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A Provincial Initial Water Rights Incentive Allocation Model with Total Pollutant Discharge Control

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Academic Editors: Guangxin Zhang and Y. Jun Xu
Received: 25 August 2016; Accepted: 2 November 2016; Published: 11 November 2016

Abstract: According to the newly introduced water resources management in China, which is the most stringent thus far, pollution limits of water functional zones should be enhanced. In response to this recent change, we propose a provincial initial water rights incentive allocation model with total pollutant discharge constraint. Firstly, three objective functions are set up, namely the maximum comprehensive economic benefits of basin, the optimal fairness and coordination of the provincial pollutant discharge rights, and the minimum losses of basin ecological environment. Based on the objective functions and constraint of total pollutant discharge, we put forward a multiple-objective provincial initial pollutant discharge rights allocation model with a self-adaptive chaotic optimization algorithm. Secondly, according to the incentive mechanism of rewarding excellence and punishing inferiority, we establish a provincial initial water rights allocation model with an incentive function which includes the amount of provincial initial pollutant discharge. Finally, we select the Taihu Basin as a case study to describe the methodology. Under water frequencies of 50%, 75%, and 90%, the empirical results of provincial initial water rights allocation of the Taihu Basin in 2030 show that Jiangsu Province will obtain the most initial water rights, followed by Zhejiang Province and Shanghai city. The incentive allocation model of the provincial initial water rights is effective and the algorithm is feasible. The model may help to assure the most stringent water resources management strategies that are effectively carried out in the Taihu Basin.

Keywords: the total pollutant discharge control; provincial initial pollutant discharge rights; incentive function; provincial initial water rights

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1. Introduction

Although China's water resources are rich, the country's available water is less than one quarter of the world average, in addition, water use efficiency and benefits are relatively low. At present, along with a rapidly growing population, industrialization, and urbanization, two thirds of China's cities suffer water shortages, and many farmlands are damaged annually by drought. Water pollution is increasing, and many aquatic ecosystems are in decline. In China, water resources now present the most important obstacle for continued economic growth and sustainable social development.

Clarification of initial water rights is the basis and prerequisite for water rights trade-offs in China. Hence, it is an effective solution to the problem of water shortages and an important approach to enhance the efficiency and benefit of water resources utilization. As an important part of basin initial water rights, provincial initial water rights include provincial initial water quantity rights and provincial initial pollutant discharge rights [1]. The allocation of provincial initial water rights is a complicated problem that involves redistribution of vested interests and needs to give consideration to the requirements of multiple participants. Facing the most stringent water resources management, the theory and practice of provincial initial water rights allocation should meet the new requirements of this institution. In addition, a reasonable allocation of provincial initial water rights, which is tied to the total water use, the water use efficiency and pollutant discharge have become the major elements and core aspects of basin initial water rights allocation during the new period of the most stringent water resources management in China.

The optimal allocation of provincial initial water rights has been an active research field both in foreign and domestic areas in recent years. Preliminary literature were concerned with quantity allocation of provincial initial water rights including hybrid allocation methods [2,3], multi-participation allocation models [3–5], multi-objective optimization methods [6–9], and interactive or harmonious allocation models [10–12]. Afterwards, considering the importance of water quality, some research paid attention to provincial initial pollutant discharge rights allocation, which can be divided into the following four aspects:

(1) Based on the principle of equity, Mostafavi et al. [13] created a waste load allocation model using a non-dominated archiving multi-colony ant algorithm. Sun et al. [14] built a basin level water waste permits allocation model based on the information entropy.
(2) Using a single-objective decision making model, Gao Zhu et al. [15] carried out research on the initial allocation of pollutant discharge based on water function regionalization. Wan Shan et al. [16] established an initial pollutant discharge allocation model based on the simulation study of both economic optimality and fairness of allocation.
(3) With a multi-objective decision making method, Huang Xianfeng et al. [17] took into consideration a two level allocation model of river emission rights. The economical optimization and water quality optimization were regarded as the objective functions. The concentration and total quantity of pollutant were the constraints and the principle of equality and continuity of the production program of the dischargers were taken into account. In addition, Huang Binbin et al. [18] carried out research on an optimal allocation model of river pollutant discharge based on pollution limits.
(4) Using a hybrid allocation model, Liu Gang et al. [19] constructed a cooperation allocating initial discharge permits system for industrial source points in the Taihu Lake basin which was regulated by the policy-oriented government, led by economy-oriented government subjects and included the participation of many stakeholders. In addition, Liu Nianlei et al. [20] studied the pollutant discharge with an entropy weighing method and improved the proportional distribution method.

