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Study on the Optimal Allocation of Water Resources Based on the Perspective of Water Rights Trading

Guangyao Wang [1], Xinyue Zhang [2,3,*], Lijuan Du [2,3], Bo Lei [2,3] and Zhenghe Xu [1]

[1] College of Water Conservancy and Environment, University of Jinan, 336 Nanxinzhuang West Road, Shizhong District, Jinan 250022, China; wgy19991125@foxmail.com (G.W.); stu_xuzh@ujn.edu.cn (Z.X.)
[2] State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, A-1 Fuxing Road, Haidian District, Beijing 100038, China; iwhr_dulj@foxmail.com (L.D.); bolei1228@hotmail.com (B.L.)
[3] China Institute of Water Resources and Hydropower Research (IWHR), A-1 Fuxing Road, Haidian District, Beijing 100038, China
* Correspondence: zhangxy@iwhr.com; Tel.: +86-13520179692

Abstract: Water rights trading plays an important role in the market mechanism to optimize the allocation of water resources. This study takes Luxian county of Sichuan province as the research area. Based on the prediction of water supply and demand, this study aims to achieve minimum water shortage and maximum economic benefits for regional water distribution, and introduces a water-saving reward and water price punishment mechanism to construct a two-layer collaborative regulation model of water rights trading for water users. The self-improved elite strategy and cogenetic algorithm (NSGA II-S) are used to solve the optimization model, and the optimal allocation of water resources and water rights trading in different towns in the planning year (2025 and 2030) under different flat and dry scenarios is studied. The results show that there would be an obvious problem in the uneven distribution of water resources between supply and demand in 2025 and 2030. The overall water shortage rates in the flat and dry scenario areas in 2025 are 13.71% and 31.99%, respectively, and the overall water shortage rates in the flat and dry scenario areas in 2030 are 11.55% and 31.94%, respectively. Water rights trading can increase the economic benefit value, with the economic benefit increasing by an average of CNY 614 million in all scenarios, an average increase of 8.68%. The research results could be helpful in alleviating the contradiction between the supply and demand of regional water resources and provide a theoretical basis for optimizing water resource allocation by means of water rights trading in the region.

Keywords: water rights trading; initial allocation of water rights; optimize configuration; water-rich region

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1. Introduction

Water resources are not only basic public resources, but also strategic economic resources with commodity attributes. With the continuous development of society, the demand for water resources is gradually increasing. In addition, population growth, the deterioration of water environments and climate change have caused the contradiction between supply and demand of water resources to become increasingly prominent [1], resulting in a shortage of water resources in most parts of the world [2,3]. China's water resources are not only poor in total, but are also uneven in their spatial and temporal distributions [4]. Therefore, in the current situation of the increasing shortage of water resources, it is of great significance to rationally optimize the spatial and temporal allocation of water resources to realize the efficient utilization of regional water resources.

Water rights trading is an effective means of allocating water resources based on the role of the market [5]. As a new model of water resource management, it is an important way of alleviating the water crisis [6]. Many countries and regions have carried out water rights trading projects [7–12], and there have been many successful cases [13–20].

The water rights trading model can solve the contradiction between the static nature of the initial allocation of water rights and the dynamic nature of social and economic development, improving the efficiency of water use and increasing the total economic income [21]. Many scholars have studied it from different angles. Fu et al. [22] combined the two-stage interval parameter stochastic programming model and the water rights trading model and applied this to the Sanjiang Plain area to obtain the optimal trading volume. Based on the dynamic game theory, Wu Dan et al. [23] constructed the regional interest game and optimization model for the Daling River Basin in Liaoning province. Chen et al. [24] introduced the theory of property rights and applied it to cross-market water rights transactions in Bayannaoer city and Ordos city. When constructing the water rights trading model, the above research did not consider the change in water demand of water users under normal and dry scenarios, and ignored the influence of key parameters on the economic benefits of the water rights trading system, resulting in the research results not meeting the actual water demand in the region and the adaptability being poor. This study constructs a two-level coordinated regulation model of water rights trading and introduces parameters, such as the trading water volume, trading price, water-saving incentive mechanism and punishment mechanism. It is of great practical significance to rationally optimize the utilization and reallocation of water resources under the scenario of water rights trading.

For regions with abundant water resources but a serious engineering water shortage, water rights trading is an effective way of alleviating the shortage of water resources between regions. Since 2017, Sichuan province has carried out the reform of water rights and water prices and selected four types of reform pilots for river basins, irrigation areas, regions and reservoirs, and achieved good reform results. In order to give full play to the advantages of regional water resources and improve the utilization efficiency and reallocation efficiency of regional water resources, this study carries out research on optimizing the allocation of regional water resources through water rights trading. The first part of this paper describes how the initial allocation model of water rights is constructed to obtain the preliminary scheme of the initial allocation of water rights. Through the water rights trading model, the optimal trading volume of water users and the maximum economic benefit value of the region are determined. The self-improved elite strategy and cogenetic algorithm (NSGA II-S) are used to solve the optimization model. In the second part, the paper describes how the reform pilot area of Luxian county, Sichuan province, is selected as the research object. Based on the prediction of water supply and demand, the optimal allocation of water resources and water rights trading in villages and towns under different scenarios in the planning year (2025 and 2030) is carried out through the two-layer coordinated regulation model of regional water users' water rights trading. The third part analyzes and discusses the results of the optimal allocation. The research results help to alleviate the contradiction between the supply and demand of regional water resources and provide an effective scheme for the region to optimize the allocation of water resources and improve the efficiency of irrigation water through water rights trading.

2. Research Methods

2.1. Model Framework

The two-level coordinated regulation model of the regional water rights trading established in this study took the minimum water shortage in the regional water distribution and the maximum economic benefit as the objective functions of the initial water rights allocation model and the water rights trading model, respectively. The initial water rights allocation model took the minimum water shortage in the region as the objective function and was used to reasonably allocate the initial water rights in the region. The model could guarantee the basic water demand in the region and coordinate the contradiction of water use between regions through water rights allocation. The water rights trading model was based on the initial allocation model of water rights and took the maximum economic benefit as the objective function to redistribute the regional water resources. The surplus water of townships was allocated to water-deficient townships through water rights trading, and the water sector with low economic benefits was allocated to the water sector with high economic benefits to improve the utilization efficiency and reallocation efficiency of regional water resources and to ensure the overall development of the regional economy and society.

The initial allocation scheme of water rights was obtained through the initial allocation model of water rights, which was used as the input data of the water rights trading model; then, the optimal trading water volume of water users and the maximum benefit value of the regional system were determined through the water rights trading model. The model constructed the topological relationship between the water-source–industry–user axis, established the initial optimal allocation model of water rights and the water rights trading model of different water users and introduced the water-saving reward and penalty water price. The two were coupled through the model and the influence of multiple key parameters (trading water volume, trading price, compensation benefit of water supply side, water-saving reward of water supply side and penalty effect of water supply side) on the overall system of water rights trading was systematically analyzed, which was conducive to improving the efficiency of water rights trading. The research framework of the two-layer collaborative regulation model of water rights trading is shown in Figure 1.

