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A Coupled Allocation for Regional Initial Water Rights in Dalinghe Basin, China

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Abstract: Regional initial water rights is a crucial part of initial water rights and clarification of it is an essential method to improve the efficiency of water use. It also promotes sustainable use of valuable water resources. Consequently, under new circumstances of China's most stringent water resources management, with water quantity and quality control, we propose a new perspective for a coupled allocation model of regional initial water rights for a typical river basin. Firstly, we design an index system following principles of the "Three Red Lines" considering the real situation of Dalinghe River Basin, China. Then, under the control of total water use, we establish an allocation model of regional initial water quantity rights by the projection pursuit technology. Secondly, under total pollutant discharge control, we established an allocation model of regional initial pollutant discharge rights considering optimized objectives of economy and society. Thirdly, considering both regional initial water quantity rights and the regional pollutant discharge rights above, we provide an incentive function to build a coupled allocation model for regional initial water rights of Dalinghe River Basin. Finally, according to the scenario of the water frequency 50% and planning year 2030, the research finding shows Chaoyang City obtains the largest quantity of regional initial water rights, followed by Jinzhou, Fuxin, Panjin and Huludao, sequentially, which approximately match the pilot plans of China's Ministry of Water Resources. The empirical research about Dalinghe River Basin further verifies effectiveness of the model in this paper. It also provides scientific decision support for implementing China's most stringent water resources management for Dalinghe River Basin.

Keywords: China's most stringent water resources management; initial regional water rights; initial regional pollutant discharge rights; coupled allocation; water quantity and quality; Dalinghe River Basin

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1. Introduction

Global warming and rapid development of social economy have sharpened the water resources supply–demand conflict, resulting in a series of severe water problems including water scarcity, accumulation of water pollution, over-pumping of aquifers and frequent floods in river basins with fragile ecologies in China. As the availability of water is becoming a major constraint to achieve harmony between economic and social sustainable development, on 29 January 2011, Central Document No. 1 was published by Chinese government. This document title was "Decision on Accelerating China's Reform and Water Conservancy Development" [1]. In this document, implementing China's most stringent water resources management becomes a crucial element [2]. Furthermore, in 2012, Chinese government issued another document titled "State Council Opinions on Implementation of China's Most Stringent Water Resources Management". "Three Red Lines" mentioned in Document No. 1 were concretized by this document [3]. "Three Red Lines" are the core aspects of China's most stringent water resources management system. They are composed of the first line of total water use control, the second line of enhancing efficiency of water use, and the third line of reducing water function zone's pollution [4].

Establishing the water rights system framework is an institutional arrangement for the development, utilization and protection of water resources. This framework is a set of rules for regulating rights, obligations and interests within government agencies and water users, which includes the definition, allocation, adjustment, protection and use of water rights [5]. Water rights have different definitions in different domains. In this paper, water rights are not used to refer to legal ownership rights, but basically regarded as the rights to allocate, take, or use water. As an indispensable section of water rights, the regional initial water rights mainly refers to the initial rights for the use of water resources and includes river basin level initial water rights and regional initial water rights.

Because transaction costs cannot be neglected, the property rights initial allocation often matters about efficiency [6]. In fact, the initial water rights can be conductive to define property rights [7]. Furthermore, the initial regional water rights allocation and water markets establishment can improve economic efficiency of water use, and help resolve the water shortages in China [8]. Meanwhile, a water rights system depends heavily on clear, certain entitlements to water. Hence, clarification and specification of the initial water rights is an effective way to achieve the explicit purpose of water rights, as well as provide a basis and prerequisite for the development of water rights transaction.

Currently, how to carry out a fair, reasonable and efficient distribution for initial water rights among the different regions and river basins, following the new benchmarks about "Three Red Lines", has become a new challenge for implementing of China's most stringent water resources management.

Dalinghe River Basin is a typical region of northern China. In recent decades, along with the rapid industrialization, and continuous population expansion and economic growth, Dalinghe River Basin has been plagued with water shortages, droughts, floods and water pollution. In order to balance economic development and environmental protection of this basin, and ensure the water quantity or water supply volume that satisfies reasonable water demand of the public and natural environment in the region of the same basin [9], Dalinghe River Basin is regarded as a pilot area of initial water rights allocation in China. Most studies on allocation for initial water rights of Dalinghe River Basin only considered the quantity components of that allocation, and not the quality aspects, including even the pilot plans of China's Ministry of Water Resources. However, water quantity and quality are naturally coupled, and it is presented as a coupled problem for initial water rights allocation facing the scenario of "Three Red Lines" that simultaneously encompass water quantity and quality aspects. Hence, new integrated approaches should be proposed to improve the existing decision making for the initial water rights allocation for Dalinghe River Basin.

This paper tries to address the issues of initial regional water rights allocation for Dalinghe Basin. Since initial regional water rights is composed of two sections, the initial regional water quantity rights and the initial regional pollutant discharge rights, to solve the above issues, we propose a coupled allocation model controlling both water quantity and water quality, which can well match the new needs of China's most stringent water resources management.

This study is organized as follows. In Section 2, a literature review regarding initial regional water allocation is carried out. In Section 3, we describe the case study area. In Section 4, we establish a projection pursuit model for the quantity allocation of regional initial water rights. And we put forward a multi-objective optimal model for the initial regional pollutant discharge rights allocation. Furthermore, we provide an incentive function to build a coupled allocation model for regional initial water rights. In Section 5, we detail our case study. In Section 6, we draw the conclusions.