The literature mentioned above is only concerned with the single perspective of water quantity or water quality. Since water quantity and water quality are two basic properties of water resources, initial water rights allocation should consider water quantity and quality simultaneously. Recently, several studies have focused on this area, but the research is still insufficient. For instance, Wang Zongzhi et al. [21] established a basin initial two-dimensional water rights allocation model in which the maximum water resource system in harmony with a river basin is regarded as an object function. However, they did not take into account the initial pollutant discharge allocation aiming at the most stringent water resources management constraints. They only established a penalty function of a higher-than-standard pollutant discharge, but ignored positive inspiration for the lower-than-standard pollutant discharge. Wu Dan et al. [22] applied the interactive iteration algorithm into the study of basin initial water rights allocation. However, they neglected incentive mechanisms of rewarding excellence and punishing inferiority in the water environmental protection. In addition, Zhang Lina et al. [23] made an analysis of the framework of basin initial water rights allocation from a coupling perspective. However, they did not carry out the specific model of this framework.

According to the existing literature, despite different perspectives, many studies have applied a considerable amount of provincial water rights allocation methods in pursuit of a more scientific and effective allocation plan. However, for the new scenarios of the most stringent water resources management, the existing studies of relevant aspects have the following defects:

- Firstly, the most stringent water resources management set the benchmark of the "three red lines", which means a "red line" for total water use, a "red line" for water use efficiency, and a "red line" for controlling pollution. The initial water rights allocation models focused on the first two "red lines", but were less concerned with the third "red line" which illustrates the pollution limits of the water functional zones that should be enhanced. The third "red line" can be considered by the allocation of initial pollutant discharge, but current models of provincial initial pollutant discharge rights allocation are insufficient, and existing research in this area also lacks a comprehensive consideration of utilization benefits including economy benefit, society benefit, and ecological environmental benefit.
- Secondly, the incentive mechanism of rewarding excellence and punishing inferiority is crucial. In the field of water resources management, it is important to punish the over standard pollutant discharge during environmental protection of water resources. However, in reality, it is also necessary to implement positive incentives to the less than standard pollutant discharge. How to embed water pollution problems into the initial water right allocation and establish the incentive function is rarely considered and really needs further discussion.

To address these issues, in this paper we apply a well-developed model that produces new insights regarding the related literature. To be specific, under the new scenario of the most stringent water resources management, according to the situation where a water shortage caused by the poor quality of water has become a bottleneck during the sustainable development of a provincial economy, we propose a provincial initial water right incentive allocation model with a total pollutant discharge constraint. More concretely, the contributions of this paper can be illustrated as follows:

- Firstly, in contrast to the existing models of provincial initial pollutant discharge rights allocation, we focus on the comprehensive consideration of utilization benefits including economic benefits, societal benefits, and ecological environmental benefits. Hence, the first contribution of this paper is that we set up three objective functions separately including the maximum comprehensive economic benefits of basin, the optimal fairness and coordination of provincial pollutant discharge rights, and the minimum losses to the ecological environment of the basin. Furthermore, based on the three objective functions and the constraints of the total pollutant discharge, we put forward a multiple-objective provincial initial pollutant discharge rights allocation model with a self-adaptive chaotic optimization algorithm.
- Secondly, none of the aforementioned papers consider the incentive mechanism for rewarding excellence and punishing inferiority in the water environmental protection; however, awarding the less than standard pollutant discharge is as important as punishing the over-standard pollutant discharge. Hence, the second contribution of this paper is that we establish an incentive function by embedding the amount of provincial initial pollutant discharge and we follow the mechanism of rewarding excellence and punishing inferiority.
- Thirdly, by using this incentive function, we attempt to embed pollutant discharge allocation into the process of initial water quantity rights allocation, so as to internalize externalities of over-standard or under-standard pollutant discharge into the initial water rights allocation. Hence, the third contribution of this paper is that we set up a provincial initial water rights allocation model with the above incentive function considering both water quantity and water quality.

The rest of the paper is organized as follows. Section 2 introduces the framework of our research. Section 3 presents a multi-objective allocation model of provincial initial pollutant discharge rights with a total pollutant discharge constraint. Section 4 provides an incentive function to build a provincial initial water rights allocation model from a coupling perspective with the dual control of water quantity and water quality. Section 5 displays the case study of the Taihu Basin. Section 6 summarizes our work.

2. Research Framework

The framework of our research will follow these basic ideas: Creation of a provincial pollutant discharge rights allocation model based on three optimal objectives including benefits to the economy, society, and ecological environment under total pollutant discharge control; a coupled provincial initial water rights incentive allocation model with dual control for water quantity and water quality; and empirical research for the Taihu Basin. It is depicted in Figure 1.