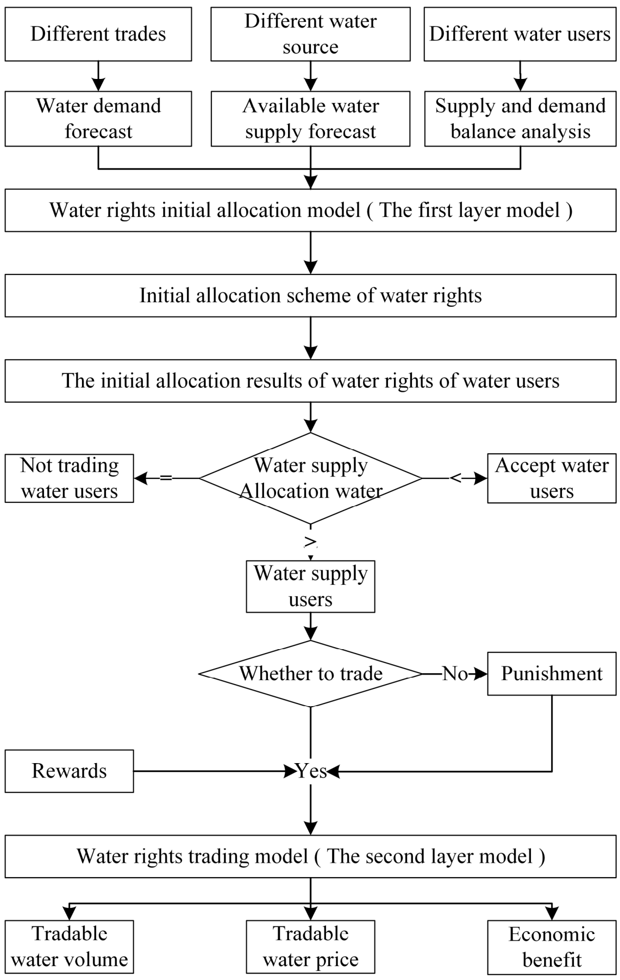


Figure 1. Research framework.

2.2. Model Construction

2.2.1. Initial Allocation Model of Water Rights

The structure of this model was divided into two layers. The first layer model was the initial allocation model of water rights. The model took the water distribution amount of different industries and different water sources as the decision variable and took the minimum water shortage of regional water distribution as the objective function. The constraints set up in the model included: domestic water demand constraints, agricultural water demand constraints, industrial water demand constraints, business water demand constraints, ecological water demand constraints, water supply constraints, external water supply constraints and non-negative constraints.

(1) Decision variables

The research took the water distribution amount of different water sources in different industries of different water users as the decision variable of the model.

(2) Objective function

Minimum regional water shortage:

$$minF = \sum_{i=1}^{n}\left[W_i^k - \sum_{j=1}^{7}\left(x_{ij}^k a_k\right)\right] \quad (1)$$

$$W_i^1 = p_0 \times (1+s)^t \times m \quad (2)$$

$$W_i^3 = V_{0i}(1+d)^t \quad (3)$$

where: F is the water shortage, which is the difference between the water demand and water distribution, 10^4 m^3; $i = 1, 2, 3, \cdots, n$ denotes different water users; n is the number of water users; $j = 1, 2, \ldots, 7$ represent ponds, reservoirs, water diversion, water pumping, wells, other water sources and external water sources, respectively; W_i^k is the water demand of each industry, 10^4 m^3; $k = 1, 2, 3, 4, 5$, respectively, represent domestic water, agricultural water, industrial water, business water and ecological water; p_0 is the total population of the current year; s is the population growth rate, ‰; t is the interval between the planning year and the current year; m is the domestic water quota, 120 L/person · d in the study; V_0 is the current annual industrial water consumption, 10^4 m^3; d is the growth rate of industrial water use,%; x_{ij}^k is the water distribution of each industry, 10^4 m^3; a_k is the water distribution coefficient of each industry and the values of each industry in the study were 0.3, 0.15, 0.15, 0.1 and 0.3, respectively.

(3) Constraints

Domestic water demand constraint:

$$W_i^1 b_1 = \sum_{j=1}^{7} x_{ij}^1 \quad (4)$$

where b_1 is the coefficient of domestic water demand; 1 was used in the study to give priority to ensuring domestic water use.

Agricultural water demand constraint:

$$W_i^2 b_2 \leq \sum_{j=1}^{7} x_{ij}^2 \leq W_i^2 \quad (5)$$

where b_2 is the agricultural water demand coefficient, which was 0.4 in the study.

Industrial water demand constraint:

$$W_i^3 b_3 \leq \sum_{j=1}^{7} x_{ij}^3 \leq W_i^3 \quad (6)$$

where b_3 is the industrial water demand coefficient, which was 0.3 in the study.

Business water demand constraint:

$$W_i^4 b_4 \le \sum_{j=1}^{7} x_{ij}^4 \le W_i^4 \tag{7}$$

where b_4 is the water demand coefficient of the business; 0.3 was taken in the study.

Ecological water demand constraint:

$$W_i^5 b_5 = \sum_{j=1}^{7} x_{ij}^5 \tag{8}$$

where b_5 is the ecological water demand coefficient; 1 was used in the study to give priority to ensuring ecological water use.

Water supply constraint of water source:

$$\sum_{i=1}^{n} \sum_{j=1}^{7} \left(x_{ij}^k a_k \right) \le \sum_{i=1}^{n} Q_i \tag{9}$$

$$Q_i = \sum_{j=1}^{7} \left(q_i^j c_j \right) \tag{10}$$

$$\sum_{j=1}^{7} \left(x_{ij}^k \right) \le q_i^j \tag{11}$$

where: Q_i is the total water supply of the water source, 10^4 m^3; q_i^j is the water supply of each industry, 10^4 m^3; c_j is the water supply coefficient of each water source and the values in the study were 0.25, 0.25, 0.2, 0.1, 0.1, 0.05 and 0.05.

Constraints of water supply of external water source:

$$\sum_{i=r} \sum_{j=7} \left(x_{ij}^k \right) \le s \tag{12}$$

where r represents the collection of water users and s represents the amount of water transferred from different reservoirs, 10^4 m^3.

Non-negative constraint:

$$x_{ij}^k \ge 0 \tag{13}$$

The purpose of solving the initial allocation model of water rights was to find the optimal value x_{ij}^k of the decision variable, obtain the optimal water allocation and minimize the water shortage. At the same time, the water allocation results could be used as the input data of the water rights trading model and then to solve the maximization of the economic benefits of the regional water rights trading system.

2.2.2. Water Rights Trading Model

The second layer model was the water rights trading model. Under the condition that the tradable target was determined, due to the different water supply and demand requirements of different water users, the transaction water price and cost water price of each water user were also different; therefore, some water users were short on water while some water users were rich in water. In this study, the excess water was traded and a penalty mechanism was introduced to deduct some benefits for water users who were unwilling to trade or traded less water so as to maximize the benefits of the transaction. The model took the transaction water volume and transaction water price of different water users as the decision variables and took the maximum economic benefit of the whole region as the objective function. We then set up the required constraints, including:

available trading water constraints, trading water shortage constraints, trading water price constraints, untraded water constraints, etc.

(1) Decision variables

The study took the trading water volume and trading water price of different water users as the decision variables.

