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Optimal Water Allocation Based on Water Rights Transaction Models with Administered and Market-Based Systems: A Case Study of Shiyang River Basin, China

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Abstract: Water-rights trade has proved to be an effective method for coping with water shortages through the transfer of water resources between users. The water allocation system is classified into two categories based on information transparency and water rights transaction goals: administered system (AS) and market-based system (MS). A multi-agent and multi-objective optimal allocation model, built on a complex adaptive system, was introduced to direct the distribution of water resources under an AS in the Shiyang River Basin; it was compared with a market-based water rights transaction model using the bulletin-board approach. Ideal economic agent equations played a dominant role in both models. The government and different water users were conceptualized as agents with different behaviors and goals in water allocation. The impact of water-saving cost on optimal water allocation was also considered. The results showed that an agent's water-saving behavior was incentivized by high transaction prices in the water market. Under the MS, the highest bid in the quotation set had a dominant influence on how trade was conducted. A higher transaction price will, thus, result in a better benefit ratio, and a lower one will result in inactivity in terms of water rights trade. This will significantly impact the economic benefit to the basin.

Keywords: water rights transaction model; optimal allocation; basin water resources; water-saving analysis; administered system; market-based system

1. Introduction

As an important productive resource, the economic characteristics of water are defined by its scarcity. With rapid population growth and economic development, water resources are becoming increasingly scarce; consequently, increasing attention is being paid to the economic characteristics of water resources. It is crucial to promote the efficient utilization and allocation of water resources and, thereby, facilitate both an incentive mechanism to save water and a restraint mechanism to avoid waste. In fact, water rights and water markets have proven to be effective economic approaches for realizing optimal water allocation. With the help of the water market, water rights are gradually transferred from users with low-efficiency use to those with high efficiency, thus, improving the overall level of water utilization and allocation.

The water rights trade market is usually categorized into the primary and secondary water markets. In the primary water market, public water use rights are distributed to organizations and individuals by authorized administrations through methods such as direct distribution, bidding, and so on. After the initial distribution, water rights can be transferred between users through commercial transactions in the secondary water market; this is considered as a readjustment of water rights distribution from the primary water market. As water rights transactions in the secondary water market are driven by individual benefit, allocation and utilization efficiency can be improved. Therefore, it is crucial to conduct research on the water rights transaction model in the secondary water market to ensure better water allocation.

Currently, major studies on the water market focus on its necessity, operation mechanisms, policies, economic efficiency, determination of transaction goals, transaction prices, and costs [1–3]. Richard et al. [4] evaluated the current policy of water shortage adaptation in the Colorado River Basin and proposed an interstate water market as an interesting reform that could be used for adapting to increased water scarcity and preserving core elements of the Colorado River Basin law. Zaman et al. [5] discussed an economic trading model combined with a hydrologic water allocation model to estimate the impacts of temporary water trading and physical water transfers, considering the key trade drivers of commodity prices, seasonal water allocations, and irrigation deliveries. The Chinese government has conducted demonstration work regarding water markets in several regions in China. In the Inner Mongolia Autonomous Region, experimental work on water rights transactions has been undertaken in the upper reaches of the Yellow River. At present, it is generally believed that water rights transaction is an effective measure for solving the problem of water resources distribution in the context of water resources shortage.

Generally, an optimal water allocation model includes an administered system (AS) and a market-based system (MS) [6]. In AS, information is completely transparent, and water resources are distributed and traded by authorities in accordance with their optimization goals. For instance, Roozbahani et al. [7] determined the maximum water-use benefit for each user and introduced an allocation model to guarantee a maximization of the minimum ratio for each stakeholder's profit to its highest possible benefit. Yu et al. [8] used linear programming techniques to simulate the water market for maximizing the aggregate net return, subject to land, water, and crop restraints. Montilla et al. [9] designed a basin-level water bank model that considered 15 representative farm types to simulate water trading. They also demonstrated that water banks are market mechanisms that facilitate the transfer of water toward uses of greater value, including environmental uses. Water banks reduce static transaction costs and help create more active water markets by increasing economic efficiency. Market operations are centralized, which allows the administration (or other agencies) to properly control potential negative externalities and prevent any kind of harmful speculation [10].