2. Literature Review

In recent years, research on initial regional water rights allocation has been given widespread attention. The existing literature on the initial regional water rights includes the following three aspects: the quantity allocation, the pollutant discharge allocation, and the coupled allocation considering both water quantity and water quality.

2.1. Quantity Allocation for the Regional Initial Water Rights

In the early stage, because fundamental differences exist between the nature and source of water rights, some countries establish different types of water rights including community-based water rights, land-based water rights, water rights of prior appropriation and riparian water rights [10]. From the current theoretical studies, hybrid allocation method, multi-participation allocation model, multi-objective optimization allocation model, and interactive and harmonious allocation method are proposed.

(1) Hybrid allocation method: Wu et al. [11] built an allocation model of initial water rights using bi-level optimization method. Benjamin Lord [12] proposed an integrated model to solve the optimize problem of water resources allocation by linear programming formulations.
(2) Allocation model of multi-participation: Ralph [13] established Water Rights Analysis Package (WRAP) simulation model for Texas. Yanping Chen et al. [14] proposed an evolutionary game model including disadvantaged and advantaged group of the same basin to find the optimal allocation problem of water rights. Read et al. [15] presented a negotiation model of water rights allocation, which includes multiple decision makers.
(3) Multi-objective optimization allocation model: Wu and Ge [16] present an allocation model about the first hierarchy initial water rights using multi-objective and semi-structural fuzzy optimization method. Ge and Wu [17] established a quantity allocation model about provincial initial water rights under China's most stringent water resources management constraints.
(4) Interactive and harmonious allocation method: Considering harmonious and disharmonious judgment principles, Wu and Ge [18] proposed an interactive allocation model about the initial water rights. Wang and Zheng [19] put forward a harmonious allocation model of water rights. Wu and Chen [20] established the harmonious allocation model about the initial water rights for a river basin.

2.2. The Pollutant Discharge Allocation for the Regional Initial Water Rights

Afterwards, the importance of water quality is gradually considered and some studies are concerned about the allocation method of the initial pollutant discharge rights.

(1) Pollutant discharge allocation according to the equity principle: Sun and Zhang [21] considered information entropy and established a waste permit allocation model for a basin. Mostafavi and Afshar [22] built a wastewater load allocation model and used the multi-colony ant algorithm to solve the model.
(2) Multi state wastewater permits allocation method: Wang et al. [23] considered equity and efficiency at the same time and performed research on two-stage optimization model of carbon permits allocation. Javier et al. [24] used decision support system shell AquaTool to set up a river water quality model under drought situations.
(3) Single objective decision making method: Gao and Li [25] discussed the water function regionalization and presented an initial allocation of pollutant discharge. Furthermore, Wan and Li [26] built a simulation model of the initial pollutant discharge allocation considering fairness and economic optimality simultaneously.
(4) Multiple objective decision making model: Huang and Wang [27] put forward an optimal river pollutant discharge allocation model under the pollution limits. Huang and Shao [28] considered

the fairness and the polluters' continuity of production while setting up an optimal multi-objective chaotic water resources deployment model. Moreover, from the perspective of water quality, Ge and Wu [29] presented multiple objective allocation method for the initial provincial pollutant discharge rights.

(5) Multi-index decision making method: Li et al. [30] designed a hierarchical structure model for the distribution of the total amount of emissions using multi-index decision-making method. The model worked by combining qualitative and quantitative analyses to describe judgment matrix.

(6) Hybrid allocation method: Liu et al. [31] did research on entropy weighing model of the pollutant discharge and studied the distribution method of improved proportion. Liu et al. [32] considered economy oriented government regulation in Taihu Basin. Based on it, they established cooperative system for initial discharge permits allocation.

2.3. The Coupled Water Quantity and Quality Allocation for the Regional Initial Water Rights

Water resources have two basic properties: quantity and quality. Initial regional water rights allocation should consider these two properties at the same time. Recently, several studies pay more attention to this area, but they are still insufficient. Wang, Hu and Wang [33,34] built a two-dimensional allocation model of the initial water rights in a typical basin. However, they did not consider the allocation of initial pollutant discharge rights within the constraints of China's most stringent water resources management. In their model, a penalty function for the over standard discharge was presented, but they did not consider the possibility of less than standard discharge occurring. Wu et al. [35] presented an interactive iteration allocation model for the initial water rights. However, their model ignored the incentive mechanism in the protection of water environmental. Furthermore, Zhang and Wu [36] proposed a framework about the coupling allocation of the initial water rights. However, they did not study a concrete model according to this framework.

Thus, the existing literature still has some of insufficiencies.

- First, the existing studies on the initial allocation for the regional water rights do not comprehensively consider key aspects such as total water use, water quality and efficiency. Considering the constraints of the stringent water resources management system, there are few allocation models of initial regional water rights, which follow the requirements of "the Three Red Lines".
- Second, few studies can be found to optimize an index system that is orientated towards the allocation problem of initial regional water rights with the concept about realizing the fair and efficient use of water simultaneously.
- Third, the research on water rights allocation considering both water quantity and quality for Dalinghe River Basin is still in its infancy. How to design an incentive function to embed pollutant elements into initial quantity allocation of regional water rights is rarely considered. Meanwhile, the allocation models of initial regional water rights can seldom be found to couple with the initial regional water quantity rights and initial regional pollutant discharge rights.

