Regional water allocation for coordinated development among the social, economic and environmental systems

Xinkui Wang, Zengchuan Dong, Wenzhuo Wang, Yaogeng Tan, Tianyan Zhang and Yalei Han

ABSTRACT

Most current water allocation strategies fail to address the unbalanced development among multiple systems. How to optimize the coordination development relationships among the social, economic and environmental systems has always been the focus. To bridge this gap, a water optimal allocation model for coordinated development was innovatively constructed and applied to the main stream of the Xiangjiang River Basin, China. The results showed the following. (i) From 2025 to 2030, the water deficit ratio of the study area will increase from 3.21 to 5.50% when $P = 50\%$ and from 4.59 to 6.85% when $P = 75\%$. The existing water supply capacity will not be able to meet the increasing water demand. (ii) Agricultural and industrial water will account for a large proportion of the total water consumption. Due to the transformation of industrial structure, measures should be formulated to bring the best benefits. (iii) Restricted by different systems, the coordinated development in each city will present spatial and temporal differences. (iv) The proposed model was proved to overcome the backwards of uncoordinated development and achieve a balance of the regional social, economic and environmental benefits. Also, some recommendations and limitations were discussed. This study provides an effective basis for enhancing regional sustainable water resources planning and management.

Key words | coordinated development, development restriction mechanism, social-economic-environmental systems, sustainable water management, water optimal allocation model

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HIGHLIGHTS

- A new water optimal allocation model for coordinated development (WOAM-CD) is designed in this study.
- The WOAM-CD can effectively deal with the uncoordinated development among the regional social-economic-environmental systems.
- According to the regional water endowment and industrial characteristics, the WOAM-CD can draw up corresponding water allocation schemes to balance the social, economic and environmental benefits.

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INTRODUCTION

With the rapid development of society and economy, water resource crisis has become one of the most serious challenges faced by human beings all over the world (Douglas *et al.* 2019; Liang *et al.* 2020). South Africa allocated 95% of its water to commercial farmers, which made up only 1.2% of the rural population. As a result, the vast majority of South African people faced water shortage (van Koppen & Schreiner 2014). The predatory development of resources and unreasonable development practices in the Haddaqi industrial corridor caused the ecological environment deterioration (Wan *et al.* 2017). The land around Lake Marriott is occupied by farmland, populated areas and fishing places, and the lake is facing tremendous environmental pressure (Kansoh *et al.* 2020). Pakistan is a country with the largest irrigation system in the world, but despite this, it still faces several major droughts and floods (Imad *et al.* 2019). Meanwhile, the over-exploitation of groundwater in Pakistan has led to the salinization of its aquifers (Bagheri *et al.* 2019). Water management in the Rio del Carmen watershed has failed to use water resources sustainably and led to social conflicts, over-exploitation of water resources and grassland degradation (Lopez Porras *et al.* 2019). Developing countries such as China are facing rapid urbanization. The large-scale migration of people from rural areas to urban areas poses several challenges and puts severe pressure on the national economy. Urbanization also affects basic facilities including water (Yang *et al.* 2019).

The sharp conflict between water resources demand and existing water resources endowments is one of the biggest threats to the sustainable development of ecosystems and socio-economic systems (Yao *et al.* 2019). From the perspective of water resources management, the main cause of such conflicts is the irrational use and management of water resources (Al-Jawad *et al.* 2019; Darbandsari *et al.* 2020). In this context, researchers have conducted a great deal of research on the influence of water resources on society, economy and environment. Roboredo *et al.* (2016) established a comprehensive social environmental sustainability index that combines soil, water and vegetation quality indicators, as well as social organization and socio-economic variables, to evaluate the overall social environmental quality from a micro perspective. Kotzee & Reyers (2016) selected 24 elasticity indicators related to the flood and its related social, ecological, infrastructure and economic aspects for three flood-affected cities in South Africa, and used principal component analysis (PCA) to analyze. Therefore, it is integrated into a comprehensive index. Díaz *et al.* (2018) used the Driver-Pressure-State-Impact-Response (DPSIR) framework to explore the interactions between the river ecosystem and the social system that include demographic, economic, social–political and cultural of Biobío Basin humans, Chile. ZamanZad-Ghavidel *et al.* (2021) constructed a Hydrological Socio-Economic Index (HSEI), which is composed of factors such as economy, population, technology and communication, health and sanitation on different time and space scales. The results showed that the increase in per capita renewable water will affect the socio-economic parameters of 14 European countries. Qi *et al.* (2019) pointed out that the establishment of comprehensive indicators of regional water resources social and economic consumption levels that are compatible with the level of regional economic sustainable development can not only promote regional economic development but also promote water resources protection. Müller *et al.* (2020) provided a conceptualization of a simultaneous assessment of water scarcity as a risk and the sustainability of water reuse measures according to the social, economic and environmental dimensions. Tsanov *et al.* (2020) proposed a water resources optimal allocation model with the goal of minimum investment and minimum water withdrawal, which can effectively alleviate the water crisis in the Vit River Basin. Zeinali *et al.* (2021) studied the relationship between water-society-technology-knowledge science using soft computing technology and pointed out that for water resources on all continents and around the world, hydrological and social-technical-knowledge indicators can be used for proper water resources management and planning.

The above studies proved that the development and utilization of water resources often affect the state of the social, economic and environmental systems. However, how to integrate these concepts and frameworks into the water resources allocation strategy is still in its infancy. Divakar *et al.* (2011) developed an optimal batch allocation model for limited available water based on economic criteria to compete in sectors such as agriculture, households, industry and hydropower. Habibi Davijani *et al.* (2016a) proposed a rational water allocation model in order to maximize the creation of employment opportunities in the industrial and agricultural sectors. Habibi Davijani *et al.* (2016b) constructed a two-objective socio-economic model for the optimum allocation of water resources to industry, agriculture and municipal water sectors. These ideas of water resources allocation have been proven to be reasonable and effective. However, these methods do not solve the problem from the perspective of coordinated development. Water conflicts caused by the coordinated development among different systems (Di Baldassarre *et al.* 2019) are still obstacles to improving water allocation patterns.

General system theory (Porvazník & Ljudvigová 2016) believes that a system is an organic whole with a certain function, which is composed of several elements connected in a certain structure. Each element in the system does not exist in isolation and plays a specific role. The elements are interrelated, making the system an indivisible whole. The proposition of 'the whole is greater than the sum of parts' (Caddy & Helou 2007) and the principle of system integrity, openness and dynamics reveal the internal mechanism of system movement and system coordination (Sujith & Unni 2020). This provides new analytical frameworks for understanding coordinated development from the overall perspective, and grasping coordinated development from the perspective of the system's internal structure, functions and the relationship among systems. The coordinated development theory (Xuejie 2018) is derived from the general system theory. It believes that the interaction between the various subsystems and elements in the open system satisfies the nonlinear relationship and is far from the equilibrium state (Liu *et al.* 2021). Under the induction of fluctuations, it enters a self-organization state and makes the system continuous structured and hierarchical, from disorder to order. Relevant scholars used the mathematical method of the Euclidean distance (Li *et al.* 2018; Sun & Cui 2018) to quantify the coordinated development relationship among multiple systems and constructed the coordinated development evaluation model. Zhou *et al.* (2016) combined the coordination development model and the full permutation polygon synthesis illustration method to analyze the coordinated development relationship between the social-economic system and the water resource system in Taihu Basin. Based on the coordinated development theory, Wang *et al.* (2019) proposed a calculation model to evaluate the coordinated development degree (CDD) among the water resources, social economy and ecological environment systems and applied in Hunan Province. Luo & Zuo (2019) established a distributed economy-water-ecological model and proposed a new framework to evaluate the coordinated development among the social, economic and ecological systems. Yang *et al.* (2021) introduced a coordinated development index (CDI) between the water resource carrying subject and carrying object as a warning indicator of water resource carrying status and applied in Nanjing City, China. The previous studies have proved that the coordinated development evaluation model can effectively quantify the coordinated development relationship of multiple systems.