Unlike AS, in which the role of the water trade market is limited, MS takes full account of the transaction process and the outcome for each water user under specific trading rules in the water market. In this context, transaction rules become major influential factors for water allocation. Giuliani et al. [11] believed that each agent represents a decision maker and that its decisions are defined by an explicit optimization problem that only considers the agent's local interests. A practical water transaction process includes both the supply and the demand sides, especially in the secondary water market. Tradable water rights and transaction prices are determined by the balance between supply and demand. It is, therefore,. necessary to continue the development of water market mechanisms to ensure that this reallocation/transaction process takes place as efficiently as possible. Under MS, water exchanges generally utilize two mechanisms: bulletin boards and sealed double-auctions [12,13]. Without the intervention of the relevant authorities, the bulletin-board approach is a relatively reasonable transaction method, as all traders, whether buyers or sellers, have to make decisions based on insufficient information. This approach requires buyers and sellers to post offers and requests for water, typically through an electronic platform. Trade transactions are executed by matching individual offers with corresponding quantity and price.

Many established water banks in the western United States are actually bulletin-board markets. The most active bulletin-board market is the Northern Colorado Water Conservancy District (NCWCD), where about 30% of the water allocated to the Colorado-Big Thompson (C-BT) project is utilized for rental transactions [14]. However, some bulletin-board markets have been less successful; for example, the Texas Water Bank has conducted only one transaction since its establishment in 1993 [15]. In this study, we established the transaction rules for water markets by using the bulletin-board approach; this seems to be a more suitable approach for describing the operation system of the planned water markets in the Shiyang River Basin. Potential buyers and sellers make their offers simultaneously; each participant has no evidence of the marginal cost and the actual evaluation of others, but the participant's decision can be influenced by other offers.

The comparison of the two systems has also garnered attention in recent decades. Many scholars have widely discussed the advantages and disadvantages of AS and MS [16,17], and others have also compared these systems directly. Matthew et al. [18] pointed out that water markets did not always function efficiently because the features of some water rights were not designed for market transactions, and in particular, the impact of hydrological uncertainty was not adequately considered. Calatrava et al. [1] showed that, compared to decentralized markets, centralized water markets lead to more efficient water resource allocation and utilization. However, such research requires more quantitative evidence.

In the context of water shortage, water saving is another important issue that has attracted people's attention, especially in terms of water-saving techniques, costs, benefits, and quantities [19]. Berbel et al. [20] used cost-effectiveness analysis to rank and select policy measures for improving the ecological status of water bodies, based on the ratio between the equivalent annual cost and the reduction of impacts. Maeda et al. [21] presented a multi-objective optimization model for allocating irrigation water in a rice paddy cultivation area after considering appropriate water-saving practices and providing an optimal solution for the water allocation problem at the regional level. Thus, it is crucial to fully consider the impact of water-saving behaviors on water resource policies and optimal allocation.

Following previous studies [22], this study introduced a multi-agent and multi-objective optimization model based on a complex adaptive system to realize the administered allocation of water resources in the Shiyang River Basin and established a market-based water transaction model using the bulletin-board approach. The results of the market-based model were further compared with the output of the AS model. Furthermore, the influence of water-saving cost on optimal water allocation was also considered.

2. Case Study

2.1. Study Area

As one of the three inland river basins in the Gansu Corridor, the Shiyang River Basin covers an area of 41,160 km^2, constituting 15.4% of the total area of inland river basins in Gansu Province (Figure 1). Mainly recharged by precipitation and meltwater in mountain areas, the runoff yield of the Shiyang River covers an area of 11,000 km^2. In terms of administrative management, the river belongs to Wuwei City and Jinchang City. The former is an agriculture-based district, while the latter is nationally renowned for its production of non-ferrous metals.

