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Construction of water resource allocation model based on green supply chain theory

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ABSTRACT

With global environmental change and population growth, the problem of water resources management is becoming increasingly prominent. Based on the theory of green supply chain, this paper discusses the effective management and allocation strategy of water resources. Through detailed data acquisition and preprocessing, the accuracy and reliability of the study are ensured. Then, a comprehensive water resource allocation model is designed and implemented. Through many experiments and verification, the model shows good stability and accuracy. This study not only provides a new perspective and method for theoretical research but also provides a valuable reference for practical water resources management. However, there are also some limitations, which provide further thinking and expansion space for future research.

Key words: data acquisition, green supply chain, model design, resource allocation, water resources management

HIGHLIGHTS

- Based on the theory of green supply chain management, its application in water resources management is explored.
- A comprehensive water resource allocation model is designed and implemented.
- It provides a new perspective and method for practical water resources management.

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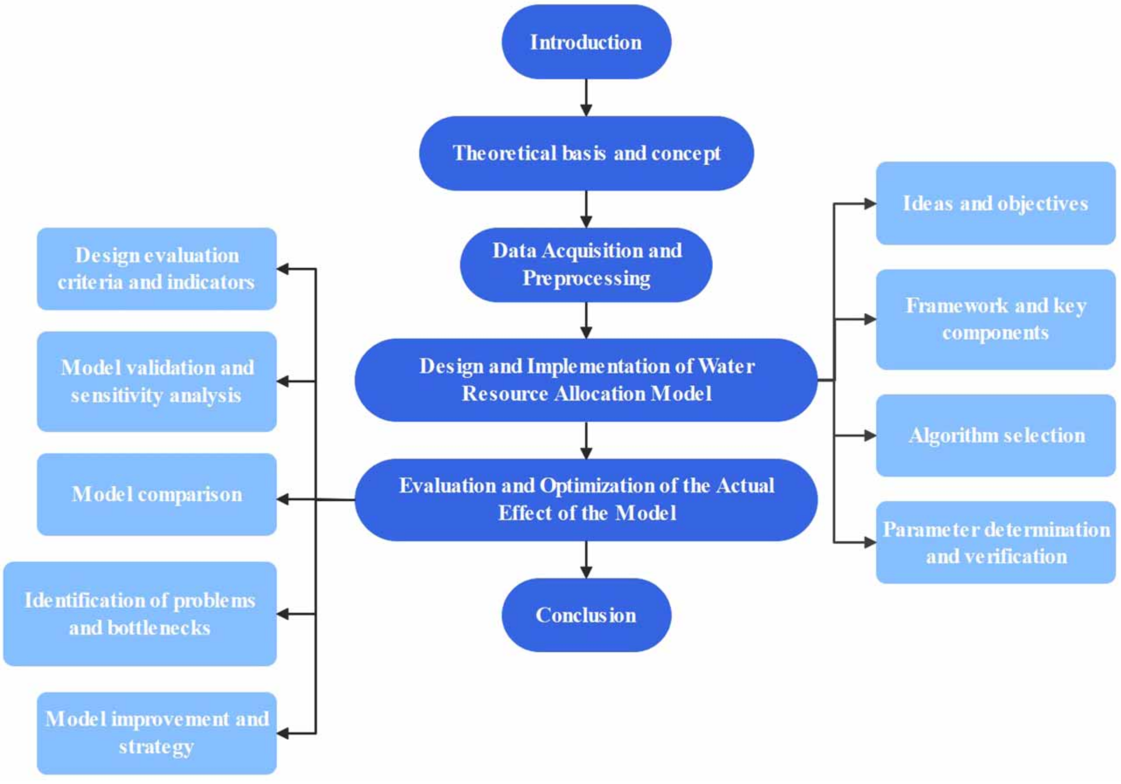
GRAPHICAL ABSTRACT



1. INTRODUCTION

With the rapid development of the global economy, all walks of life are facing a high demand for resources, especially for water. Water is a key resource for maintaining ecological balance, supporting life and driving economic development. However, with population growth, accelerating industrialization and the impact of climate change, many parts of the world are facing water shortages. In this context, the traditional supply chain management model has been unable to meet the current needs, especially in terms of resource utilization and allocation. The traditional supply chain often takes economic benefits as the ultimate goal and lacks comprehensive consideration of the environment and society, resulting in resource waste and environmental pollution. Therefore, it is particularly important to explore a sustainable, efficient and environmentally friendly supply chain management model. As a new management thinking, green supply chain management (GSCM) emphasizes environmental protection and sustainable utilization of resources. It not only pays attention to economic benefits but also pays more attention to ecological benefits and social benefits. In water resources management, the concept of the green supply chain can provide new perspectives and methods for the efficient, just and sustainable allocation of water resources.

With the change in the global environment and the increasing shortage of water resources, the effective management and distribution of water resources are becoming more and more important. In recent years, scholars have done a lot of research and discussed a variety of water resource allocation models and methods. Shen *et al.* (2021) built a water resource allocation model based on the synergy theory, which showed high efficiency and stability in a variety of situations. At the same time, Zhang *et al.* (2023) emphasized the importance of coordinating the interests of regional multi-level water resource managers and proposed an optimal water resource allocation model for this purpose. These models all involve the dynamic adjustment and allocation of resources. In addition, Hou *et al.* (2023) studied the dynamic mechanism of water resources allocation and proposed a method to formulate water resources allocation scheme. On this basis, Wu (2023) applied Krutila–Fisher model to study the irreversibility of water resource allocation and the allocation of natural resources, which provided useful guidance for practical application. Fan *et al.* (2023) established a coupling model from the perspective of water resource allocation and

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canal optimization to improve the efficiency of water allocation. Similarly, Yan *et al.* (2018) also studied the problem of water resource recharge with ecological flow and proposed an improved water resource allocation model. In order to respond to various water resources challenges, some studies, such as Lin *et al.* (2020) and Qi *et al.* (2020), respectively, proposed a rule-based object-oriented water resource system simulation model and a multi-source and multi-user water resources allocation method based on genetic algorithm. At the same time, many scholars, such as Du *et al.* (2022) and He *et al.* (2019) emphasized the importance of multi-objective water resource allocation services and proposed corresponding application methods in the context of digital water networks. Overall, the current research has covered a variety of water resource allocation models and methods, but further research is needed to adapt to complex and changing actual needs and challenges.

In today's era, water management faces numerous challenges, such as resource scarcity, growing demand and uneven distribution. In order to manage and allocate water resources more efficiently, fairly and sustainably, this study aims to construct a water resource allocation model combining green supply chain theory. Through this combination, the study hopes to provide a new, more holistic approach to water management that takes into account economic, ecological and social benefits. In addition, the concept and practice of GSCM have been widely applied and verified in many fields, but the research on water resource allocation is still limited. Therefore, this study also aims to fill this academic gap and provide reference and inspiration for scholars and practitioners in related fields.

