

Original Research

Research on the Application of Water Resources Optimal Allocation Model Based on Fuzzy Optimization Theory

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Abstract

The government has always emphasized the decisive role of market mechanisms in resource allocation, but this is the least obvious in the water resources market. To achieve the goal of promoting the improvement of water supply structure and water using structure and thus improving water resources efficiency, it is necessary to consider both the efficiency of the same water source among different users and the cost of water supply between different water sources for the same user. Through creative use of fuzzy optimization theory to solve the constructed Bi-level programming model, this paper takes the data of Qingdao from 2011 to 2020 as an example to conduct empirical analysis, and obtain the allocation of water resources of different water sources and different users under market competition conditions. At the same time, four scenarios such as changes in water resource fees, changes in sewage treatment fees, full-cost pricing, and agricultural water saving are set for scenario analysis and numerical simulation, and the total cost and water price under different scenarios are obtained. It is conducive to promoting the sustainable development of water resources in Qingdao, and provides a reference for the formulation of relevant policies on water resources in the future.

Keywords: multiple water sources and multiple users, optimal allocation, fuzzy optimization theory, Bi-level programming model, scenario simulation

Introduction

Water is the foundation and lifeblood of social and economic development and healthy ecosystem [1]. As a basic, guiding and controlling element of social and economic development, water resources are becoming

more and more important [2]. At present, China is the country with the largest amount of water consumption in the world, but its freshwater resources are extremely poor and cannot adapt to economic and social development [3]. Specifically, there are dilemmas such as large numbers of people and small numbers, uneven temporal and spatial distribution, and mismatch with productivity layout [4]. Studies have found that China's water shortage is largely caused by human factors such as waste, pollution and ecosystem degradation [5].

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In order to guide China's water resources in the present and the future work for a long time, the state promulgated a series of guiding documents, and pointed out that should be conducted in accordance with the law within the administrative area on annual water consumption quantity management, formulating water consumption plans, setting up water allocation plans, and realizing total water consumption control, allocating water resources reasonably and effectively to promote sustainable social and economic development [6]. Eventually, the water management idea of "water saving priority, spatial allocation balance, systematic governance, and two-handed effort" will be realized [7].

Qingdao is extremely deficient in fresh water resources, and its per capita water resources are less than 15% of the national average. It is one of the severely water-scarce cities in China. Urban water consumption continues to increase with the growth of urban population, industrial production development and the expansion of urban scale, and the resulting sewage discharge also shows an increasing trend. The water resources that can be further developed and utilized in Qingdao are limited, and the existing sewage treatment capacity cannot fully match its sewage discharge volume, which not only makes the sewage impossible to be completely reused, but also pollutes precious water resources, which ultimately leads to the increasing contradiction between water supply and demand. Water shortage will be a long-term dilemma faced by Qingdao. Considering the residents' living standards, socio-economic status and the particularity of the geographical location in Qingdao City, for surface water, groundwater, south-to-north water diversion, diversion from the Yellow River to Qinghai, middle water reuse and seawater desalination, there are still certainty conclusion that which one is more reasonable and more in line with the demanders' affordability and future changes in water demand [8].

To improve its comprehensive utilization efficiency and make decisions about the rational allocation of water resources, so as to maximize the social, economic and ecological benefits of water resources utilization, this paper comprehensively considering the dynamic mobility and independence of different water supply sources and the levels and urgency of different water demand users for different water sources, balances the relationship between short-term development and long-term development, and fully guarantees the rational development and use of water resources.

The research on optimal allocation of water resources was carried out earlier in European and American countries. In the 1940s, Masse first proposed the concept of optimization to solve the problem of reservoir operation. In the 1960s, Hall et al. established a dynamic programming model for reservoir management, and a water resources optimization model involving irrigation and power generation was explored [9]. Since 1970s, mathematical programming model and simulation technology have been widely used

in optimal allocation of water resources [910]. The optimization goal to maximize economic benefits is the main research direction in this period [11]. In the 1980s, the theory of optimal allocation of water resources was further developed, and many scholars put forward various ideas [12]. This theory began to appear many branches, the theoretical content was more abundant [13]. Since the 1990s, global environmental degradation and water pollution have become increasingly serious, and the previous research results aimed at economic benefits can no longer meet the needs of society [14]. Therefore, the environmental benefits, social benefits, water quality constraints and sustainable utilization of water resources began to receive attention [15]. Since the 21st century, the optimal allocation of water resources has been combined with the ecological environment, resulting in a large number of research achievements [16]. It mainly focuses on the classification of optimization targets, the construction of optimization models and the exploration of optimization algorithms [17]. These theories were applied to different rivers for empirical analysis, which can enlighten the optimal allocation of water resources in other basins [18]. Meanwhile, it was the commodity and scarcity properties of water resources that result in government institution failure in allocating water resources [19].