In 2010, the total water supply of the Shiyang River Basin was 2522 million m^3, consisting of 1744 million m^3 (69.2%) of surface water, 766 million m^3 (30.4%) of groundwater, and 12 million m^3 (0.4%) from other sources, such as reused wastewater and rainfall utilization (Table 1). The total water consumption of the Shiyang River Basin was 2522 million m^3, including 2172 million m^3 (86.1%) in agriculture; 145 million m^3 (5.7%) in industrial production; 69 million m^3 (2.7%) in domestic use; 62 million m^3 (2.5%) in ecological environment protection; 58 million m^3 (2.3%) in forestry, animal husbandry, sideline production, and fishery; and 17 million m^3 (0.7%) in urban public use (Table 2).

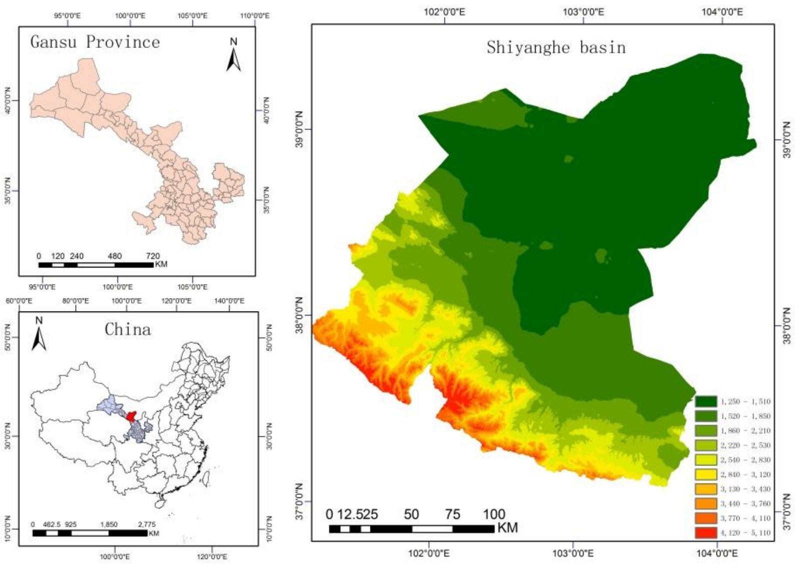

Figure 1. The study area.

Table 1. Actual water supply in the Shiyang River Basin in 2010 (million m^3).

City	Surface Water Supply					Groundwater Supply	Other			Total
	Storage	Diversion	Lifting	Inter-Basin Transfer	Sum		Waste Reuse	Rainfall	Sum	
Jinchang	449	26	0	40	515	102	3	0	3	641
Wuwei	803	303	2	121	1229	664	2	7	9	1922
Total	1252	329	2	161	1744	766	5	7	12	2522

Table 2. Actual water consumption in the Shiyang River Basin in 2010 (million m^3).

City	Agriculture	FASF	Industry	Public	Domestic	Ecological	Total
Jinchang	488	26	88	6	17	14	640
Wuwei	1683	32	78	11	48	69	1882
Total	2171	58	166	17	65	83	2522

Note: FASF represents forestry, animal husbandry, sideline production, and fishery.

2.2. Data Sources

In this study, the multi-year (2007–2012) parameters and economic equations of all agents were collected or calculated based on the data from the Water Resource Bulletin and the Water Resource Planning Report of the Shiyang River Basin. Detailed socio-economic data, such as current water price, water-saving cost, water-saving efficiency, and purifying capacity of pollutants, were collected through field surveys in the Shiyang River Basin.

