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Synergetic Theory-Based Water Resource Allocation Model

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Abstract

To promote the harmonious development of human and water resources, the scarcity and ecological value of water resources should be considered in water resource allocation. In this paper, synergetic theory was applied to the process of water resource allocation, and we constructed a synergetic theory-based water resource allocation model by investigating the synergetic principle of each link of water resource allocation. The objective equation was established for determining the optimal comprehensive benefit of the composite system. Multidimensional constraint conditions were constructed from the perspective of the social benefit, economic benefit and ecological benefit of water supply, and balance equations were established. Order parameters were selected for the social, economic and ecological subsystems, and the order degrees of the three subsystems and the synergetic degrees of allocation schemes were calculated by using the fuzzy mathematics method to provide a basis for the recommendation of an optimal scheme. Finally, we proposed a multicycle iterative algorithm to realize the overall objective of "harmonious development between humans and water resources", which provides an effective calculation tool for water resource synergetic allocation. This model was applied in Jilin, and an optimal scheme was recommended on the basis of a synergetic degree analysis, which shows that the water supply of conventional water sources will be saved by an increase in the reclaimed water supply. In addition, after the implementation of an external diversion project by 2030, the amount of groundwater withdrawal will be gradually reduced, and the water deficit rate will be significantly reduced.

Keywords Synergetic theory · Water resource allocation · Synergetic degree · Multiple loop iteration algorithm · Jilin

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1 Introduction

Traditional water resource allocation usually regards the maximization of social and economic benefits as the primary objectives and ignores ecological benefits, which leads to unrestrained and one-sided development of the social economy and eventually results in a vicious circle of ecosystem degradation. In view of this phenomenon, Wu Meimei et al. investigated the evaluation index system of urban water resource utilization benefits and examined the system under the conditions that the relative importance of indices is determined and the exact weights are unknown (Wu et al. 2020). Qin Jianan et al. also investigated the benefit compensation mechanism in water resource management, and a Stackelberg game theoretical model was used to derive the agent disagreement utility based on consideration of their spatial heterogeneity in terms of water accessibility (Qin et al. 2020). In addition, with an increased focus on ecological benefits, studies on sewage collection and reuse of reclaimed water have been conducted (Castañer et al. 2020; Dehaghi and Khoshfetrat 2020). However, these problems should be gradually extended to the field of water resource allocation.

In the new century, with the progress and improvement of intelligent optimization algorithms, such as immune genetic algorithms and neural network algorithms, these algorithms have been widely applied in the field of water resource allocation. Scholars have also investigated the mechanism of water resource allocation in a broader field to essentially resolve the contradiction of water resource allocation (Perera et al. 2005; Sethi et al. 2006; Abolpour et al. 2007; Zaman et al. 2009; de Lange et al. 2010). Simultaneously, with the development of equilibrium theory, game theory and other theories, the development of socioeconomic models and hydrological models has opened up a new field for the development of water resource allocation modelling systems. Minsker et al. (2000) constructed a multi-objective water resource allocation model based on a genetic algorithm through the uncertainty of hydrological elements and vividly described the uncertain factors in the water resource allocation process. Rosegrant et al. (2000) constructed a hydrologic-economic coupling model for evaluating the efficiency of water resource utilization. Mahan et al. (2002) and Kralisch et al. (2003) applied the neural network algorithm to various water source allocation problems. Kucukmehmetoglu (2012) constructed a model for solving the problem of water resource allocation in cross-border basins, which coupled game theory and Pareto optimal theory to expand water resource allocation to the field of national macro-control. Overall, the studies on water resource allocation started from a single subject, with a single objective as the starting point, and gradually expanded to multiple fields and developed into the current stage of integrating multiple subjects to solve multiple objectives (Nasiri-Gheidari et al. 2018; Pourmand and Mahjouri 2018; Kicsiny and Varga 2019).

Research on water resource allocation in China has entered the stage of harmonious development between humans and water resources. In this stage, sustainable development should be regarded as the starting point for protecting the economic benefits of water resources and emphasizing the water resource attributes and ecological environmental benefit to realize balanced development between humans and the water environment and promote the sustainable development of human society. Wang et al. (2003) proposed the "natural-artificial" dual water cycle theory, which innovatively integrated the water cycle process into the process of social and economic development and injected new ideas into the study of water resource allocation. Xie et al. (2002) fully considered the carrying capacity of water resources and developed water resource allocation models that are suitable for sustainable economic and social development in Ningxia and Xinjiang. Subsequently, the theory of "cubic equilibrium" allocation (Wang et al. 2003) was proposed, which further promoted the expansion of the water resource allocation field. During this period, the water resource allocation model, in combination with the concept of sustainable development, was practically applied in various regions (Chen et al. 2002; Xie et al. 2002). This marked the gradual establishment of the water resource allocation stage of harmonious development between human beings and the water environment. Zhao (2006) and Pei et al. (2007) regarded generalized water resources as the allocation object, the water quantity and quality requirements of each water use unit as the control index, and the "natal-artificial" dual water cycle simulation as the driving factor and realized the sustainable development of the population, water resources and ecological environment in the basin through an optimized decision-making mechanism. Wei et al. (2012) constructed the total factor optimization water resource allocation model based on multiple water resource attributes from a "artificial - natural" binary water cycle theory system, fully considered the regional economic development and water requirement characteristics of each social economic sector, and systematically expounded the theory of total factor optimization allocation of water resource system. The practical application of water resource allocation based on the harmonious development of human and water resources largely coordinates the relationship between socioeconomic development and the sustainable utilization of water resources, alleviates the contradiction between water supply and demand in the process of sustainable development, and makes an important contribution to the improvement of the ecological environment (Liu et al. 2010; Li et al. 2018).

Nowadays, the harmonious development of human and water resources and the solution of multiple objectives has been considered in water resource allocation (Kucukmehmetoglu 2012; Mianabadi et al. 2014; Das et al. 2015; Chang et al. 2016; Zeng et al. 2017; Tian et al. 2019; Wang et al. 2019; Dadmand et al. 2020; Li et al. 2020; Pourmand et al. 2020; Sarband et al. 2020). To guarantee harmonious development with nature and realize a socioeconomic development mode that matches the carrying capacity of water resources, the scarcity of water resources and their ecological value should be further considered in the process of water resource allocation. The objective of this study is to propose a set of model calculation methods with three main synergetic allocations, namely, 'synergetic water supply from various water sources in the water resource subsystem', 'synergetic water requirements among the social, economic and ecological subsystems' and 'synergetic balance between the water supply in the water resource subsystem and the water demands in the social, economic and ecological subsystems', which are subject to five total amount controls, namely, 'total water use control', 'total water consumption', 'total groundwater intake', 'total reclaimed water supply' and 'total ecological water demand in the channel', for the realization of water resource synergetic allocation.

2 Methodology

2.1 Modelling Principle

2.1.1 Internal Relationships in the Composite System

The internal relationships in the composite system are illustrated in Fig. 1. As the resource provider, the water resource subsystem plays an important role in the composite system. In the social subsystem and economic subsystem, first, it is necessary to judge whether the domestic