3. Materials

3.1. The Case Study Area

Dalinghe, located in northeast China, is the longest river of western Liaoning Province, measuring about 435 kilometers. It flows through Liaoning Province, Hebei Province and Inner Mongolia, and then empties into the Bohai Sea near the city of Panjin in Liaoning Province. Dalinghe River Basin has a cool climate of continental monsoon. The average annual precipitation is approximately 450–600 mm, which is concentrated in July and August. The average annual temperature is about 8.5 °C. The average annual runoff of this basin is about 1633 million cubic meters, the maximum runoff is 15,600 cubic meters per second and the minimum flow is about 0.09 cubic meters per second.

The whole Dalinghe River Basin ranges approximately from 119°00′E to 122°00′E, and from 40°30′N to 42°30′N, with the total drainage area of 23,500 square kilometers. The administration areas of Dalinghe River Basin are Liaoning Province, Hebei Province and Inner Mongolia. The basin area in Liaoning Province accounts for more than 85% of the whole river basin. For this reason, we choose this area including Jinzhou, Fuxin, Chaoyang, Panjin and Huludao Cities as a pilot study area. This empirical study area is shown in Figure 1. In these five cities, domestic, agricultural, ecological and industrial water is supplied by Dalinghe. Along with the population growth, the gap between water demand and supply has gradually widened. Conflicts over water use between these five cities have increased. Furthermore, water scarcity caused by the poor water quality has become an obstacle for the sustainable development.

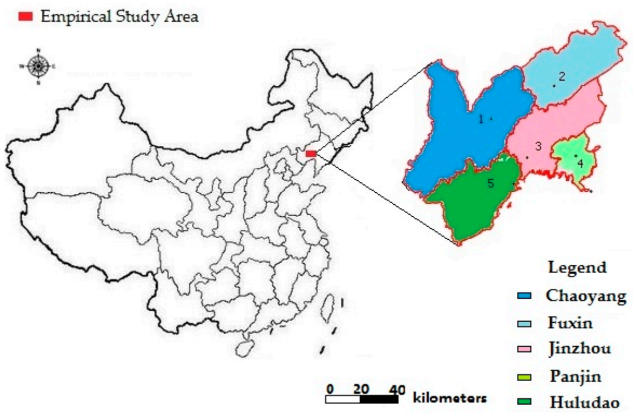

Figure 1. The location about the case study area. Dalinghe River Basin's administrative divisions: 1: Chaoyang City; 2: Fuxin City; 3: Jinzhou city; 4: Panjin city; and 5: Huludao city.

3.2. Data

In this paper, the related social and economic data are obtained from Liaoning Province's statistics yearbooks [37].The relevant data about water resources are mostly processed from water resources official reports of Liaoning Province, which were released by LPDWR (Liaoning Provincial Department of Water Resources). The other data are collected by the partial survey data of this pilot study area. Considering the planning year 2030, under the water frequency 50%, the distributable total initial water rights of Dalinghe River Basin will be 1.286 billion m^3 [11], and the total amount of COD (chemical oxygen demand) discharge will be 12,182.96 t/a. The specific relevant data of Dalinghe River Basin in planning year 2030 with the water frequency 50% [20] are illustrated in Table 1.

Table 1. Specific relevant data of Dalinghe River Basin (under water frequency 50%, in planning year 2030).

Index	Region				
	Jinzhou	**Fuxin**	**Chaoyang**	**Panjin**	**Huludao**
Current water use (10^8 m^3)	13,833	13,713	36,107	4245	3684
Regional water yield (10^8 m^3)	27,987	19,402	97,672	382	17,874
Population (10^4 person)	65.37	98.08	255.7	0.5	28.6
effective irrigation area (10^4 ha)	4.18	1.67	11.84	1.26	0.69
Current scale of water supply project (10^8 m^3)	1440	3190	3420	100	720
per capita water use (m^3/person)	213	1239	143	1500	129
Water use volume of irrigation per unit area (m^3/ha)	1545	1320	1230	3000	1425
10^4 Yuan GDP water use (m^3)	89.01	37.03	69.14	75.914	90.56
Per capita GDP (Yuan)	48,025	61,885	31,442	40,053	18,775
standard discharge rate of waste water (%)	60.35	57.2	49.77	70.53	61.54
the total amount of COD discharge (t/a)	4104.6	3346.4	1838.2	0.0	717.0
green coverage rate (%)	20.34	27.00	23.10	6.13	16.5

4. Methodology

Considering the new requirements of China's most stringent water resources management, our coupled allocation for initial regional water rights under the both constraints of water quantity and quality for Dalinghe Basin can be proposed by the following four steps:

- Step 1: Construct a quantity allocation model for the regional initial water rights in Dalinghe River Basin. According to "Three Red Lines" restriction, this involved calculating an index system which can influence the initial regional water rights allocation under China's most stringent water resources management.
- Step 2: Based on projection pursuit technology, construct a regional initial water quantity rights allocation model, in order to get the quantity allocation result of water rights between different regions of Dalinghe River Basin.
- Step 3: Build a regional allocation model of pollutant discharge rights. Considering the control of the total pollutant, we set up a regional allocation model of initial pollutant discharge with optimization goals of economic and social outcomes. According to the above model, we can get the solutions of initial pollutant discharge rights for the different regions in Dalinghe River Basin.
- Step 4: Develop a coupled allocation model of initial regional water rights. We set up an incentive function based on water quantity and quality constraints. Furthermore, we obtain allocation results of initial regional water rights.