Therefore, this study innovatively incorporates the coordinated development evaluation model into the actual water resource allocation strategy formulation and is committed to constructing a water optimal allocation model that takes into account social equity, economic efficiency and environmental sustainability. To fully understand the importance of this study, the main aspects of this work are summarized as below. (i) In order to solve the problem of one-sided pursuit of certain benefits and neglect the overall coordinated development of the region, a water optimal allocation model for the coordinated development of regional social, economic and environmental systems is constructed. (ii) The model was applied to the Xiangjiang River Basin, and the water allocation schemes in 2025 and 2030 under the inflow frequency of 50 and 75% were obtained. Meanwhile, the water deficit situation and water consumption structure of different water consumption units and departments were analyzed. (iii) Based on the analysis of the social, economic and environmental benefits in the study area, the factors leading to uncoordinated development were diagnosed, and some corresponding development recommendations were proposed. (iv) Through comparisons with the results of water allocation schemes without considering coordinated development, it is verified that the proposed model skills can effectively improve regional coordinated development.

The remainder of this paper is organized as follows. Section 'Materials' presents the uncoordinated development problems faced by the study area and the data sources. Section 'Methods' introduces the water demand forecasting methods, the coordinated development evaluation models and the water optimal allocation model for coordinated development (WOAM-CD). Section 'Results and discussion' gives the analysis of the water allocation schemes, water consumption structure, and the social, economic and environmental benefits. Also, some potential recommendations and the limitations are discussed. Finally, the last section concludes the paper.

MATERIALS

Study area

The Xiangjiang River Basin (110°31′E–114°15′E, 24°31′N–29°52′N) is located south of the Yangtze River. The main stream flows through Yongzhou, Hengyang, Zhuzhou, Xiangtan, Changsha and finally merges into Dongting Lake (Figure 1). The main stream of the Xiangjiang River is 856 km long, with a drainage area of 94,600 km^2. The Xiangjiang River Basin is located in the radiation zone of the Yangtze River Economic Belt and the South China Economic Circle, which is not only the core area of economic and social development in Hunan Province but also the most important population, city and economic dense area in the central region of China. The basin only accounts for 40% of the total area of Hunan Province, but it bears about 60% of the province's population and contributes more than 75% of the GDP.

The Xiangjiang River Basin has a humid subtropical climate with four distinct seasons and abundant water and heat. The annual average temperature is 16–18 °C and the annual average precipitation is about 1,400–1,700 mm. The precipitation is mostly concentrated in April to June, which can account for the annual precipitation. More than 40% of the total annual floods and peak water levels occurred in May and June. The rainfall in the Xiangjiang River Basin not only shows an uneven distribution in time but also unevenly in space (Tian et al. 2017). There is more rainfall in the north and south areas along the Xiangjiang River but less in the central area. The Xiangjiang River Basin has a multi-year average water resource of 69.61 billion m^3, a multi-year average water consumption of 169.13 billion m^3 and a development utilization rate of 24.3%. Water consumption in the Xiangjiang River Basin is mainly concentrated in agriculture and industry, accounting for approximately 54.27 and 29.21%, respectively.

With population growth and urban development, the water demand in the Xiangjiang River Basin has grown rapidly, and the total amount of water used is approaching the upper limit of water resources development and utilization. Economic and social development is facing the problem of insufficient water resources carrying capacity (Xu 2019). At the same time, water efficiency and benefits in the basin are low, and extensive water management is difficult to enable water resources to support sustainable economic and social development. In some areas, water resources are out of balance with economic structure and layout, and the adaptability of water resources conditions to economic and social development is facing challenges (Liu & Mao 2020). Due to historical limitations, in the industrial layout of the Xiangjiang River Basin, water resources conditions have not been fully considered. In some areas with water shortages and fragile ecological environment, the blind construction of high-water consumption and heavy pollution projects, 'high consumption, high pollution, low efficiency'. The problem of 'low output' is prominent, destroying the ecological environment and exacerbating the water crisis (Fang et al. 2019).

Data sources

Five prefecture-level cities in the Xiangjiang River Basin, including Changsha, Zhuzhou, Xiangtan, Hengyang and Yongzhou, were selected as the water consumption units. We selected 2025 and 2030 as the short-term planning and long-term planning year, respectively. For the prediction of water inflow in different years, based on the long series of runoff data of the Xiangjiang River Basin from 1959 to 2018, natural runoff with an inflow frequency of 50 and 75% is selected as the available water in the basin, which

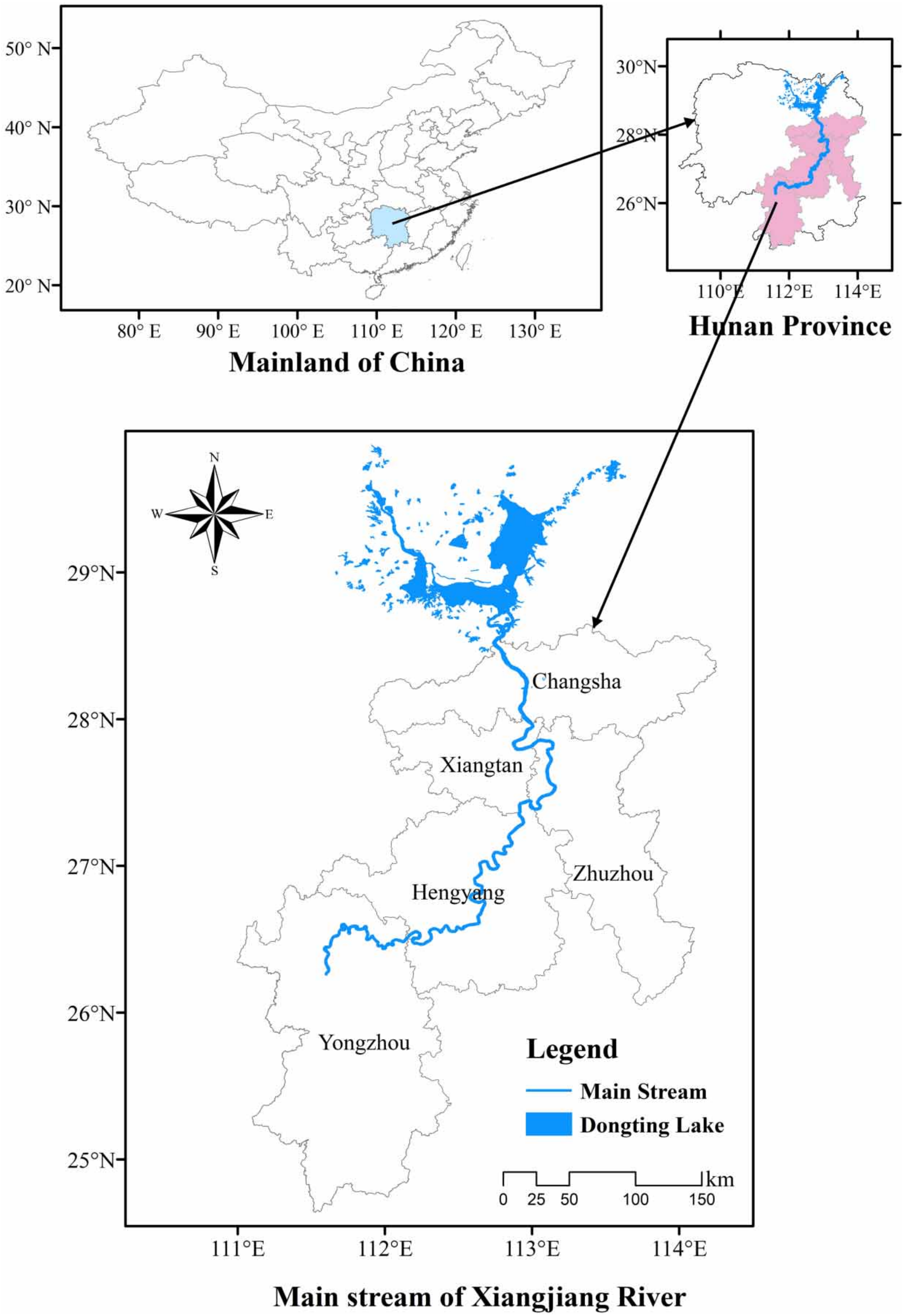

Figure 1 | Location of the main stream of the Xiangjiang River Basin.