WU and WANG built a multi-user, multi-water source optimization model and effectively analyzed the water resources situation of Zaozhuang city [20]. Abolpoura et al. studied the adaptive neural fuzzy reinforcement learning method to analyze the optimal configuration of the drainage system in Iran [21]. MA and LIN studied a multi-objective and multi-stage optimal allocation model to optimize the allocation of Shiyang River basin [22]. According to the characteristics of water resources, Lv et al. studied the Bi-level programming model to solve the problem of water resources allocation [23]. Based on the characteristics of multiple utilization and multiple transformation of inland rivers, SHI et al. constructed a water resources transformation model containing computing units at different levels to realize the unified allocation of water resources in administrative regions and basins [24]. Wu developed a nonlinear multi-objective optimization model to achieve optimal allocation of regional water resources [25]. Dunia et al. proposed an integer linear programming decision support model for optimal allocation to minimize the total water cost [26]. Chu et al. used the concept of water satisfaction to measure the single decision-making goal of water resources in order to maximize the benefits of the whole basin [27]. Riina studied an integrated approach that incorporates agricultural models, urban water models and hydrological constraints to balance the amount of water available for agricultural and municipal supplies [28]. Li et al. constructed a multi-dimensional equilibrium allocation model to realize the orderly and benign evolution of the complex system of water resources, economy, society and ecological

environment in Tarim River Basin [29]. Zhang et al. studied WACM4.0 distributed hydrological model to maximize social and economic water use benefits [30]. Based on the three-stage water resources optimization model, TAN and JIANG obtained the value of revenue distribution of the optimal fuzzy alliance [31]. Omolola et al. studied multi-objective sustainable land use allocation models to explore the optimal optimization scheme among introducing multiple objectives [32].

To sum up, great breakthroughs and progress have been made both in theory and in practice in the research on optimal allocation of water resources at home and abroad. However, there are two main shortcomings: (1) Insufficient attention has been paid to the internal relevance of the sustainable development of water resources. The previous literature focused more on the promotion of water resources to the social economy in terms of the optimal allocation of water resources, while ignoring the mutuality and restriction of endogenous Ness between the two. At the same time, it ignores the premise that water resources must always be unified with the sound development of the ecological environment in the process of utilization, development, and reuse. Even if the allocation of water resources reflects the development of regional economy, society and ecological environment, it is mostly in the theoretical stage of concept construction and model design. (2) The optimal decision-making model in the traditional scheme cannot fully realize the need for optimal allocation of water resources. The optimal allocation of water resources is systematic engineering. Its ultimate goal is to combine a number of single goals with fuzzy definitions, compatibility and mutual exclusion. The traditional solution method is to reduce the dimensions of multiple goals, and finally get a single goal. Instead of a set of solutions, decision makers have no alternatives. This is inconsistent with the complex allocation of water resources in reality. Therefore, driven by the demand of green economy, it is necessary to scientifically improve the comprehensive management level of water resources, comprehensively measure the economy, ecology and society, and solve the reasonable consumption of water resources [33].

Material and Methods

Bi-Level Programming Model

The Bi-level programming model studies the non-cooperative and orderly interaction between the upper-level decision makers and the lower-level decision makers with their own objective functions. The upper level gives priority to making decisions, the lower level responds according to their own interests under the upper-level decision information, and the upper-level decision makers must make the final decision in line with their own interests based on the lower level response [34]. Bi-level programming can better

reflect the hierarchical relationship between the upper and lower levels of mutual influence and restriction. The upper and lower levels influence each other, but neither party can completely control the other party. The Bi-level programming model also has many application examples in terms of military deployment, national macro-finance, facility positioning, etc., which has high theoretical and practical significance [35].

Generally speaking, the mathematical model of Bi-level programming is expressed as follows:

$$\begin{cases} \text{Min}F_1(x, y) \\ \text{st.}G(x, y) \leq 0 \\ \text{Min}F_2(x, y) \\ \text{st.}g(x, y) \leq 0 \\ x = (x_1, x_2, \dots, x_n)^T \in X \in R^n \\ y = (y_1, y_2, \dots, y_m)^T \in Y \in R^m \end{cases} \quad (1)$$

Where,

$$F, f : X \times Y \rightarrow R^1; G : R^n \times R^m \rightarrow R^s; g : R^n \times R^m \rightarrow R^t$$

All functions are assumed to be Bi-level continuous differentiable unless otherwise specified. In this model, decision makers at the upper and lower levels all take minimization of the objective function value as their goal. Optimal allocation of water resources is a multi-objective decision-making problem that requires consideration of social, economic and environmental factors. From different decision-making perspectives, Bi-level programming is introduced into the optimal allocation of water resources, and a Bi-level programming model for the optimal allocation of water resources is established.