This approach is illustrated empirically by researching the Dalinghe River Basin, China. In Figure 2, the outline of this paper is described.

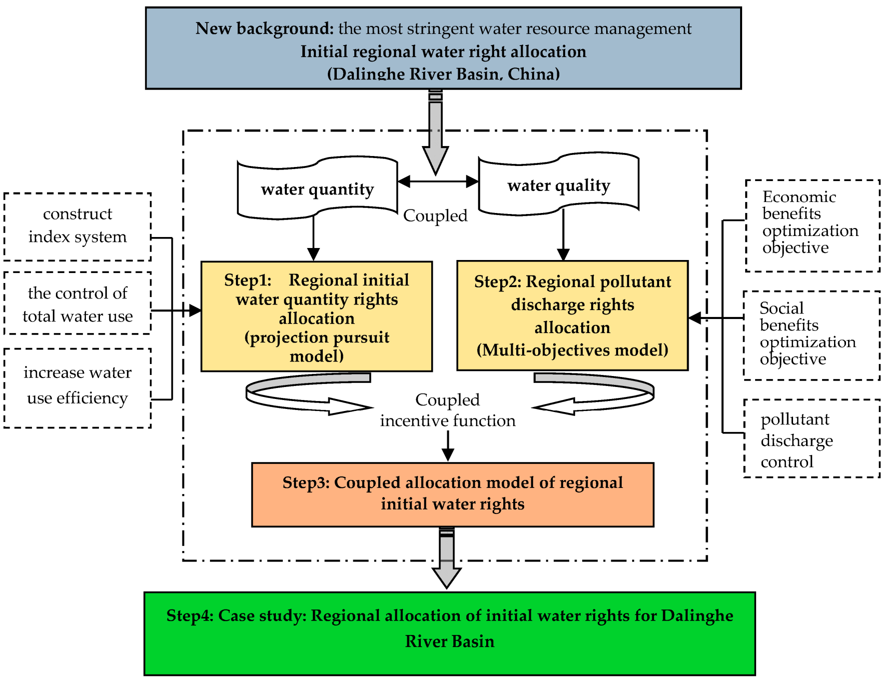

Figure 2. Outline of regional allocation of initial water rights for Dalinghe River Basin.

4.1. *Regional Initial Water Quantity Rights Allocation Model*

4.1.1. Establish Index System

According to the availability and representativeness of the relevant data, and considering the requirements of "Three Red Lines", the index system about initial allocation of regional water rights for Dalinghe River Basin is presented in Table 2.

Table 2. Index system about initial regional water rights allocation for Dalinghe River Basin.

Object	Principle	Index	No.	Attribute
Initial regional water rights allocation	Control of total water use	Current water use (10^8 m^3)	P_1	Profit
		Regional water yield (10^8 m^3)	P_2	Profit
		Population (10^4 person)	P_3	Profit
		Effective irrigation area (10^4 ha)	P_4	Profit
	Increase water use efficiency	Current scale of water supply project (10^8 m^3)	P_5	Profit
		Per capita water use (m^3/person)	P_6	Profit
		Water use volume of irrigation per unit area (m^3/ha)	P_7	Profit
		10^4 Yuan GDP water use (m^3)	P_8	Cost
		Per capita GDP (Yuan)	P_9	Profit
	Control of pollutant discharge	Standard discharge rate of wastewater (%)	P_{10}	Profit
		The total amount of COD discharge (t/a)	P_{11}	Cost
		Green coverage rate (%)	P_{12}	Profit

4.1.2. Projection Pursuit Allocation Model

Regional water rights quantity allocation under the total water use control is a typical multidimensional, nonlinear decision problem. We use projection pursuit method to get the allocation solutions of initial regional water quantity rights. In fact, the projection pursuit method can overcome the difficulties of determining the weights of indexes which are required by existing methods.

(1) Basic data processing

① P_i is the index, $i = 1, ..., m$; R_j is the region, $j = 1, ..., n$.

② x_{ij} is the value of index P_i of region R_j. The index analysis matrix is described as follows.

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} = (x_{ij})_{m\times n} \quad (1)$$

where $i = 1, ..., m$ and $j = 1, ..., n$.

③ Remove dimensions from indexes, and then matrix X can be normalized.

The non-dimensional value of x_{ij} is defined as e_{ij}. When x_{ij} is type of profit, e_{ij} is obtained by Equation (2).

$$e_{ij} = \frac{x_{ij}}{\max\limits_{j=1,2...,n} x_{ij} + \min\limits_{j=1,2...,n} x_{ij}} \quad (2)$$

Moreover, when x_{ij} is a type of cost, e_{ij} is acquired by Equation (3).

$$e_{ij} = 1 - \frac{x_{ij}}{\max\limits_{j=1,2,...,n} x_{ij} + \min\limits_{j=1,2,...,n} x_{ij}} \quad (3)$$

where $i = 1, 2, ..., m$ and $j = 1, 2, ..., n$.

④ Normalized matrix E can be expressed by Equation (4).

$$E = \begin{bmatrix} e_{11} & e_{12} & \cdots & e_{1n} \\ e_{21} & e_{22} & \cdots & e_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ e_{m1} & e_{m2} & \cdots & e_{mn} \end{bmatrix} = (e_{ij})_{m\times n} \quad (4)$$

where $i = 1, ..., m$ and $j = 1, ..., n$.