(2) Objective function

Maximum regional economic benefits:

$$maxF = \sum_{i=a}\sum_{j=1}^{7} F_{a\ i,j} + \sum_{i=b}\sum_{j=1}^{7} F_{b\ i,j} + \sum_{i=c}\sum_{j=1}^{7} F_{c\ i,j} \tag{14}$$

where F is the total revenue of the system, i represents the different water users, a represents water users, b represents water users, c represents other water users who were not involved in the transaction, j represents different water sources; $j = 1, 2, \ldots, 7$ represent ponds, reservoirs, water diversion, water pumping, wells, other water sources and external water sources; $F_{a\ i,j}$, $F_{b\ i,j}$ and $F_{c\ i,j}$ represent the benefits of the water supply side, water-receiving side and nontrading water users, respectively.

$$F_{a\ i,j} = x_{ij}^{k} m_{i,j} + (v_{i,j} - x_{i,j}) m_{i,j} + x_{i,j} y_{i,j} - (v_{i,j} - x_{i,j}) n_{i,j} - x_{ij}^{k} y_{i,j}^{0} + v_{i,j} y_{i,j}^{2} \tag{15}$$

$$y_{i,j} = d_j e^{-0.01 x_{i,j}} \tag{16}$$

$$n_{i,j} = \frac{d_j (v_{i,j} - x_{i,j})}{v_{i,j}} \tag{17}$$

$$y_{i,j}^{2} = n_{i,j} + 0.2 \tag{18}$$

where x_{ij}^{k} is the initial allocation of water resources, m^3, which is the water distribution result output of the initial allocation model of water rights in the first layer model; $m_{i,j}$ is the marginal benefit of different water sources for different water users, CNY/m^3; $v_{i,j}$ is the tradable water volume, m^3; $Q_{i,j}$ represents the water supply, m^3; $x_{i,j}$ represents the amount of trading water, m^3; in this study, the model proposed by Qin et al. [25] was used for the calculations; $y_{i,j}$ is the transaction water price of water resources in the region, CNY/m^3; d_j is the water conservancy conversion coefficient of different industries; $n_{i,j}$ represents the penalty water price, CNY/m^3; $y_{i,j}^{0}$ is the current water price set by the government, CNY/m^3; $y_{i,j}^{2}$ is the water-saving reward water price, CNY/m^3. In order to promote water rights trading, the study increased CNY 0.2 on the basis of punishing the water price.

$$F_{b\ i,j} = x_{ij}^{k} m_{i,j} - x_{i,j} y_{i,j} (1 + 5\%) + x_{i,j} m_{i,j} - x_{ij}^{k} y_{i,j}^{0} \tag{19}$$

where due to the two sides of the transaction being dominated by the government, the water user would need to hand over 5% of the transaction cost to the government.

$$F_{c\ i,j} = x_{ij}^{k} m_{i,j} - x_{ij}^{k} y_{i,j}^{0} \tag{20}$$

(3) Constraints

Trading availability constraints:

$$\sum_{j=1}^{7} x_{i,j} \le v_{i,j} \tag{21}$$

Trading water shortage constraints:

$$\sum_{j=1}^{7} x_{i,j} \leq q_{i,j} \tag{22}$$

where $q_{i,j}$ is the water shortage, which is the positive difference between the water supply and the initial water distribution, m^3.

Trading water price constraints:

$$y_{i,j}^{0} \leq y_{i,j} \leq y_{i,j}^{1} \tag{23}$$

where $y_{i,j}^{1}$ is the highest water price that the water user could bear, CNY/m^3.

Untraded water volume constraint:

$$\sum_{j=1}^{7} \left(v_{i,j} - x_{i,j}\right) \leq p_i \tag{24}$$

$$p_i = \sum_{k=1}^{3} \left(W_{i,k} - x_{ij}^{k}\right) \tag{25}$$

where p_i is the water shortage of the water supply side's water users.

Non-negative constraint:

All the variables and parameters involved in the model included: the transaction water volume, the transaction water price, the penalty water price and the water saving reward water price. These were all non-negative.

The purpose of solving the water rights trading model was to find the optimal value of the decision variable $x_{i,j}$, obtain the optimal trading water price $y_{i,j}$ and maximize the economic benefits of the region. Next, this study took Luxian county in southwest China as an example, applied the above research methods and carried out research on the optimal allocation of water resources and water rights trading based on regional water supply and demand predictions. The results showed that the supply and demand of water resources were quite different under different hydrological years. After the initial optimal allocation of water resources, the regional water shortage improved significantly, and water rights trading had a significant effect on improving regional economic benefits.

2.3. Model Solving

Based on the theory of Section 2.2, this study first constructed a mathematical optimization model and then used the self-improved elite strategy and cogenetic algorithm (NSGA II-S) to solve the optimization model. The algorithm was based on the NSGA-II genetic algorithm. It has better applicability than the traditional genetic algorithm, and the solution process is faster and more convenient [26,27]. It can accurately and quantitatively represent the changes of water resources and provide a scientific basis for the adaptive development and utilization of water resources under the dynamic changes of water resources [28,29]. The implementation process of the NSGA II-S used MATLAB R2019 b to call its own Linprog function through GUI for the programming calculation. The principle and solution process of the NSGA II-S algorithm are shown in Figure 2.

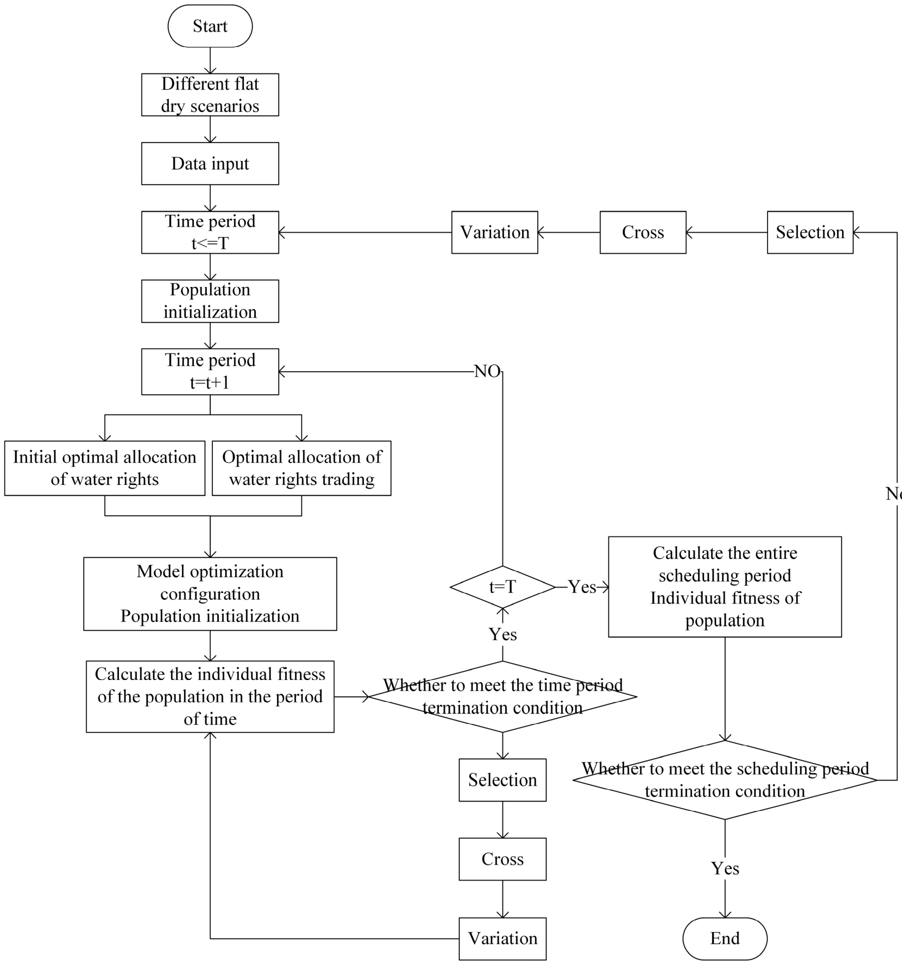


Figure 2. The solving process of NSGA II-S algorithm.