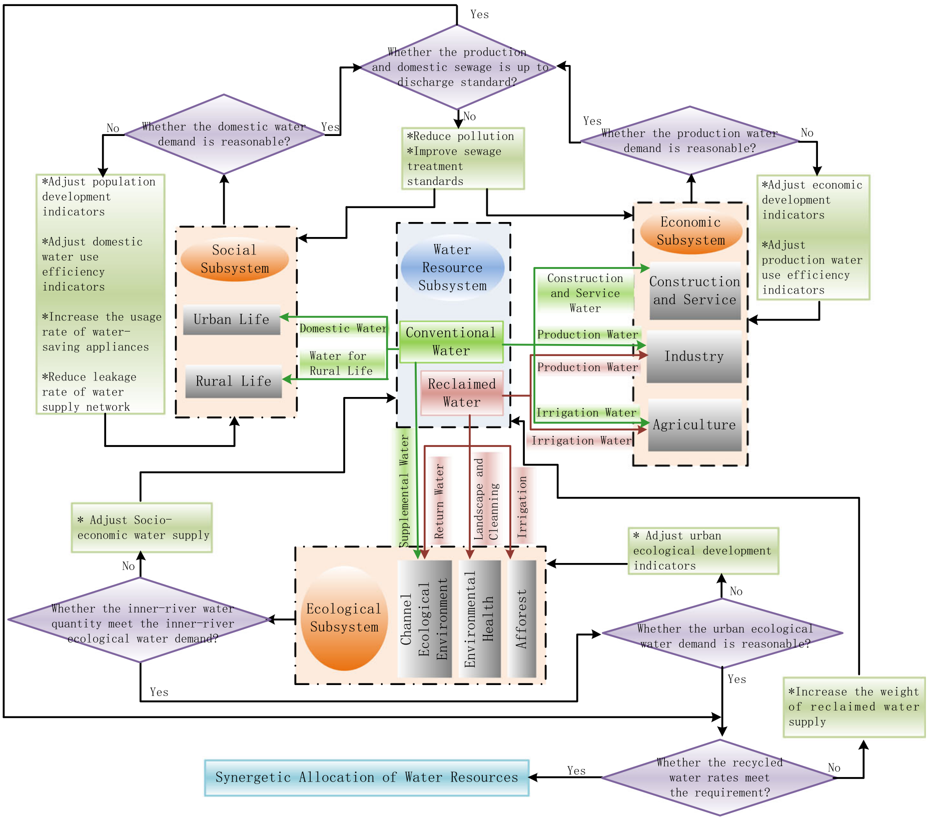

Fig. 1 Internal relationships in the composite system

water demand and production water demand match the water resource carrying capacity. If yes, proceed to the second judgement of whether the production and domestic sewage meet the standards. In the ecological subsystem, the most important principle is to ensure that the inner-river water quantity can satisfy the inner-river ecological water demand. The next step is to judge whether the urban ecological water demand can be satisfied. If yes, proceed to the last judgement of whether the recycled water rates, which correspond to the recycled water that is used in three subsystems, meet the requirement. If yes, the synergetic allocation of water resources can be conducted.

2.1.2 Synergetic Water Demand Module that Is Based on the Benefit Hierarchy Obedience Principle

The relationship between synergetic theory and water resource allocation in this study is illustrated in Fig. 2. Sometimes, human activities do not lead to the synergy of economic, social and ecological benefits, and it is necessary to adjust the order of economic, social and ecological benefits according to the regional resources, the environmental carrying capacity, and the development demand to formulate a hierarchical development plan (Guo and Shen 1991; Gui 2001). In this study, the study area was divided into key development zones, restricted development zones and strictly controlled development zones.

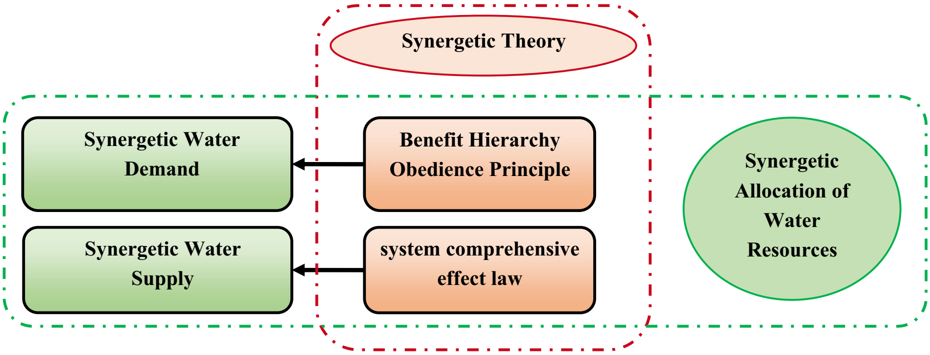

Fig. 2 Synergetic theory and water resource allocation

In the key development zones, economic benefits and social benefits should be given equal attention, and ecological benefits should be subordinated to social and economic benefits. Hence, in areas with abundant resources and large environmental carrying capacities, it is equally important to guarantee the domestic and industrial water supplies, and the water supply for the ecological environment can be suitably reduced. In restricted development zones, economic benefits should be of the same importance as ecological benefits and subordinate to social benefits, namely, in areas with low resources and environmental carrying capacities, the domestic water supply should be guaranteed first, and production and ecological water use should be maintained cooperatively. In strictly controlled development zones, ecological benefits should be subordinated to social benefits and economic benefits to ecological benefits. Hence, in areas with low resource and environmental carrying capacities, the domestic water supply should be prioritized, water ecological protection should be strictly implemented, and the water supply for economic development should be restricted if necessary.

2.1.3 Synergetic Water Supply Module that Is Based on the System Comprehensive Effect Law

The combination of established and planned water supply projects and water sources will be optimized and the available water supply from various water sources will be analysed according to the regional water resource conditions and water demand structure to provide a basis for the water supply constraint of water resource synergetic allocation. The water supply efficiency will be maximized through the orderly combination and synergetic allocation of various water sources (Guo and Shen 1991; Gui 2001).

From the perspective of water resource quality, water sources with satisfactory water quality should be prioritized domestically to realize higher water supply benefits. The reclaimed water supply to industries with low water quality requirements should be increased, which can yield not only water-saving benefits but also ecological benefits by reducing pollution sources. In terms of water resource quantity, the areas with abundant surface water should be prioritized for surface water supply, and groundwater resources can be regarded as strategic reserve water sources. In areas with limited surface water resources but with groundwater as the main source, external water diversion projects should be planned and implemented, and the local groundwater and limited surface water should be regarded as strategic reserve water sources. From the perspective of water demand, it is necessary to increase the recycling rate of water resources and enhance the reclaimed water quality to satisfy irrigation water quality requirements in industrial and agricultural areas. Meanwhile, the reclaimed water supply to the urban ecological environment should be increased to conserve conventional water resources and guarantee water supply security.

2.1.4 Synergetic Degree Analysis Module

The synergetic degree analysis module is used mainly to evaluate and analyse the synergetic degrees of social, economic, and ecological subsystems based on water resource allocation schemes and recommend a water resource allocation scheme with an optimal synergetic degree for policymakers (Liu and Chen 2009; Lei et al. 2017).

Order Parameter Selection in each Subsystem In this paper, two order parameters are selected for each subsystem and are presented in Table 1. The social benefits mainly reflect the degrees to which the water supply satisfies the population and economic development demands. Therefore, the per capita water supply and the comprehensive Gini coefficient of the water supply are selected as the order parameters to reflect the social benefits (Liqin et al. 2015; Dai et al. 2018).

$$Gini_j = 1 - \sum_{i=1}^{n}(X_i - X_{i-1})(Y_i + Y_{i-1}) \tag{1}$$

$$Gini = \lambda_1 Gini_1 + \lambda_2 Gini_2 + \lambda_3 Gini_3 \tag{2}$$

where $Gini_j$ is the Gini coefficient of subitem j (j = 1,2,3); X_i represents the cumulative percentage of population, GDP, and water resources in the ith administrative region; Y_i represents the cumulative percentage of water consumption in the ith administrative region; and λ_1, λ_2, and λ_3 represent the influencing weight coefficients on the water consumption allocation fairness of each sub-Gini coefficient, which satisfy $\lambda_1 + \lambda_2 + \lambda_3 = 1$. According to the equal subsystem importance law of synergetic theory, $\lambda_1 = \lambda_2 = \lambda_3 = 1/3$. The economic benefit is mainly reflected by the relationship between the water supply and water deficit. The water supply of each industry is selected as the positive order parameter of the economic subsystem, and the total water deficit is selected as the reverse order parameter of the economic subsystem. The order degree of the ecological subsystem is affected mainly by water environment problems and ecological environmental protection measures. Therefore, the ecological benefits are increased mainly by reducing the discharge of sewage into rivers and increasing the ecological environment water supply. In this paper, the sewage recycling rate is selected as an order parameter of the ecological subsystem to reflect the ecological benefit of reducing sewage discharge, and the water supply for the ecological environment is selected as another order parameter of the ecological subsystem.