⑤ E^+ is the positive ideal matrix, which is presented by Equation (5):

$$e_{ij}^{+} = \max\{ e_{ij} | j = 1, ..., n \} \tag{5}$$

⑥ E^- is negative ideal matrix, which is described as follows:

$$e_{ij}^{-} = \min\{ e_{ij} | j = 1, ..., n \} \tag{6}$$

(2) Decision variable description

In our model, decision variables are defined as follows: $d(j)$ is value of one-dimensional projection; $\theta = (\omega_1, ...\omega_m)$ is projection direction; ω_m is weight of index P_i; $d^*(j)$ is best projection value; ω_{R_j} is initial water rights allocation ratio of region R_j; and w_{R_j} is initial water quantity rights of region R_j.

(3) Establish projection objective function

The purpose of establishing projection objective function is dimensionality reduction.

① According to matrix E, the one-dimensional projection value $d(j)$ is expressed as follows.

$$d(j) = \frac{\sqrt{\sum_{i=1}^{m} \omega_i (e_{ij} - e_{ij}^{-})^2}}{\sqrt{\sum_{i=1}^{m} \omega_i (e_{ij} - e_{ij}^{+})^2} + \sqrt{\sum_{i=1}^{m} \omega_i (e_{ij} - e_{ij}^{-})^2}} \tag{7}$$

Projection direction is $\theta = (\omega_1, ...\omega_m)$. $d(j)$ is between positive and negative ideal solution of region R_j.

② In order to decentralize $d(j)$ as much as possible, the projection index function $f(\theta)$ is set up as follows.

$$f(\theta) = S_d = \sqrt{\frac{\sum_{j=1}^{n} [d(j) - \overline{d(j)}]^2}{n-1}} \tag{8}$$

where $j = 1, 2, ..., n$ and $\overline{d(j)}$ is mean value of $d(j)$.

③ To obtain the best $d(j)$, using Equation (9), we can obtain maximum value of projection indexes function.

$$\begin{cases} \max f(\theta) = S_d \\ s.t. \begin{cases} c_1(\theta) = \sum_{i=1}^{m} \omega_i - 1 = 0 \\ \omega_i > 0, i = 1, ..., m \end{cases} \end{cases} \tag{9}$$

Then, we can calculate Equation (9) to get the best projection value $d^*(j)$ for region R_j. Furthermore, region R_j can acquire more initial regional water rights when the $d^*(j)$ is bigger.

(4) Results of quantity allocation for regional initial water rights

Let ω_{R_j} denote to the allocation ratio of initial regional water rights for the region R_j. ω_{R_j} can be described by Equation (10):

$$\omega_{R_j} = \frac{d^*(j)}{\sum_{j=1}^{n} d^*(j)} \tag{10}$$

In the typical basin, total quantity of initial water rights can be defined as W. Hence, we can calculate the initial regional water rights of region R_j by Equation (11).

$$w_{R_j} = W \times \omega_{R_j} = W \times (d^*(j) / \sum_{j=1}^{n} d^*(j)) \quad (11)$$

4.2. Initial Regional Pollutant Discharge Rights Allocation Model

The region can be defined as R_j, $j = 1, ..., n$. x_{R_j} denotes the pollutant discharge amount of the region R_j, $j = 1, ..., n$.

4.2.1. Model Construction

(1) Objective Functions Design

① First objective function is defined as F_1, which reflects optimization of the economic benefit. F_1 represents the maximal economic benefit of the river basin, which can be described by Equation (12).

$$F_1 = \max f_1(X) = \max \sum_{j=1}^{n} F_{1j} = \max \sum_{j=1}^{n} f_j(X) = \max \sum_{j=1}^{n} GDP_j\left(x_{R_j}\right) \quad (12)$$

where $F_{1j} = f_{1j}(X) = GDP_j(x_{R_j})$, and the revenue function of the region R_j is $GDP_j(x_{R_j})$.

② The second objective function of the model can be presented as F_2. F_2 is the optimization objective function of the social benefits. F_2 represents the best coordination and equality during the allocation of pollutant discharge [20].

$$F_2 = \min f_2(X) = \min \sum_{j=1}^{n} F_{2j} = \min \sum_{j=1}^{n} f_{2j}(X) = \min \sum_{i=1}^{n} \sum_{j=1}^{n} [\frac{x_{R_i}}{x_{R_j}} - \sum_{l}^{3} \beta_l \cdot \gamma_l(\frac{R_i}{R_j})]^2 \quad (13)$$

where $i \neq j$ and $F_{2j} = f_{2j}(X) = [\frac{x_{R_i}}{x_{R_j}} - \sum_{l}^{3} \beta_l \gamma_l(\frac{R_i}{R_j})]^2$; $\gamma_1(\frac{R_i}{R_j})$ represents proportion of population between region R_i and R_j; $\gamma_2(\frac{R_i}{R_j})$ reflects proportion of area between region R_i and R_j; and $\gamma_3(\frac{R_i}{R_j})$ presents the proportion of GDP index value between region R_i and R_j. β_l is the population, area, and GDP relative importance between region R_i and R_j, and $\beta_1 + \beta_2 + \beta_3 = 1$.