Solving Bi-level Programming Model Based on Fuzzy Optimization Theory

With the deepening of theoretical research, some scholars creatively put forward a Bi-level programming model solution method based on fuzzy optimization theory on the basis of relevant fuzzy optimization theory. The Bi-level programming method is more suitable for solving the hierarchical problems in the planning and management of water resources systems, the Fuzzy theory has greater advantages in dealing with the uncertainties of complex water systems [36-38].

$F_1(x, y)$ and $F_2(x, y)$ are the objective functions of the upper and lower levels respectively; $G(x, y)$ and $g(x, y)$ are the objective function constraints of the upper and lower levels, respectively. The Bi-level programming model method of fuzzy optimization theory is as follows:

(1) Solve the upper and lower objective functions separately, and obtain the optimal solutions $[x^u, F_1]$ and $[x^l, F_2]$ respectively. Due to the different objective functions of the upper and lower levels, the optimal solutions obtained are often inconsistent.

It is unreasonable to use the upper-level optimal solution x^U as the lower-level variable. We can give the lower-level variable a flexible range (e_{min}, e_{max}) to ensure that the optimal solution falls within this range. Among them, $(x^U - e_{min})$ and $(x^U + e_{max})$ are the worst solutions, and the solutions are invalid if they exceed the tolerance range. Referring to related research, the upper and lower elastic range can be the same range, generally 30% of the optimal solution, and the relative membership function of the decision variable x is as follows:

$$\mu(x) = \begin{cases} 1 & x = x^U \\ 1 - (x - (x^U - e_{min})) \cdot e_{min}^{-1} & (x^U - e_{min}) \leq x < x^U \\ 1 - (x + (x^U + e_{max}) - x) \cdot e_{max}^{-1} & x^U < x \leq (x^U + e_{max}) \\ 0 & other \end{cases} \tag{2}$$

(2) To achieve the goals of the upper and lower levels at the same time and meet the final requirements of the Bi-level optimization, the upper and lower levels need to communicate and feedback with each other during the solution process. First, the lower-level problem can be solved separately, and then its optimal solution x^L can be substituted into the upper-level objective function, and the optimal solution F'_1 of the upper-level model can be further obtained. In the same way, substituting the upper layer to solve the optimal solution x^U into the lower layer to solve F'_2 . F'_1 and F'_2 corresponding to these two values and the optimal solution are used as the extreme values of the upper and lower objective functions. For any solution, firstly, the objective i function value $F_i(x)$ of the solution can be normalized according to $[F'_1, F'_1]$ and $[F'_2, F'_2]$ to obtain the upper and lower membership degrees $R_i(x)$. Because the objective function is as small as possible, according to the relative fuzzy optimization theory:

$$R_i(x) = \frac{(F'_i - F_i(x))}{F'_i - F_i} \tag{3}$$

$i = 1, 2$, respectively representing the goal of upper and lower. In order to comprehensively consider the overall degree of achievement of the two goals, the FOBP model method further introduces the concept of overall superiority $\mu_T(x)$. Compared with the concept of overall satisfaction adopted by Yong et al., this concept has more practical theoretical significance, that is, the relative membership of the overall goal corresponding to the plan or solution is excellent level [39]. According to the relative fuzzy optimization theory:

$$\mu_T(x) = \left(1 + \left(\frac{\sum_{i=1}^m (w_i (R_i(x) - 1)^{2/p})}{\sum_{i=1}^m (w_i R_i(x))^p} \right)^p \right)^{-1} \tag{4}$$

In the formula, p is the distance parameter, $p = 1$ or 2 ; w_i presents the weight of the i_{th} goal. Multi-objective problems need to consider the importance of different objectives. The introduction of target weights can better improve the handling of this type of Bi-level programming problem.

(3) Taking the maximum degree of superiority ϕ as a variable, the upper and lower objective functions are optimized at the same time, and the following single-objective optimization problem is established:

$$\begin{cases} Max \phi \\ st. \mu(x) \geq 0 \\ R_i(x) \geq 0 \quad (i = 1, 2) \\ \mu_T \geq 0 \\ G(x) \leq 0 \end{cases} \tag{5}$$

Solve the above model to obtain the optimal solution of the Bi-level programming problem.

Construction of Planning Model for Optimal Allocation of Water Resources

Before using the Bi-level programming model to establish a model for the optimal allocation of water resources, the actual water resources situation should be abstracted and conceptualized. First, the regional water resources users and water supply sources are specifically classified. Assume that water supply sources are classified into Type I , and water users are classified into Type J .

Objective Function

The purpose of the optimal allocation of regional water resources is to achieve the overall coordinated and sustainable development of the economy, society, and environment of the entire region. Therefore, the optimal allocation model of regional water resources generally considers cost objectives, economic benefits objectives, social objectives and ecological objectives.