is 136.09×10^8 m^3 and 134.15×10^8 m^3. Related parameters such as population, GDP output, water supply revenue, unit water consumption cost, water quota, emission coefficient and pollutant emission concentration of each water department in each city were derived and calculated from the *Xiangjiang River Basin Comprehensive Planning Report* (2015), *Hunan Province Hydrological Statistical Yearbook* (2004–2018), *Hunan Province Statistical Yearbook on National Economic and Social Development* (2004–2018) and *Hunan Province Statistical Yearbook on Ecology and Environment* (2004–2018).

METHODS

Research framework

The research framework is introduced as follow. First, the water demand prediction model is used to predict the water demand of various units and departments in the Xiangjiang River Basin under the water inflow frequency of $P = 50\%$ and $P = 75\%$ in 2025 and 2030, respectively. According to the coordinated development theory and previous studies, the evaluation model of CDD is introduced, and the calculation process and related parameter settings are described. Then, a WOAM-CD among the social, economic and ecological systems is constructed, and the concept of coordinated development is incorporated into the model as a constraint to ensure that each water use unit meets the 'Primary coordinated development (V4)' and above standards. By using the NSGA-II to solve the model, the water allocation schemes of the Xiangjiang River Basin in 2025 and 2030 with $P = 50\%$ and $P = 75\%$ can be obtained. Finally, some conclusions and suggestions can be drawn from the full text, and a sustainable water allocation model for the coordinated development among the social, economic and environmental systems will be provided. The research flowchart is shown in Figure 2.

Water demand forecast method

Water demand forecast refers to the amount of water required in a certain period of time under a certain level of development in the future, mainly including the water

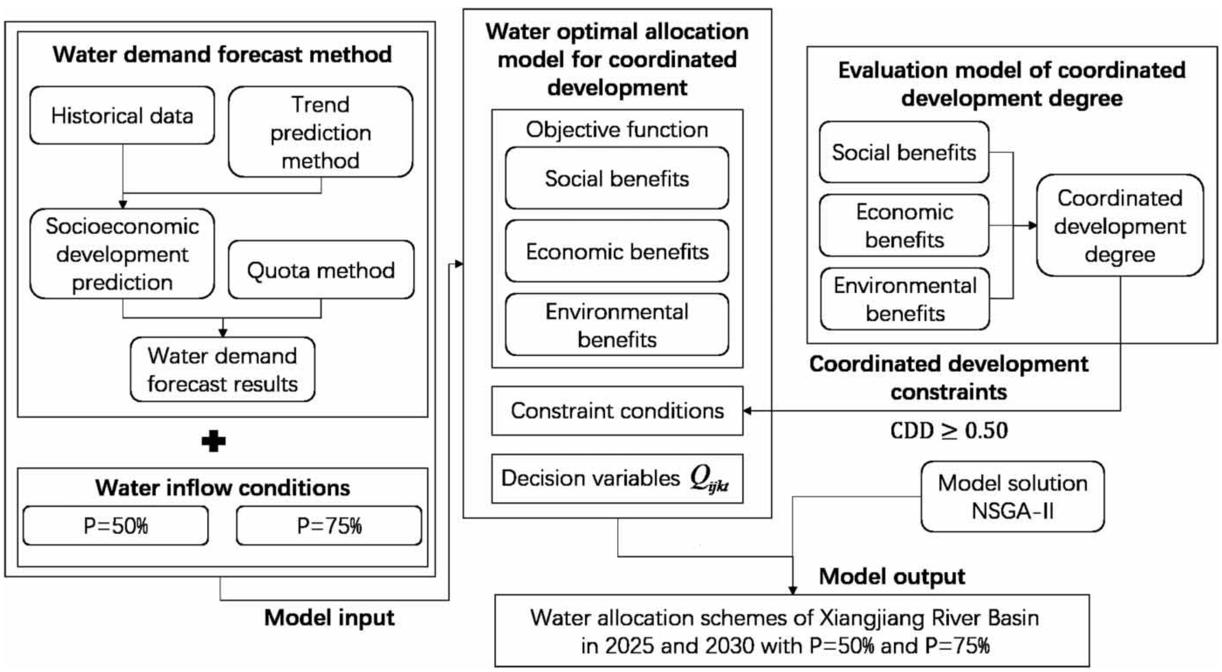

Figure 2 | The research flowchart.

demand of various regions and departments. In this study, the trend prediction method is used to forecast the domestic water (DW), industrial water (IW), service water (SW), agricultural water (AW) and environmental water (EW) in the study area in 2025 and 2030.

Water demand forecasting is mainly divided into two steps.

Step 1: forecast of the level of social and economic development. This research mainly involves social and economic indicators such as population value, agriculture, industry and service industry output value. Trend prediction method is used to forecast the total population and the output value of various departments. Trend prediction method is a method of using the average growth rate over the years to calculate the forecast value. Assuming that the forecast object W_t is a function of time t. Within a certain range, W_t changes regularly with time t, so W_t can be derived by trend extension.

$$W_t = W_0(1 + d)^n \tag{1}$$

where W_t is the predicted value, W_0 is the value of the starting year, d is the average annual growth rate and n is the number of inter-year intervals.

Step 2: water demand forecast by a quota method. Based on the prediction of the level of social and economic development, the water demand results of various regions and departments are calculated through the quota method. The quota for the planning year refers to the *Xiangjiang River Basin Comprehensive Planning Report* (2015) and is determined through consultation with the management department.

$$W_i = P_i \times K_i \tag{2}$$

where W_i is the water demand of the department i (10^8 m³), P_i is the output value of the department i (10^4 CNY) and K_i is the water quota for the department i (m³/10^4 CNY). In particular, DW is calculated by multiplying the population and the per capita water consumption quota (m³/person). The EW is directly obtained according to the relevant regulations of the *Xiangjiang River Basin Comprehensive Planning Report* (2015) issued by the local government.

Water optimal allocation model for coordinated development (WOAM-CD)

Objective function

In this study, we focus on the impact of water allocation results on the coordinated development of social, economic and environmental systems. It is necessary to select the corresponding indexes to represent the benefits value of each system.

Maximize social benefits. For the social system, the social benefits usually refer to maximizing the use of limited resources to meet people's growing material needs (Singh *et al.* 2020; Singh & Samsher 2021). During the implementation of the water distribution plan, different regions and different departments hope to meet their water requirements to the maximum (Chen *et al.* 2020). Therefore, each water supply gap should be reduced as much as possible. The square sum of the water deficit ratio (SSWDR) of each consumption department in each consumption unit can effectively quantify the water supply and demand contradiction (Liao *et al.* 2020). Therefore, we choose to minimize the SSWDR in various units and departments as the social benefits goal.

$$\min f_1(Q) = \sum_{i=1}^{I} \sum_{j=1}^{J} \left(\frac{D_{ijt} - \sum_{k=1}^{K} Q_{ijkt}}{D_{ijt}} \right)^2 \tag{3}$$

where Q_{ijkt} is the water volume from supply source k to consumption department j in consumption unit i in year t; D_{ijt} is the water demand of consumption department j in consumption unit i in year t; I is the total number of the water consumption units; J is the total number of the water consumption departments and K is the total number of the water supply sources.