Table 1 Order parameters of the three subsystems

Subsystem	Order Parameters
Social Subsystem	+ Per Capita Water Supply - Comprehensive Gini Coefficient of the Water Supply
Economic Subsystem	+ Water Supply - Water Deficit
Ecological Subsystem	+ Sewage Recycle Rate + Water Supply for Ecological Environment

Calculation of the Order Degrees in the Subsystems The order degree in a subsystem reflects the order degree of the interaction between subsystem elements, which is calculated via the fuzzy mathematical method. The order parameters in subsystems include positive order parameters, which are assigned the '+' tag in Table 1, and reverse order parameters, which are assigned the '-' tag. The larger the value of the positive order parameter, the higher the order degree of the subsystem. The order degree of the i^{th} positive order parameter e_{ji} of the j^{th} subsystem is calculated via formula (3). In contrast, the smaller the reverse order parameter is, the higher the order degree of the system. The order degree of the i^{th} reverse order parameter e_{ji} of the j^{th} subsystem is calculated via formula (4) (Yao et al. 2017).

$$F_j(e_{ji}) = \frac{e_{ji}\text{-}\beta_{ji}}{\alpha_{ji}\text{-}\beta_{ji}} \tag{3}$$

$$F_j(e_{ji}) = \frac{\alpha_{ji}\text{-}e_{ji}}{\alpha_{ji}\text{-}\beta_{ji}} \tag{4}$$

where α_{ji} and β_{ji} are the threshold values of the i^{th}-order parameter of the j^{th} subsystem and $\beta_{ji} \le e_{ji} \le \alpha_{ji}$. The value of each order parameter is between 0 and 1, and the larger the $F_j(e_{ji})$ value is, the greater its contribution to the order degree of its subsystem. The order degree $F_j(e_j)$ of the j^{th} subsystem is calculated via formula (5), where λ_i is the influencing weight coefficient of the i^{th}-order parameter of the subsystem.

$$\begin{cases} F_j(e_j) = \sum_{i=1}^{n} \lambda_i F_j(e_{ji}) \\ \lambda_i > 0 \\ \sum_{i=1}^{n} \lambda_i = 1. \end{cases} \tag{5}$$

Synergetic Degree Calculation of Water Resource Allocation Schemes The synergetic degree of a water resource subsystem is affected by the order degrees of the social, economic and ecological subsystems, and the synergetic degree is calculated via formula (6), where γ_j is the influencing weight coefficient of the order degree of the j^{th} subsystem.

$$\begin{cases} D = \sum_{j=1}^{k} \gamma_j F_j(e_j) \\ \gamma_j > 0 \\ \sum_{j=1}^{k} \gamma_j = 1 \end{cases} \tag{6}$$

2.2 Modelling Specification

2.2.1 Objective Functions of Synergetic Allocation Based on the Optimal System Comprehensive Benefit Law

In the process of water resource allocation, the optimal comprehensive benefit is regarded as the objective, which includes the benefit objectives of the social, economic and ecological subsystems, which are denoted by F_1, F_2, and F_3, respectively, and the comprehensive benefit of water resource allocation is maximized by optimally combining the benefits of the three

Table 2 Definitions of the variables

Formula Number	Variable Name	Definition	Formula Number	Variable Name	Definition
(8)/(16)/(24)	SF^C	Local available water supply for urban life	(12)/(16)/(28)	SF^E	Local available water supply for the ecological environment
(8)/(17)/(24)	G^C	Groundwater supply for urban life	(12)/(17)/(28)	G^E	Groundwater supply for the ecological environment
(8)/(18)/(24)	D^C	Diverted water supply for urban life	(12)/(18)/(28)	D^E	Diverted water supply for the ecological environment
(8)/(24)	S^C	River surface water supply for urban life	(12)/(19)	T^E	Reclaimed water supply for the ecological environment
(9)/(16)/(27)	SF^R	Local available water supply for rural life	(12)/(28)	S^E	River surface water supply for the ecological environment
(9)/(17)/(27)	G^R	Groundwater supply for rural life	(13)/(14)/(28)	M^E	Water deficit for the ecological environment
(9)/(18)/(27)	D^R	Diverted water supply for rural life	(13)/(21)/(24)	M^C	Water deficit for urban life
(9)/(27)	S^R	River surface water supply for rural life	(13)/(21)/(25)	M^I	Water deficit for industry
(10)/(16)/(26)	SF^A	Local available water supply for agriculture	(13)/(26)	M^A	Water deficit for agriculture
(10)/(17)/(26)	G^A	Groundwater supply for agriculture	(13)/(27)	M^R	Water deficit for rural life
(10)/(18)/(26)	D^A	Diverted water supply for agriculture	(14)/(21)/(22)	T^R	Reclaimed water supply
(10)/(19)/(26)	T^A	Reclaimed water supply for agriculture	(24)	P^C	Pumping water supply for urban life
(10)/(26)	S^A	River surface water supply for agriculture	(25)	P^I	Pumping water supply for industry
(11)/(16)/(25)	SF^I	Local available water supply for industry	(26)	P^A	Pumping water supply for agriculture
(11)/(17)/(25)	G^I	Groundwater supply for industry	(26)	SN^A	Channel holds water supply for agriculture
(11)/(18)/(25)	D^I	Diverted water supply for industry	(27)	P^R	Pumping water supply for rural life
(11)/(19)/(25)	T^I	Reclaimed water supply for industry	(28)	P^E	Pumping water supply for the ecological environment
(11)/(25)	S^I	River surface water supply for industry			

Table 3 Definitions of the parameters

Formula Number	Parameter Name	Definition	Formula Number	Parameter Name	Definition
(16)	$SF^{P\text{-}C}$	Runoff coefficient in the calculation units	(21)	$T^{P\text{-}ID}$	Industrial sewage discharge rate
(16)	SF^{P}	Runoff in the calculation units	(21)	$T^{P\text{-}IT}$	Industrial sewage treatment rate
(17)	$G^{P\text{-}U}$	Upper limit coefficient of groundwater exploitation in the time period	(21)	$T^{P\text{-}IR}$	Industrial sewage reuse rate
(17)	G^{Q}	Available groundwater	(21)/(24)	W^{C}	Gross water demand for urban life
(18)	D^{Q}	Available diverted water supply	(21)/(25)	W^{I}	Gross water demand for industry
(19)	T^{Q}	Available reclaimed water supply	(22)	T^{S}	Sewage treatment volume
(21)	$T^{P\text{-}CD}$	Urban sewage discharge rate	(23)	R	River overcurrent capacity
(21)	$T^{P\text{-}CT}$	Urban sewage treatment rate	(26)	W^{A}	Gross water demand for agriculture
(21)	$T^{P\text{-}CR}$	Urban sewage reuse rate	(27)	W^{R}	Gross water demand for rural life
(21)	$S^{P\text{-}C}$	Effective utilization coefficient of the urban living water supply	(28)	W^{E}	Gross water demand for ecology
(21)	$S^{P\text{-}I}$	Effective utilization coefficient of the industrial water supply			

subsystems. The objective functions are presented as formula (7) to formula (15). The variables and parameters in these formulas are defined in Tables 2 and 3.

The social benefit objective is reflected mainly by the security level of the water supply. Multisource synergetic water supply for various industries should be conducted in each allocation unit. Reasonable weight coefficients for the water supply from various water sources should be set according to the water source conditions and water demands of the industries to determine the optimal water security level.

$$F_1 = Max(f_C + f_I + f_A + f_E + f_R) \tag{7}$$

$$f_C = \sum_{i=1}^{m} a_i^C \cdot \sum_{j=1}^{c} \left(\alpha_j^{sur-C} \cdot S_{ij}^C + \alpha_j^{gra-C} \cdot G_{ij}^C + \alpha_j^{slf-C} \cdot SF_{ij}^C + \alpha_j^{div-C} \cdot D^C ij \right) \tag{8}$$

$$f_R = \sum_{i=1}^{m} a_i^R \cdot \sum_{j=1}^{c} \left(\alpha_j^{sur-R} \cdot S_{ij}^R + \alpha_j^{gra-R} \cdot G_{ij}^R + \alpha_j^{slf-R} \cdot SF_{ij}^R + \alpha_j^{div-R} \cdot D^R ij \right) \tag{9}$$

$$f_A = \sum_{i=1}^{m} a_i^A \cdot \sum_{j=1}^{c} \left(\alpha_j^{sur-A} \cdot S_{ij}^A + \alpha_j^{gra-A} \cdot G_{ij}^A + \alpha_j^{slf-A} \cdot SF_{ij}^A + \alpha_j^{div-A} \cdot D^A ij + \alpha_j^{rec-A} \cdot T^A ij \right) \tag{10}$$

$$f_I = \sum_{i=1}^{m} a_i^I \cdot \sum_{j=1}^{c} \left(\alpha_j^{sur-I} \cdot S_{ij}^I + \alpha_j^{gra-I} \cdot G_{ij}^I + \alpha_j^{slf-I} \cdot SF_{ij}^I + \alpha_j^{div-I} \cdot D^I ij + \alpha_j^{rec-I} \cdot T^I ij \right) \tag{11}$$