More importantly, the effective management and distribution of water resources is not only related to the survival and development of enterprises but also directly affects the health and stability of communities and ecosystems. Therefore, the significance of the research is not limited to theoretical exploration, but also reflected in the positive impact on the real world, especially in the context of increasing global water stress. Looking at and addressing this issue through a green supply chain lens will help drive more just, efficient and sustainable water management practices.

Based on the theory of GSCM, this study explores its application in water resources management. The specific contents are as follows: Explore the core ideas and concepts of green supply chain in depth, and analyze the uniqueness and current challenges of water resources management. Through the combination of the two, a theoretical framework aimed at solving the problem of water resource allocation is constructed. In order to construct an effective water resource allocation model, this study will analyze data requirements and select appropriate collection means and tools. Once the relevant data has been collected, the quality and integrity of the data will also be verified, as well as the necessary preprocessing and standardization. Based on the above theoretical framework and data, this study will design a water resources allocation model, and clarify its design ideas, framework, key components and related algorithms. At the same time, the parameters of the model will be determined and verified to ensure the accuracy and effectiveness of the model. The completed model will be evaluated for practical effects. This study will develop evaluation criteria and indicators to validate the model based on actual data. According to the problems and bottlenecks, the corresponding improvement strategies are proposed to optimize the performance of the model. After completing the above research, this paper will summarize the main conclusions, and explore the contribution and possible impact of this research in practical applications. At the same time, according to the limitations of the research and the future development direction, the author puts forward relevant suggestions and opinions.

Through the in-depth study of these contents, this paper hopes to provide new ideas and methods for water resources management and promote the application of green supply chain theory in more fields.

2. GREEN SUPPLY CHAIN THEORY AND WATER RESOURCES MANAGEMENT

2.1. Core views and concepts of green supply chain

GSCM is the expansion and further development of traditional supply chain management, which emphasizes the integration of environmental protection and sustainable use of resources in the whole process of the supply chain. This management mindset stems from the growing awareness of the environmental and social responsibility of companies, as well as increasingly stringent environmental regulations and growing public demand for green products and services worldwide (Fu *et al.* 2023; Weng *et al.* 2023).

One of the core ideas is integration, which means that a green supply chain does not just focus on the environmental performance of a single company, but emphasizes that all participants in the supply chain, from raw material suppliers to end consumers, should be involved in environmental protection activities. This requires companies to consider not only their own production processes but also the environmental behavior of suppliers and distributors.

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Life cycle thinking is another core idea. It means that when assessing the environmental impact of a product or service, the entire life cycle of raw material procurement, production, use and waste should be considered. This helps identify and mitigate potential environmental risks in the supply chain.

The basic concepts of GSCM include green procurement (ensuring that the production of raw materials and components has a minimum environmental impact), green production (using environmentally friendly production methods and technologies), green distribution (optimizing logistics to reduce energy consumption and carbon emissions), and green recovery and reuse (ensuring that products are effectively recycled and reused after use) (Liu *et al.* 2021; Wu *et al.* 2022).

Combined with these perspectives and concepts, GSCM emphasizes a circular, efficient and sustainable system that aims to meet customer needs while minimizing negative environmental impacts.

2.2. Uniqueness and challenge of water resources

Water resources, as one of the most precious natural resources on earth, has its unique characteristics, which makes its management and distribution face a series of challenges.

2.2.1. Uniqueness

Irreplaceable: Water is necessary for the survival of all living things, no matter in production, life or ecosystem, no other substance can completely replace the role of water (Tan *et al.* 2019).

Regional: The distribution of water resources is significantly regional, with some areas rich in water and others extremely scarce.

Seasonality and chronicity: Water availability is affected by seasonal variations, such as rainy and dry seasons, which are further exacerbated by climate change and anthropogenic activities.

Water is generally considered a public good, i.e. its use does not cause it to be depleted, but overuse or pollution degrades its quality and affects other users (Liu *et al.* 2018).

2.2.2. Challenges

Supply and demand imbalance: As the global population grows and industrialization accelerates, the demand for water continues to grow, while supply is limited in many regions.

Water quality decline: With the economic development, the improvement of industrial production level and the increase of population, the demand for water resources is increasing, resulting in a serious shortage of water resources, accompanied by serious water pollution (Musa 2021). Industrial development, urbanization, and agricultural activities have polluted water bodies and reduced the quality of available water resources.

Cross-border management: Many important rivers and lakes cross national borders, and the fair and effective sharing and management of these transboundary water resources is a major challenge.

Impacts of climate change: Climate change may lead to changes in precipitation patterns and an increase in drought and flood events, affecting water availability and demand. Climate change is mainly attributed to the natural cycle and the disturbance of the earth's climate system, and these disturbances will inevitably cause changes in the water cycle, change the temporal and spatial distribution of water resources and the quantity of water resources, hinder social and economic development, and destroy the ecological environment (Feng 2021; Wang *et al.* 2022).

In the face of these unique characteristics and challenges, traditional water management methods may be difficult to adapt. Therefore, finding and adopting new management strategies and models, such as combining green supply chain theory, is of great significance to ensure the sustainable use of water resources.

2.3. Water resource management strategies combined with green supply chain

Looking at water management in conjunction with green supply chain theory creates a new perspective that emphasizes sustainability and ecological benefits throughout the water supply chain (Yue *et al.* 2022). The following are several water management strategies that integrate green supply chains:

Life cycle assessment: Similar to the full life cycle assessment of a product from raw material to waste in a green supply chain, water resources should also be assessed throughout the process of water intake, use, treatment and discharge to identify and reduce environmental impacts throughout the life cycle.

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Green procurement strategy: For industrial and agricultural users, green procurement strategies can be adopted, choosing to use technology and equipment with higher water efficiency and lower pollutant emissions, thereby reducing dependence on water resources and impact on water quality (Li *et al.* 2020a).

Optimal allocation of water resources: Through efficient allocation of water resources, ensuring that basic needs are met while ecosystem needs are taken into account in order to protect biodiversity and maintain ecological services (Wei *et al.* 2023).

Continuous improvement and innovation: Encourage technological innovation and the sharing of best practices to continuously improve water efficiency throughout the supply chain, reduce waste, increase reuse rates and reduce emissions.

Cross-sectoral and cross-border cooperation: Due to the regional nature of water resources and the nature of public goods, involving multiple stakeholders, there is a need to establish cooperation mechanisms between different sectors, industries and even countries to jointly develop and implement green supply chain strategies (Li *et al.* 2020b).