3. Model

3.1. Model Structure

Based on the complex adaptive system theory, a multi-agent and multi-objective optimization model was utilized to realize optimal water allocation in the basin [22]. Two types of users—government agent and water consumption agents—were conceptualized in the model (Table 3). The multi-agent model is used for describing the behaviors and goals of each individual, while the complex adaptive system theory is combined to visualize the information transfer and functional mechanism between the agents. Specifically, stakeholders in a basin, including multi-level governments and various departments within the government, are defined as one government agent at the basin level; it is also the water supply agent. The behaviors of this agent include investigating current population situations and forecasting future growth, making macro-economic policies, meeting ecological demands, distributing initial water rights through macro-control means, determining the water prices of different industries, improving water market regulations, and establishing ecological protection goals. Likewise, users from various industries in different administrative districts can be considered as water consumption agents, representing the demand side for water; this mechanism aims to maximize the economic benefits from the utilization of allocated initial water rights, water rights purchased through trade, and those saved through water-saving techniques. Due to the sheer contradiction between the two agents in terms of behaviors and objectives, there is obviously a game between multiple stakeholders, highlighting the necessity of optimizing water allocation at a basin level e.

Table 3. Summary of the main agents in the Shiyang River Basin.

Water Supply	River Basin Government Agent	
Water consumption	Primary industry of Wuwei City	A1
	Secondary industry of Wuwei City	A2
	Tertiary industry of Wuwei City	A3
	Primary industry of Jinchang City	B1
	Secondary industry of Jinchang City	B2
	Tertiary industry of Jinchang City	B3

Note: A1, A2, A3, B1, B2, and B3 are references adopted for water consumption agents.

This study's model structure follows the principle of water demand management. Simultaneously, the concepts, definitions, calculation methods, and relevant symbols adopted in the research are also based on previous studies [22]. As production agents, users from primary and secondary industries are perceived as research targets, and their water consumption behaviors can be classified into four types: using water, buying water, selling water, and saving water.

(1) Using, buying, and selling water

The behavior objective of production agents is to maximize their economic benefits. The generation and selection of behaviors are determined by economic agent equations. The equation for production agents can be expressed as

$$F_i(x_i) = f_i(x_i) - p(x_i, w_i) - c(x_i, w_i)\delta \tag{1}$$

where x_i and w_i are the water consumption quantity and the initial water rights of the ith agent, respectively. $F_i(x_i)$ and $f_i(x_i)$ are the total and production profits, respectively. $p(x_i, w_i)$ is the water price cost based on water consumption quantity x_i and initial water right w_i. $c(x_i, w_i)$ is the tax expenditure when buying or selling water resources. δ can be 0 or 1—$\delta = 0$ when selling water and $\delta = 1$ when buying water—meaning that taxes are paid by the buyers.

Assuming that the agents will sell their extra water rights or buy rights if there is a shortfall and that the price follows the principle of the ladder water price (Figure 2), the water price cost and taxes paid when buying water are

$$p(x_i, w_i) + c(x_i, w_i)\delta = \begin{cases} \int_0^{x_i} (p_0 + tx)dx - p_h(w_i - x_i), x_i \le w_i \\ \int_0^{w_i} (p_0 + tx)dx + p_h(x_i - w_i) + c(x_i - w_i), x_i \ge w_i \end{cases} \tag{2}$$

where p_0 and t represent the basic price and the ladder coefficient in the water price ladder model, respectively. p_h represents the transaction price in the water market.

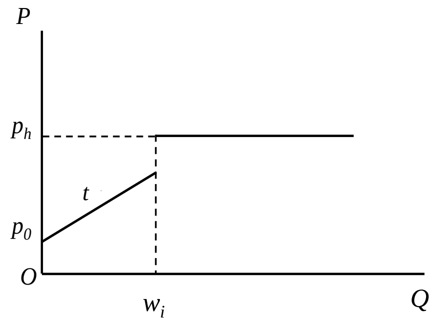

Figure 2. Water price ladder model.