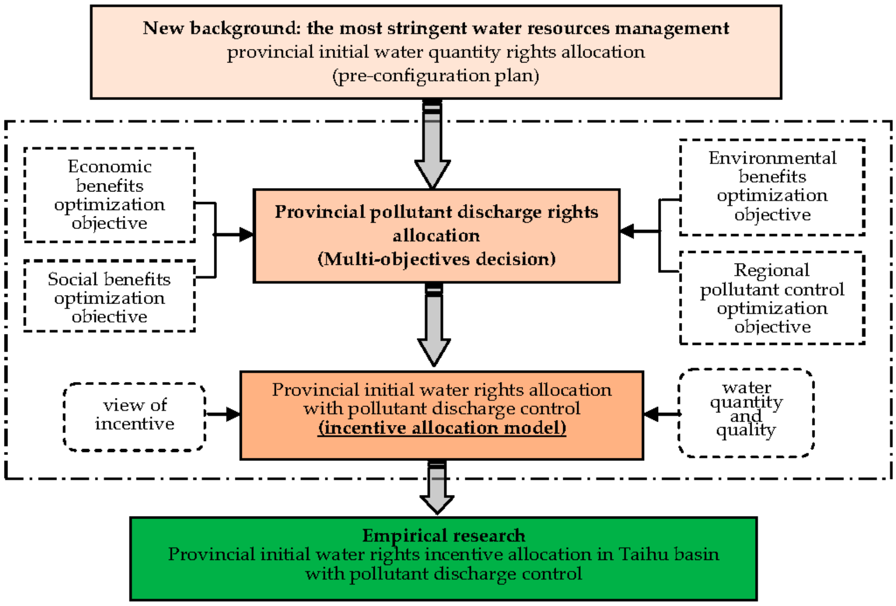

Figure 1. Framework of provincial initial water right incentive allocation.

As is clearly indicated in Figure 1, the specific framework includes three steps: (1) building the provincial pollutant discharge rights allocation model. According to the requirement of total pollutant control, we adopt three optimization goals for economy, society, and ecological environment to establish a provincial initial pollutant discharge allocation model and obtain an initial pollutant discharge rights solution for different provinces; (2) developing a coupled provincial initial water rights allocation model. With total pollutant discharge control, we set up an incentive function according to the mechanism of rewarding excellence and punishing inferiority. As the incentive allocation model of provincial initial water rights with water quantity and quality is proposed, we can get the provincial initial water rights allocation results; (3) illustrating empirical research for the Taihu Basin.

3. Multi-Objective Provincial Initial Pollutant Discharge Rights Allocation Model

We divide the comprehensive utilization benefits into those for economy, society, and the ecological environment. This is mainly based on the following considerations: Firstly, economic benefits reflect the utilization level of water resources and the production efficiency. Secondly, social benefits show the equality of social allocation and the harmonious relationship in a region; Thirdly, ecological benefits mainly represent pressure or maintenance because the pollutant discharge into the river affects the ecological system. Based on these, considering the three optimization objectives of economic, social, and ecological environmental benefits, we put forward a provincial initial pollutant discharge rights allocation model to meet the total pollutant discharge control.

3.1. Model Construction

S_k denotes the province, $k = 1, 2, ..., q$. x_{S_k} denotes the pollutant discharge amount of the province S_k, $k = 1, 2, ..., q$.

3.1.1. The Objective Functions of the Model

Objective function 1: let economic benefit optimization be F_1 which means the biggest general economic benefit. This can be presented by Equation (1).

$$F_1 = \max f_1(X) = \max\sum_{k=1}^{q} F_{1k} = \max\sum_{k=1}^{q} f_{1k}(X) = \max\sum_{k=1}^{q} GDP_k(x_{S_k}) \quad (1)$$

where $F_{1k} = f_{1k}(X) = GDP_k\left(x_{S_k}\right)$, $GDP_k\left(x_{S_k}\right)$ is the revenue function of province S_k when it obtains the pollutant discharge rights x_{S_k}.

Objective function 2: let social benefits optimization objective function be F_2 which reflects the best equality and coordination of provincial pollutant discharge allocation. This can be described by Equation (2).

$$F_2 = \min f_2(X) = \min\sum_{k=1}^{q} F_{2k} = \min\sum_{k=1}^{q} f_{2k}(X) = \min\sum_{i=1}^{q}\sum_{j=1}^{q}[(x_{Si}/x_{Sj}) - \sum_{l}^{3}\beta_l\gamma_l(S_i/S_j)]^2, i \neq j \quad (2)$$

where $F_{2k} = f_{2k}(X) = [(x_{Si}/x_{Sj}) - \sum_{l}^{3}\beta_l\gamma_l(S_i/S_j)]^2$, $\gamma_l(S_i/S_j)$ separately represents the ratio of population, area, and GDP index value between province S_i and province S_j, $l = 1,2,3$. β_l reflects the relative importance of population, area, and GDP index value between province S_i and province S_j, and $\sum_{l=1}^{3}\beta_l = 1$.