Public engagement and education: raise public awareness of the value of water, through education and training, so that they can adopt green consumption habits in their daily lives, such as saving water and reducing pollution.

Water management strategies integrated with green supply chains not only ensure the efficient use and long-term availability of water resources but also minimize the negative impact on the environment and society, thus achieving sustainable development in the true sense of the word.

3. DATA ACQUISITION AND PREPROCESSING

3.1. Data requirement analysis

In order to ensure the accuracy and feasibility of water resource allocation models based on green supply chain theory, the research first needs to clarify the data requirements. Data requirement analysis aims to identify, clarify and prioritize data that are critical to model construction and validation. Here's a breakdown of the data requirements:

(1) Water resources supply data: the amount of available water resources (by season and year), the location and regional characteristics of the water source, and water quality data (such as pollutant concentration).
(2) Water demand data: the water consumption of various sectors (such as agriculture, industry, domestic), the expected growth rate of water use, and the water reuse rate of various sectors.
(3) Environmental and ecological demand data: the minimum amount of water required by the ecosystem, the sewage treatment capacity and its effect, the types of pollutants and their impact on the ecology.
(4) Technology and cost data: existing water treatment and distribution technologies, investment and operating costs of new technologies, water prices and fee structures
(5) Socio-economic data: regional population data and projected growth rates, local economic development trends and industrial structure, public attitudes and perceptions of water conservation.

Based on the above data requirements, a data collection table can be formulated, as shown in Table 1.

After the data requirement analysis is completed, the study will further identify data acquisition methods and tools to ensure data integrity, accuracy and timeliness.

3.2. Selection of collection means and tools

After analyzing data requirements, you need to select appropriate data collection methods and tools to ensure that the obtained data are accurate, reliable and complete. The following are the collection methods and tools selected for different types of data:

3.2.1. Data collection means

Official statistics: obtained directly from the websites of relevant government departments or through official channels.
Field investigation: Obtain original data through field investigation, measurement and questionnaire survey.
Research literature: Extract and cite data from relevant research literature and reports.
Web crawler: Use web crawler technology to automatically collect publicly published data from websites.

3.2.2. Data acquisition tools

Statistical software: such as SPSS, Excel, etc., for data sorting and preliminary analysis.
GIS software, such as ArcGIS, is used to collect and analyze geographical location data.

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Table 1 | Data requirements and collection

Data class	Data name	Data type	Data source
Water resources supply	Amount of available water resources	Value/time series	Water department official statistics
	Location of water source	Geographical coordinates	Maps, GIS data
	Water quality data	Numerical value	Environmental protection department monitoring data
Water demand	Agricultural water consumption	Numerical value	Agricultural sector statistics
	Industrial water consumption	Numerical value	Industrial sector statistics
	Domestic water consumption	Numerical value	City administration data
Environmental and ecological needs	Ecological water requirements	Numerical value	Environmental research reports, literature
	Sewage treatment data	Numerical value	Environmental protection department, sewage treatment plant data
Technology and cost	Water treatment technology	Text description	Technical manuals, research reports
	Investment and operating costs	Numerical value	Project budget, investment analysis report
Social economy	Regional population	Numerical value	Census Bureau, public reports
	Economic development trend	Text description/ numerical value	Economic research institutions, literature
	Public attitude survey	Percentage/Questionnaire	Social surveys and research reports

Web crawler tools: such as Python's Scrapy framework, used to automate the collection of network data.
Questionnaire survey tools: such as Wenxing, Tencent questionnaire, etc., used for online questionnaire design and data collection.
As shown in Table 2, the selection of various data collection means and tools is described in detail.
Through reasonable collection means and tool selection, the data quality can be guaranteed, and the data can be more comprehensive and detailed, which can better meet the needs of model construction and analysis.

Table 2 | Selection of data acquisition means and tools

Data class	Acquisition means	Tool or platform	Remark
Water resources supply	Official statistics	Official website, Excel	Ensure that data are official and accurate
	Field investigation	Measuring equipment, questionnaire survey	Get real-time and detailed data information
Water demand	Official statistics	Official website, Excel	Obtain the water consumption of each department
	Scientific research literature	Academic database	Explore the water use characteristics of different departments
Environmental and ecological needs	Field investigation	GIS software, measuring equipment	Get specific geographic location and environmental parameters
	Official statistics	Official website, Excel	Obtain data related to wastewater treatment
Technology and cost	Scientific research literature	Academic database, professional magazine	Grasp the current technical status and development trend
Social economy	Web crawler	Python (Scrapy)	Get online statistics automatically
	Questionnaire survey	Questionnaire star, Tencent questionnaire	Understand public attitudes and socio-economic conditions

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3.3. Data quality and integrity verification

Verifying the quality and integrity of data is an important step in data preprocessing to ensure the accuracy, consistency and availability of data. The following are the methods and criteria for verifying the quality and integrity of all types of data:

3.3.1. Verification criteria

Accuracy: Whether the data correctly reflect the real situation.
Consistency: Whether the data are consistent across different data sources.
Integrity: Whether the data are missing and available for analysis.
Timeliness: Whether the data are up to date and reflect the current situation.

3.3.2. Verification method

Comparative validation: Compare data with other reliable sources to check for consistency and accuracy.
Logical verification: Check whether the data are logical and common sense, for example, whether the water consumption is within a reasonable range.
Expert review: Ask experts in the relevant fields to review the data and obtain professional opinions.
Statistical analysis: Through statistical analysis, check the rationality of the data, for example, look at the distribution and outliers of the data.

3.3.3. Verification process

Table 3 shows the data quality and integrity verification process.

Through the verification process of the system, it can ensure that the collected data meet the needs of the research and provide a reliable data basis for the subsequent model construction and analysis.

3.4. Data preprocessing and standardization

Data preprocessing is an important part of data mining, ensuring that the process of data cleaning, conversion and normalization can obtain high-quality and usable data sets. For the study of water resource allocation, the accuracy and consistency of the data are crucial.

3.4.1. Data cleaning

In the process of data verification, the research found some data missing and inconsistent problems. The goal of data cleansing is to fix these problems and ensure data integrity and accuracy.
Missing value processing: For missing data of water demand, the median filling method is used to complete.
Outlier processing: The outliers identified by statistical analysis are replaced with the mean of the data set.

3.4.2. Data conversion

For non-numerical data, such as the name of a region or the type of water source, coding methods are used to convert it into numerical data for easy model processing.