3. Application Case

3.1. Overview of the Research Area

Luxian county is in the southern part of Sichuan province, China (Figure 3). The county area is 1525.24 km^2, of which 761 km^2 is cultivated land, accounting for 49.9% of the whole region. Luxian county is in the middle subtropical warm and humid monsoon climate zone in the upper reaches of the Yangtze River on the southern margin of the Sichuan Basin. The average annual temperature is 17.5 °C and the average annual rainfall is 1030.8 mm. The rainfall is abundant but unevenly distributed, which often causes alternating droughts and floods. The river network is densely distributed, the water area is vast and the water resources are abundant. The surface runoff of the whole county is approximately 6.24×10^8 m^3, the groundwater resource reserve is approximately 0.37×10^8 m^3 and the exploitable groundwater resource is approximately 0.21×10^8 m^3. The terrain elevation varies from larger values with reference to the northeast part of the area to smaller values for the southwest part, most of which are hilly areas. Such a terrain is not conducive to the storage of water, and natural precipitation is not fully utilized.

At present, the water supply infrastructure in Luxian county includes three types of water supply projects: surface water source, groundwater source and other water sources. By 2017, Luxian built 134 reservoirs with a total storage capacity of 1.70×10^8 m^3, 9053 ponds with a total volume of 4.58×10^7 m^3, 1713 pits (ponds) in Luxian, 315 pumping stations and 69 rural centralized water supply projects. The annual maximum water intake capacity of Luxian's water diversion and water lifting projects is 2.12×10^7 m^3, the county's electromechanical wells total 164,200 and the total water supply of Luxian's groundwater intake wells is 1.26×10^7 m^3. Luxian county is a large grain-producing county in a hilly area with a population of one million. It is an advanced county of national grain production and advanced county of water conservancy construction. At the end of 2020, the county's registered population was 1.06 million. Luxian county, under the jurisdiction of 1 street, 19 towns and a total of 20 water users, in this article is numbered as T1, T2, T3, . . ., T20.

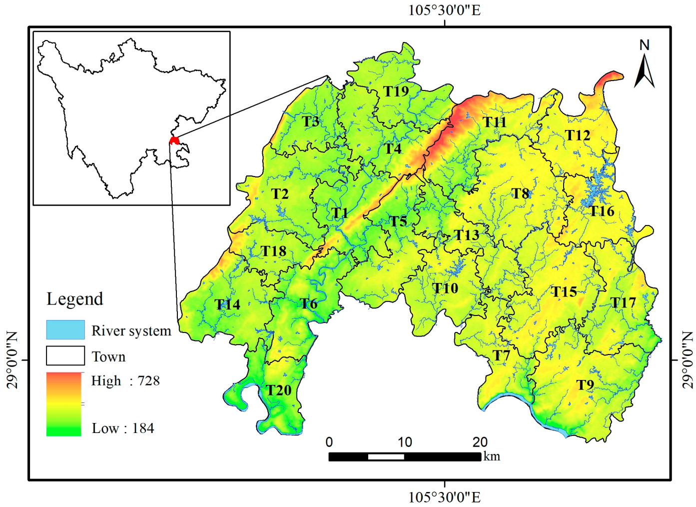


Figure 3. Location of Luxian county.

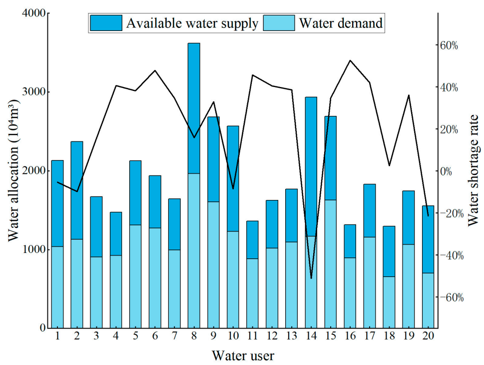
3.2. Data Sources

Considering the availability of data, this study used 2020 as the base year and 2025 and 2030 as the planning years to construct a two-layer coordinated regulation model of regional water rights trading for water users. The original data sources were 'Luxian County Water Resources Bulletin', 'Luxian County Statistical Yearbook', 'Luxian County' fourteenth five-year 'Water Conservancy Development Plan', 'Luxian County Water Resources Comprehensive Plan', 'Luxian County Water Price Reform Pilot Program', 'Sichuan Province Water Quota' and other related results [30].

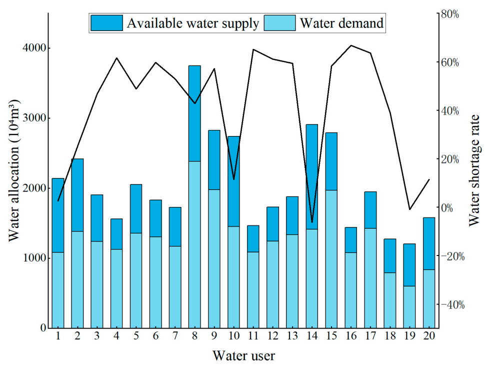
3.3. Supply and Demand Analysis

Based on the data obtained over the years and combined with the relevant planning results of Luxian county, the study predicted the water supply and demand of 20 township units under the jurisdiction of Luxian county in the planning year. The comparative analysis of water demand forecasting methods showed that the quota method could be dynamically adjusted according to various factors and policies, and is widely used [31]. Therefore, this study chose this method to predict and took the amount of water permitted for water intake approved by Luxian county in the current year as the upper limit of the industrial water demand in the planning level year of 2025. On this basis, the water demand in 2030 was predicted. It was calculated that the total water demand of Luxian county in 2025 would be 2.26×10^8 m^3 and 2.63×10^8 m^3, respectively, in a normal year and dry year. The total water demand in a normal year and dry year in 2030 would be 2.24×10^8 m^3 and 2.66×10^8 m^3, respectively. The prediction of an available water supply was based on the analysis of the current water supply and consumption structure of Luxian county, combined with local water resources and water supply projects and based on the socioeconomic development status and planning and development measures of the year to predict the available water supply in the planning year. It was calculated that the available water supply in Luxian county in 2025 would be 1.77×10^8 m^3 and 1.49×10^8 m^3 in a normal year and dry year, respectively. The available water supply in a normal year and dry year in 2030 would be 1.82×10^8 m^3 and 1.53×10^8 m^3, respectively. Under the normal year scenario, the overall water shortage rate in Luxian county would increase from 18.55% in 2025 to 40.88% in 2030. Under the dry year scenario, the overall water shortage rate in Luxian county would increase from 21.07% in 2025 to 41.31% in 2030. According to the prediction results, with the continuous development of the social economy, the water demand in the planning year showed a significant growth trend. However, under the condition of the current water supply facilities, subject to the limitation of the total water supply and the planning and construction of water conservancy projects, it was difficult for the water supply capacity in the planning year to meet the increasing water demand, and the contradiction of an engineering water shortage was still prominent.