(2) Establish the constraints

① The first constraint can be described as Equation (14). It reflects the total pollutant discharge of all regions should not exceed pollutant discharge P_{total} of the basin.

$$\sum_{j=1}^{n} \left(x_{R_j}\right) \leq P_{total} \quad (14)$$

② The second constraint of the model can be presented by Equation (15). This constraint represents the variables are required to be non-negative.

$$x_{R_j} \geq 0 \quad (15)$$

where $j = 1, 2, ..., n$.

4.2.2. Solution of the Model

The model is presented as Equations (12)–(15). The solution procedures of this model in detail can be illustrated as follows.

(1) Dimensionless treatment to objective functions

We turn objective function F_1 into minimal function using Equation (16):

$$F_1 = \max f_1(X) = \min[-f_1(X)] = \min[-\sum_{j=1}^{n} GDP_j\left(x_{R_j}\right)] \tag{16}$$

Because of the different scales of the objective function F_1 and F_2, we convert them into non-dimensional ones, which are expressed as $F_1{}'$, and $F_2{}'$. In order to remove dimensions of F_1, and F_2, we adopt ideal point method for multi-objective planning.

① First, we set up two single-objective planning models of F_1 and F_2, which can be illustrated as follows.

$$\begin{cases} F_1 = \min[-f_1(X)] \\ S.T. \begin{cases} \sum\limits_{j=1}^{n} \left(x_{R_j}\right) \le P_{total} \\ x_{R_j} \ge 0 \end{cases} \end{cases} \tag{17}$$

$$\begin{cases} F_2 = \min[f_2(X)] \\ S.T. \begin{cases} \sum\limits_{j=1}^{n} \left(x_{R_j}\right) \le P_{total} \\ x_{R_j} \ge 0 \end{cases} \end{cases} \tag{18}$$

② Second, the optimal solutions of Equations (17) and (18) can be expressed by $-f_1(X^*)$ and $f_2(X^*)$. Using ideal point method for multi-objective planning, non-dimensional objective function $F_1{}'$ and $F_2{}'$ can be expressed as Equations (19) and (20).

$$F_1{}' = \frac{f_1(X) - f_1(X^*)}{f_1(X^*)} \tag{19}$$

$$F_2{}' = \frac{f_2(X) - f_2(X^*)}{f_2(X^*)} \tag{20}$$

(2) Deformation of the former multi-objective model

According to Equations (19) and (20), the deformation of former multi-objective model, which were represented by Equations (12)–(15), can be illustrated as Equation (21).

$$\begin{cases} \min F' = (F_1{}')^2 + (F_2{}')^2 \\ S.T. \begin{cases} \sum\limits_{j=1}^{n} \left(x_{R_j}\right) \le P_{total} \\ x_{R_j} \ge 0 \end{cases} \end{cases} \tag{21}$$

Here, Equation (21) is non-linear programming (NP), which can be solved by MATLAB 7.01 (MathWorks, Natick, MA, USA).

4.3. Coupled Allocation Model of Regional Initial Water Rights

4.3.1. Incentive Mechanism of "Rewarding Excellence and Punishing Inferior"

The basic idea of how to make coupling analysis of water quantity and quality for regional water quantity rights w_{R_j} and pollutant discharge rights x_{R_j} can be described as follows:

- We absorb mechanism of "rewarding excellence and punishing inferior" to establish an incentive function. Suppose that ${x_{R_j}}^{real}$ is the real pollutant discharge of region R_j, when ${x_{R_j}}^{real}$ is greater than x_{R_j}, we should implement negative incentive to reduce this region's initial water rights.
- When ${x_{R_j}}^{real}$ is less than x_{R_j}, we should carry out positive incentive to increase this region's initial water rights.

4.3.2. Coupled Allocation Model Base on Incentive Mechanism

Step 1: the incentive function of the coupled allocation of initial regional water rights is expressed as follows.

$$\mu({x_{R_j}}^{real}/x_{R_j}) = ({x_{R_j}}^{real}/x_{R_j})/[{x_{R_j}}^{real}/x_{R_j} + c] \tag{22}$$

where c is a constant.

Step 2: Adjust the initial water rights proportion of region R_j, according to the incentive function illustrated by Equation (23).

$${\omega_{R_j}}' = \begin{cases} \omega_{R_j}(1 + \mu({x_{R_j}}^{real}/x_{R_j})) & when \quad x_{R_j} > {x_{R_j}}^{real} \\ \omega_{R_j} & when \quad x_{R_j} = {x_{R_j}}^{real} \\ \omega_{R_j}(1 - \mu({x_{R_j}}^{real}/x_{R_j})) & when \quad x_{R_j} < {x_{R_j}}^{real} \end{cases} \tag{23}$$

where ω_{R_j} is calculated using Equation (10). The adjusted initial regional water rights proportion of region R_j is defined as ${\omega_{R_j}}'$.

Step 3: ${\omega_{R_j}}'$ can be normalized by Equation (24).

$${\omega_{R_j}}'' = \frac{{\omega_{R_j}}'}{\sum\limits_{j=1}^{n} {\omega_{R_j}}'} \tag{24}$$

where $j = 1, ..., n$, and the normalized allocation proportion of initial regional water rights for region R_j can be expressed as ${\omega_{R_j}}''$. Thus, the final amount of initial regional water rights for region R_j is showed as follows.

$${w_{R_j}}' = W \times {\omega_{R_j}}'', \; j = 1, ..., n \tag{25}$$

5. Results and Discussion

5.1. Calculation of Quantity Allocation for Regional Initial Water Rights in Dalinghe River Basin

Using Equations (2) and (3), we can remove dimension of index in Table 1 and obtain the non-dimensional value of indexes, as shown in Table 3.