Objective function 3: set ecological environment optimization objective function to F_3 which means the smallest damage to the ecological environment. This can be illustrated by Equation (3).

$$F_3 = \min f_3(X) = \min\sum_{k=1}^{q} F_{3k} = \min\sum_{k=1}^{q} f_{3k}(X) = \min\sum_{k=1}^{q} \eta_k P_k(x_{S_k}) \quad (3)$$

where $F_{3k} = f_{3k}(X) = \eta_k P_k\left(x_{S_k}\right)$, η_k is the environmental damage coefficient of province S_k after receiving the pollution, $k = 1,2,...,q$. When η_k is bigger, the damage situation of province S_k is worse. $P_k\left(x_{S_k}\right)$ is the environmental damage function of province S_k after receiving pollution x_{S_k}, $k = 1,2,...,q$.

3.1.2. The Constraint Condition of Model

Constraint condition 1: the total amount of every province's pollutant discharge cannot exceed the amount of the basin's pollutant discharge P_{total}, which can be expressed by Equation (4).

$$\sum_{k=1}^{q}\left(x_{S_k}\right) \leq P_{total} \quad (4)$$

Constraint condition 2: non-negative constraints of variables which can be described by Equation (5).

$$x_{S_k} \geq 0 \quad (5)$$

where $k = 1,2,...,q$.

3.2. Model Calculation

We construct our model using Equations (1)–(5). The model includes the three important objective functions of economic benefits, social benefits and ecological environmental benefits. The detailed procedures of calculation can be described as follows.

3.2.1. Non-Dimension of Objective Functions

Objective function F_1 should be turned into function minimization as follows:

$$F_1 = \max f_1(X) = \min[-f_1(X)] = \min[-\sum_{k=1}^{q} GDP_k(x_{S_k})] \tag{6}$$

However, the objective function F_1, F_2, and F_3 have different scales; therefore, it is necessary to transform them into non-dimensional ones which can be represented by F_1', F_2', and F_3'. Here, we use the ideal point method of multiple objective planning to remove dimensions or balance magnitude differences.

Firstly, three single-objective planning models can be expressed by Equations (7)–(9).

$$\begin{cases} F_1 = \min\left[-f_1\left(X\right)\right] \\ S.T. \begin{cases} \sum\limits_{k=1}^{q}\left(x_{S_k}\right) \leq P_{total} \\ x_{S_k} \geq 0 \end{cases} \end{cases} \tag{7}$$

$$\begin{cases} F_2 = \min\left[f_2\left(X\right)\right] \\ S.T. \begin{cases} \sum\limits_{k=1}^{q}\left(x_{S_k}\right) \leq P_{total} \\ x_{S_k} \geq 0 \end{cases} \end{cases} \tag{8}$$

$$\begin{cases} F_3 = \min\left[f_3\left(X\right)\right] \\ S.T. \begin{cases} \sum\limits_{k=1}^{q}\left(x_{S_k}\right) \leq P_{total} \\ x_{S_k} \geq 0 \end{cases} \end{cases} \tag{9}$$

Secondly, the optimal solutions of Equations (7)–(9) can be expressed by $-f_1\left(X^*\right) f_2(X^*)$ and $f_3(X^*)$. In order to remove the dimensions of the objective function F_1, F_2, and F_3, we define F_1' as the non-dimensional objective function of F_1, define F_2' as the non-dimensional objective function of F_2, and define F_3' as the non-dimensional objective function of F_3. Then, according to the ideal point method of multiple objective planning to remove dimensions, F_1', F_2' and F_3' can be illustrated as follows:

$$F_1' = \left[f_1\left(X\right) - f_1\left(X^*\right)\right] / f_1\left(X^*\right) \tag{10}$$

$$F_2' = \left[f_2\left(X\right) - f_2\left(X^*\right)\right] / f_2\left(X^*\right) \tag{11}$$

$$F_3' = \left[f_3\left(X\right) - f_3\left(X^*\right)\right] / f_3\left(X^*\right) \tag{12}$$

Simplify the vector optimization problem of the three objective functions F_1, F_2, and F_3 into scalar optimization and it can be written as follows:

$$F' = \left(F_1'\right)^2 + \left(F_2'\right)^2 + \left(F_3'\right)^2 \tag{13}$$

3.2.2. The Transformation of the Multi-Objective Planning Model

Transfer the former multi-objective planning model into a nonlinear problem which can be expressed by Equation (14).

$$\begin{cases} \min F' = (F_1')^2 + (F_2')^2 + (F_3')^2 \\ S.T. \begin{cases} \sum\limits_{k=1}^{q}(x_{S_k}) \leq P_{total} \\ x_{S_k} \geq 0 \end{cases} \end{cases} \tag{14}$$

3.2.3. Solving the Model

In order to obtain the amount of initial pollutant discharge rights x_{S_k} for the different province S_k, $k = 1, 2, ..., q$, we need to solve Equation (14) which is a single-objective nonlinear planning equation. The regular methods to solve Equation (14) can be adopted, including the chaotic optimization algorithm (COA), genetic algorithm (GA), and simulated annealing algorithm. As a new optimization technique, COA is developed with the characteristics of sensibility, pseudo-randomness, ergodicity, and self-similar fractals, but it needs to calculate many objective functions and its disadvantage it its slow convergence [24]. Although GA is an easy solution, it still has many disadvantages including precocious, inferior local search ability. The simulated annealing algorithm has a better local search capability and a shorter running time, but its global search capability is poor, and it is easily affected by parameters.