$$f_E = \sum_{i=1}^{m} a_i^E \cdot \sum_{j=1}^{c} \left(\alpha_j^{sur-E} \cdot S_{ij}^E + \alpha_j^{gra-E} \cdot G_{ij}^E + \alpha_j^{slf-E} \cdot SF_{ij}^E + \alpha_j^{div-E} \cdot D^E ij + \alpha_j^{rec-E} \cdot T^E ij \right) \quad (12)$$

where f_C, f_I, f_A, f_E, and f_R are the water supply benefits of urban life, industry, agriculture, ecology and rural life, respectively; α_i^C, α_i^I, α_i^A, α_i^A, and α_i^A are the weights of the water supply for urban life, industry, agriculture, ecology and rural life, respectively, in the i^{th} water source area; $\alpha_j^{sur-C(I,A,E,R)}$,$\alpha_j^{gra-C(I,A,E,R)}$,$\alpha_j^{slf-C(I,A,E,R)}$, and $\alpha_j^{div-C(I,A,E,R)}$ are the weight coefficients of the river surface water, groundwater, local surface water and diverted water supply for urban life, industry, agriculture, ecology and rural life, respectively, of the j^{th} calculation unit; and $\alpha_j^{rec-I(A,E)}$ is the weight coefficient of the reclaimed water supply for agriculture and ecology of the j^{th} calculation unit.

The economic benefit objective is reflected by the water deficit. For industries, the smaller the water deficit is, the higher the economic benefit of the water supply. Each industry should be assigned a corresponding water deficit weight coefficient according to the industry structure and water requirements in the allocation units to minimize the area water deficit and realize synergetic economic development.

$$F_2 = Min \sum_{j=1}^{n} \left(\beta_j^C \cdot M_j^C + \beta_j^I \cdot M_j^I + \beta_j^A \cdot M_j^A + \beta_j^E \cdot M_j^E + \beta_j^R \cdot M_j^R \right) \quad (13)$$

where β_j^C, β_j^I, β_j^A, β_j^E, β_j^R are the weight coefficients of the urban living water deficit, industrial water deficit, agricultural water deficit, ecological water deficit and rural living water deficit, respectively, of the j^{th} calculation unit.

The ecological benefit objective considers two main factors: the reclaimed water supply for the urban ecological environment and the inner river ecological water supply. The reclaimed water supply for the urban ecological environment is maximized, and the inner river ecological water deficit is minimized. The objective function is expressed as follows:

$$F_3 = Max \sum_{j=1}^{n} \left(\gamma_j^{rec} \cdot T_j^R - \gamma_j^E \cdot M^E j \right) + Max \sum_{x=1}^{k} [S_x(t)/D_x(t)] \quad (14)$$

where γ_j^{rec} and γ_j^E are the weight coefficients of the reclaimed water supply for the urban ecological environment and the water deficit for the ecological environment, respectively, of the j^{th} calculation unit, and $S_x(t)$ and $D_x(t)$ are the inner river water supply and the inner river ecological water demand, respectively, of the x^{th} reach in time period t.

The final objective is to realize the optimal comprehensive benefit of water resource allocation. The water resources and ecological environment carrying capacity are comprehensively considered in the allocation units according to the water supply benefit hierarchy obedience principle, and reasonable weight coefficients are assigned to the water supply benefit objectives of the subsystems.

$$F = \mu_1 F_1 + \mu_2 F_2 + \mu_3 F_3 \quad (15)$$

where F is the final objective and μ_1, μ_2, and μ_3 are the weight coefficients of the social objective, economic objective and ecological objective, respectively.

2.2.2 Constraint Conditions

The constraint conditions consist mainly of available water supply constraints, economic benefit constraints and ecological benefit constraints. The available water supply constraints include the local available water supply constraint, groundwater supply constraint, diverted water supply constraint and reclaimed water supply constraint, as expressed in formulas (16) to (19).

$$SF^{Cj}_{tm} + SF^{Ij}_{tm} + SF^{Aj}_{tm} + SF^{Ej}_{tm} + SF^{Rj}_{tm} \le SF^{P-Cj} \cdot SF^{Pj}_{tm} \tag{16}$$

$$G^{Cj}_{tm} + G^{Ij}_{tm} + G^{Aj}_{tm} + G^{Ej}_{tm} + G^{Rj}_{tm} \le G^{P-Uj} \cdot G^{Qj}_{tm} \tag{17}$$

$$D^{Cj}_{tm} + D^{Ij}_{tm} + D^{Aj}_{tm} + D^{Ej}_{tm} + D^{Rj}_{tm} \le D^{Qj}_{tm} \tag{18}$$

$$T^{Ij}_{tm} + T^{Aj}_{tm} + T^{Ej}_{tm} \le T^{Qj}_{tm} \tag{19}$$

The economic benefit constraints include mainly the benefits per cubic metre water supply for industry and GDP, as expressed in formula (20).

$$\begin{cases} \sum_{j=1}^{n} I^{j} \ge I_s \\ \sum_{j=1}^{n} G^{j} \ge G_s \end{cases} \tag{20}$$

where I^{j} and G^{j} are the per cubic metre water benefit values of industry and GDP, respectively, of the j^{th} calculation unit, and I_s and G_s are the planned target per cubic metre water benefits of industry and GDP, respectively.

The ecological benefit constraints include mainly sewage reuse constraints of the calculation unit and ecological constraints of river courses, as expressed in formulas (21)–(23), where λ^{j} is the planned sewage recycling rate of the j^{th} calculation unit.

$$T^{Rj}_{tm} = \left(W^{Cj}_{tm} - M^{Cj}_{tm}\right) \cdot S^{P-Cj}_{tm} \cdot T^{P-CDj}_{tm} \cdot T^{P-CTj}_{tm} \cdot T^{P-CRj}_{tm} + \left(W^{Ij}_{tm} - M^{Ij}_{tm}\right) \cdot S^{P-Ij}_{tm} \cdot T^{P-IDj}_{tm} \cdot T^{P-ITj}_{tm} \cdot T^{P-IRj}_{tm} \tag{21}$$

$$\sum_{j=1}^{n} T^{Rj}_{tm} \ge \lambda^{j} \cdot T^{Sj}_{tm} \tag{22}$$

$$R^{l}_{\max} \ge R^{l} \ge R^{l}_{\min} \tag{23}$$

2.2.3 Balance Equation

The balance equations of the water allocation model in the calculation units are presented as formulas (24) to (28).

$$W^{Cj}_{tm} = SF^{Cj}_{tm} + S^{Cj}_{tm} + D^{Cj}_{tm} + P^{Cj}_{tm} + G^{Cj}_{tm} + M^{Cj}_{tm} \tag{24}$$

$$W^{Ij}_{tm} = SF^{Ij}_{tm} + S^{Ij}_{tm} + D^{Ij}_{tm} + P^{Ij}_{tm} + T^{Ij}_{tm} + G^{Ij}_{tm} + M^{Ij}_{tm} \tag{25}$$

$$W^{Aj}_{tm} = SF^{Aj}_{tm} + S^{Aj}_{tm} + D^{Aj}_{tm} + P^{Aj}_{tm} + T^{Aj}_{tm} + SN^{Aj}_{tm} + G^{Aj}_{tm} + M^{Aj}_{tm} \tag{26}$$

$$W^{Rj}_{tm} = SF^{Rj}_{tm} + S^{Rj}_{tm} + D^{Rj}_{tm} + P^{Rj}_{tm} + G^{Rj}_{tm} + M^{Rj}_{tm} \tag{27}$$

$$W^{Ej}_{tm} = SF^{Ej}_{tm} + S^{Ej}_{tm} + D^{Ej}_{tm} + P^{Ej}_{tm} + T^{Ej}_{tm} + G^{Ej}_{tm} + M^{Ej}_{tm} \tag{28}$$

2.3 Multiple Iteration Algorithm of the Model

The technical process of the model includes three main layers: the basic system layer, the input layer and the allocation scheme generation layer. The calculation processes are illustrated in Fig. 3.