Maximize economic benefits. For the economic system, the economic benefits usually refer to the proportional relationship between gross production value and production costs

(Darbandsari *et al.* 2020). Due to the differences in the cost of water supply and the economic value produced by different regions and departments, it is necessary to optimize the water distribution of different users in order to maximize the economic benefits (Habibi Davijani *et al.* 2016a). The total GDP output (TGO) of each department in each water consumption unit can effectively quantify the economic benefits (Tilmant *et al.* 2012). Therefore, we choose to maximize the TGO in various units and departments as the social benefits goal.

$$\max f_2(Q) = \sum_{i=1}^{I}\sum_{j=1}^{J}\left(\sum_{k=1}^{K} u_{ijt}Q_{ijkt} - \sum_{k=1}^{K} v_{ijkt}Q_{ijkt}\right) \quad (4)$$

where u_{ijt} is the water supply income per unit water consumption of consumption department j in consumption unit i in year t; v_{ijkt} is the cost of water supply per unit water consumption from supply source k to consumption department j in consumption unit i in year t; I is the total number of the water consumption units; J is the total number of the water consumption departments and K is the total number of the water supply sources.

Maximize environmental benefits. For the environmental system, the environmental benefits usually refer to the positive or negative impacts of various production activities on the environment (Wang *et al.* 2020). Different fields have the different quantification of environmental benefits. In water-related production activities, the discharge of pollutants is the significant factor affecting the water environment (Bai *et al.* 2019; Cordier *et al.* 2020). One of the most important indicators is COD emissions (Zhang *et al.* 2020). The total COD emission (TCE) of each water consumption department in each water consumption unit can effectively quantify the environmental benefits (Meng *et al.* 2018). Therefore, the environmental benefits value can be calculated by the following formula, which is a negative index.

$$\min f_3(Q) = \sum_{i=1}^{I}\sum_{j=1}^{J} d_{ijt}p_{ijt}\sum_{k=1}^{K} Q_{ijkt} \quad (5)$$

where d_{ijt} is the concentration of pollution factors in the waste water discharged by consumption department j in consumption unit i in year t; p_{ijt} is the discharge coefficient of consumption department j in consumption unit i in year t; I is the total number of the water consumption units; J is the total number of the water consumption departments and K is the total number of the water supply sources.

Decision variables

Q_{ijkt} is the decision variable, which represents the water supply quantity from source k to water consumption department j of water consumption unit i in year t.

Constraint condition

Coordinated development constraints. In this study, a high CDD value means that the region is in a high level of coordinated development state. Therefore, referring to the recommendations of the local management department, in this study, the coordinated development status of the region should be guaranteed to be at the 'Primary coordinated development (V4)' and above standards. The details of the calculation model of the CDD and the classification and standard division will be introduced in detail in the 'Evaluation model of CDD' section.

$$\mathrm{CDD}_{i,t} \geq 0.50 \quad (6)$$

where $\mathrm{CDD}_{i,t}$ is coordinated development degree of water consumption unit i in year t.

Water availability constraints. The sum of the water supplies to each water consumption department in each water consumption unit shall not exceed the amount of water available in the region.

$$\sum_{i=1}^{I}\sum_{j=1}^{J} Q_{ijkt} \leq W_{kt}, \quad (7)$$

where W_{kt} is the available water supply quantity from source k in year t, which is the value after considering the minimum water demand of ecological environment and relevant factors in the river channel.

Water demand constraints. The water supply of each water consumption department in each water consumption unit of regional supply should not exceed its water demand.

$$\sum_{k=1}^{K} Q_{ijkt} \leq D_{ijt} \tag{8}$$

where D_{ijt} is the water demand of the water consumption department j of water consumption unit i in year t.

Water supply capacity constraints. The water transfer projects such as water delivery channels and pumping stations in the region have their own water supply capacity. The water supply to each unit should not be greater than its maximum water delivery capacity.

$$\sum_{j=1}^{J} Q_{ijkt} \leq U_{ikt}^{\max} \tag{9}$$

where $U_{ikt}^{\max}$ is the discharge capacity of the water transfer project from the water supply source k to water consumption unit i in year t.

Water environment quality constraints. The total amount of COD discharged by the pollution sources of each water consumption unit in the region should be less than the TCE limit of the water consumption unit.

$$\sum_{k=1}^{K} \alpha_{ijt} \times Q_{ijkt} \leq \mathrm{COD}_{it}^{\mathrm{Re}} \tag{10}$$

where α_{ikt} is the COD emission coefficient of water department j in water unit i in year t, $\mathrm{COD}_{it}^{\mathrm{Re}}$ is the total COD emission limit of water unit i in year t.

Non-negative variables constraints. All variables mentioned in the above modeling process are non-negative variables.

Model solution

In this study, a weighted method is used to integrate the multi-objective function into a single objective problem (Eum & Simonovic 2010; Zhou & Guo 2013).

$$\min F(X) = \min\left(\omega_1 \frac{f_1 - f_{1\omega}}{f_{1o} - f_{1\omega}} - \omega_2 \frac{f_2 - f_{2\omega}}{f_{2o} - f_{2\omega}} + \omega_3 \frac{f_3 - f_{3\omega}}{f_{3o} - f_{3\omega}}\right) \tag{11}$$

where F is the equality objective function for basin authority; X is the vector for the decision variables; ω_1, ω_2 and ω_3 are weight factors to measure the importance of f_1, f_2 and f_3; and clearly $\omega_1 + \omega_2 + \omega_3 = 1$. The objective f_o represents the optimal value of f and f_ω represents the worst value of f. Through consultation with the local management department, it is determined that the development weights of the three benefits are equal. Therefore, the water allocation schemes in this study adopt the equilibrium weight ($\omega_1 = \omega_2 = \omega_3$).

NSGA-II design

Genetic algorithm (Bradford *et al.* 2018) is a computational model of the biological evolution process that simulates the natural selection and genetic mechanism of Darwin's biological evolution theory. The algorithm transforms the solving process of the problem into a process similar to the crossover and mutation of chromosome genes in biological evolution by means of the mathematical method and computer simulation (Haoyuan *et al.* 2018). In this study, the Nondominated Sorting Genetic Algorithms-II (NSGA-II) was used to solve the WOAM-CD. The NSGA-II algorithm originated from the GA algorithm and was then improved by Deb to form the NSGA-II algorithm (Deb *et al.* 2002). The detailed flowchart of the NSGA-2 algorithm (Chen *et al.* 2019) to optimize the WOAM-CD is shown in Figure 3. In this study, the population number is 100, the maximum iteration number is 1,000, the crossover probability is 0.5 and the mutation probability is 0.05.