Table 3 | Data quality and integrity verification

Data class	Verification standard	Verification method	Verification result	Remark
Water resources supply	Accuracy	Contrast verification	Up to standard	Consistent with official figures
	Consistency	Expert review	Up to standard	Experts consider the data reliable
Water demand	Integrality	Logical verification	Below standard	Partial data missing
	Timeliness	Contrast verification	Up to standard	The data are current
Environmental and ecological needs	Accuracy	Logical verification	Up to standard	Data rationalization
	Consistency	Contrast verification	Below standard	Different from other sources
Technology and cost	Integrality	Expert review	Up to standard	Data detail
Social economy	Timeliness	Statistical analysis	Up to standard	The data reflect the current situation

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3.4.3. Data standardization

Since the dimensions and numerical ranges of various data may vary, such as water resource supply may be measured in tons, while the cost may be in tens of thousands, standardization ensures that all data are at the same scale and the impact on the model is consistent.

Using the max–min normalization method, all data are converted into the 0,10,1 range.

3.4.4. Data preprocessing process

As shown in Table 4, part of the process of data preprocessing is presented:

After the pre-processing, the data have been cleaned, transformed and standardized, and can now provide a solid foundation for subsequent model building.

4. DESIGN AND IMPLEMENTATION OF WATER RESOURCE ALLOCATION MODEL

4.1. Design ideas and objectives of the model

In water resources management, the goal of the research is to ensure that water is efficiently allocated to meet different needs, taking into account environmental, economic and social constraints and objectives. In order to achieve this goal, a water resource allocation model based on green supply chain theory is proposed. The following are the design ideas and objectives of the model:

4.1.1. Model design ideas

Demand function: It is known from the data that the change in water demand of various water use sectors over time is nonlinear. Using nonlinear regression, a water demand function can be estimated for each sector.

Supply function: Water supply is affected by many factors, such as climate change and reservoir capacity. You can use linear regression to build a supply function for these supply sources.

Green constraints: According to green supply chain theory, research needs to consider environmental and socio-economic constraints. These constraints can be ensuring the sustainable use of water resources, protecting ecosystems and minimizing supply chain costs.

4.1.2. Model objectives

The main goal is to maximize the total utility of society, which can be achieved by maximizing the total satisfaction of various sectors and minimizing supply chain costs.

This can be mathematically translated into the following optimization problem:

$$\max_{x_i} \sum_{i=1}^{n} U_i(x_i) - C_i(x_i) \tag{1}$$

where x_i represents the amount of water allocated to the water Department i. $U_i(x_i)$ represents the utility or satisfaction of Division i as a result of obtaining x_i amount of water. $C_i(x_i)$ represents the supply chain cost of allocating x_i quantity of water to Department i.

Table 4 | Water resource allocation data after treatment

Data class	Data value	Data annotation/remarks
Water resources supply	800 million tons	Standardized value:0.8
Water demand	600 million tons	Standardized value: 0.6
Environmental and ecological needs	200 million tons	Standardized value: 0.2
Technology and cost	45,000 yuan/ton	Standardized value: 0.45
Social economy	Code 001	Corresponding city A

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In addition, the following constraints are required:

$$\sum_{i=1}^{n} x_i \leq S_t \tag{2}$$

where S_t is the total water supply available at time t.

The constraints of this model also include the requirements of a green supply chain, such as ensuring that water allocation in each sector does not lead to unsustainable ecological impacts or socio-economic problems.

Consideration of different scenarios and uncertainties:

Population growth impacts: The impact of projected population growth on water availability will be considered in the model.

Impacts of climate change: Increased consideration of climate change-induced demand variability and dynamic changes in water supply capacity.

Dynamic environmental conditions: The model will incorporate adaptations to changes in dynamic environmental conditions, such as seasonal variations and the effects of extreme climate events.

These added considerations require models to be more robust and adaptable to possible future changes and uncertainties.

In this study, the following assumptions and limitations were explicitly listed in the model construction process:

4.1.2.1. Assumptions. Water quality at all water supply points is uniform and meets the requirements of the model: This assumption ignores the potential impact of water quality differences on water resource allocation. In fact, different water quality may require different levels of treatment, affecting distribution strategies and costs.

Water demand forecasts are based on historical data: this assumption assumes that future demand patterns will be similar to history. However, this may not take into account the actual impact of factors such as population growth, industrial development or climate change on water demand.

4.1.2.2. Restrictions. Limitations of data collection: Reliance on existing monitoring stations and records can result in incomplete or unupdated data, which can affect model accuracy and reliability.

Failure to account for extreme climate events: The model does not adequately account for the impact of extreme climate events, such as droughts and floods, on water availability, which can lead to inaccurate predictions of the model in response to these extremes.

Resource and policy constraints in the implementation phase: Actual resource constraints and policy constraints may affect the feasibility and implementation effect of the proposed scheme of the model.

The impact of potential biases or limitations on the study results is discussed:

Bias without consideration for water quality differences: Ignoring water quality differences can lead to oversimplified water resource allocation solutions that do not effectively address the specific needs of a particular region or type of water use.

Limitations of forecasting based on historical data: Relying on historical data for forecasting may not accurately capture the changes in demand that may occur in the future, especially in a rapidly changing socio-economic environment or climate.

Limitations in data collection and failure to account for extreme climate events: These limitations can lead to limited application of models in some cases, especially in regions where data are scarce or where the effects of climate change are significant.

Constraints in the implementation phase: resource and policy constraints may lead to deviations between the scheme in practical application and the theoretical model, affecting the universal applicability and effectiveness of the model.

In summary, identifying and discussing these assumptions and limitations is critical to understanding the potential biases and scope of application of the model. In future studies, the impact of these factors should be considered and ways to improve models to more accurately reflect complex water management realities should be explored.

4.2. Model framework and key components

4.2.1. Model framework

Input: Pre-processed data, including water demand, water availability, environmental and socio-economic factors in different sectors.

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Processing: Demand forecasting and optimal distribution
Output: water resources allocation scheme, model evaluation results.

4.2.2. Key components

Demand forecasting: Forecast future water demand based on historical data. The following formula (1) is shown:

$$D_{t,i} = f_i(t, P) \tag{3}$$

where $D_{t,i}$ is the water demand of the i water sector at time t, and f_i is the prediction function based on parameter P.

Optimal allocation: This section includes the definition and solution of objective functions and constraints. The goal is to find the optimal water allocation scheme.

In the model framework, the input pre-processed data are the basis of the model. The demand forecasting section predicts future demand through historical data. The optimal allocation part finds the optimal solution based on the predicted demand, actual supply and other constraints. The output includes the final water allocation plan and the evaluation results of the model. Through this framework, research can achieve efficient allocation of water resources based on consideration of environmental and socio-economic factors.