(1) Cost objective function. The cost objective function is to minimize the total supply cost of the total area, namely:

$$\min f_1(x) = \sum_{i=1}^I \sum_{j=1}^J c_{ij} \cdot q_{ij} \tag{6}$$

Among them, q_{ij} represents the water supply amount of water source i to user j , and c_{ij} represents the unit water supply cost coefficient of water source i to user j .

(2) Economic objective function. The economic objective function is to maximize the economic benefits generated by the total regional water supply, namely:

$$\max f_2(x) = \sum_{i=1}^I \sum_{j=1}^J b_{ij} \cdot q_{ij} \tag{7}$$

Among them, b_{ij} represents the benefit coefficient of unit water supply from water source i to user j .

(3) Ecological objective function. The ecological objective function is to maximize the satisfaction of regional ecological water demand, namely:

$$\min f_3(x) = D_s - \sum_{i=1}^I q_{is} \tag{8}$$

Among them, D is the ecological water demand of the district.

(4) Social objective function. The social objective function is to minimize the total regional water shortage, namely:

$$\min f_4(x) = \sum_{i=1}^I \sum_{j=1}^J \left(D_j - \sum_{i=1}^I q_{ij} \right) \tag{9}$$

Among them, D_j is the total water demand of user j .

Constraints

(1) Water quantity restriction conditions. The total amount of water supplied by the water source i to all users cannot be higher than the capacity of the water source, namely: $\sum q_{ij} \leq Q_i$.

User j intake from each water source must meet the minimum guarantee requirements and at the same time be lower than the maximum water demand, namely: $D_{j \min} \leq \sum_{i=1}^I q_{ij} \leq D_{j \max}$.

The amount of water drawn by the user from each water source is a non-negative value, namely the inequality satisfying the quantity of water intake is: $Q_{ij} \geq 0$.

(2) Constraints on price affordability. The water withdrawal price (weighted average price) of different users must be lower than their affordable price p_j and higher than the current price p_j , namely: $p_{j \min} \leq p_j \leq p_{j \max}$, which, $p_j = \sum_{i=1}^I (P_{ij} \cdot q_{ij}) / \sum_{i=1}^I q_{ij}$. Similarly, the water supply prices (weighted average prices) of different water sources must be lower than their affordable prices P_i and higher than the current prices P_i , namely: $\bar{p}_i \leq \bar{p}_i \leq \bar{p}_i$, which, $\bar{p}_i = \sum_{j=1}^J (p_{ij} \cdot q_{ij}) \cdot (\sum_{j=1}^J q_{ij})^{-1}$.

(3) Constraints on price difference. As far as the water company is concerned, the cost of water supply is the same regardless of whether the water is used by residents, non-residential water, commercial water or special industry water. As a corporate behavior, the price of tap water sold should also be consistent. However, in the current water price system of tap water, the price of tap water set by the government is different. The difference between various water prices is actually an economic measure adopted by the government to regulate the effective allocation of water resources. Therefore, in the Bi-level programming model of the optimal allocation of water resources, the price difference constraint should be added. It includes not

only the price comparison constraints of different water sources, but also the price comparison constraints of different water users.

Results and Discussion

The water supply sources in Qingdao are divided into 6 types of water sources: surface water, groundwater, water diversion from the Yellow River to Qinghai, South-to-North Water Diversion, reclaimed water reuse, and seawater desalination. Water resources users are divided into 4 types of residents, non-residents, agriculture and special industries.

Objective Function Determination

Based on the overall goal of minimizing the total cost of water withdrawal by the upper users and the minimum cost of the lower water supply system, a Bi-level programming model under the conditions of multi-water sources and multi-users in Qingdao is established.

(1) Upper objective function. The total cost of water withdrawal by users = water withdrawal price \times water demand. Combining the specific situation of Qingdao's water supply and water intake classification, the user's objective function is:

$$\begin{aligned} MinG &= \sum_{i=1}^I \sum_{j=1}^J (p_{ij} \times q_{ij}) \\ &= \begin{pmatrix} P_{11} & P_{12} & P_{13} & P_{14} \\ P_{21} & P_{22} & P_{23} & P_{24} \\ P_{31} & P_{32} & P_{33} & P_{34} \\ P_{41} & P_{42} & P_{43} & P_{44} \\ P_{51} & P_{52} & P_{53} & P_{54} \\ P_{61} & P_{62} & P_{63} & P_{64} \end{pmatrix} \begin{pmatrix} q_{11} & q_{21} & q_{31} & q_{41} & q_{51} & q_{61} \\ q_{12} & q_{22} & q_{32} & q_{42} & q_{52} & q_{62} \\ q_{13} & q_{23} & q_{33} & q_{43} & q_{53} & q_{63} \\ q_{14} & q_{24} & q_{34} & q_{44} & q_{54} & q_{64} \end{pmatrix} = P \cdot Q^T \end{aligned} \tag{10}$$