Evaluation model of CDD

Standardization of the social, economic and environmental benefits

According to the introduction in the 'Objective function' section, we quantify the social, economic and

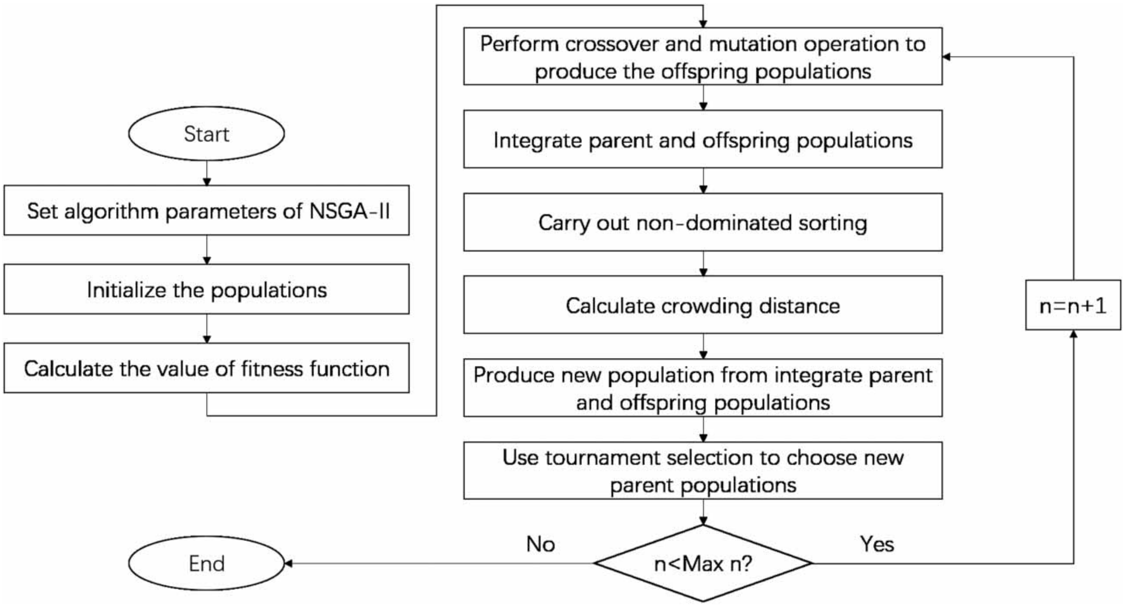

Figure 3 | The flowchart of NSGA-II.

environmental benefits as the SSWDR, the TGO and the TCE, respectively. In order to eliminate the influence caused by the units, dimensions and orders of magnitude of the selected indexes, standardization methods should be used before calculating the CDD (Jia *et al.* 2018).

In this study, the regularization method (Zhang *et et al.* 2018; Zeng *et al.* 2019) was used by calculating the L-2 norm (Hu *et al.* 2019) of each index. For the two negative indexes f_1 and f_3, this study took the reciprocal and converted them into positive indicators before regularization.

$$f^*_{i,t,n} = \frac{f_{i,t,n}}{\sqrt{\sum_{i=1}^{I} (f_{i,t,n})^2}} \quad (12)$$

where $f_{i,t,n}$ and $f^*_{i,t,n}$ are the benefits n of water consumption unit i in year t before and after the standardized treatment; $n = 1, 2, 3$.

Construction of CDD

In this study, CDD is a quantitative index to describe the degree of coordination of various systems within a region. The calculation model of CDD is derived from the theory of regional coordinated development, system theory and the theory of the minimum deviation coefficient (Sun *et al.* 2018). CDD is coupled by coordination degree (CD) and development degree (DD). For water consumption unit i in year t, CDD is defined as

$$\text{CDD}_{i,t} = \sqrt{\text{CD}_{i,t} \times \text{DD}_{i,t}} \quad (13)$$

The CD of regional water consumption unit i in year t is:

$$\text{CD}_{i,t} = \left[\frac{\prod_{n=1}^{N} f^*_{i,t,n}}{\left((1/N) \sum_{n=1}^{N} f^*_{i,t,n} \right)^N} \right]^{\mu} \quad (14)$$

where $f^*_{i,t,n}$ is the benefits n of water consumption unit i in year t after standardized treatment, N is the total number of benefits and μ is the adjustment coefficient. In this study, the coordination among three benefits is considered, so $N = 3$ and $f^*_{i,t,1}$, $f^*_{i,t,2}$ and $f^*_{i,t,3}$ represent the social, economic and ecological benefits, respectively. Meanwhile, it is proved that when calculating the CD among three systems, $\mu = 3$ was proved to have a good model skill performance (Luo & Zuo 2019; Liu *et al.* 2021). The $\text{CD}_{i,t}$ is of the value between 0 and 1. When $\text{CD}_{i,t} = 1$, the degree of coordination is extremely high, and the system tends to coordinate the orderly structure. When $CD_{i,t} = 0$, the degree of coordination is minimal, and the system tends to develop in disorder.

The DD of regional water consumption unit i in planning year t is:

$$DD_{i,t} = \sum_{n=1}^{N} \lambda_{i,t,n} \times f^{*}_{i,t,n} \tag{15}$$

where $\lambda_{i,t,n}$ ($n = 1, 2, 3$) represents the undetermined development coefficient of the social, economic and ecological benefits of water consumption unit i in year t, respectively, and $\lambda_{i,t,n} \geq 0$, $\sum_{n=1}^{N} \lambda_{i,t,n} = 1$. After consultation with the local management department, the Xiangjiang River Basin, which is a rapidly developing region in China, is considered to have prominent conflicts among the social, economic and ecological systems. Therefore, these three systems are considered as of equal significance and the weight of each system in this study adopts the equilibrium weight ($\lambda_{i,t,1} = \lambda_{i,t,2} = \lambda_{i,t,3}$).

Classification and standard division

In order to present the development status of the region, it is necessary to classify and standardize the CDD. This study focuses on the coordinated development of the three systems. Therefore, according to the previous studies (Cheng *et al.* 2019; Yao *et al.* 2019), 0.01 is used as the boundary standard to classify the CDD, and each type of coordinated development is classified to obtain the classification and evaluation standards, as shown in Table 1.

Table 1 | Classification and evaluation criteria of coordinated development

Category	CDD	Subclass
Coordination category	0.80–1.00	High coordinated development (V6)
	0.60–0.79	Moderate coordinated development (V5)
Transition category	0.50–0.59	Primary coordinated development (V4)
	0.40–0.49	Light disorder recession (V3)
Recession category	0.20–0.39	Moderate disorder recession (V2)
	0.00–0.19	Serious disorder recession (V1)

RESULTS AND DISCUSSION

Water demand forecast results

According to the actual water use situation of each water department in the Xiangjiang River Basin, combined with the relevant planning and the statistical yearbook of the Xiangjiang River Basin, the water demand of various regions and departments in 2025 and 2030 is shown in Table 2.

Water allocation schemes

The NSGA-II was used to obtain the water allocation schemes of the Xiangjiang River Basin in 2025 and 2030 at 50 and 75% water inflow frequency. The specific water allocation schemes are shown in Figure 4. The water deficit ratio (WDR) of each city is shown in Table 3.

As shown in Figure 4 and Table 3, with the economic development and the acceleration of urbanization, cities in the Xiangjiang River Basin have different degrees of water deficit problems. In 2025, the overall WDR of the Xiangjiang River Basin will be 3.21 and 4.59% when $P = 50\%$ and $P = 75\%$. In 2030, they will be 5.50 and 6.85%, respectively. Marked water deficit is found in Hengyang and Yongzhou, which are the important food production areas in Hunan Province. In particular, in 2025, the AD in Hengyang will reach 1.45×10^8 m^3 and 1.72×10^8 m^3 when $P = 50\%$ and $P = 75\%$. And in 2030, they will reach 2.21×10^8 m^3 and 2.40×10^8 m^3, respectively. Changsha, Zhuzhou and Xiangtan are the core growth poles of Hunan's economic development. The region's economy is developing rapidly, with rich types of industries, and water shortages are mainly concentrated in the industrial sectors. In the future, with the population growth and industrial development of Changsha, which is the provincial capital city of Hunan, the deficit of DW and IW will be a significant challenge. Meanwhile, the water environment pollution caused by sewage discharge is also worthy of attention.

According to the water allocation schemes, the water consumption structures of the Xiangjiang River Basin under various scenarios can be further analyzed.