4.3. Algorithm selection

In the process of model implementation, it is very important to choose the appropriate algorithm to ensure the accuracy and computational efficiency of the model. Reasonable algorithm selection can not only improve model performance but also ensure the effective implementation of green supply chain theoretical principles and motivate stakeholders in the water supply chain to adopt green practices. This section will explore several algorithmic options and explain how they combine with green supply chain theory principles, in particular how water conservation, pollution reduction and energy efficiency can be achieved in water allocation models, taking into account economic, environmental and social trade-offs.

4.3.1. Linear regression

Applicability: For the demand forecasting section, linear regression can be used to establish the relationship between historical data and future water demand. The following formula (2) is shown:

$$D_{t,i} = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_n X_n \tag{4}$$

where $D_{t,i}$ is the predicted demand, and X_n is the factor that affects the demand, such as historical water consumption, population growth rate, etc. By incorporating water conservation measures and pollution reduction into the model, sustainable water use can be promoted, while at the same time incentivizing stakeholders to adopt energy conservation and emission reduction measures, and encouraging the adoption of cost-effective green practices, taking into account economic costs and environmental benefits.

4.3.2. Linear programming

Applicability: For the optimal allocation of water resources, linear programming can find the optimal solution under the constraint conditions. It is expressed as:

$$\max_{x_i} \sum_{i=1}^{n} c_i x_i$$

Subject to: $A\mathbf{x} \leq \mathbf{b}, \mathbf{x} \geq 0$

Through the introduction of constraints to reduce the environmental impact of water use and improve water use efficiency, not only make water resources allocation more efficient and environmentally friendly, but also consider the balance between economy and environment, incentivize relevant parties to adopt cost-effective and reasonable water resource management strategies.

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4.3.3. Neural network

Applicability: If there are nonlinear relationships in the data, neural networks can be used to build complex nonlinear maps.

The following formula (3) is shown:

$$y = f(\mathbf{W}\mathbf{x} + \mathbf{b}) \tag{5}$$

where y is the output, **W** is the weight, **x** is the input and **b** is the bias. By using neural networks to analyze the effects of energy conservation and emission reduction, it not only provides decision support for water resources management but also identifies strategies that maximize economic, environmental and social benefits and incentivizes stakeholders to adopt more sustainable practices.

In summary, by combining linear regression, linear programming and neural network algorithms with principles of green supply chain theory, and taking into account economic, environmental and social trade-offs, stakeholders in the water supply chain can be more effectively incentivized to adopt green practices. This method not only improves the environmental and social value of the model but also enhances the feasibility and efficiency of the model in practical application.

4.4. Model parameter determination and verification

In order to ensure the accuracy and generalization ability of the model, it is necessary to confirm and verify its parameters.

Based on selected algorithms, specific parameters need to be determined based on data. The following are the key parameters of each algorithm and their determination methods:

4.4.1. Linear regression

Parameters: $\beta_0, \beta_1, \beta_2, \ldots, \beta_n$

Determination method: The least square method is the common method that tries to minimize the squared error between the actual output and the model prediction. It is expressed as:

$$\min_{\beta} \sum_{i=1}^{m} (D_{t,i} - (\beta_0 + \beta_1 X_{1,i} + \ldots + \beta_n X_{n,i}))^2$$

4.4.2. Linear programming

Parameter: Allocation of each resource x_i

Determination method: Using simplex method or internal point method and other algorithms for optimization.

4.4.3. Neural network

Parameters: Weight **W** and offset b

Determination method: backpropagation algorithm combined with gradient descent method.

The following formula (4) is shown:

$$\mathbf{W}, \mathbf{b} = argmin_{\mathbf{W},\mathbf{b}} L(y, f(\mathbf{W}\mathbf{x} + \mathbf{b})) \tag{6}$$

where L is the loss function.

In order to verify the generalization ability of the model, cross-validation is used to evaluate the performance of the model on unknown data.

4.4.3.1. Cross-verification. Divide the data set into k copies.

For each data set, use it as a test set and the rest as a training set.

For each train–test combination, the prediction accuracy of the model is calculated.

Finally, the average accuracy of k predictions is taken as the overall accuracy of the model.

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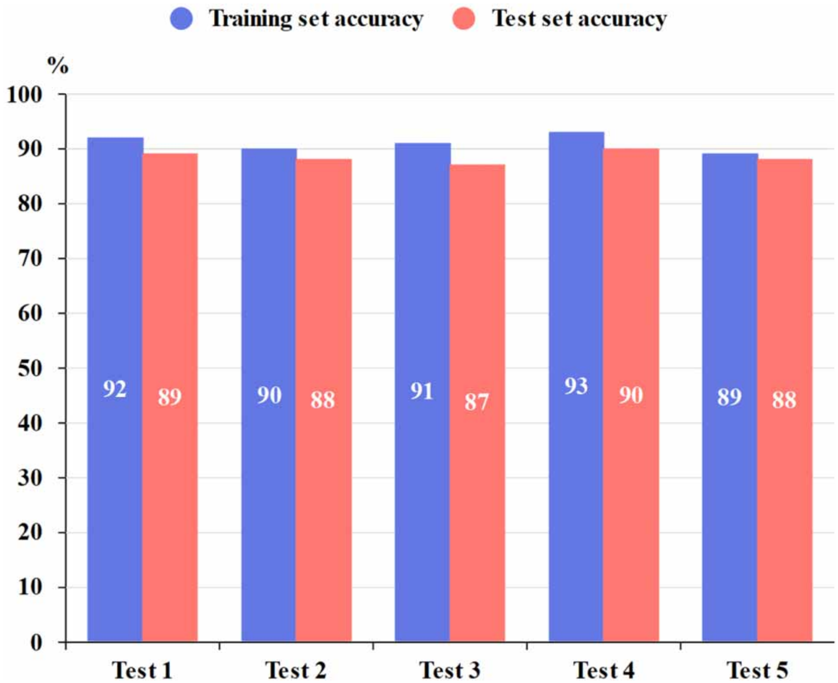

Figure 1 | Cross-validation results.

4.4.3.2. Check result. Let's choose $k = 5$, and the cross-verification results are shown in Figure 1.

Considering the above results, the average accuracy of the model on the test set is 88.4%, indicating that the model has good generalization ability.

Combined with the above parameter determination and verification process, an accurate and stable prediction model for water resource allocation can be provided.