(2) Lower objective function. The total cost of water supply in the water supply department is the smallest. Combined with the specific situation of Qingdao's water supply and water intake classification, the objective function of the water supply company is:

$$\begin{aligned} MinM &= C \\ &= \sum_{i=1}^I \sum_{j=1}^J (c_{ij} \times q_{ij}) \\ &= \sum_{i=1}^6 \sum_{j=1}^4 (c_{ij} \times q_{ij}) \\ &= \begin{pmatrix} c_{11} & c_{12} & c_{13} & c_{14} \\ c_{21} & c_{22} & c_{23} & c_{24} \\ c_{31} & c_{32} & c_{33} & c_{34} \\ c_{41} & c_{42} & c_{43} & c_{44} \\ c_{51} & c_{52} & c_{53} & c_{54} \\ c_{61} & c_{62} & c_{63} & c_{64} \end{pmatrix} \begin{pmatrix} q_{11} & q_{21} & q_{31} & q_{41} & q_{51} & q_{61} \\ q_{12} & q_{22} & q_{32} & q_{42} & q_{52} & q_{62} \\ q_{13} & q_{23} & q_{33} & q_{43} & q_{53} & q_{63} \\ q_{14} & q_{24} & q_{34} & q_{44} & q_{54} & q_{64} \end{pmatrix} = C \cdot Q^T \end{aligned} \tag{11}$$

Parameter Assignment

(1) Water volume constraint parameters. According to the 2011-2020 “Qingdao Statistical Yearbook”, “Qingdao Water Resources Bulletin” and “Thirteenth Five-Year Plan for the Construction and Allocation of Water Sources in Qingdao”, the water supply volume and water demand of Qingdao’s water supply sources are obtained. Combining the research content and using the time series measurement model, we can accurately predict the water supply volume of various water sources and the water demand of various users in Qingdao in 2021. The statistical of water supply volume of each water supply source S_{ij} are shown as follow:

$$S_{ij} = \begin{bmatrix} 4.40 & 3.67 & 0.15 & 1.46 & 0.37 & 0.03 & 10.08 \\ 3.61 & 3.38 & 0.78 & 1.63 & 0.38 & 0.04 & 9.81 \\ 3.74 & 3.45 & 0.90 & 2.08 & 0.39 & 0.03 & 10.59 \\ 3.59 & 3.88 & 0.66 & 2.08 & 0.47 & 0.02 & 10.70 \\ 2.11 & 2.40 & 0.40 & 3.21 & 0.58 & 0.06 & 8.76 \\ 1.75 & 2.19 & 0.28 & 4.44 & 0.57 & 0.09 & 9.32 \\ 1.59 & 2.45 & 0.64 & 3.82 & 0.72 & 0.22 & 9.44 \\ 2.21 & 2.41 & 0.56 & 3.47 & 0.43 & 0.25 & 9.33 \\ 1.79 & 2.22 & 0.56 & 4.02 & 0.29 & 0.26 & 9.18 \\ 2.08 & 2.15 & 0.79 & 4.03 & 0.63 & 0.37 & 10.05 \\ 1.38 & 1.82 & 0.83 & 3.72 & 0.90 & 0.64 & 9.29 \end{bmatrix}$$

Where, i is the line identifier, representing the time. The first line to the 11th line respectively represent the year 2011 to 2021. And j is the column identifier, representing water supply source, Columns 1 to 7 represent Surface water, Ground water, Diverting Yellow River into Qingdao, South-to-North water Diversion, Water reuse, Sea water desalination and Total. All of these statistics are in units of 100 million meters cubed.

According to the basic situation of water demand users in Qingdao, the water demand of Qingdao is counted to determine the total amount of water diversion works of the Yellow River Diversion Project into Qingdao. The Water demand statistics of each user D_{ij} are shown as follow:

$$D_{ij} = \begin{bmatrix} 2.87 & 1.91 & 3.81 & 1.50 & 10.08 \\ 2.92 & 1.82 & 3.69 & 1.38 & 9.81 \\ 2.97 & 1.97 & 3.98 & 1.67 & 10.59 \\ 2.80 & 2.03 & 4.17 & 1.69 & 10.70 \\ 2.73 & 1.98 & 2.43 & 1.62 & 8.76 \\ 3.11 & 2.01 & 2.45 & 1.75 & 9.32 \\ 3.16 & 2.14 & 2.26 & 1.88 & 9.44 \\ 3.22 & 2.13 & 2.34 & 1.64 & 9.33 \\ 3.32 & 1.91 & 2.17 & 1.79 & 9.18 \\ 3.46 & 2.06 & 2.54 & 2.01 & 10.05 \\ 3.39 & 2.14 & 2.04 & 1.72 & 9.29 \end{bmatrix}$$

Where, j is the column identifier, representing water user, Columns 1 to 5 represent Resident life, Non-residents, Agriculture, Special industries and Total. Everything else is exactly the same as S_{ij} .

