,300.23	0
Below Yukou	2030	15,931.53	939.10	7,091.61	1,356.70	2.48	3,940.47	13,330.3	16.33
Heihe River Basin	2030	18,255.26	1,093.40	8,033.16	1,548.40	16.23	5,672.4	16,630.6	16.33

1,548.40 Wm<sup>3</sup>, the water supply for tertiary production and construction is 16.23 Wm<sup>3</sup>, and the water supply for ecology is 5,672.4 Wm<sup>3</sup>. The total water supply is 16,630.6 Wm<sup>3</sup>, and the water shortage is 2,601.168 Wm<sup>3</sup>.

(3) The result of the configuration scheme is reasonable

According to the water resource allocation scheme with guarantee rates of 50 and 75%, the water shortages in 2025 and 2030 with a 50% guarantee rate are 467.496 Wm<sup>3</sup> and 212.468 Wm<sup>3</sup>, respectively, and the water shortages in 2025 and 2030 with the 75% guarantee rate are 1,741.901 Wm<sup>3</sup> and 2,601.168 Wm<sup>3</sup>, respectively. The water shortage under the 50% guarantee rate is less than that under the 75% guarantee rate, and the water shortage areas are all below the Heihe valley mouth. To meet the water supply demand of the users, two methods are adopted: saving water for the users and transferring water to the Han Jiwei and Xu Jihe projects to replenish the water supply.

## CONCLUSION

This paper takes economy, society and ecology as the objective function of the configuration model, determines the constraint conditions, establishes the multi-objective cooperative configuration model and solves the configuration model according to the multiple iteration algorithm. In the topological digital water network environment, the operational application of the water resource allocation model is realized, and the configuration scheme in 2025 and 2030 is obtained under guarantee rates of 50 and 75%, respectively. The rationality analysis of the configuration scheme shows that the configuration schemes in 2025 and 2030 with 50 and 75% guarantee rates are reasonable. In the water resource allocation scheme obtained, the water shortages in 2025 and 2030 with a 50% guarantee rate are 4,674,996 m<sup>3</sup> and 2,124,668 m<sup>3</sup>, respectively, and the water shortages in 2025 and 2030 with a 75% guarantee rate are 17,419,001 m<sup>3</sup> and 26,0168 m<sup>3</sup>, respectively. The water shortage under the 50% guarantee rate is less than that under the 75% guarantee rate, and the water shortage areas are all below the Heihe valley mouth. Combined with the actual watershed and the construction of a water diversion project, the identified layout of water supply projects in the river basin in planning years 2025 and 2030 is as follows: a new water storage project (Tianyu reservoir); surface water to be replaced with Xu Ji Hei; surface water to be replaced with Han Ji Wei River and Han Ji River; groundwater exploitation; and the river basin tapping its own potential (water-saving, rainwater utilization and reclaimed water reuse). The research results have responded positively to the national policy requirements of rational allocation of water resources. At the same time, it can provide technical support for the rational control and optimal scheduling of water resources in Xi'an Heihe River Basin. It can also provide solutions to similar water resources problems in other basins.

## ACKNOWLEDGEMENTS

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## DATA AVAILABILITY STATEMENT

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

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