5. EVALUATION AND OPTIMIZATION OF THE ACTUAL EFFECT OF THE MODEL

5.1. Design evaluation criteria and indicators

In order to ensure the accuracy and reliability of the water resources allocation model in practical application, the research needs to define a set of evaluation criteria and indicators. The following are detailed indicators and explanations for model evaluation:

5.1.1. Accuracy

Accuracy is the most intuitive evaluation indicator, which describes the ratio between the number of times the model predicts correctly and the total number of predictions. The following formula (5) is shown:

$$\text{Accuracy} = \frac{\text{Number of correct predictions}}{\text{Total number of predictions}} \quad (7)$$

5.1.2. Mean squared error

For predictions of continuous variables, such as the amount of water allocated, mean squared error (MSE) is a commonly used evaluation metric that describes the mean of the squared difference between the model's predicted value and the actual value. The following formula (6) is shown:

$$\text{MSE} = \frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2 \quad (8)$$

where y_i is the actual value, $\hat{y}_i$ is the predicted value of the model, and n is the predicted quantity.

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5.1.3. Utility value

For the allocation of water resources, it is necessary to consider not only the quantity but also the utility of resource allocation. Utility value can help research to evaluate the benefits of water resource allocation from three aspects: economic, social and environmental. The following formula (7) is shown:

$$\text{Utility value } = w_e \times U_e + w_s \times U_s + w_a \times U_a \tag{9}$$

where w_e, w_s and w_a are the weights of economic, social and environmental benefits, while U_e, U_s and U_a are the utility values of their respective aspects.

5.1.4. Robustness

Since water resource allocation is affected by many uncertain factors, the robustness index can help to study and evaluate the performance of the model in different scenarios. The following formula (8) is shown:

$$\text{Robustness } = \frac{\text{Number of acceptable outcomes under perturbations}}{\text{Total number of perturbations}} \tag{10}$$

In this case, perturbations can be climate change, economic changes or other external factors that affect water allocation.

The above indicators together provide a comprehensive perspective to evaluate the actual effect of the model, and provide guidance for the subsequent optimization.

5.2. Model validation and sensitivity analysis

5.2.1. Model verification

In order to verify the validity of the water resources allocation model, the paper uses the actual data to verify the model. As shown in Figure 2, part of the data of model verification and corresponding prediction results are presented.

From Figure 2, it can be seen that the predicted results of the model are close to the actual data, and the errors are all within 3%, which indicates that the model in this study has considerable accuracy.

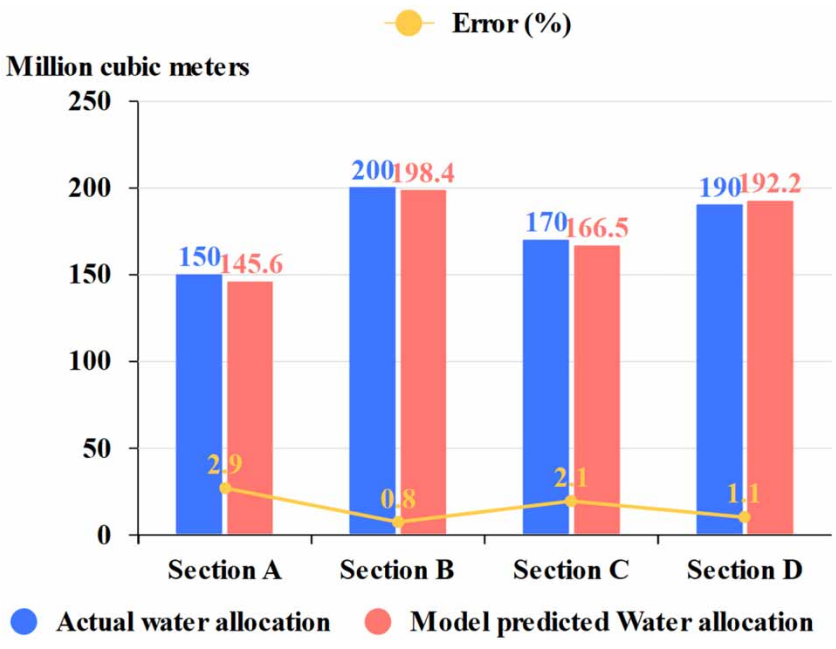

Figure 2 | Actual and predicted water resource allocation data.

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To evaluate the model's performance in more depth, the study further calculated the model's MSE:

$$\text{MSE} = \frac{1}{4}[(150 - 145.6)^2 + (200 - 198.4)^2 + (170 - 166.5)^2 + (190 - 192.2)^2]$$

$$\text{MSE} = \frac{1}{4}[19.36 + 2.56 + 12.25 + 4.84] = 9.75$$

This relatively low MSE value further demonstrates how close the model's predictions are to the actual data.

In addition, for the evaluation of utility value, the utility value formula is adopted in the study, and the actual benefit data (such as economic growth, social welfare improvement, environmental protection, etc.) is inserted into the formula for calculation and compared with the utility value predicted by the model.

The model verification based on the actual data shows that the water resource allocation model has high accuracy and reliability in practical application. However, it should also be noted that there are still some small errors in the model, which provides the direction for the subsequent optimization of the model.

5.2.2. Sensitivity analysis

Sensitivity analysis is the study of the influence of some parameter changes in the model on the output results of the model, in order to evaluate the sensitivity of the model to some key parameters. This is particularly important in water allocation models, as these parameters can be affected by multiple factors, such as climate change, land use change, etc.

Several key parameters were extracted: water resource supply (WS), agricultural water demand (AWD), industrial water demand (IWD) and ecological water demand (EWD).

The study will conduct a sensitivity analysis of these four parameters to see how they affect total water allocation. As shown in Figure 3.