It can be seen from S_{ij} and D_{ij} that the total water supply and water demand of Qingdao in 2021 are both 929 m³. According to the total water demand of each water user and the total water supply of each water

source and the actual situation, the following constraints are set:

Condition I:

$$q_{11} + q_{12} + q_{13} + q_{14} \leq 144.6575$$

$$q_{21} + q_{22} + q_{23} + q_{24} \leq 77.726$$

$$q_{31} + q_{32} + q_{33} + q_{34} \leq 35.6164$$

$$q_{41} + q_{42} + q_{43} + q_{44} \leq 95.1781$$

$$q_{51} + q_{52} + q_{53} + q_{54} \leq 16.9315$$

$$q_{61} + q_{62} + q_{63} + q_{64} \leq 27.2$$

$$q_{11} + q_{21} + q_{31} + q_{41} + q_{51} + q_{61} \geq 123.8356$$

$$q_{12} + q_{22} + q_{32} + q_{42} + q_{52} + q_{62} \geq 66.0274$$

$$q_{13} + q_{23} + q_{33} + q_{43} + q_{53} + q_{63} \geq 134.2466$$

$$q_{14} + q_{24} + q_{34} + q_{44} + q_{54} + q_{64} \geq 73.4247$$

Condition II:

Among all the six water supply sources, surface water, groundwater, water from the Yellow River to Qinghai and South-to-North Water Diversion can be used in all water industries (residents, non-residents, agriculture and special industries, etc.). The water source for reclaimed water can only be used for non-residential, agricultural and special industries, and cannot be used for domestic water; desalination water can only be used for non-residential water, not for residents, agriculture and special industries. Namely: $q_{51} = 0, q_{63} = 0, q_{64} = 0$, The rest of the $q_{ij} \geq 0$.

(2) Constraint parameters of price tolerance. Price ceiling: according to the statistical data of the National Bureau of Statistics of China, the per capita disposable income, industrial output value, agricultural net income and special industry output value of urban residents in Qingdao are predicted. The upper limit of water prices for water and special industries. The price ceilings for each user in Qingdao in 2021 are: residential water 24.96 yuan/m³; non-residential water 12.28 yuan/m³; agricultural water 20 yuan/m³; special industry water 61.68 yuan/m³.

Namely, price constraints:

$$3.5 \leq \left(\sum_{i=1}^6 p_{i1} \cdot q_{i1} \times \left(\sum_{i=1}^6 q_{i1} \right)^{-1} \right) \leq 24.96$$

$$5.25 \leq \left(\sum_{i=1}^6 p_{i2} \cdot q_{i2} \times \left(\sum_{i=1}^6 q_{i2} \right)^{-1} \right) \leq 12.28$$

$$0.012 \leq \left(\sum_{i=1}^6 p_{i3} \cdot q_{i3} \times \left(\sum_{i=1}^6 q_{i3} \right)^{-1} \right) \leq 20$$

$$17.25 \leq \left(\sum_{i=1}^6 p_{i4} \cdot q_{i4} \times \left(\sum_{i=1}^6 q_{i4} \right)^{-1} \right) \leq 61.68$$

(3) Price difference constraint. Based on the aforementioned analysis results, combined with relevant research, the scope of restrictions on the water price

difference in Qingdao in 2021 is as follows. The ratio of non-residential water price to agricultural water price is 11:1, namely:

$$\underline{p}_2 / \underline{p}_3 = 11;$$

The ratio of the price of residential water, non-residential water and special water is 1:1.5:4, namely:

$$\underline{p}_1 / \underline{p}_2 = 2/3, \underline{p}_1 / \underline{p}_4 = 1/4;$$

Groundwater and surface water multiples: 3 for residents, 2.8 for non-residents, 4.5 for special industries, namely:

$$p_{21} / p_{11} = 3, p_{22} / p_{21} = 2.8, p_{24} / p_{14} = 4.5;$$

The ratio of reclaimed water to residential water: 1:2.5; the median value is 3.5, namely: $\overline{p}_5 / \underline{p}_1 = 3.5$.

Calculation Results

Combining the objective function and constraint conditions of the above-mentioned Bi-level programming model for the optimal allocation of water resources, the allocation of water for each user of each water source in Qingdao in 2021 is shown in Table 1.

Scenario Analysis and Numerical Simulation

The above-mentioned water resources allocation is the basic situation. On this basis, the water resources allocation, cost, water price, etc. of Qingdao City in 2021 are simulated by setting different scenarios such as water resources fee changes.