By substituting Equation (2) into Equation (1), the water consumption quantity $\hat{x}_i$ in optimal production conditions can be calculated from Equation (3) as follows:

$$\begin{aligned} &\hat{x}_i = \text{argmax}\{F_i(x_i) = f_i(x_i) - p(x_i, w_i) - c(x_i, w_i)\delta; x_i \geq 0\} \\ &f_i{}'(\hat{x}_i) - p'(\hat{x}_i, w_i) - c'(\hat{x}_i, w_i)\delta = 0 \end{aligned} \tag{3}$$

If the optimal water consumption quantity is smaller than the initial water rights allocation $\hat{x}_i \leq w_i$, the selling quantity of the ith production agent is

$$D_i = w_i - \hat{x}_i \tag{4}$$

If the optimal water consumption quantity is larger than the initial allocation of water rights $\hat{x}_i \geq w_i$, extra water should be purchased. Thus, agent behavior under the limited initial water rights allocation system depends entirely on the individual economic agent equation.

(2) Saving water

Under an effective water rights system, water consumption agents will take water-saving measures and develop water-saving techniques to reduce water costs or obtain additional profits by selling water when raised water prices increase their willingness to save water. Two aspects—the water-saving effect and the input cost—are considered as measures for the influence of water saving on the behavior of water consumption agents.

Let us suppose that the water-saving cost K_i of each agent is related to water consumption quantity Q_i. The cost function for water saving is

$$K_i = E_i(Q_i) \tag{5}$$

The efficiency coefficient of water saving is defined as a_i; a_i varies depending on the agents in each industry. By substituting water-saving cost K_i and coefficient a_i into Equation (1), the formula becomes

$$\begin{aligned} &F_i(y_i) = f_i(x_i) - p(y_i, w_i) - c(y_i, w_i)\delta - K_i \\ &y_i = (1 - a_i)x_i \end{aligned} \tag{6}$$

It is assumed that the water consumption quantity $y_i = (1 - a_i)x_i$ after taking water-saving measures will produce the same benefits as the water consumption quantity x_i before savings.

There are economic relationships between water saving, selling, and buying; this means that water consumption agents will make water-saving decisions based on an economic viewpoint. If the demand for water is larger than the initial water right, and the agent's water-saving coefficient is a_i, water resources $a_i x_i$ will be saved if a water-saving strategy is adopted. However, if the water resource shortfall is compensated for by purchasing water entirely from the water trading market, a cost $a_i x_i p_h$ must be paid. The production agents will compare these two costs:

$$\begin{array}{c} a_i x_i p_h \geq K_i, \text{saving water} \\ a_i x_i p_h < K_i, \text{buying water} \end{array} \tag{7}$$

3.2. Water Rights Transaction Model

3.2.1. Administered System (AS)

The behavioral objective of the government agent is water resource allocation optimization in the whole basin, which will maximize economic, social, and environmental benefits in the meantime. In fact, AS is a top-down water rights transaction system in which information is open to all stakeholders, and each trader is regulated by the government and rational. This system includes several potential assumptions as follows:

(1) The water price p_h in the water market is fixed.
(2) The trading process is conducted by the government; this means that the water seller first sells its extra water rights to the government at price p_h, and then, the buyer purchases it at the same price with additional taxes from the government.
(3) All information related to the trading process is completely transparent.

Generally, the quantity of available water rights for trading (S) in the water market is less than the total water demand of the buyers (T). Therefore, the optimization creates a maximization of gross benefits for all sellers instead of maximum profits for just one individual.

Optimal water allocation in a basin is a multi-objective optimization process based on the aforementioned three conditions, which can be described as follows:

$$F(X) = opt\{f_1(X), f_2(X), f_3(X)\} \tag{8}$$

where the functions $f_1(X), f_2(X)$ and $f_3(X)$ represent economic, social, and environmental benefits, respectively (see details in [22]).

3.2.2. Market-Based System (MS)

In MS, complete reasonable macro-control by the government ceases to exist, and free trade between water consumption agents becomes possible. Given that each buyer has different marginal benefits of water utilization, competition arises for the limited quantity of tradable water rights; thus, the buyer willing to pay the highest price is the first to obtain sufficient water rights. Therefore, the market water price is not fixed but determined by the buyers' demand. Each buyer is, thus, required to propose an offer and make a deal according to its own situation. Correspondingly, other stakeholders can alter/change their offers and finalize a trade transaction that matches their desired quantity and price. This context is, thus, better suited to the rules of the bulletin-board approach.