As shown in Figure 5, the AW and IW account for a large proportion of the total water consumption in the

Table 2 | Water demand forecast results in 2025 and 2030 (10^8 m^3)

Year	Cities	DW	IW	SW	AW	EW	Total
2025	Hengyang	4.29	6.58	0.60	20.90	0.49	32.86
	Yongzhou	2.38	3.52	0.16	21.04	0.23	27.33
	Changsha	4.41	12.50	3.56	17.01	0.71	38.19
	Zhuzhou	2.10	8.61	1.16	11.05	0.23	23.15
	Xiangtan	1.77	7.55	0.58	9.00	0.17	19.07
2030	Hengyang	4.52	7.09	0.61	21.01	0.54	33.77
	Yongzhou	2.47	3.90	0.14	21.57	0.25	28.33
	Changsha	4.39	12.89	3.73	16.85	0.76	38.62
	Zhuzhou	2.16	9.03	1.22	10.89	0.25	23.55
	Xiangtan	1.89	8.04	0.65	8.97	0.19	19.74

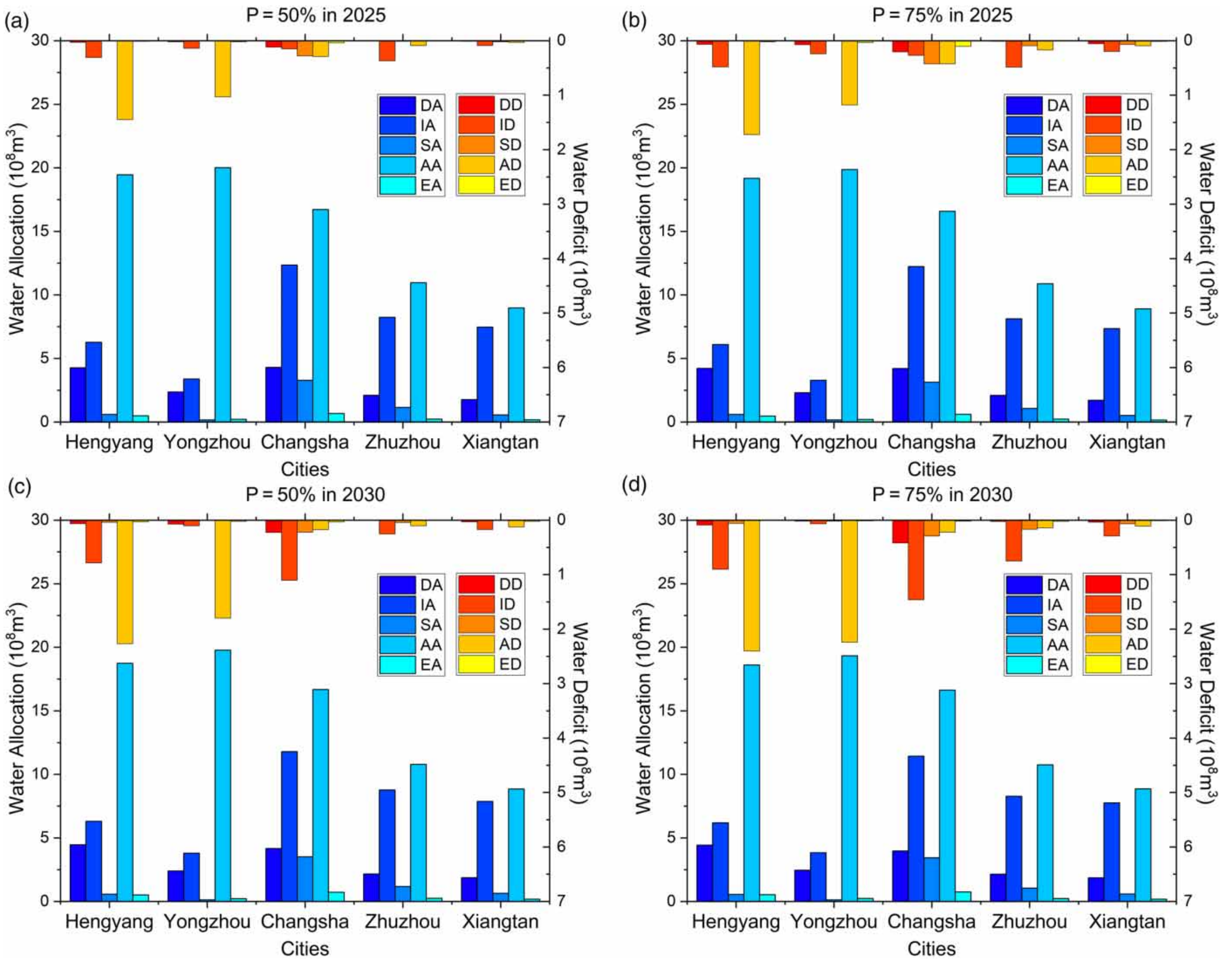

Figure 4 | Water allocation schemes of the Xiangjiang River Basin in 2025 and 2030 with $P = 50\%$ and $P = 75\%$. Water consumption departments include domestic allocation (DA), industrial allocation (IA), service allocation (SA), agricultural allocation (AA), environmental allocation (EA), domestic deficit (DD), industrial deficit (ID), service deficit (SD), agricultural deficit (AD) and environmental deficit (ED).

Xiangjiang River Basin. In 2025, the proportion of the AW and IW will reach 55.93 and 27.70% when $P = 50\%$, and they will reach 56.21 and 27.64% when $P = 75\%$. In 2030, the proportion of the AW and IW will reach 54.21 and 28.68% when $P = 50\%$, and they will reach 55.29 and 27.94% when $P = 75\%$. Compared with 2025, the

Table 3 | Water deficit ratios in the Xiangjiang River Basin under various scenarios

Year	Frequency	Hengyang	Yongzhou	Changsha	Zhuzhou	Xiangtan	Total
2025	$P = 50\%$	5.48%	4.43%	2.30%	2.03%	0.79%	3.21%
	$P = 75\%$	6.99%	5.60%	3.74%	3.29%	2.27%	4.59%
2030	$P = 50\%$	9.44%	7.09%	5.08%	1.72%	1.82%	5.50%
	$P = 75\%$	10.25%	8.33%	6.25%	4.71%	2.62%	6.85%

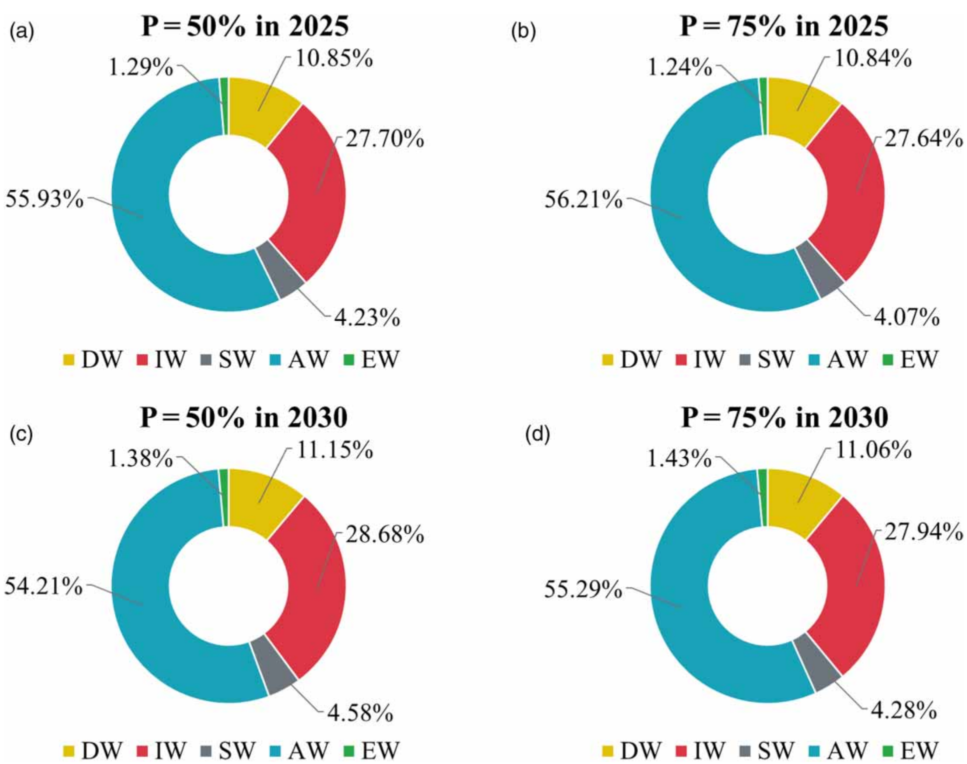

Figure 5 | Water consumption structures of the Xiangjiang River Basin in 2025 and 2030 with $P = 50\%$ and $P = 75\%$.

proportion of AW in 2030 will decrease, while the proportion of other water consumption departments will increase. In the future, in order to achieve sustainable development, the Xiangjiang River Basin should choose better planting methods, promote water-saving irrigation techniques and improve the efficiency of water use. The local government should speed up the economic restructuring, encourage the use of clean energy and reduce local sewage discharge. Meanwhile, the promotion of reclaimed water reuse technology (Mohapatra *et al.* 2014) will help ensure rapid economic development and reduce damage to the ecological environment.