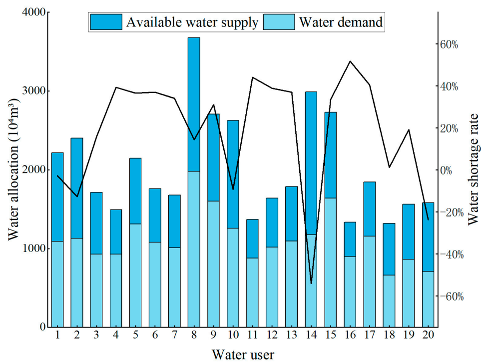
Figure 4 shows the water supply and demand of each township unit in Luxian county under the normal and dry scenarios in the planning year. Due to the supply and demand situation of Luxian county under the normal and dry scenarios in different planning years being highly similar, the 2025 planning year was taken as an example for the analysis. Under the scenario of a normal flow year, the water demand of T1, T2, T10, T14 and T20 was satisfied with a surplus. Among the water shortage towns, T16 had the highest water shortage, 4.70×10^6 m^3, where the water shortage rate was 52.61%. In the dry year scenario, except for the water demand of T14, the rest of the towns had different degrees of water shortages. Among them, T16 had the highest water shortage, which was 4.64×10^6 m^3, and the water shortage rate was 51.67%. There was an obvious problem in the uneven distribution of supply and demand water resources among water users in Luxian county. The uneven distribution of regional water resources between supply and demand would directly cause water shortages among different water users; therefore, the water resources could not be optimized in sectors with higher economic benefits. The allocation efficiency was low, which, in turn, affected the industrial production efficiency. Therefore, in the current situation of an increasing shortage of water resources, in order to give full play to the advantages of regional water resources and promote the efficient use of water resources, it was necessary to rationally allocate and redistribute water resources.



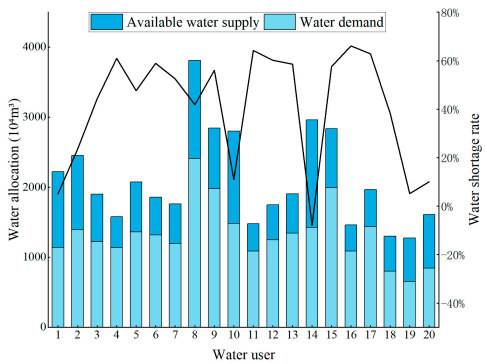
(**a**) A total of 50% in 2025.



(**b**) A total of 75% in 2025.



(**c**) A total of 50% in 2030.



(**d**) A total of 75% in 2030.

Figure 4. The regional water supply and demand under the flat and dry scenario in the planning year.

4. Results and Analysis

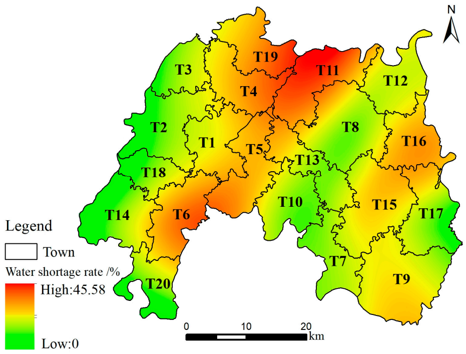
4.1. Analysis of Initial Allocation Results of Water Rights

Based on the prediction of the water supply and demand in order to ensure the rational allocation of regional water use in Luxian county according to different water conditions and to the order of water supply for urban and rural residents' domestic water, basic ecological water, agricultural irrigation, basic indispensable production water and other production water, priority was given to the protection of urban and rural residents' domestic water, ensuring the ecological basic water demand, optimizing the allocation of water production and ensuring the rational allocation of agricultural water and the rational allocation of other production and operation water. This study analyzed the water resource allocation of villages and towns in the planning year (2025 and 2030) of Luxian county and obtained the initial optimal allocation results of water rights in the planning year (2025 and 2030).

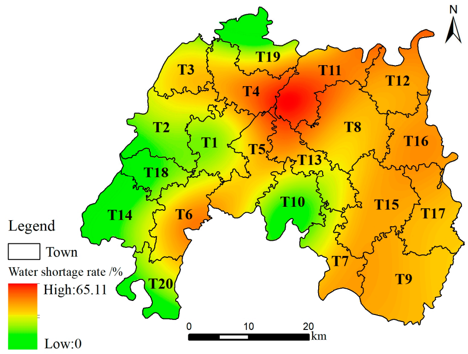
The spatial distribution characteristics of the water shortage rate in Luxian county are shown in Figure 5. It can be seen from the figure that although the results of the allocation of villages and towns in different planning years were not the same, the overall difference was not large. Under the normal year scenario, the overall water shortage rate in Luxian county decreased from 13.71% in 2025 to 11.55% in 2030 and the distribution of the water shortage rate showed obvious central high characteristics. In the dry year scenario, the overall water shortage rate in Luxian county decreased from 31.99% in 2025 to 31.94% in 2030 and the distribution of the water shortage rate continued to spread to the east. The main reason for the spatial distribution characteristics of the water shortage rate in Luxian county in the normal water year was that most of the current water conservancy projects in Luxian county are distributed in the western part of the county. At the same time, because most of the central and eastern parts are mountainous areas, the amount of water resources is relatively small compared with the western part, so the water supply of townships in the western part is relatively easier to meet the local economic and social water demand; under the low-water year scenario, the available water supply in Luxian county greatly reduced. At the same time, due to the high terrain of most towns in the middle and eastern part of Luxian county, there are certain difficulties in the utilization of water resources. Therefore, the water shortage rate of towns in the middle and eastern parts of Luxian county generally increased rapidly under the low water year scenario.

There was a significant spatial difference in the allocation of water resources in Luxian county, and the spatial distribution difference was similar under different scenarios in different planning years. According to the spatial distribution characteristics of the water shortage rate in the dry years, it could be concluded that the supply and demand of water resources in the central and eastern towns of Luxian county were greatly affected due to hydrological frequency. The distribution characteristics of the water shortage rate in Luxian county could provide a reference for the future layout of water resource spatial planning and the construction of related water conservancy projects in Luxian county.

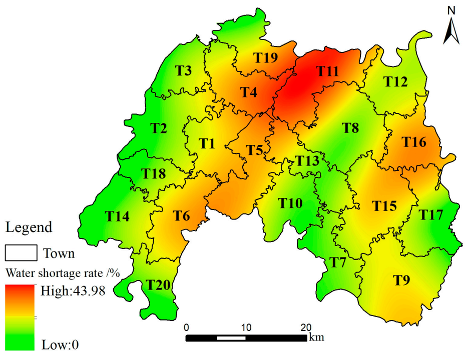
In order to intuitively reflect the allocation of water quantity and its corresponding relationship between each township unit, water industry and water source, the water source structure diagram of each industry was drawn (Figure 6). According to the figure, the water allocation of Luxian county in 2025 was 1.95×10^8 m^3, among which T8 had the highest water allocation, which was 1.96×10^7 m^3, and T11 had the lowest water allocation, which was 4.80×10^6 m^3. Under the scenario of the dry year in 2025, the water allocation of Luxian county was 1.73×10^8 m^3, of which T10 had the highest water allocation, which was 1.43×10^7 m^3, and T11 had the lowest water allocation, which was 3.80×10^6 m^3. Under the scenario of a normal water year in 2030, the water allocation amount of Luxian county was 1.99×10^8 m^3, among which T8 had the highest water allocation amount, 1.95×10^7 m^3, and T11 had the lowest water allocation amount, 4.92×10^6 m^3. Under the scenario of the dry year in 2030, the water allocation in Luxian county was 1.76×10^8 m^3, among which T8 had the highest water allocation, which was 1.54×10^7 m^3, and T11 had the lowest water allocation, which was 3.89×10^6 m^3.