To overcome the problems of the above algorithms, we adopt the following method: (1) improve the quality of individuals of the initial group through chaotic ergodicity; (2) according to the adaptability of crossing operators and mutation operators, the search capability and the convergence rate of the genetic algorism can be improved. Furthermore, the algorithm makes it almost impossible to fall into local optimization; (3) the whole annealing selection model with the parent involved competition is used to increase diversity. In order to avoid premature convergence, we choose a hybrid parent body Therefore, we adopt a self-adoptive chaotic optimization algorithm [25] to solve Equation (14). The detailed steps of the self-adoptive chaotic optimization algorithm are as follows:

Step 1: Parameter initializing. Set B to the population size, set M to the chaotic iteration, set T_0 to the initial temperature, set T_{END} to the final temperature, set P_{c1}, P_{c2}, P_{m1}, and P_{m2} to the self-adaptive parameters.

Step 2: Initial population generation. Chaotic equation is produced by the logistic map formula in Equation (15).

$$X_{k+1,j} = \vartheta \cdot X_{k,j} \cdot \left(1 - X_{k,j}\right) \tag{15}$$

where ϑ is the control parameter, then when $\vartheta = 4$ the system is in chaos. According to Equation (15), we can randomly generate several initial populations formed by chaotic series.

Step 3: Evaluation of the individual fitness function. Make the objective function in Equation (15) be the self-adaption evaluate function, and punish the individuals who break the constraint conditions. Record the best individual of every generation, after solving it, replace the individual whose fitness is the lowest. Then the best individual is ensured to enter into the next generation.

Step 4: Calculation. According to the whole annealing mechanism [26], allow the parent to take part in the competition. According to the fitness of the individual, the formula of self-adaption, and the formula of selection probability [25], we can determine the crossover probability and the mutation rate, then process the crossover calculation and mutation calculation. Finally, we can get the next generation by this formula of selection probability.

Step 5: Judgment of the termination of algorithm. The descent rate of temperature T_k can be presented by Equation (16).

$$T_k = 1/\ln\left(k/T_0 + 1\right) \tag{16}$$

where k is iteration time. When temperature T_k is bigger than the final temperature T_{END}, go back to Step 3, and evaluate fitness of the individual. Or, we can eventually obtain the amount of initial pollutant discharge rights x_{S_k} for the different province S_k, where $k = 1, 2, ..., q$.

4. Provincial Initial Water Rights Incentive Allocation Model

4.1. Basic Design Idea of the Incentive Mechanism

Assume that the total amount of initial allocation water rights is W, then the pre-configuration allocation plans of provincial initial water quantity rights w_{S_k} can be presented by Equation (17).

$$w_{S_k} = W \times \omega_{S_k} \tag{17}$$

where ω_{S_k} is the pre-configuration allocation proportion of the initial water quantity rights of province S_k; in this paper we assume this is already known. Then water quantity rights w_{S_k} need to be coupled with provincial initial pollutant discharge rights x_{S_k} which were calculated by Equation (14). In order to achieve this goal, we absorb the idea from "rewarding excellence and punishing inferiority" to design the incentive mechanism which can be described as follows:

- Set the real amount of pollutant discharge of province S_k to ${x_{S_k}}^R$. When the real amount of pollutant discharge ${x_{S_k}}^R$ exceeds the initial pollutant discharge rights x_{S_k}, the negative incentive should be implemented to reduce its initial water quantity rights.
- When the real provincial amount of pollutant discharge ${x_{S_k}}^R$ is lower than the initial pollutant discharge rights x_{S_k}, the positive incentive should be implemented to increase its initial water quantity rights.

4.2. Model of the Incentive Allocation

According the above incentive mechanism, different provinces in the same basin can get their own initial water rights through the coupling control of total water use and total pollutant discharge. The specific processes can be presented as follows:

Step 1: Set the incentive function to $\mu({x_{S_k}}^R/x_{S_k})$, and then the incentive function can be designed by Equation (18).

$$\mu({x_{S_k}}^R/x_{S_k}) = \begin{cases} \left|x_{S_k}/{x_{S_k}}^R - 1\right|^{\partial} & x_{S_k} < {x_{S_k}}^R \\ 1 & x_{S_k} = {x_{S_k}}^R \\ \left|{x_{S_k}}^R/x_{S_k} - 1\right|^{\partial} & x_{S_k} > {x_{S_k}}^R \end{cases} \tag{18}$$

where ∂ is an adjustment coefficient which reflects the degree of incentive $\partial \in [2, 10]$. When the value of ∂ is higher, the changing trend of incentive degree is smoother.