3 Case Study

3.1 Study Area and Data

Jilin City is located in east Jilin Province. The main river of this city is the Songhua River, which has a watershed area of 15,120 km^2 and a river length of 432 km within the territory of Jilin city. In addition to the trunk stream of the Songhua River and its main tributaries of the Huifa River and Yinma River, there are 9 tributaries with watershed areas of more than 500 km^2, which are presented in Fig. 4. Moreover, Jilin has abundant rainfall and a developed urban water system. The abundant water resources and various types of water supply and drainage projects can fully reflect the diversity and synergy of water sources and water supply projects. Additionally, the industry structure of Jilin is gradually transforming from agriculture and heavy industry to light manufacturing and service industries, which is representative of the industry structure of China. Finally, the spatial distribution of water resources in Jilin is uneven, and the contradictions between water supply and water demand differ among parts of this city, which can fully reflect the diversity of contradictions between socioeconomic development and environmental carrying capacity.

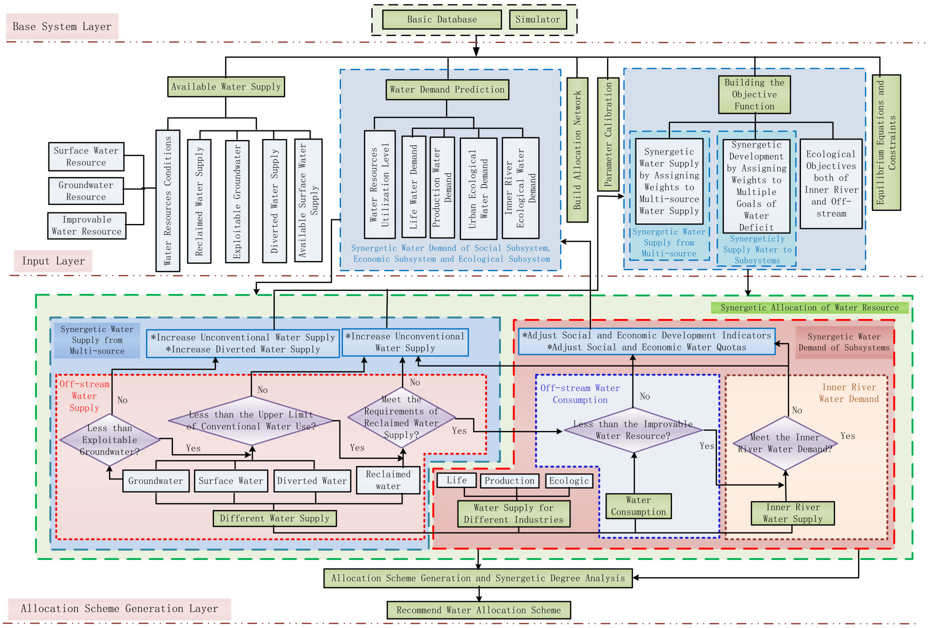

Fig. 3 Multiple iteration algorithm of the model

In this study, long-series groundwater data from 2006 to 2016 and long-series channel and project node runoff data from 1956 to 2016 were collected from the Hydrographic Office of Jilin. The drainage data, water supply data and the scales of water conservancy projects were

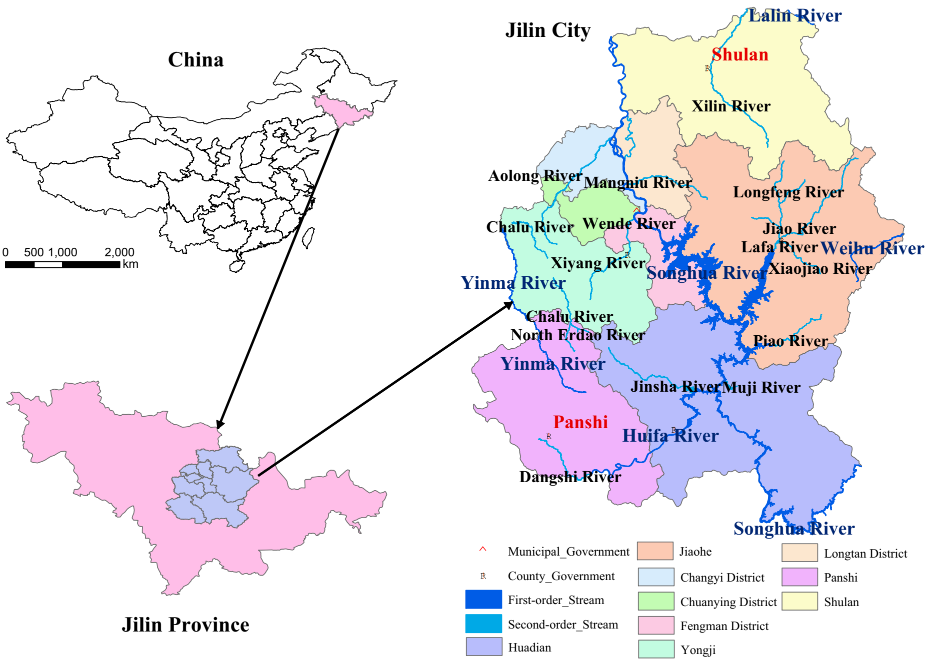

Fig. 4 River system in Jilin

collected from the Water Conservancy Bureau of Jilin. To reduce the error that was caused by the uncertainty regarding the agricultural and ecological water demands, long-series monthly data were used to simulate the water supply and demand configuration.

3.2 Regional Development Hierarchy Positioning

According to the benefit hierarchy obedience principle, the positioning of regional development levels is determined, which is presented in Table 4. The first development level is the key development zone, where the urbanization and industrialization development speed exceeds those in other areas of the city. The second development level is the restricted development zone, where the urbanization and industrialization development speed is lower than that of the first level. The third development level is the strict control zone, where the urbanization and industrialization development speed is the lowest among the three levels.

3.3 Water Resource Allocation Schemes

In this study, two development models of high-speed development and moderate development were proposed. The social and economic indicators were predicted based on the indicators in the base year. Two water-saving plans for strengthening water savings and moderate water savings were also proposed. The water use efficiency indices were predicted based on the indices in the base year. The growth plans of social and economic indicators were combined with the water-saving plans to generate four water demand prediction schemes, which are denoted as Scheme I, Scheme II, Scheme III and Scheme V and are presented in Table 5. Since the predicted result of Scheme V is similar to that of Scheme I and high-speed development with the moderate water saving scheme better conforms to the requirements of sustainable development, Scheme V was abandoned. Scheme I, Scheme II and Scheme III were designated as the high-water-demand scheme, the medium-water-demand scheme and the low-water-demand scheme, respectively.

3.4 Construction of the Water Resource Allocation Network

A network diagram of the water resource allocation system is presented in which is Fig. 5. It illustrates the topological relationships among calculation units, important water conservancy projects, various types of water flow transmission systems, and important control sections and nodes.

Table 4 Positioning of the regional development levels

Development Level	Area
1st Level, Key Development Zone	Urban District Shulan
2nd Level, Restricted Development Zone	Panshi Yongji
3rd Level, Strictly Controlled Development Zone	Jiaohe Huadian

Table 5 Water demand schemes

Water Demand Scheme	Development and Efficiency Degrees
Scheme I, High-Water-Demand Scheme	High-speed Development & Moderate Water Savings
Scheme II, Medium-Water-Demand Scheme	High-speed Development & Strengthening Water Savings
Scheme III, Low-Water-Demand Scheme	Moderate Development & Strengthening Water Savings
Scheme V, Abnegated Scheme	Moderate Development & Moderate Water Savings