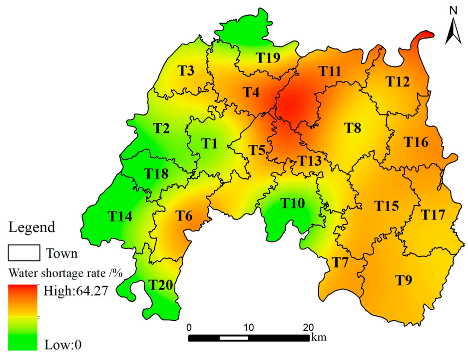
(**a**) A total of 50% in 2025.



(**b**) A total of 75% in 2025.

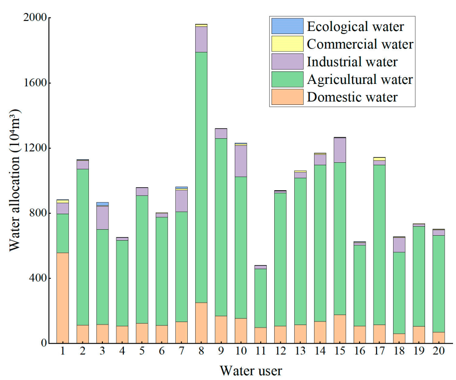


(**c**) A total of 50% in 2030.

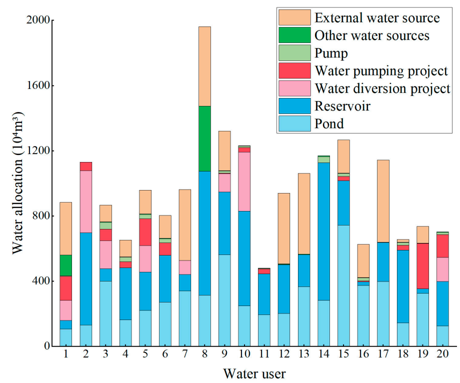


(**d**) A total of 75% in 2030.

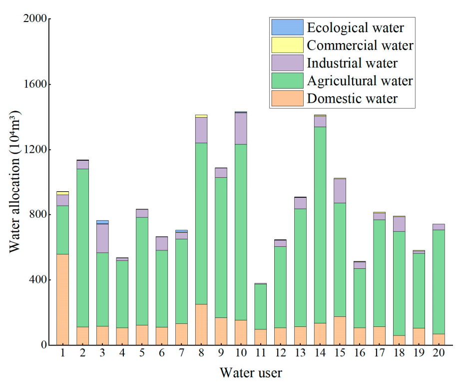
Figure 5. Spatial distribution of water shortage rate.



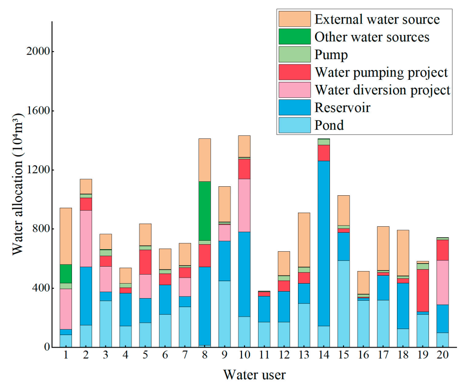
(**a**)



(**b**)



(**c**)



(**d**)

Figure 6. *Cont.*

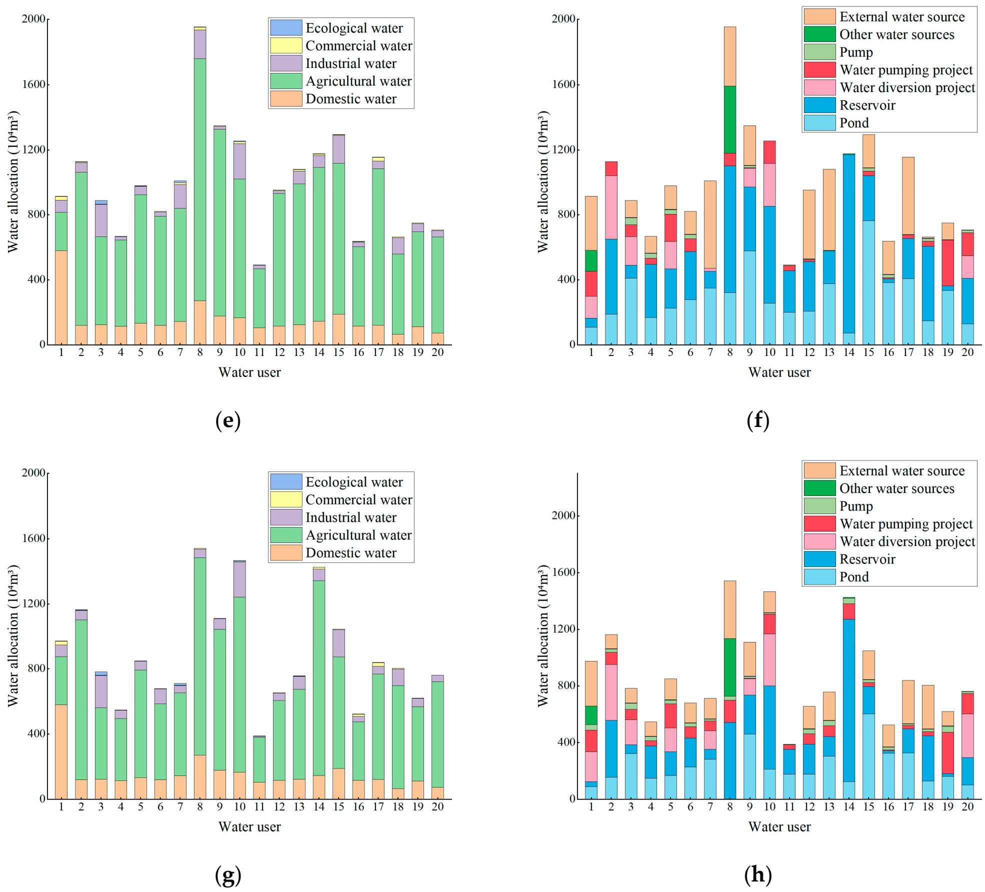


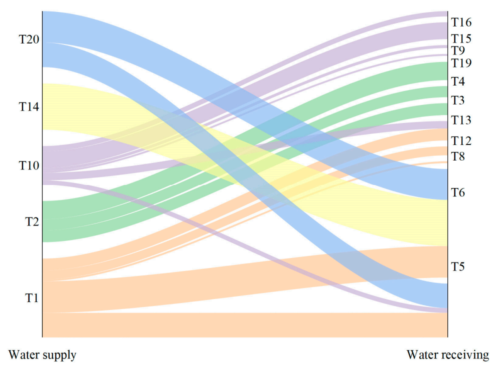
Figure 6. Industry water source structure. (**a**) A total of 50% of water distribution by different industries in 2025. (**b**) A total of 50% water distribution from different water sources in 2025. (**c**) A total of 75% of water distribution by different industries in 2025. (**d**) A total of 75% of water distribution from different water sources in 2025. (**e**) A total of 50% of water distribution by different industries in 2030. (**f**) A total of 50% water distribution from different water sources in 2030. (**g**) A total of 75% of water distribution by different industries in 2030. (**h**) A total of 75% of water distribution from different sources in 2030.