Step 2: According to the incentive function, the adjustment of the proportion of the water rights allocation of province S_k can be described by Equation (19).

$${\omega_{S_k}}' = \begin{cases} \omega_{S_k}\left(1 - \mu\left({x_{S_k}}^R/x_{S_k}\right)\right) & x_{S_k} < {x_{S_k}}^R \\ \omega_{S_k} & x_{S_k} = {x_{S_k}}^R \\ \omega_{S_k}\left(1 + \mu\left({x_{S_k}}^R/x_{S_k}\right)\right) & x_{S_k} > {x_{S_k}}^R \end{cases} \tag{19}$$

where ${\omega_{S_k}}'$ is the adjusted allocation proportion of the initial water rights of province S_k.

Step 3: ${\omega_{S_k}}'$ can be normalized by Equation (20).

$${\omega_{S_k}}'' = {\omega_{S_k}}' / \sum_{k=1}^{q} {\omega_{S_k}}' \tag{20}$$

where $k = 1, 2, ..., q$ and ${\omega_{S_k}}''$ is the normalized allocation proportion of initial water rights of province S_k.

Step 4: Finally, we can figure out the final quantity of initial water rights of province S_k by Equation (21).

$$w_{S_k}{}' = W \times \omega_{S_k}{}'' \quad (21)$$

where $k = 1, 2, ..., q$.

5. Empirical Study

5.1. Data Source

The administration areas in the Taihu Basin mainly include Jiangsu province, Zhejiang province, and Shanghai city. The map of the main administrative divisions in Taihu Basin are illustrated in Figure 2. The Taihu Basin is one of the most developed and most modernized regions in China. The amount of annual water use has reached 36.5 billion cubic meters, while the amount of the perennial water resources of the basin is only 19.6 billion cubic meters, so the demand-supply gap is huge. The problems of water shortage, worsening water pollution, and increasing demand for water resources have imposed undue pressure on the carrying capacities of the water resources and water environment in the Taihu Basin.

Figure 2. The map of the main administrative division of the Taihu Basin.

According to the materials of the Taihu Basin and Southeast Rivers Water Resources Bulletin and the Water Quality Bulletin of Taihu Basin and Important Water Function Areas of Southeast Rivers, and others, the pre-configuration allocation plan of the initial water rights for the Taihu Basin can be set as follows: the ratios of the initial water quantity rights of Jiangsu province, Zhejiang province, and Shanghai city are, respectively, 35.62%, 31.94%, and 32.45%. Furthermore, the area of those three provinces are 19,399 square kilometers, 12,093 square kilometers, and 5178 square kilometers, respectively. The specific relevant data of the Taihu Basin from 2011 to 2014 are shown in Table 1.

Table 1. The index values of the provinces in the Taihu Basin from 2011 to 2014.

Province	Year	Population (Ten Thousand Persons)	Per Capita GDP (Yuan)	Pollutant Discharge (One Hundred Million Cubic Meters)
Jiangsu	2011	2939	8.21	29.0
	2012	2960	8.97	29.1
	2013	2985	9.84	29.2
	2014	2996	10.68	28.3
Zhejiang	2011	1763	6.54	12.1
	2012	1775	6.97	12.1
	2013	1791	7.53	12.6
	2014	1797	7.98	12.9
Shanghai	2011	1175	12.01	22.6
	2012	1184	12.53	23.1
	2013	1194	13.44	22.9
	2014	1198	14.47	22.9

Notes: Data source: Taihu Basin and Southeast Rivers Water Resources Bulletin (2011–2014) and Water Quality Bulletin of Taihu Basin and Important Water Function Areas of Southeast Rivers (2011–2014).

5.2. Calculation of Provincial Initial Pollutant Discharge Rights Alloction

According to the materials of the Taihu Basin and Southeast Rivers Water Resources Bulletin in planning year 2030, the total amount of pollutant discharge rights will be 54.46 hundred million cubic meters. Using the data in Table 1, according to a multi-objective provincial initial pollutant discharge rights allocation model which is expressed by Equation (14), we can obtain relevant solutions which are shown in Table 2.

Table 2. Solutions of provincial initial pollutant discharge rights allocation (Taihu Basin, planning year 2030).