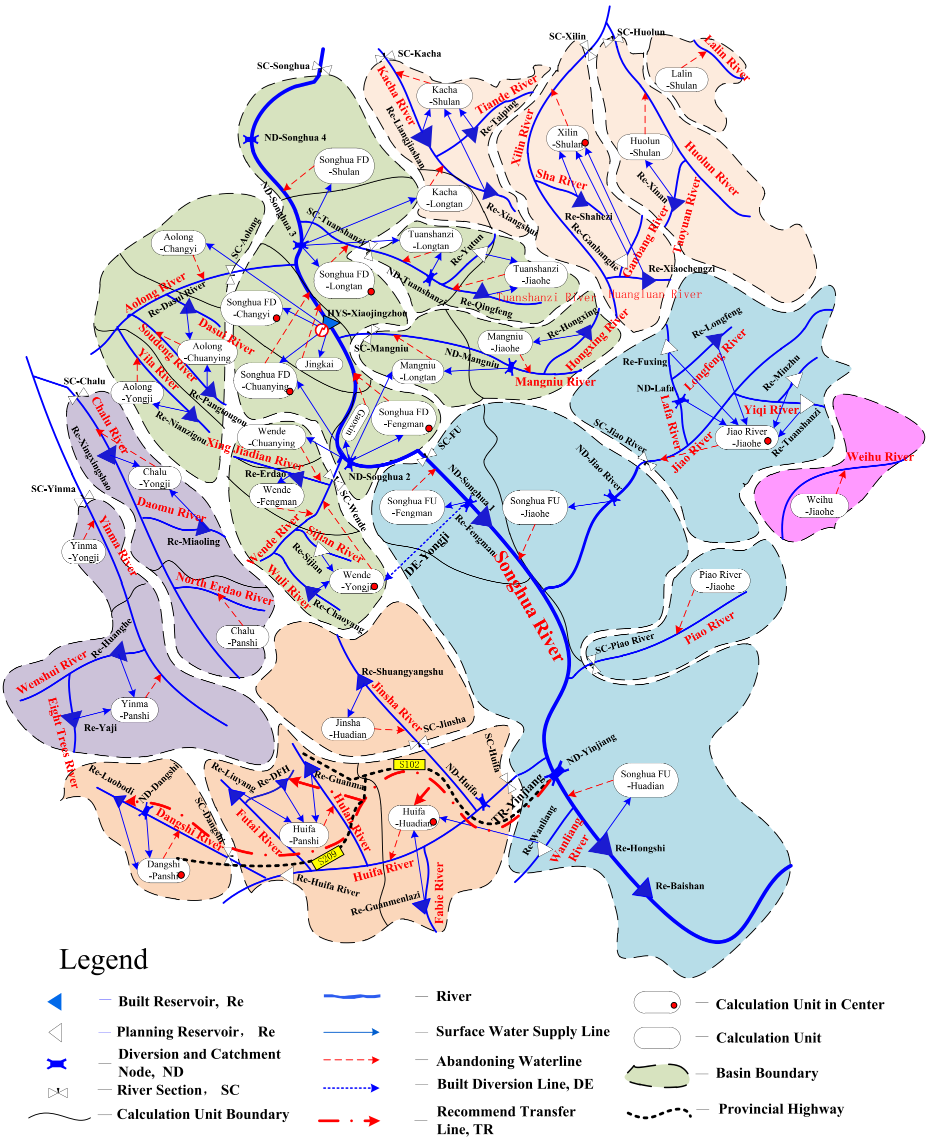

Fig. 5 Water resource allocation network diagram of Jilin

Table 6 Value standard of the Gini coefficient

Value Range	Grade
Less than 0.2	Absolutely matched
0.2–0.3	Matched
0.3–0.4	Relatively matched
0.4–0.5	Unmatched
More than 0.5	Substantial disparity

3.5 Determination of the Order Parameter Thresholds of the Subsystems

In this paper, the critical values are determined according to the constraint conditions of each order parameter. In the social subsystem, for the per capita water supply, 440 m^3 of the national per capita water supply was selected as the lower threshold, and the per capita available water supply was selected as the upper threshold. For the comprehensive Gini coefficient of the water supply, we selected 0 ~ 0.4 as its critical threshold to ensure that the water resource allocation and socioeconomic development can at least realize a relative matching level according to the value standard of the Gini coefficient, which is presented in Table 6. In the economic subsystem, for the water supply, the actual water consumption in the base year was selected as the lower limit, and the available water supply in the planning level year was selected as the upper limit. For the water deficit, the full water supply with a water deficit of 0 was selected as the lower limit, and the annual water deficit in special dry years was selected as the upper limit. In the ecological subsystem, 20% and 35% were selected as the lower limit and the upper limit, respectively, of the sewage recycling rate according to the conditions in this study area. For the ecological water supply, the ecological water

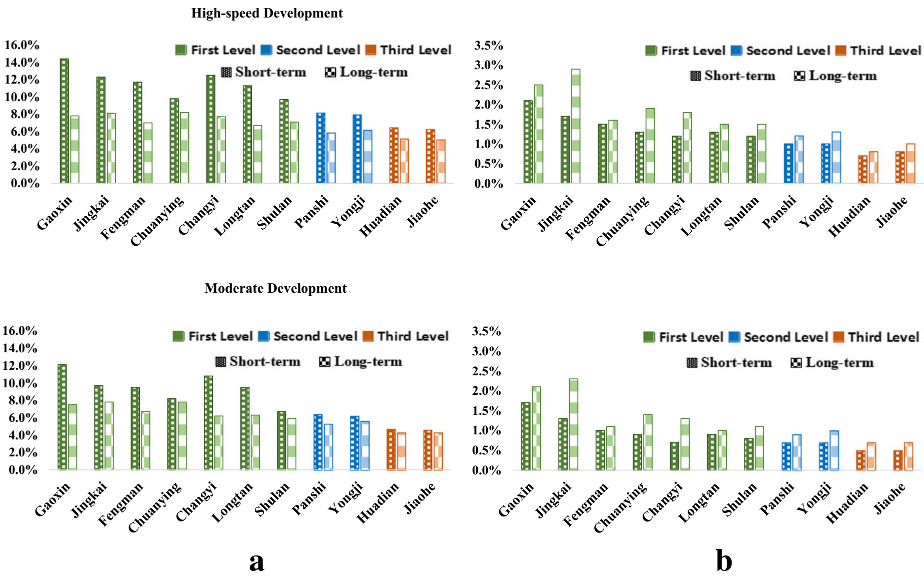

Fig. 6 Hierarchically predicted average annual growth rate. (**a**) GDP and (**b**) Population

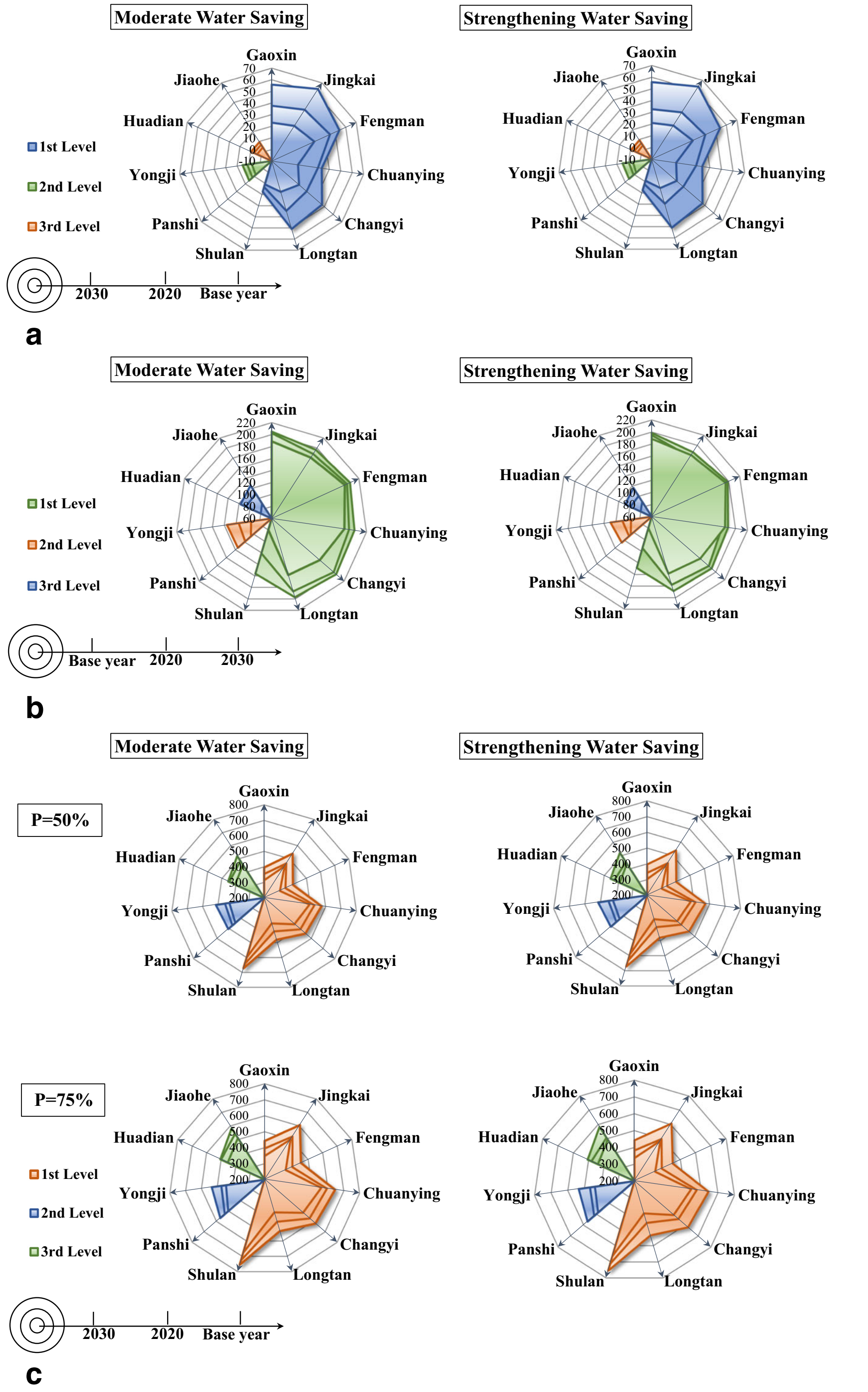

Fig. 7 Prediction of the water demand quota. (a) Ten thousand yuan GDP; (b) domestic; and (c) agriculture