According to Equation (9), the initial regional water rights allocation results of Dalinghe River Basin can be presented in Table 4, including the results of optimal projection value $d^*(k)$, optimal projection direction $\theta = (\omega_1, ..., \omega_{12})$, and allocation proportion of the initial regional water rights ω_{R_j}.

Table 3. The non-dimensional index value of Dalinghe River Basin in planning year 2030 under water frequency 50%.

Indexes (the Non-Dimensional Value)	Region				
	Jinzhou	Fuxin	Chaoyang	Panjin	Huludao
Current water use	0.348	0.345	0.907	0.107	0.093
Water yield	0.285	0.198	0.996	0.004	0.182
Population	0.255	0.383	0.998	0.002	0.112
The effective irrigation area	0.333	0.133	0.944	0.100	0.056
Current scale of water supply project	0.409	0.906	0.972	0.028	0.205
Per capita water use	0.131	0.761	0.088	0.921	0.079
Water use volume of irrigation per unit	0.365	0.312	0.291	0.709	0.337
10^4 Yuan GDP water use	0.302	0.710	0.458	0.405	0.290
Per capita GDP	0.595	0.767	0.390	0.497	0.233
Standard discharge rate of waste water	0.502	0.475	0.414	0.586	0.512
The total amount of COD discharge	0.000	0.185	0.552	1.000	0.825
Green coverage rate	0.614	0.815	0.697	0.185	0.498

Table 4. The initial regional water rights allocation results of Dalinghe River Basin in planning year 2030 under water frequency 50%.

Quantity Allocation about Initial Regional Water Rights	Related Results
Optimal projection direction $\theta = (\omega_1, \ldots, \omega_{12})$	(0.373, 0.046, 0.233, 0.290, 0.041, 0.001, 0.003, 0.001, 0.004, 0.001, 0.006)
Optimal projection value $d^*(k)$, here, $k = 1, 2, 3, 4, 5$	① *Jinzhou*: $d^*(1) = 0.351$; ② *Fuxin*: $d^*(2) = 0.352$; ③ *Chaoyang*: $d^*(3) = 0.767$; ④ *Panjin*: $d^*(4) = 0.141$; ⑤ *Huludao*: $d^*(5) = 0.106$
Ratio of regional initial water quantity rights allocation ω_{R_j}	① *Jinzhou*: $\omega_{R_1} = 20.4\%$; ② *Fuxin*: $\omega_{R_2} = 20.5\%$ ③ *Chaoyang*: $\omega_{R_3} = 44.7\%$; ④ *Panjin*: $\omega_{R_4} = 8.2\%$; ⑤ *Huludao*: $\omega_{R_5} = 6.2\%$

5.2. Solutions of Initial Regional Pollutant Discharge Rights in Dalinghe River Basin

Using data in Table 3, according to regional initial pollutant discharge allocation model in this paper, we can calculate solutions for Dalinghe River Basin (Table 5).

Table 5. Calculations of initial regional pollutant discharge rights allocation in Dalinghe River Basin in planning year 2030 under water frequency 50%.

Allocation of Regional Pollutant Discharge Rights	Related Results	
Objective function F_1	Revenue function of pollutant discharge rights:	*Jinzhou* : $F_{11} = GDP_1(x_1) = 278.9x_1 - 26318$
		Fuxin: $F_{12} = GDP_2(x_2) = 976.4x_2 - 41893$
		Chaoyang: $F_{13} = GDP_3(x_3) = 375.4x_3 - 1001$
		Huludao: $F_{15} = GDP_5(x_5) = 169.3x_5 - 78230$
Objective function F_2	Parameters selected: $\beta_i = 1/3, i = 1, 2, 3$	
	Using Equation (2) to calculate: $F_{21} = (x_1/x_2 - \beta_1 \times 0.666 - \beta_2 \times 2.508 - \beta_3 \times 0.776)^2$; $F_{22} = (x_1/x_3 - \beta_1 \times 0.256 - \beta_2 \times 0.353 - \beta_3 \times 1.527)^2$; $F_{24} = (x_1/x_5 - \beta_1 \times 2.286 - \beta_2 \times 6.007 - \beta_3 \times 2.558)^2$; $F_{25} = (x_2/x_3 - \beta_1 \times 0.384 - \beta_2 \times 0.141 - \beta_3 \times 1.968)^2$; $F_{27} = (x_2/x_5 - \beta_1 \times 3.429 - \beta_2 \times 2.395 - \beta_3 \times 3.296)^2$; $F_{29} = (x_3/x_5 - \beta_1 \times 8.941 - \beta_2 \times 17.011 - \beta_3 \times 1.675)^2$;	
Constraint condition	$x_1 + x_2 + x_3 + x_5 \leq 12182.969$; $x_1 >$, $x_2 > 0$, $x_3 >$, $x_5 > 0$	
Initial regional pollutant discharge rights (10^8)	The results can be acquired by Equation (22): *Jinzhou*: $x_{R_1} = 3.39$; *Fuxin* : $x_{R_2} = 2.39$; *Chaoyang*: $x_{R_3} = 5.14$; *Huludao*: $x_{R_5} = 1.27$	

5.3. Calculation of Coupling Allocation for Regional Water Rights in Dalinghe River Basin

Using the allocation proportion for regional initial water quantity rights ω_{S_k} in Table 4, and the initial regional pollutant discharge x_{R_j} in Table 5, we can calculate results by the coupled allocation model in this paper (Table 6).