Provincial Initial Pollutant Discharge Rights Allocation	Calculation Results
Objective function F_1	Revenue function of Jiangsu's pollutant discharge rights [1]: $F_{11} = GDP_1\,(x_1) = 1410.8x_1 - 32200$
	Revenue function of Zhejiang's pollutant discharge rights: $F_{12} = GDP_2\,(x_2) = 1200.7x_2 - 10586$
	Revenue function of Shanghai's pollutant discharge rights: $F_{13} = GDP_3\,(x_3) = 4248.8x_3 - 80597$
	$F_1 = \max f_1(X) = \min[-f_1(X)] = \min[(32200 - 1410.8x_1) + (10586 - 1200.7x_2) + (80597 - 4248.8x_3)]$ Solving the Equation (7), $f_1(X^*) = 16359$; Using Equation (10), $F_1' = \min(0.086x_1 + 0.073x_2 + 0.26x_3 - 8.542)$
Objective function F_2	Parameters selected [2]: relative importance of province population, area, and GDP index: $\beta_1 = 1/3$, $\beta_2 = 1/3$, $\beta_3 = 1/3$
	Using Equation (2) to calculate: $F_{21} = (x_1/x_2 - \beta_1 \times 1.667 - \beta_1 \times 1.604 - \beta_1 \times 2.500)^2$; $F_{22} = (x_1/x_3 - \beta_1 \times 2.500 - \beta_1 \times 3.746 - \beta_1 \times 0.625)^2$; $F_{23} = (x_2/x_3 - \beta_1 \times 1.500 - \beta_1 \times 2.335 - \beta_1 \times 0.250)^2$; $F_2 = F_{21} + F_{22} + F_{23} = \min[f_2(X)] = \min[(x_1/x_2 - 1.92)^2 + (x_1/x_3 - 2.29)^2 + (x_2/x_3 - 1.36)^2]$; Solving the Equation (8), $f_1(X^*) = 0.0172$; Using Equation (11), $F_2' = \min[(x_1/x_2 - 1.92)^2 + (x_1/x_3 - 2.29)^2 + (x_2/x_3 - 1.36)^2 - 0.0172]/0.0172$
Objective function F_3	Parameters selected: environment damage coefficient [3]: Jiangsu $\eta_1 = 0.6$; Zhejiang $\eta_2 = 0.5$; Shanghai $\eta_3 = 0.5$
	Environmental damage function of Jiangsu province [4]: $P_1\,(x_{S_1}) = 3075.6x_1 - 47695$; Environmental damage function of Zhejiang province: $P_2\,(x_{S_2}) = 2890.2x_2 - 9226.2$; Environmental damage function of Zhejiang province: $P_3\,(x_{S_3}) = 1062.9x_3 - 13426$; $F_3 = \min[f_3(X)] = \min[0.6 \times (3075.6x_1 - 47695) + 0.5 \times (2890.2x_2 - 9226.2) + 0.5 \times (1062.9x_3 - 13426)]$; Solving the Equation (7), $f_3\,(X^*) = 12292$; Using Equation (11), $F_3' = \min(0.150x_1 + 0.118x_2 + 0.043x_3 - 4.25)$

Table 2. *Cont.*

Provincial Initial Pollutant Discharge Rights Allocation	Calculation Results
Constraint condition	$x_1 + x_2 + x_3 \leq 54.46;\ x_1 \geq 0; x_2 \geq 0; x_3 \geq 0$
Algorism parameter selecting	Initial population size B = 200, Chaotic iteration M = 100, Initial temperature T_0 = 100
Initial pollutant discharge of province (a hundred million cubic meters)	Using the Equation (14) to obtain the results as follows: Jiangsu $x_{S_1} = 27.55$; Zhejiang $x_{S_2} = 14.93$; Shanghai $x_{S_3} = 11.98$

Notes: [1] Revenue function of pollutant discharge can be obtained mainly by fitting analysis between the GDP of the province and the total pollutant discharge of the province; [2] Considering the population, area, and GDP as equally important to the initial water rights allocation, we assume $\beta_1 = 1/3, \beta_2 = 1/3, \beta_3 = 1/3$; [3] The environmental damage coefficients are obtained by the combination of actual provincial situation and expert opinion approach; [4] Environmental damage function can be obtained by fitting analysis between the pollution footprint and the pollutant discharge of the province according to the evaluation model of the water environmental ecological damage [27].

5.3. Provincial Initial Water Rights Incentive Allocation Calculation

In planning year 2030, using the amount of provincial initial pollutant discharge x_{S_k} in Table 2, according to the coupled provincial initial water rights incentive allocation model which is expressed by Equations (18)–(21), we can obtain the normalized allocation ratios of the initial water rights of the provinces which are shown in Table 3.

Table 3. The normalized allocation ratios of initial water rights incentive allocation (Taihu Basin, planning year 2030).