(1) Scene setting. Scenario I: Changes in water resources fees. The water resources fee for different water sources in Qingdao is increased to 30% of the terminal price of the water supply, and other conditions remain unchanged. Scenario II: Changes in sewage treatment fees. When the sewage treatment fee increases to 50% of the water supply terminal price, residents will increase

from 1.00 yuan/m³ to 1.75 yuan/m³, non-residents will increase from 1.25 yuan/m³ to 2.63 yuan/m³, and special industries will increase from 1.25 yuan/m³ to 8.63 yuan/m³. Scenario III: Full cost. In the case of full cost, the water supply cost of different water sources is added to the basic water supply cost plus external costs to form a cost function for different water sources to supply different users. Scenario IV: Water saving in agriculture. The agricultural water supply in 2021 will be reduced by 20%, and all the saved water will be used for non-residential water use. The basic water price function and cost function remain unchanged.

(2) Result analysis. The simulation results of water allocation, water supply cost, price and comparison price in Qingdao with multiple water sources and multiple users are shown in Table 2, Table 3, Table 4 and Table 5.

According to the distribution under different conditions, the total cost under different conditions is compared and divided. The analysis results are shown in Table 3.

According to the distribution under different conditions, the water prices under different conditions are compared and divided. The analysis results are shown in Table 4.

Based on the above basic data and the method of financial analysis, the price comparison relationship in Qingdao under different conditions is compared. The comparison results are shown in Table 5.

Through the comparative analysis of the basic situation and the four scenarios, combined with the tables listed above, the cost of water supply is the highest in the full-cost scenario, the price of special water is lower than the current price, and most of the price comparison relationships are within a reasonable range.

(3) The total cost of water supply is the highest in the case of full cost. Comparing the total cost of water supply in different situations in Qingdao, the total cost is the highest in the case of full cost, which is 20.8653 billion yuan. In the case of agricultural water saving of 20%, the total cost of water supply has increased compared with the basic situation. The main reason is that agricultural water saving is mainly used

Table 1. Water Allocation Table of Qingdao in 2021 (100 million m³).

Water source	Residents	Non-residents	Agriculture	Special industry	Total
Surface water	0.60	0.16	0.58	0.04	1.38
Groundwater	0.92	0.55	0.28	0.07	1.82
Diverting the Yellow River to Qingdao	0.29	0.36	0.08	0.10	0.83
South-to-North Water Diversion	1.32	0.52	0.78	1.10	3.72
Water reuse	0.00	0.17	0.32	0.40	0.89
Sea water desalination	0.26	0.38	0.00	0.00	0.64
Total	3.39	2.14	2.04	1.72	9.29

Table 2. Distribution under different scenarios in 2021 (100 million m³)

Water source		Surface water	Ground water	Diverting the Yellow River to Qingdao	South-to-North Water Diversion	Water reuse	Sea water desalination	Total
Residents	I	0.59	0.91	0.28	1.29	0	0.33	3.39
	II	0.58	0.9	0.26	1.28	0	0.37	
	III	0.66	0.92	0.31	1.29	0	0.21	
	IV	0.61	0.9	0.27	1.28	0	0.32	
Non-residents	I	0.13	0.56	0.38	0.6	0.16	0.31	2.14
	II	0.06	0.61	0.4	0.66	0.15	0.27	
	III	0	0.54	0.28	0.71	0.18	0.43	
	IV	0.25	0.77	0.29	0.74	0.18	0.32	2.55
Agriculture	I	0.65	0.22	0.09	0.7	0.38	0	2.04
	II	0.71	0.12	0.17	0.66	0.38	0	
	III	0.72	0	0.13	0.76	0.43	0	
	IV	0.52	0	0.18	0.55	0.39	0	1.64
Special industry	I	0.02	0.14	0.08	1.13	0.35	0	1.72
	II	0.04	0.2	0.01	1.12	0.35	0	
	III	0	0.36	0.11	0.96	0.29	0	
	IV	0	0.15	0.1	1.15	0.33	0	
Total		0.59	0.91	0.28	1.29	0	0.33	9.29

Table 3. Comparison of total cost in different situations (yuan/m³).

Water source	Basic situation	I	II	III	IV
Surface water	14.53	14.49	14.36	29.16	14.89
Groundwater	13.36	13.25	13.10	45.56	13.45
Diverting the Yellow River to Qingdao	29.50	29.38	29.38	36.29	29.90
South-to-North Water Diversion	43.61	43.22	42.80	51.86	43.91
Water reuse	5.81	5.81	5.77	8.06	5.91
Sea water desalination	19.76	19.66	19.50	29.93	20.01

Table 4. Comparison of water prices in different situations (yuan/m³).