Benefits analysis

The SSWDR represents the social benefits and the fairness of water allocation. The higher the SSWDR value, the lower the social benefit of the region. As shown in Table 4, compared with 2025, the SSWDR in 2030 will increase to a certain extent, which indicates that the social benefits will decline over time. Comparing the two scenarios of water inflow frequency, the social benefits under the dry year ($P = 75\%$) are markedly lower than those under the normal year ($P = 50\%$). Unfair water allocation is prominent in Yongzhou (0.012 when $P = 50\%$ in 2025), Changsha

Table 4 | The SSWDR of the Xiangjiang River Basin in 2025 and 2030

Year	Frequency	Hengyang	Yongzhou	Changsha	Zhuzhou	Xiangtan	Total
2025	$P=50\%$	0.007	0.012	0.011	0.002	0.001	0.033
	$P=75\%$	0.014	0.031	0.039	0.010	0.023	0.117
2030	$P=50\%$	0.026	0.021	0.012	0.002	0.015	0.076
	$P=75\%$	0.039	0.030	0.029	0.035	0.016	0.149

(0.039 when $P=75\%$ in 2025) and Hengyang (0.026 when $P=50\%$ in 2025 and 0.039 when $P=75\%$ in 2030).

The TGO represents the economic benefits and the efficiency of water allocation. The higher the TGO value, the higher the economic benefit of the region. As shown in Table 5, compared with 2025, the TGO in 2030 will increase significantly. It indicates that the economic benefits of the Xiangjiang River Basin will be greatly improved over time. Comparing the two scenarios of water inflow frequency, the economic benefits under the dry year ($P=75\%$) are lower than those under the normal year ($P=50\%$). The economic benefits of Changsha, the provincial capital, are much higher than other cities, and this gap will increase over time.

The TCE represents the environmental benefits and the sustainability of water allocation. The higher the TCE value, the lower the environmental benefit of the region. As shown in Table 6, compared with 2025, the TCE in 2030 will decrease slightly. It indicates that the environmental benefits of the Xiangjiang River Basin will be improved over time. Comparing the two scenarios of water inflow frequency, the environmental benefits under the dry year ($P=75\%$) are higher than those under the normal year ($P=50\%$). The environmental benefits of Changsha and Hengyang are relatively low compared with other cities. This is mainly due to the large population and rapidly developing industries of Changsha and Hengyang, which will lead to the discharge of large amounts of domestic and industrial sewage.

It can be summarized that the coordinated development of Hengyang will be restricted by the social and environmental benefits. Yongzhou will be restricted by the social and economic benefits. Xiangtan will be restricted by the economic benefits. Changsha will be restricted by the environmental benefits and Zhuzhou will maintain a stable and sustainable state of coordinated development. For cities with the low social benefits, local governments should concentrate on resolving water conflicts, formulating water rights allocation plans and achieving fair and reasonable enjoyment of water rights by all water users. For cities with low economic benefits, local governments should optimize the local industrial structure and improve water

Table 5 | The TGO of the Xiangjiang River Basin in 2025 and 2030 (10^{12} CNY)

Year	Frequency	Hengyang	Yongzhou	Changsha	Zhuzhou	Xiangtan	Total
2025	$P=50\%$	1.11	0.62	7.04	1.29	0.82	10.88
	$P=75\%$	1.09	0.62	6.95	1.27	0.81	10.74
2030	$P=50\%$	2.40	1.31	18.41	3.04	1.85	27.00
	$P=75\%$	2.37	1.28	18.36	2.94	1.83	26.79

Table 6 | The TCE of the Xiangjiang River Basin in 2025 and 2030 (ton)

Year	Frequency	Hengyang	Yongzhou	Changsha	Zhuzhou	Xiangtan	Total
2025	$P=50\%$	59.82	28.99	69.81	49.39	34.14	242.15
	$P=75\%$	58.87	28.65	68.89	48.75	33.65	238.80
2030	$P=50\%$	56.16	26.61	65.43	44.70	30.49	223.38
	$P=75\%$	55.61	26.24	64.57	43.36	30.22	220.00

efficiency. Meanwhile, further planning and deployment should be drafted to balance the regional economic development. For cities with low environmental benefits, related technologies such as reclaimed water reuse and the use of clean and alternative energy sources are worth promoting.

Comparisons of considering and not considering coordinated development

This study compares and analyzes the differences between water allocation schemes that consider coordinated development constraints and those that do not consider coordinated development constraints in 2025 and 2030 with $P = 50\%$ and $P = 75\%$.

Figure 6 shows that the CDD among the regional social, economic and environmental systems considering that the coordinated development constraint is significantly higher. In 2025, the WOAM-CD will increase the regional CDD from 0.48 to 0.54 ($P = 50\%$) and from 0.47 to 0.52 ($P = 75\%$), respectively. The coordinated development stage of the Xiangjiang River Basin will be upgraded from 'Light disorder recession (V3)' to 'Primary coordinated development (V4)' ($P = 50\%$ and $P = 75\%$). In 2030, WOAM-CD increased the CDD of the entire region from 0.56 to 0.52 ($P = 50\%$) and from 0.54 to 0.49 ($P = 75\%$), respectively. The coordinated development stage of the Xiangjiang River Basin will be maintained at 'Primary coordinated development (V4)' ($P = 50\%$) and upgraded from 'Light disorder recession (V3)' to 'Primary coordinated development (V4)' ($P = 75\%$). This shows that the proposed model can effectively promote the coordinated development among the social, economic and environmental systems of the Xiangjiang River Basin