Variables for Initial Water Rights Incentive Allocation	Calculation Results
Parameters Selected	According to the Ratio between Real Pollutant Discharge and Initial Pollutant Discharge and the Expert Opinion Approach, We Select the Adjustment Coefficient $\partial = 3$
Adjusted value of incentive function for provinces	Using Equation (18) to calculate: Jiangsu Province: $(1 - 27.55/28.97)^2 = 0.002$; Zhejiang Province: $(1 - 11.97/14.93)^2 = 0.039$; Shanghai City: $(1 - 11.98/22.66)^2 = 0.222$
Pre-configuration allocation ratio of the initial water quantity rights of province	According to [28], the pre-configuration allocation ratio of the initial water quantity rights of province can be expressed as follows: Jiangsu Province $\omega_{S_1} = 35.63\%$; Zhejiang Province $\omega_{S_2} = 31.94\%$; Shanghai City $\omega_{S_3} = 32.45\%$
Adjusted allocation ratio of initial water rights of province	Using Equation (19) to calculate: Jiangsu Province $\omega_{S_1}{}' = 35.53\%$; Zhejiang Province $\omega_{S_2}{}' = 33.20\%$; Shanghai City $\omega_{S_3}{}' = 25.24\%$
The normalized allocation ratio of initial water rights of province	Using Equation (20) to calculate: Jiangsu Province $\omega_{S_1}{}'' = 37.81\%$; Zhejiang Province $\omega_{S_2}{}'' = 35.33\%$; Shanghai City $\omega_{S_3}{}'' = 26.86\%$

According to the materials of Water Resources Planning for Taihu Basin (2012–2030), under three different water frequencies of 50%, 75%, and 90%, in the planning year 2030, the amount of initial allocation water rights of Taihu Basin are, respectively, 329.2 hundred million cubic meters, 363.3 hundred million cubic meters, and 392.6 hundred million cubic meters.

Using the Equation (21), in the planning year 2030, the provincial initial water rights allocation plans in the Taihu Basin under water frequencies of 50%, 75%, and 90% can be calculated and are shown in Table 4.

For comparison with the "water use efficiency" allocation method provided by [28], the provincial initial water rights allocation plans are also presented in Table 4. The contrasted result can be shown as follows: (1) Under the different water frequencies of 50%, 75%, and 90%, in planning year 2030, our solutions are approximately consistent with the results of the "water use efficiency" allocation method, namely, Jiangsu Province obtains the most initial water rights, followed by Zhejiang Province and Shanghai City; (2) According to the pollutant discharge, due to our incentive function of rewarding excellence and punishing inferiority, when water frequency is the same, compared with the result of the "water use efficiency" allocation method, our result for Shanghai City is lower, while our results for Jiangsu province and Zhejiang province are higher. Since water resources have natural coupling characteristics of quantity and quality, our incentive allocation model emphasizes that considering both water quantity and quality is important to the provincial initial water rights allocation.

Table 4. The solutions and comparison for different allocation methods of provincial initial water rights in the Taihu Basin (under water frequencies of 50%, 75%, and 90%, planning year 2030).

Different Scenarios	Jiangsu Province			Zhejiang Province			Shanghai City		
	Different Water Frequency			Different Water Frequency			Different Water Frequency		
	50%	75%	90%	50%	75%	90%	50%	75%	90%
Our incentive allocation plans (a hundred million cubic meters)	124.47	137.36	148.44	116.31	128.35	138.71	88.42	97.58	105.45
"Water use efficiency" allocation model (a hundred million cubic meters)	117.25	129.39	139.83	105.13	116.02	125.38	106.82	117.89	127.39

6. Conclusions

In the context of the newly introduced water resources management in China, which is the most stringent thus far, the major elements and the core aspects of the basin initial water rights allocation are: considering a reasonable allocation of provincial initial water rights tied to the total water use, the water use efficiency and pollutant discharge. This research is focused upon the provincial initial water rights allocation model based on the dual control of water quantity and quality, which supports policy making decisions for the government with respect to sustainable water resources development. It also contributes to the policy implementation of the most stringent water resources management. In this paper, according to the provincial initial water rights incentive allocation model with total pollutant discharge constraint, the empirical result of the Taihu Basin shows that, under the different water frequencies of 50%, 75%, and 90%, in planning year 2030, Jiangsu Province obtains the most initial water rights, followed by Zhejiang Province and Shanghai City. Through the comparison with the "water use efficiency" allocation method, this paper illustrates that the province initial water rights incentive allocation model with the mechanism of rewarding excellence and punishing inferiority is effective and the algorithm is feasible. The incentive allocation model in this paper provides an important reference for similar research in the other basins. Of course, this study still has limitations. How to design a more reasonable incentive function will be our future research focus and requires further discussion.

Acknowledgments: The authors would like to thank the National Natural Science Foundation of China (Grant No. 71301063; Grant No. 41271537), sponsorship provided by "Jiangsu Overseas Research & Training Program for University Prominent Young & Middle-aged Teachers and Presidents", and "333" high-caliber talents cultivation project of Jiangsu Province (No. (2013)III-2110) for their financial support.

Author Contributions: Min Ge designed the research and drafted the manuscript; Feng-Ping Wu conducted the model simulation, reviewed, commented on, and revised the manuscript; Min You collected the data and participated in the model simulation. All authors have read and approved the final manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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