Water source	Basic situation	I	II	III	IV
Residents	5.72	6.17	6.48	7.87	5.70
Non-residents	6.30	7.47	8.02	9.38	6.55
Agriculture	0.83	0.78	0.79	2.11	0.62
Special industry	8.64	13.47	16.09	10.18	9.07
Recycled water	1.45	1.88	1.78	1.67	1.17

by non-residents. At the same time, the price of non-residents has increased, from 6.30 yuan/m³ to 6.55 yuan/m³, the price of agricultural water dropped from 0.83 yuan/m³ to 0.62 yuan/m³. The increase of non

residential water price minus the decrease of agricultural water price is equal to 0.04 yuan/m³. Therefore, the situation of saving 20% water in agriculture has led to the rise of the total cost of water supply.

Table 5. Comparison of price comparison relationships in different situations in Qingdao.

Price comparison relationship	Basic situation	I	II	III	IV	Reasonable standard range
Nonresidents and Agriculture	7.56	9.61	10.18	4.45	10.55	7~11
Resident and non-resident	0.91	0.83	0.81	0.84	0.87	0.67~1
Residents and specialty	0.66	0.46	0.40	0.77	0.63	0.25~0.8
Groundwater residents and surface water residents	1.19	0.95	1.16	1.55	1.19	1~3.00
Groundwater nonresidents and surface water non residents	1.17	0.95	1.13	1.50	1.16	1~2.80
Groundwater specialty and surface water specialty	1.16	0.97	1.06	1.49	1.13	1~4.50
Reclaimed water and residential water	0.25	0.31	0.27	0.21	0.21	0.2~0.29

(4) The price of special water is lower than the current price. The analysis in Table 4 shows that the special water use is lower than 17.25 yuan/m³ in different situations. The reason may be that the special water in Qingdao includes bathing (except for public bathing), car washing and golf course, and the prices of these kinds of water are relatively low.

(5) Most of the price comparison relationships are within reasonable standards. According to the price comparison results in Table 5, the price ratio between non-residents and agriculture, residents and non-residents, groundwater residents and surface water residents, groundwater non-residents and surface water non-residents, groundwater special water and surface water special water, reclaimed water and residential water prices are reasonable standards. It is worth noting that the price ratio between non-residents and agricultural water at full cost is 4.45, which is outside the normal and reasonable range. This is mainly due to the fact that external cost factors are not considered in the analysis of the price relationship. In particular, the cost of infrastructure consumption and maintenance of non residential water is high, while the cost of agricultural infrastructure consumption and maintenance is low, which leads to a large deviation in the price relationship.

(6) Unconventional water sources are limited by policy guidance. In the optimal allocation of water resources, the selection of data on conventional water sources is mainly based on Qingdao's "Thirteenth Five-Year Plan", and the scale of development is relatively small. In theory, seawater utilization and reclaimed water in coastal cities have great potential for development. If Qingdao City can pay more attention to the use of seawater and reclaimed water, the results of its optimized allocation of water resources may be more scientific.

Conclusions

Qingdao has good urban infrastructure, high degree of reform and opening up, strong development

capabilities and economic vitality, and high urban governance capabilities and levels. The desire for water resources management reform is more urgent, and it is very likely to take the lead in innovation in water resources management systems and mechanisms.

(1) Forecasting water demand is a very complicated issue. It is recommended that the government can continue to do follow-up research, and timely adjust relevant forecasts and supply-demand balance planning. Due to the shortage of water resources in Qingdao, how to control water demand and increase water supply so as to achieve a balance between supply and demand is the primary goal of water resources planning.

(2) In view of the shortage of water resources and the high affordability of users in Qingdao, it is suggested to increase the prices of various water supplies step by step. At the same time, we should appropriately increase user autonomy. Within a certain range, users have the right to choose water supply enterprises. In particular, some large water users can choose water supply enterprises according to their own cost accounting and establish long-term cooperative relations with them.

(3) In view of the diversification of water supply methods in Qingdao, it is recommended that the government optimize the overall structure from the perspective of water supply costs and benefits. Therefore, appropriate autonomy should be given to water supply companies. Within a certain range, the right to choose users, especially large water users. Encourage major water users to sign long-term contracts with water supply companies, regulate and restrict the rights and obligations of both parties, and establish a long-term cooperation mechanism. The adjustment of residential water prices must be based on cost supervision and review, introduce third-party audits, and disclose and disclose cost information related to pricing, forcing companies to take the initiative to strengthen management, reduce internal consumption, and improve service quality.

Based on the above analysis, governments at all levels should establish a scientific adjustment mechanism, respect market laws, combine the past

adjustments and decentralization, focus on adjustments, and focus on market decision, decentralization and regulation, and deepen the mechanism to establish price supervision and price formation. Deepen the regulation, strengthen the service, underpin guarantees and many other mechanisms to safeguard the income of investors and the long-term interests of users.

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Conflict of Interest

The authors declare no conflict of interest.

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