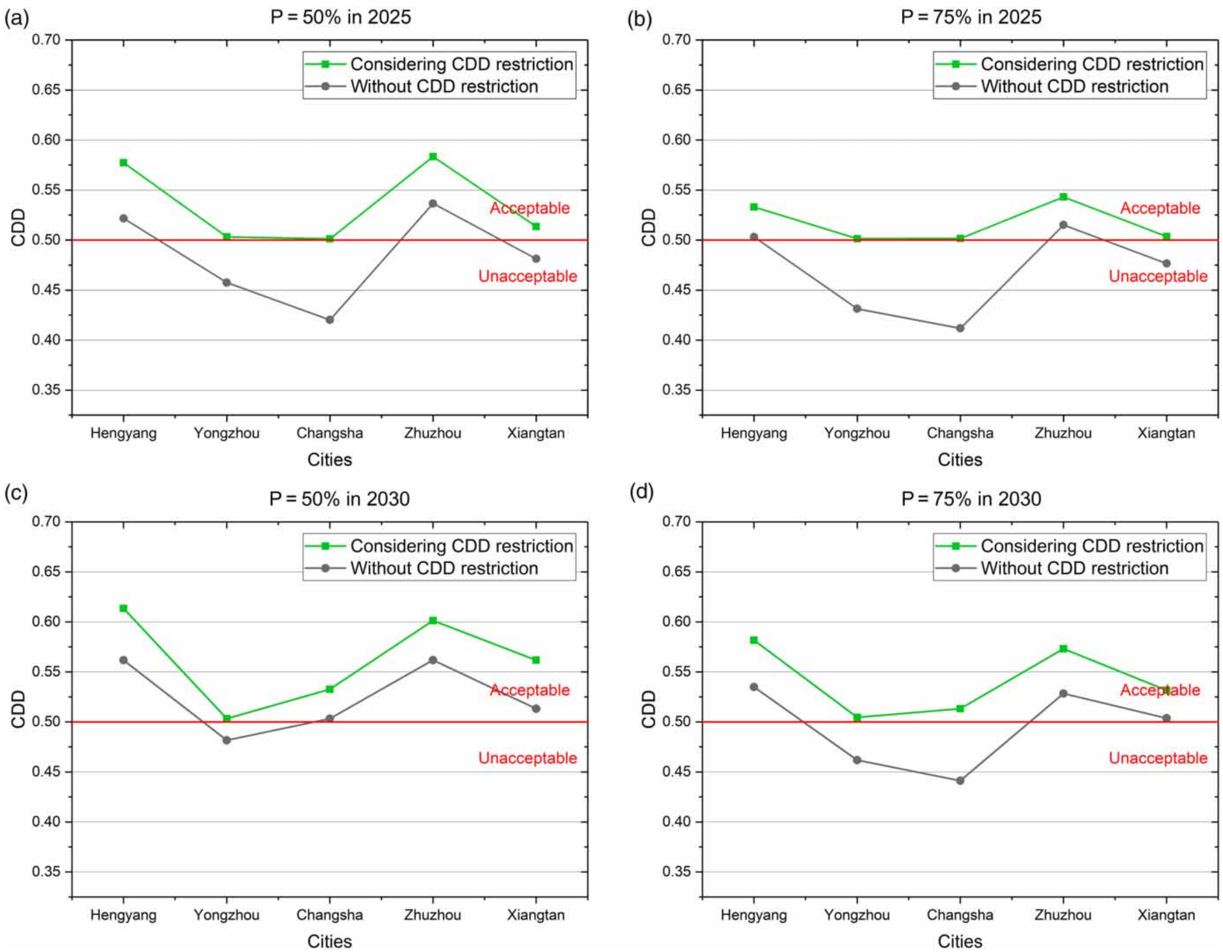

Figure 6 | Comparisons of the CDD of the Xiangjiang River Basin that do and do not consider coordinated development in 2025 and 2030 with $P = 50\%$ and $P = 75\%$.

and ensure the fairness, efficiency and sustainability of regional water allocation to the greatest extent.

Due to the differences of the development characteristics, the CDD of each city will be different. The CDD of Hengyang and Zhuzhou will be in the leading position in the Xiangjiang River Basin, whereas the CDD of Changsha and Yongzhou will be at a relatively low level. As Changsha is the capital city of Hunan Province, its economic development is much higher than other cities. Its social and environmental benefits are relatively lagging, which will lead to the problem of uncoordinated development. Therefore, in the future, relevant measures should be taken to limit the development of industries with high-water consumption and high pollution, and pay more attention to the protection of the ecological environment. However, the situation in Yongzhou is just the opposite. Yongzhou is located in a hilly area with a sparse population and low economic development. The lagging economic development may restrict the local coordinated development. Therefore, the management department should encourage the acceleration of the transformation of the industrial structure, rationally allocate water from the high-water consumption, low-output agricultural department to the fast-growing industries and improve local economic development.

Recommendations and limitations

Based on the above analysis and discussion, this study puts forward some recommendations on how to apply this WOAM-CD to practical applications and discusses some limitations of the model.

Most existing water allocation strategies cannot achieve coordinated development among the social, economic and environmental systems and cannot guarantee the sustainable water use. Since water is a shared, multi-purpose, one-way flow resource (Di Baldassarre *et al.* 2019), the issues of ensuring social equity, economic efficiency and environmental protection are the core of any decision regarding the water allocation. In this study, the CDD is used as an indicator to measure the coordinated development state of regional social, economic and environmental systems, so as to constrain the water allocation of each water consumption unit and department. For the government or decision makers, it is necessary to formulate key policies to encourage the establishment of a water allocation system based on coordinated development in order to achieve a sustainable water resource utilization model. The strategy proposed in this study supports the optimization of regional and sectoral water use in order to achieve the regional coordinated development and has established a long-term water use path. However, although people have realized that the uncoordinated development will affect the sustainability, the corresponding policies and regulations to solve the availability competition among different regions and departments are inefficient and ineffective. Therefore, for those countries and regions facing the unbalanced development problems, the government needs to formulate key policies and regulations to encourage the development of sustainable water allocation plans based on local conditions to avoid the imbalance of various systems in the process of water use. It is worth noting that full consideration should be given to the growth of water demand, the priority of various types of water use and local industrial structure (Del Giudice *et al.* 2020; Marques De Oliveira *et al.* 2020). Meanwhile, some water conservancy facilities (Dong *et al.* 2020) are supposed to be built and reasonably used to match the water resources allocation schemes.

Although some parameters of the water optimal allocation model proposed in this study are calibrated using collected data, there are still some assumptions about different weight settings. In the absence of reliable data, this study assumed the values of some parameters through communication with river basin management and reasonable engineering judgments. Therefore, by modifying and improving the accuracy of the control equations of different systems, and more considering the details of the management planning of different regions and departments (for example, increasing the weight of economic system for areas with backward economic development), the quality of results can be improved. Meanwhile, the survey-based determinations of the development weights being used for finding different regions may provide more realistic results, which remains for future studies. In addition, future studies should focus on exploring more accurate methods to simulate the uncertain factors, such as the loss rate of water transmission from river basin to water consumption units and departments (Xu *et al.* 2019), and the availability of various water resources to different stakeholders' utilities and their interactions (Darbandsari *et al.* 2020). Using historical data time series for determining the best management policy among a finite set of strategies, the hydrological stochasticity was not fully incorporated in this study. Further studies could employ stochastic models (Dralle *et al.* 2017) to simulate the variability of hydrological variables for finding optimal management policies in a continuous searching space.

CONCLUSION

Through the above analysis, it can be summarized that different from previous studies (Yang *et al.* 2021), we proposed a more sustainable model aiming at improving coordinated development among the regional social, economic and environmental systems. A case study from the five prefecture-level cities in the Xiangjiang River Basin, China, was conducted. The results showed the following. (i) In 2025, the WDR of the Xiangjiang River Basin will be 3.21% when $P = 50\%$ and 4.59% when $P = 75\%$. In 2030, it will be 5.50% when $P = 50\%$ and 6.85% when $P = 75\%$. The existing water supply capacity will not be able to meet the increasing water demand. (ii) AW and IW account for a large proportion of the total water consumption in the Xiangjiang River Basin. Due to the transformation of industrial structure, related policy needs to be formulated to adapt to changes in water demand of various regions and departments and bring the best benefits. (iii) Restricted by different systems, the coordinated development in each city will present spatial and temporal differences. The coordinated development of Hengyang will be restricted by the social and environmental benefits. Yongzhou will be restricted by the social and economic benefits. Xiangtan will be restricted by the economic benefits. Changsha will be restricted by the environmental benefits and Zhuzhou will maintain a stable and sustainable state of coordinated development. It is necessary to develop and utilize water resources according to the regional water resources endowment conditions and industrial structure characteristics. (iv) Compared with water allocation schemes without considering the coordinated development, the proposed model can overcome the backwards of uncoordinated development among multiple systems and achieve a balance of the regional social, economic and environmental benefits. Further studies can focus on improving this model in terms of parameter settings and hydrological uncertainties.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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DATA AVAILABILITY STATEMENT

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

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