Table 6. Allocation plan of initial regional water rights of Dalinghe River Basin in planning year 2030 under water frequency 50%.

Allocation Variables	Related Results
Parameters Selected	Parameters selected: $c = 10$; $\mu({x_{S_k}}^R / x_{S_k}) = ({x_{S_k}}^R / x_{S_k}) / [{x_{S_k}}^R / x_{S_k} + 10]$
Adjusted ratio of regional initial water rights allocation	① *Jinzhou*: ${\omega_{R_1}}' = \omega_{R_1} \times 0.89 = 0.204 \times 0.89 = 0.182$; ② *Fuxin*: ${\omega_{R_2}}' = \omega_{R_2} \times 0.88 = 0.205 \times 0.88 = 0.180$; ③ *Chaoyang*: ${\omega_{R_3}}' = \omega_{R_3} \times 1.03 = 0.447 \times 1.03 = 0.462$; ④ *Panjin*: ${\omega_{R_4}}' = \omega_{R_4} \times 1 = 0.082 \times 1 = 0.082$; ⑤ *Huludao*: ${\omega_{R_5}}' = \omega_{R_5} \times 1.05 = 0.062 \times 1.05 = 0.065$
Normalized ratio of regional initial water rights allocation	① *Jinzhou*: ${\omega_{R_1}}'' = 0.188$; ② *Fuxin*: ${\omega_{R_2}}'' = 0.185$; ③ *Chaoyang*: ${\omega_{R_3}}'' = 0.476$; ④ *Panjin*: ${\omega_{R_4}}'' = 0.085$; ⑤ *Huludao*: ${\omega_{R_5}}'' = 0.065$

We compare the solutions with Dalinghe River Basin's pilot allocation plans, which were published by Ministry of Water Resources in China in 2008, and the results can be found in Table 7.

Table 7. The comparison between solutions of this model and pilot plans of Ministry of Water Resources in China (water frequency 50%, planning year 2030, in Dalinghe River Basin).

Ratio of Regional Initial Water Rights Allocation (%)	Region				
	Jinzhou	Fuxin	Chaoyang	Panjin	Huludao
Solutions of this model	18.77%	18.52%	47.58%	8.46%	6.67%
Pilot plans of Ministry of Water Resources	21.62%	21.77%	44.29%	7.78%	4.54%

Compared to the existing pilot plans of China's Ministry of Water Resources, we can obtain the following results: (1) our results are largely consistent with the allocation results of pilot plans in planning year 2030 under water frequency 50%, namely Chaoyang City acquires the most quantity of initial regional water rights, and then Jinzhou, Fuxin, Panjin and Huludao follow, sequentially; and (2) concerning the pollutant discharge, according to our incentive function, compared with the result of pilot plans, our results for Jinzhou and Fuxin is relatively low, while Chaoyang, Panjin and Huludao are comparatively high. Considering water quantity and water quality are the natural coupling characteristics about water resources, this coupled allocation method emphasizes water quantity and water quality should be considered simultaneously during initial regional water rights allocation.

6. Conclusions

The fair, reasonable and efficient allocation plans of initial water rights among different regions are a significant measure to solve the crisis of water resources scarcity. However, most previous research on allocation for regional initial water rights only considered the quantity components of that allocation, not the quality aspects. Under both constraints of water quantity and quality, we provide a new perspective for coupled allocation model of regional initial water rights for Dalinghe River Basin, China.

First, the study finds that, with the new circumstances of China's most stringent water resources management, and the requirements of "Three Red Lines", the construction of index system should consider total water use, water quality and water use efficiency simultaneously during allocation of initial regional water quantity rights.

Second, the total pollutant discharge of all regions should not exceed pollutant discharge of the basin. Under this control, the optimized objectives of economy and society should both be considered during the allocation of initial regional pollutant discharge rights.

Third, since initial regional water rights are composed of initial regional water quantity rights and initial regional pollutant discharge rights, we can design an incentive function that embeds the regional water pollution element into quantity allocation model of the initial regional water rights. This coupled allocation model for regional initial water rights not only reflects penalty function for over standard discharge, but also the positive incentives for less than standard discharge.

Fourth, water quantity and quality are naturally coupled. Initial water rights allocation of Dalinghe River Basin is a coupled problem for facing the situation of "Three Red Lines", which includes both water quantity and quality aspects. This study addresses the problem of regional initial water rights allocation for Dalinghe River Basin. Considering an integrated view of water quantity and quality, the initial regional pollutant discharge rights should be considered as crucial aspect of allocation plans of the initial regional water rights. It expands previous pilot plans for Dalinghe River Basin, which only pay close attention to water quantity.

Fifth, the empirical analysis results indicates that, in Dalinghe River Basin in year 2030, with water frequency 50%, Chaoyang City acquires the most quantity of initial water rights, and Jinzhou, Fuxin, Panjin and Huludao follow in turn. By comparing with existing pilot plans of China's Ministry of Water Resources, this paper proposes the coupled allocation method of initial regional water rights. Empirical results reflect this integrated model and relative algorithm is feasible. Similar research on other basins can use this model for reference. However, this paper still has its limitations. Our future research will focus on establishing a more reasonable function to fit the incentive mechanism well.

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