In 2025 and 2030, the living and ecological water distribution of each township in Luxian county would meet the water demand, and there was no phenomenon that urban construction water would occupy ecological water. The water shortage industries under different scenarios were concentrated in industry, agriculture and business. Under the normal year scenario, the industry with the highest regional water shortage rate was business, with water shortage rates of 41.71% and 39.82%, respectively, followed by industry with water shortage rates of 24.14% and 19.88%, respectively, and the third was agriculture with water shortage rates of 14.58% and 14.06%, respectively. In the dry year scenario, business in the region was still an industry with a large water gap. The overall water shortage rates of business were 60.66% and 56.08%, respectively, followed by agriculture with water shortage rates of 42.45% and 42.11%, respectively. The third was industry with water shortage rates of 19.70% and 23.09%, respectively.

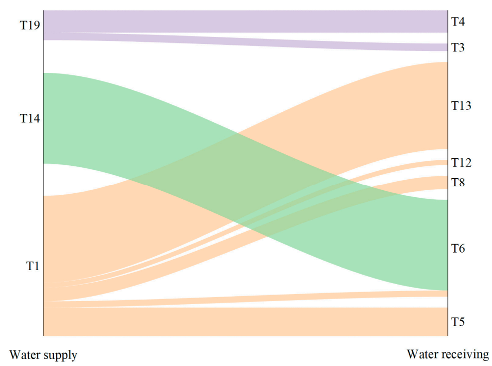
From the perspective of the water supply source side, there was no change in the type of water supply in the planning year, but the water source structure was optimized, which mainly manifested in the increase in the proportion of surface water supply and the decrease in the proportion of external water supply. Under the normal year scenario, the proportion of surface water supply would increase from 98.68% in 2025 to 98.92% in 2030 and the proportion of external water supply would decrease from 20.13% in 2025 to 19.56% in 2030. Under the dry year scenario, the proportion of surface water supply would increase from 97.26% in 2025 to 97.28% in 2030 and the proportion of external water supply would decrease from 19.07% in 2025 to 18.57% in 2030. According to the optimal allocation of water resources in different planning years and different scenarios, agriculture would be the industry with the largest water consumption in Luxian county, while business would be the industry with the most serious water shortage. Due to Luxian county being in a mountainous area, the development of groundwater exploitation and other water source migration projects could be easily affected by natural factors, and there was an obvious uneven distribution of water resources among water users in Luxian county. Therefore, in order to give full play to the comprehensive utilization efficiency of existing water resources, it would be necessary to establish and improve the water rights distribution system and carry out water rights trading.

4.2. Analysis of Water Rights Trading Results

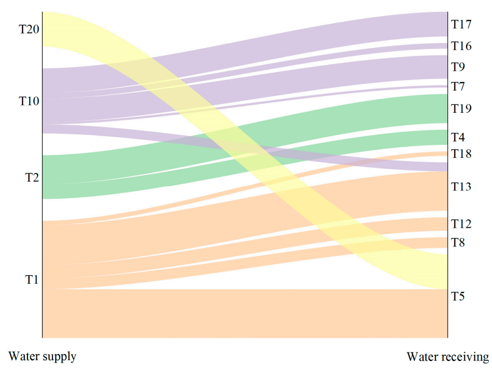
Based on the initial allocation of water rights and the allocation objectives and constraints of 1.2.2, the water rights trading model was used to redistribute water resource transactions in Luxian county in 2025 and 2030, obtaining the trading results under different planning years. In order to intuitively reflect the trading water volume of each township unit and its corresponding relationship, the results of different scenarios of water rights trading water volume were drawn (Figure 7). It can be seen from the figure that although the results of the water rights trading volume in each township under different planning years were different, the two parties involved in water rights trading under the normal and dry scenarios were consistent; therefore, the 2025 planning year was taken as an example for the analysis.



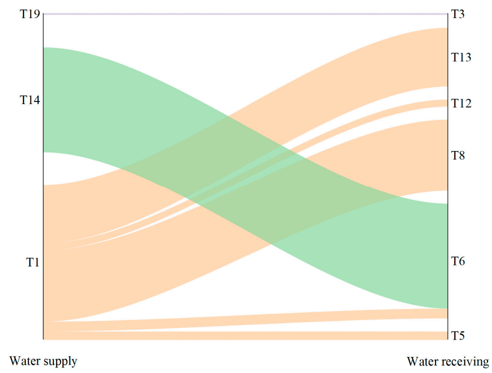
(**a**) A total of 50% in 2025.



(**b**) A total of 75% in 2025.



(**c**) A total of 50% in 2030.



(**d**) A total of 75% in 2030.

Figure 7. Trading water volume.

The trading water volume and the corresponding trading water price of each township under the flat and dry scenarios in the 2025 planning year are shown in Tables 1 and 2.

According to the table, under the normal water year scenario, the water supply users were T1, T2, T10, T14 and T20, with trading water volumes of 2.11 × 10^6 m^3, 1.11 × 10^6 m^3, 1.05 × 10^6 m^3, 1.24 × 10^6 m^3 and 1.51 × 10^6 m^3, respectively. Among them, the largest trading water volume was 3.61 × 10^6 m^3, followed by agriculture with a trading water volume of 2.12 × 10^6 m^3 and, finally, business, with a trading water volume of 6.41 × 10^5 m^3. In the low water year scenario, the water supply users were T1, T14 and T19, and the trading water volumes were 1.15 × 10^6 m^3, 7.37 × 10^5 m^3 and 2.39 × 10^5 m^3, respectively. Among them, the largest trading water volume was 1.64 × 10^6 m^3, followed by business with a trading water volume of 3.14 × 10^5 m^3 and, finally, the industry of which the trading water volume was 1.79 × 10^5 m^3. In the normal year scenario, the water shortage in various industries was not obvious, and trading water to industry was an effective means to improve economic benefits. In the dry year scenario, the competition for water in various industries intensified, and the shortage of water resources was severe. As the main industry of Luxian county, agriculture should give priority to water supply to ensure food security.

Table 1. Output result table of water rights trading model in normal year of 2025.

Water Supply Towns	Penalty Water Price (CNY/m^3)			Water Receiving Towns	Trading Water Volume (10^4 m^3)			Trading Water Price (CNY/m^3)		
	Agriculture	Industry	Business		Agriculture	Industry	Business	Agriculture	Industry	Business
T1	0.28	3.60	6.43	T5	61.68	0	4.80	0.18	0	4.38
				T6	27.37	50.63	5.50	0.26	2.82	4.35
				T8	4.70	0	0	0.32	0	0
				T12	0	20.22	3.99	0	3.82	4.42
				T13	0	32.06	0	0	3.40	0
				T18	0	0	0	0	0	0
T2	0.43	1.71	6.31	T3	0	25.73	6.03	0	3.62	4.33
				T4	0	26.96	3.50	0	3.57	4.44
				T19	17.45	31.33	0	0.29	3.42	0
T10	0.47	2.18	5.29	T5	8.19	0	4.80	0.31	0	4.38
				T7	0	0	0	0	0	0
				T9	0	0	4.69	0	0	4.39
				T13	0	19.85	0	0	3.84	0
				T15	0	0	8.21	0	0	4.24
				T16	0	38.39	6.81	0	3.19	4.30
				T17	0	14.43	0	0	4.05	0
T14	0.45	6.43	6.84	T6	68.27	50.63	5.50	0.17	2.82	4.35
				T18	0	0	0	0	0	0
T20	0.21	4.66	6.43	T5	61.68	0	4.80	0.18	0	4.38
				T6	28.12	50.63	5.50	0.26	2.82	4.35
Total					211.50	360.86	64.13			

Table 2. Output result table of water rights trading model in dry year of 2025.