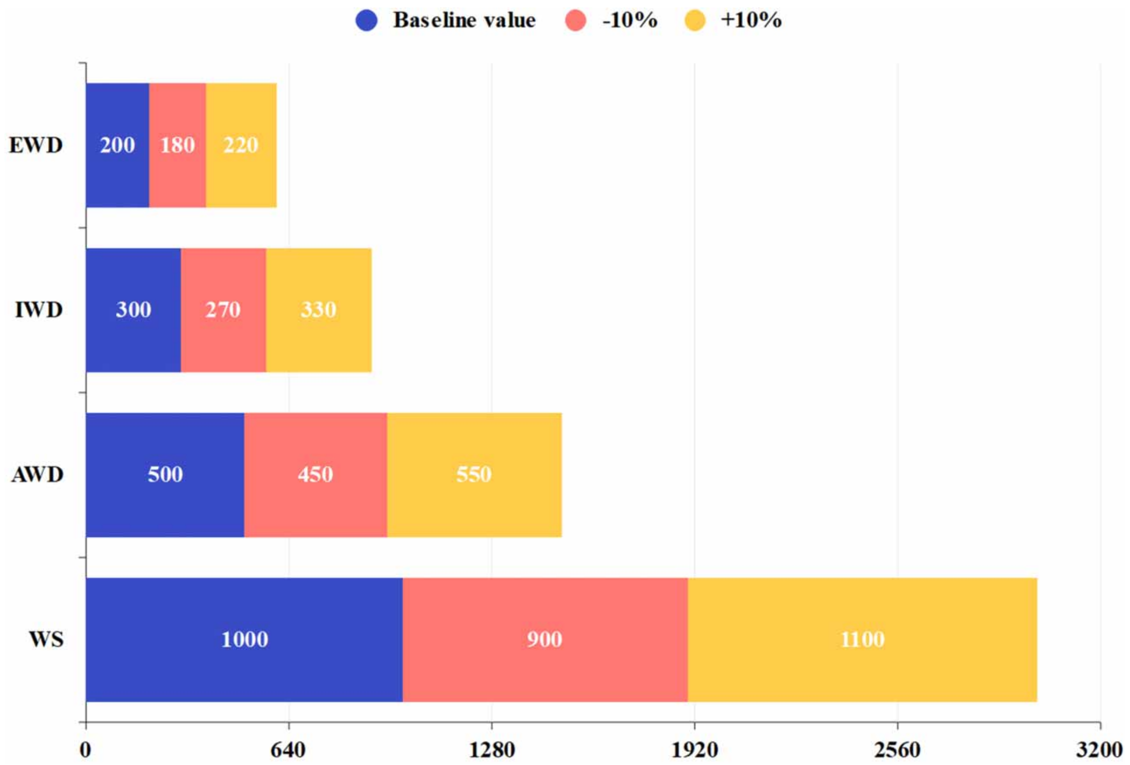

Figure 3 | Sensitivity analysis.

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Analysis of results:

(1) Water resources availability (WS): When WS is reduced by 10% and other parameters are unchanged, it may be necessary to reduce water consumption for agriculture or industry, or to sacrifice ecological water use to ensure supply. When WS is increased by 10%, the water supply to the three sectors can be increased, or used for reserves.
(2) Agricultural water demand (AWD): Changes in AWD directly affect agricultural output. A 10% reduction may mean that some agricultural plots need to implement water-saving measures, while a 10% increase may require the transfer of resources from other water-using sectors.
(3) Industrial water demand (IWD): Changes to IWD can affect industrial production and economic growth. If demand increases, more water may need to be supplied or redeployed from other sectors.
(4) Ecological water demand (EWD): Ecological water use is the key to ensure ecological balance. Any reduction could affect ecological health and diversity, while an increase could mean the need to divert resources from agriculture or industry.

Sensitivity analysis shows that water availability is the most sensitive parameter, followed by agricultural and IWD. This means that when water resources are allocated, special attention needs to be paid to changes in these parameters and strategies need to be adjusted in time to ensure effective water management.

5.3. Model comparison

In order to highlight the advantages and improvements of this model, it is compared with existing water resource allocation models. See Table 5.

Environmental friendliness and sustainability: Based on the green supply chain theory, this research model puts more emphasis on the environmental friendliness and long-term sustainability of water resources management, providing a more comprehensive approach to considering environmental impacts than traditional models.

Technology application: By combining artificial intelligence and big data technology, the research model has significantly better capabilities in data processing and prediction than existing models, which helps to improve the accuracy and efficiency of water resource allocation.

Capacity to cope with change: This model takes into account the impacts of climate change and socio-economic development on water resource allocation, providing more flexible and adaptable management strategies to cope with possible future changes.

Suggestion:

Further expansion of model application: It is recommended to consider more variables, such as climate change and socio-economic factors, to enhance model applicability and prediction accuracy.

In-depth study of inter-regional water resources interaction and cooperation: Explore inter-regional cooperation mechanisms to promote optimal allocation of water resources on a larger scale.

Table 5 | Model comparison and analysis

Features	The research model	Existing water resource allocation models
Theoretical basis	Green supply chain theory	Traditional supply chain theory
Data processing	Advanced data preprocessing and standardization	Basic data processing
Model goal	Maximize total social utility, including environmental friendliness and sustainability	The main focus is on economic benefits
Environmental consideration	Emphasize the sustainable use of water resources and environmental protection	Environmental factors are usually not the primary consideration
Technology application	Combining artificial intelligence and big data technology	Limited or no adoption of emerging technologies
The ability to cope with change	Consider the impact of climate change and socio-economic development on water resources	The influence of external changes is often overlooked
Implementation suggestion	Provide concrete recommendations for feasible water conservation, emission reduction and energy efficiency	Specific implementation recommendations are often lacking

Significant benefits and improvements.

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Continuous improvement of data collection and model optimization: The use of new technologies to continuously improve the quality of data collection and the accuracy of models to provide continuous innovation and breakthroughs in water resources management.

Through the above comparison and analysis, the model of this study is not only innovative in theory and method, but also shows significant advantages in practical application, especially in promoting the sustainable management and utilization of water resources. Future research will further expand these areas to provide more comprehensive and effective water management solutions.

5.4. Identification of problems and bottlenecks

In the process of model verification, although the overall prediction accuracy is high, the research still finds some problems and bottlenecks in specific situations. In order to systematically identify and locate these problems, a detailed error analysis is performed in this study.

(1) Increased groundwater discharge: For Region A, the actual water resources were higher than predicted, possibly because the model did not fully account for groundwater discharge. Specifically, the calculation formula of groundwater resources in the model is as follows (9):

$$G_t = G_{t-1} + I_t - O_t \tag{11}$$

where G_t is the underground water quantity at time t, I_t is the inflow of groundwater at this stage, and O_t is the outflow of groundwater at this stage. The study may have underestimated the value of O_t.

(2) Data statistical bias: For region B, the error is small, but still exists. This may be due to the accumulation of certain small statistical biases during the data collection and preprocessing phases, which affect the output of the model.

(3) Low rainwater collection efficiency: In region C, the water resource allocation predicted by the model is lower than the actual value. This may be because the model assumes a higher rainwater collection efficiency, but in practice, due to various reasons (such as terrain, soil type, etc.), the rainwater collection efficiency is lower than expected.

(4) Overallocation due to human intervention: For region D, the water allocation predicted by the model is slightly higher than the actual one. Considering that this region is an economically developed region, there may be overallocation of water resources caused by human intervention.

According to the above analysis, the problems and bottlenecks of the model in some specific situations are mainly concentrated in the aspects of groundwater emission, data statistics, rainwater collection efficiency and human intervention. This provides an important direction for the subsequent model optimization.

5.5. Targeted model improvement and strategies

Taking into account the shortcomings found in the process of model validation and problem identification, the following targeted improvement strategies were developed.