Table 7 Prediction results of the water demand/10^4 m^3

Level Year		Domestic	Industry, Construction and Tertiary Industry	Agriculture		Ecology	Summation	
				P=50%	*P*=75%		P=50%	P=75%
Base Year		15,400	120,142	127,380	140,667	5238	268,161	281,448
Scheme I	2020	22,658	171,718	133,221	147,473	8154	335,751	350,004
	2030	31,014	255,114	129,565	143,379	10,872	426,565	440,379
Scheme II	2020	20,572	149,144	129,589	143,414	8154	307,460	321,285
	2030	29,018	215,867	126,804	140,294	10,872	382,561	396,051
Scheme III	2020	19,570	128,098	122,660	135,802	7129	277,457	290,599
	2030	26,710	181,726	119,987	132,892	8655	337,079	349,984

consumption in the base year was selected as the lower limit, and the ecological water demand in the planning lever year, which could fully satisfy the ecological water demand, was selected as the upper limit.

4 Results and Discussion

4.1 Synergetic Water Demand Schemes that Are Based on the Benefit Hierarchy Compliance Principle

As illustrated in Fig. 6, in the areas that were designated as the first level, the GDP and population growth rates of both the high-speed and moderate development models exceed those in the areas of the second level and the third level.

Moreover, to increase the water-use efficiency, the water demand quotas for a GDP of ten thousand yuan, domestic and agricultural sectors are also predicted hierarchically, as illustrated in Fig. 7. For both the moderate water saving mode and the strengthening water saving mode, the water demand quotas of the 1st level areas exceed those of the 2nd level areas, and those of the 3rd level areas are the lowest. The prediction results for water demand are presented in Table 7.

The water demand structure of each water demand scheme has the same variation trend from the base year to 2030, which is shown in Fig. 8. In the base year, agriculture accounts for the largest proportion of water consumption, followed by industry. The service industry and ecological environment account for lower proportions. In 2020 and 2030, the industrial,

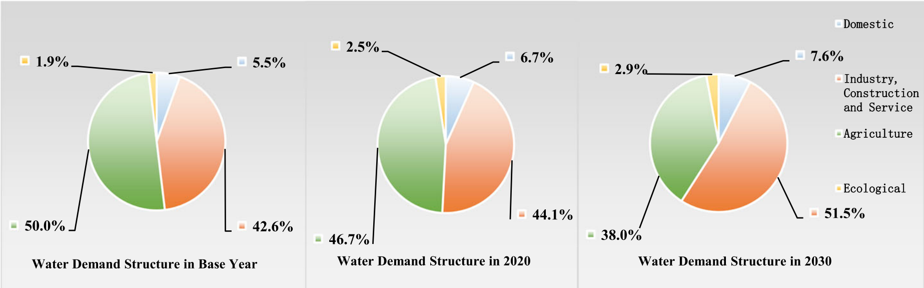

Fig. 8 Prediction of the water demand structure

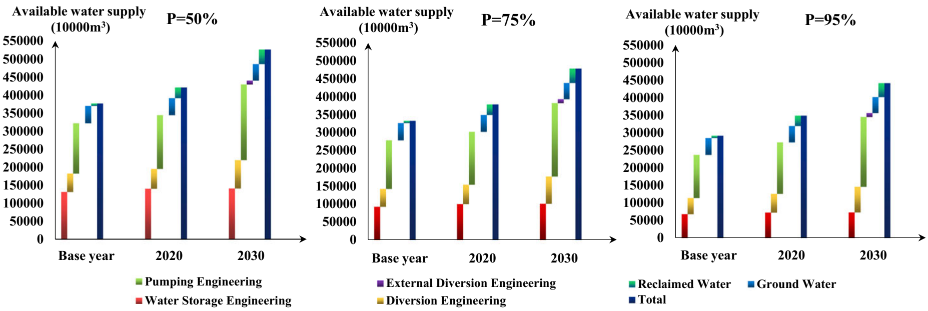

Fig. 9 Prediction results of the available water supply

construction, service, domestic, and ecological water demands will gradually increase with the development of urbanization and industrialization. Meanwhile, with the development of water-saving irrigation technology and ecological agriculture, the water demand of agriculture will show a decreasing trend.

4.2 Synergetic Water Supply Schemes that Are Based on the System Synthesis Effect Law

The main water supply source of Jilin in the base year is conventional water, such as surface water and groundwater. However, reclaimed water is underutilized. To maintain ecological benefits, the utilization of reclaimed water should be increased in the future to realize a synergetic water supply from multiple water sources. By 2020, a reduction in groundwater withdrawal is planned along with an increase in the reclaimed water supply. Meanwhile, the available water supplies of the established water supply projects and the planned water supply projects can satisfy the three water demand schemes in 2020. Therefore, no additional water supply project planning is conducted in 2020 in this study. By 2030, strategic water reserves must be available to match the development model with the carrying capacity of resources and the environment in various regions. In addition to reducing groundwater withdrawal, the

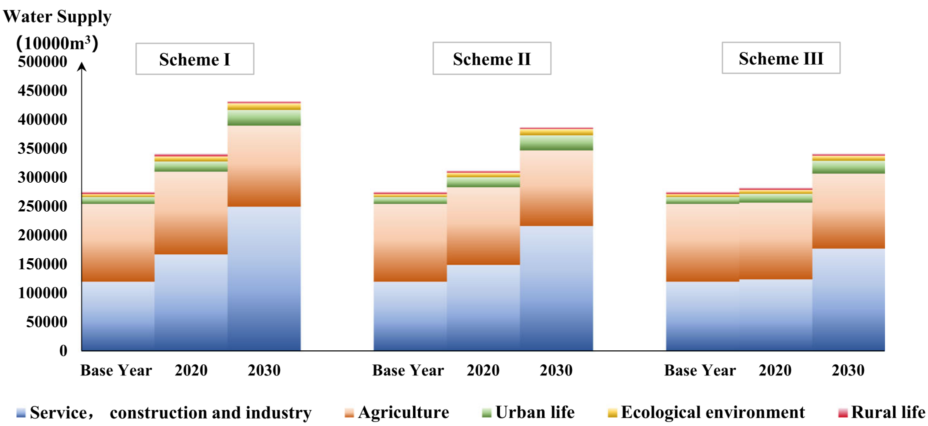

Fig. 10 Water resource synergetic allocation schemes

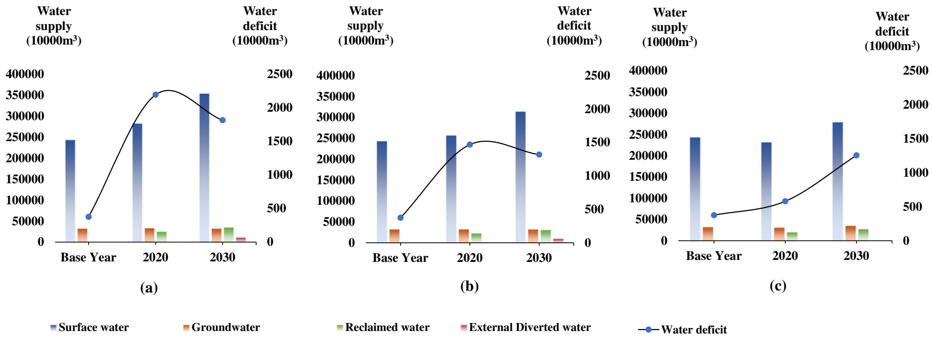

Fig. 11 Water resource synergetic allocation results: (**a**) Scheme I, (**b**) Scheme II, and (**c**) Scheme III

establishment of new water storage projects, diversion projects, pumping projects and reclaimed water plants is proposed.