Water Supply Towns	Penalty Water Price (CNY/m^3)			Water Receiving Towns	Trading Water Volume (10^4 m^3)			Trading Water Price (CNY/m^3)		
	Agriculture	Industry	Business		Agriculture	Industry	Business	Agriculture	Industry	Business
T1	0.09	7.02	5.71	T5	18.57	0	4.80	0.28	0	4.38
				T6	0	0	5.50	0	0	4.35
				T8	11.47	0	0	0.30	0	0
				T12	0	0	3.99	0	0	4.42
				T13	65.31	0	5.59	0.18	0	4.35
				T18	0	0	0	0	0	0
T14	0.11	7.02	6.47	T6	68.27	0	5.50	0.17	0	4.35
				T18	0	0	0	0	0	0
T19	0.51	1.77	5.16	T3	0	0	0	0	0	0
				T4	0	0	6.03	0	0	4.33
				T19	0	17.89	0	0	3.91	0
Total					163.64	17.89	31.40			

The economic benefits before and after regional water rights trading in different planning years are shown in Figure 8. It can be seen from the figure that water rights trading could increase the economic benefits. Under all scenarios, the economic benefits increased by an average of CNY 614 million, with an average increase of 8.68%. With the improvement in water use level and water saving in the industry, the economic benefits of water rights trading gradually reduced. In the normal year scenario of 2025, the economic benefits before and after the transaction were CNY 6.421 billion and CNY 7.441 billion, respectively, with an increase of 15.87%. In the dry year scenario of 2025, the economic benefits before and after the transaction were CNY 70.06 billion and CNY 75.13 billion, respectively, an increase of 7.23%; under the normal year scenario in 2030, the economic benefits before and after the transaction were CNY 7330 million and CNY 7835 million, respectively, an increase of 6.89%; in the dry year scenario of 2030, the economic benefits before and after the transaction were CNY 7.55 billion and CNY 7.98 billion, respectively, with an increase of 5.65%.

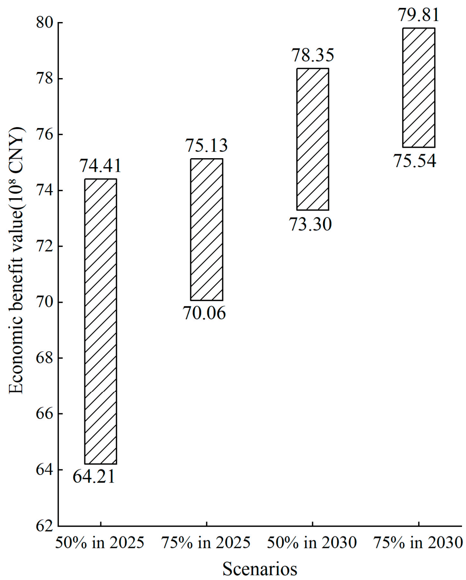


Figure 8. Economic benefits before and after water rights trading.

In summary, the role of each region in the water right transaction in the model was adjusted according to the different water supply, not fixed. The model could intelligently compare the needs of each water user, determine the distribution plan of maximizing the regional economic benefit value and encourage the regional water user to reasonably switch between the water supply side and the water receiving side. Compared with rigidly stipulating the water consumption of each region or stipulating the role of the region in water rights trading, the model could give full play to the initiative of each region and reflect the adaptability of the overall model.

At present, according to the water right allocation scheme and the water right trading rules, Luxian county has completed the first single-purpose water right transaction in Sichuan province on the Chinese water right trading platform, marking a breakthrough in the market-oriented trading of water rights in Sichuan province. Through this water rights transaction, the dilemma of insufficient water use in enterprises was effectively solved, and the efficiency and benefit of water resource utilization were improved. It was a useful exploration for Sichuan province to play the role of the market mechanism in promoting the optimal allocation of water resources and the high-quality development of the economy and society, providing experience for Sichuan province to promote the reform of water rights. Next, the water right trading of various industries in Luxian county were be carried out in an all-round way.

5. Conclusions

To solve the problem of regional water shortage and give full play to the market mechanism of water rights trading to optimize the allocation of water resources, this paper took Luxian county of Sichuan province as the research area. Based on the prediction of regional water supply and demand, a two-layer coordinated control model of regional water rights trading was constructed and the optimal allocation of water resources and water rights trading was carried out. The conclusions were as follows:

The planned annual water demand showed a significant growth trend, but it was difficult for the water supply capacity to meet the increased water demand, and the contradiction of the engineering water shortage was more prominent. The supply and demand of water resources were greatly affected by hydrological frequency. Under the normal year scenario, the overall water shortage rate in Luxian county increased from 18.55% in 2025 to 40.88% in 2030. In the dry year scenario, the overall water shortage rate in Luxian county increased from 21.07% in 2025 to 41.31% in 2030.

The allocation of water resources in Luxian county had significant spatial differences. After the initial optimal allocation of water resources, the regional water shortage situation improved significantly, but there were still obvious problems of an uneven distribution of water resources between the supply and demand. Under the normal year scenario, the overall water shortage rate in Luxian county decreased from 13.71% in 2025 to 11.55% in 2030, and the distribution of the water shortage rate showed obvious central high characteristics. In the dry year scenario, the overall water shortage rate in Luxian county decreased from 31.99% in 2025 to 31.94% in 2030, and the distribution of the water shortage rate continued to spread to the east.

Water rights trading could significantly increase the value of regional economic benefits. Under all scenarios, the economic benefits increased by an average of CNY 614 million, with an average increase of 8.68%. With the improvement in the water use level and industry water saving, the economic benefit growth rate of water rights trading gradually reduced. The role of the model in the water right transaction could be adjusted according to the different amounts of water, which was not fixed. It could also intelligently compare the water demand of each township and determine the maximum distribution plan of the regional economic benefit value so that the regional water users could reasonably switch between the water supply side and the water receiving side to ensure the adaptability of the model.

This study systematically and comprehensively analyzed the total amount of initial water rights that could be allocated to surface water and other incoming water in Luxian county, adopting the principles and methods of 'supply–demand' and the quota method, supplemented with a dynamic adjustment and further allocating the initial water rights of townships to water users in different industries according to the characteristics of the initial allocation of regional water rights. A multiobjective optimization model of regional water rights trading was constructed to provide a reference for the potential assessment of regional water rights trading. At present, this study only conducted water rights transactions and accounting between various industries and water users within the region on a regional basis. Follow-up studies could consider cross-regional water rights transactions on a regional basis. In future research, the cost of water conveyance in the process of water right transactions should be calculated to obtain more accurate conclusions. In addition, in the aspect of the optimal allocation of regional water resources, the cross-regional circulation of water right transactions and the realization of the optimal allocation of water resources in a wider range are also worthy of further exploration.

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