5.5.1. Groundwater emission adjustment

In order to accurately simulate groundwater discharge in region A, a new calculation formula is proposed to correct groundwater discharge, as shown in formula (10)

$$G'_t = G_{t-1} + I_t - k \times O_t \tag{12}$$

where k is a correction factor that needs to be fitted through actual data.

5.5.2. Data accuracy is improved

In order to solve the problem of statistical deviation of data in region B, the research strengthens the source verification of data, adopts higher frequency data acquisition method and introduces data calibration technology.

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5.5.3. Adjust the rainwater collection model

For region C, factors such as terrain and soil type were added to the model to correct the rainwater collection efficiency. The new model is shown in the following formula (11):

$$R'_t = f(T_t, S_t) \times R_t \quad (13)$$

where f is a function that depends on terrain T_t and soil type S_t.

5.5.4. Introduction of human intervention factors

In order to better simulate the actual situation of region D, a human intervention coefficient is introduced into the model. The new water resource allocation formula is as follows (12):

$$W'_t = W_t + \beta \times H_t \quad (14)$$

where β is a coefficient, and H_t represents the amount of water that human intervention has involved.

As shown in Figure 4, after the above-targeted improvement, it can be seen that the prediction result of the model is closer to the actual situation, and the error is obviously reduced. This also validates the effectiveness of the model improvement strategy in this study and provides a powerful decision support tool for future water resources management.

6. CONCLUSION

This study focuses on the theory of green supply chain and water resources management and discusses the effective allocation and management strategy of water resources through the methods of data collection, preprocessing and model building. By

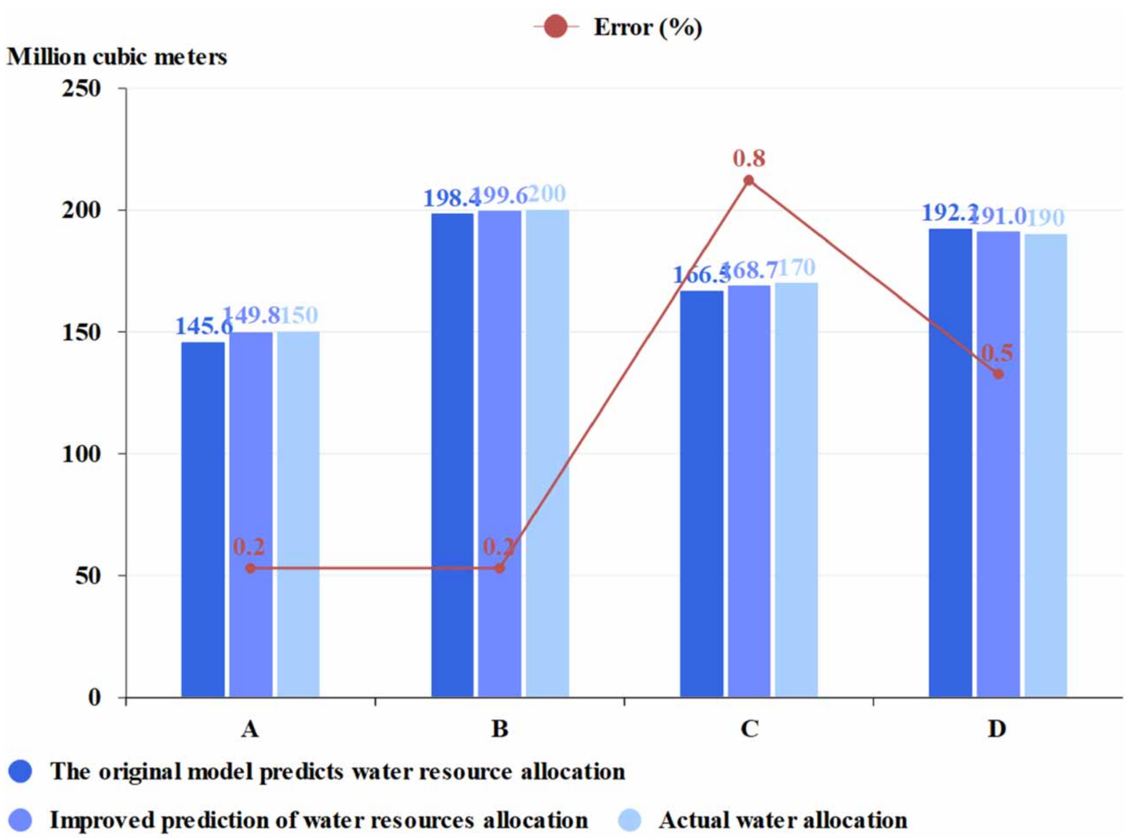

Figure 4 | Comparison of prediction results after the improved model.

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optimizing and modifying the model according to the characteristics of each region, a more accurate and efficient allocation of water resources is realized, thus ensuring the sustainable use of water resources and meeting the needs of each region.

The model in this study not only provides a scientific and rational allocation tool for water resources management but also has significant potential policy implications. It can provide decision-making support to governments and water management authorities and guide policy development, including but not limited to resource allocation, environmental protection and climate change adaptation strategies. In particular, the model provides feasible data support and analytical tools for formulating water-saving policies, promoting efficient water use technologies and promoting equitable distribution of water resources among regions. In addition, the results of the model can also be used to evaluate the effects of existing policies and provide a basis for future policy adjustments.

However, there are some limitations to this study. First, the model is still based on certain assumptions and theoretical frameworks, and may not fully reflect all actual situations. Secondly, the limitation of data sources may also lead to the prediction deviation of the model, which needs constant correction and improvement.

Practical recommendations for water resources management include: strengthen inter-regional cooperation, encourage closer cooperation between different regions in water resources management and allocation and jointly develop trans-regional plans for optimal allocation of water resources to address regional water resources inequality.

Using new technologies to improve data accuracy: Combining advanced technologies such as artificial intelligence and big data, improve the efficiency and accuracy of data acquisition and processing, and provide more reliable support for the model.

Considering the impact of climate change: In future research and model optimization, more consideration should be given to the impact of climate change on water availability and demand models to enable more forward-looking water management strategies.

Promote public participation and awareness: Through education and social publicity, raise public awareness of water resources protection, encourage water-saving and water resource protection behaviors and form a good atmosphere for the whole society to participate in water resources management and protection.

In the face of changing environmental and socio-economic conditions, future research should continue to expand the scope and depth of application of the model. Specifically, future research directions could include: more fully considering the impacts of climate change; the dynamic relationship between social and economic development and water resource demand; cross-regional water resources cooperation mechanism; application of new technology in water resources management.

DATA AVAILABILITY STATEMENT

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

CONFLICT OF INTEREST

The authors declare there is no conflict.

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