As shown in Fig. 9, available water supply schemes with various water supply guarantee rates are predicted. With the closure of self-contained wells, the available groundwater supply is gradually reduced from the base year to 2030. However, the available reclaimed water supply and available water supply from water storage engineering, pumping engineering and diversion engineering are gradually increasing. In 2030, the commissioning of external diversion engineering will be necessary to meet the increasing water demand.

4.3 Water Resource Synergetic Allocation Schemes with the Optimal System Comprehensive Benefit

The synergetic water allocation schemes illustrated in Figs. 10 and 11 are established under the multiyear average water supply guarantee rate. Among the three allocation schemes, only Scheme III is a low-speed socioeconomic development scheme. To maximize the economic benefits of the external diverted water supply, external diversion engineering only provides water for the high-speed socioeconomic development schemes, namely, Scheme I and Scheme II. The allocation results demonstrate that by 2020,

Table 8 Synergetic degrees of water resource allocation schemes

Subsystems		Scheme I		Scheme II		Scheme III	
		2020	2030	2020	2030	2020	2030
Social Subsystem	Order of the comprehensive Gini coefficient of the water supply	0.2	0.11	0.22	0.14	0.26	0.17
	Order of the water supply per capita	0.74	0.76	0.57	0.69	0.44	0.57
	Degree of the subsystem order	0.47	0.43	0.39	0.41	0.35	0.37
Economic Subsystem	Order of the water supply	0.85	0.94	0.79	0.91	0.47	0.88
	Order of the water deficit	0.81	0.73	0.85	0.74	0.99	0.84
	Degree of the subsystem order	0.83	0.83	0.82	0.83	0.73	0.86
Ecological Subsystem	Order of the sewage recycling rate	0.43	0.81	0.46	0.87	0.37	0.77
	Order of the ecological water supply	0.45	0.67	0.65	0.83	0.56	0.58
	Degree of the subsystem order	0.44	0.74	0.55	0.85	0.47	0.67
Synergetic Degree		0.58	0.67	0.59	0.7	0.51	0.63

Table 9 Recommended scheme for synergetic water allocation/$10^4 m^3$, %

Level Year	Assurance	Water Demand	Water Supply from Sources					Water Supply for Users	
								City	
			Sum	Surface Water	Underground Water	Reclaimed Water	Songhua River Diversion Engineering	Life	Industry
Base Year	50%	268,161	268,157	236,669	31,488	0	0	11,647	120,143
	75%	281,448	280,353	248,096	32,257	0	0	11,647	120,143
	95%	282,028	269,452	230,418	39,035	0	0	11,647	120,143
	Multi-year Average	275,225	274,850	242,707	32,143	0	0	11,647	120,143
2020	50%	307,460	306,771	251,836	32,065	22,870	0	17,069	149,145
	75%	321,285	319,688	263,900	32,629	23,160	0	17,069	149,145
	95%	321,285	311,264	248,015	37,450	25,798	0	17,069	149,145
	Multi-year Average	313,158	311,689	256,060	32,455	23,174	0	17,069	149,145
2030	50%	382,561	382,411	318,355	26,217	28,092	9746	26,220	215,867
	75%	396,051	394,689	320,284	33,206	31,452	9746	26,220	215,867
	95%	396,791	391,688	307,453	39,126	35,463	9746	26,220	215,867
	Multi-year Average	387,665	386,346	313,174	32,414	31,012	9746	26,220	215,867

Level Year	Water Supply for Users						Water Deficit	Water Deficiency Ratio
	City		Rural			Sum		
	Ecology	Subtotal	Life	Agriculture	Subtotal			
Base Year	5238	137,028	3753	127,376	131,129	268,157	4	0
	5195	136,985	3753	139,616	143,369	280,353	1095	0.39
	4630	136,419	3753	129,280	133,033	269,452	12,576	4.46
	5222	137,011	3753	134,086	137,839	274,850	375	0.14
2020	8154	174,368	3503	128,900	132,403	306,771	689	0.22
	8096	174,310	3503	141,876	145,379	319,688	1596	0.5
	7462	173,676	3503	134,086	137,588	311,264	10,021	3.12
	8137	174,350	3503	133,836	137,339	311,689	1469	0.47

Table 9 (continued)

Level Year	Water Supply for Users						Water Deficit	Water Deficiency Ratio
	City		Rural			Sum		
	Ecology	Subtotal	Life	Agriculture	Subtotal			
2030	10,872	252,958	2799	126,654	129,452	382,411	150	0.04
	10,780	252,866	2799	139,024	141,823	394,689	1362	0.34
	9913	251,999	2799	136,890	139,689	391,688	5102	1.29
	10,849	252,935	2799	130,612	133,411	386,346	1319	0.34

The water supply for industry in this table includes supplies for the tertiary industry and the construction industry portions of the groundwater and surface water supplies will be replaced with the increased reclaimed water supply. By 2030, the increased reclaimed water supply and externally diverted water supply will result in significant savings in the local surface and groundwater supplies. The water deficit rate will decrease significantly, especially after the implementation of external diversion engineering.

4.4 Synergetic Degree Analysis and the Recommendation of a Water Resource Allocation Scheme

The synergetic degree analysis results are presented in Table 8. The social subsystem order degree of Scheme III exceeds those of Scheme II and Scheme I, but the economic subsystem and the ecological subsystem order degrees of Scheme III are below those of Scheme II and Scheme I, which do not support ecological civilization construction. T economic subsystem, the economic subsystem order degree of Scheme I and Scheme II are higher than Scheme III, and the two schemes are corresponding to the high-speed development mode, but the ecological subsystem order degree of Scheme I is lower than Scheme II and Scheme III, and Scheme I has a lower water-saving strength; hence, it is not recommended as the optimal scheme. In terms of the ecological subsystem, Scheme II has the highest synergetic degree, which also has the highest order degree of the ecological subsystem. In addition, Scheme II corresponds to strengthening water savings, which can not only guarantee the rapid development of the social economy but also provide high water supply security, and it is the most conducive to the harmonious development of the three subsystems. Therefore, Scheme II is selected as the recommendation, which is presented in Table 9.

5 Conclusion

(1) This paper analyzed the relationships between water resource subsystem and the three subsystems of society, economy and ecology. Provided the theoretical basis for synergetic water demand of the three subsystems, synergetic water supply from various water sources and the synergetic allocation of water resources is provided. Synergetic theory, which includes the benefit hierarchy obedience principle and the system comprehensive effect law, was applied to water resource allocation.

(2) We constructed a water resource allocation model, which includes a data pre-processing module, a synergetic water demand module that is based on the benefit hierarchy obedience principle, a synergetic water supply module that is based on the system comprehensive effect law, and a synergetic degree analysis module. In addition, we proposed a multicycle iterative algorithm for realizing the overall objective of "harmonious development between human and water resources", which provides an effective calculation tool for water resource synergetic allocation.

(3) Finally, the model was applied in Jilin, and Scheme II was recommended as the optimal scheme through a synergetic degree analysis. The water supply of the conventional water source will be conserved due to an increase in the reclaimed water supply. In addition, after the implementation of an external diversion project by 2030, the amount of groundwater withdrawal will be gradually reduced, and the water deficit rate will be significantly reduced.

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Authors Contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Xiaojing Shen, Xu Wu and Xinmin Xie. The first draft of the manuscript was written by Xiaojing Shen. Software was performed by Xu Wu and Chuanjiang Wei, Editing and visualization were performed by Liqin Li and Jingjing Zhang. All authors commented on previous versions of the manuscript, and authors read and approved the final manuscript.

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Data Availability Not applicable, The data sets supporting the results of this article were described in the '*3.1 Study Area and Data*' part.

Code Availability Not applicable.

Declarations

Ethical Approval Not applicable.

Consent to Participate Not applicable.

Consent to Publish The authors confirm that the work described has not been published before, and not under consideration for publication elsewhere. Its publication has been approved by all co-authors, and we agree to publish this article in the journal of WARM by Springer.

Conflict of Interest None.

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