Considering the scarcity of water resources, the water market is a sell-side marketplace. In such a situation, the model defines the rules for transaction as follows.

After collecting offers from all participants, the organizers of the trading transactions will make separate priority lists for buyers and sellers, where buyers with higher bids will achieve higher priority in terms of purchasing water rights, and sellers with lower bids will have higher priority in terms of water sale rights.

(1) For buyers

For the ith buyer, take the derivative of water consumption x_i in its economic agent equation. When the first-order differential equation equals zero, the economic benefit of the ith agent is maximized, which is provided by

$$F_i{}'(x_i) = f_i{}'(x_i) - p'(x_i, w_i) - c'(x_i, w_i)\delta = 0 \tag{9}$$

By substituting Equation (2) into Equation (9), the formula becomes

$$f_i{}'(\hat{x}_i) - c - p = 0 \tag{10}$$

By defining the bid price of the ith agent as p_{bi} and introducing the water rights purchased in the market $b_i = \hat{x}_i - w_i$ into Equation (10), the formula becomes

$$p_{bi} = f_i{}'(b_i + w_i) - c \tag{11}$$

When $b_i = 0$, the critical bid price p_{bic} can be calculated. Therefore, the interval of the buyer's quotation is (0, p_{bic}), and correspondingly, the interval of the water rights purchased is (b_{ic},0). b_{ic} is defined as the purchased water rights when bid price equals 0.

In this way, the quotations of all buyers in the water market can be listed in Table 4.

Table 4. Quotations of all buyers in the water market.

Priority	Bid Price	Amount Purchased
Buyer 1	p_1	$b_1 = g_1(p_1)$
2	p_2	$b_2 = g_2(p_2)$
3	p_3	$b_3 = g_3(p_3)$
…	…	…

Note:$p_1 \geq p_2 \geq p_3$; $b_i = g_i(p_{bi})$ is the inverse function of Equation (11).

(2) For sellers

Similarly, priorities, tradable water rights, and selling price can also be calculated using economic agent equations. The seller with the highest priority will be the first to make deals with the buyers in the appropriate order (bid from highest to lowest) until all buyers' demands are met or until the seller sells all tradable water rights and reaches the optimum. In this way, trade continues sequentially according to the sellers' priority, following the same pattern.

Before the ith buyer participates in the trade, the remaining quantity of water rights of the jth seller is $w_{j,i-1}$, and the benefit obtained after the deals with all previous $i-1$ buyers is $S_{j,i-1}$. When the ith buyer proposes the bid price p_{bi}, the economic agent equation of the jth seller becomes

$$F(x_j) = f(x_j) - \int_0^{x_j} (p_0 + tx)dx + p_{bi}(w_{j,i-1} - x_j) + S_{j,i-1} \tag{12}$$

The trading rules are as follows:

(1) After the derivation of Equation (12), if the optimum water consumption exceeds the quantity of remaining initial water rights, which is $\hat{x}_j \geq w_{j,i-1}$, the trade will stop.

(2) If $\hat{x}_j < w_{j,i-1}$, the jth seller can provide the ith buyer with water rights amounting to no more than $z_i = w_{j,i-1} - \hat{x}_i$ under the circumstance that,

(2a) if $z_i < g_i(p_{bi})$, the seller can only provide the ith buyer with water rights equaling z_i, and trade will stop;

(2b) if $z_i \geq g_i(p_{bi})$, the seller can satisfy all demands of the ith buyer, which is $g_i(p_{bi})$.

(3) In circumstance (2b), after completing a full trade transaction with the *i*th buyer, the remaining initial water rights of the *j*th seller are provided by $w_{j,i} = w_{j,i-1} - g_i(p_{bi})$, and the total benefit of selling water is represented as $S_{j,i} = S_{j,i-1} + p_{bi} \times g_i(p_{bi})$. Now, update Equation (12) and go to rule (1) to check if trade can be conducted with the *i* + 1th buyer. If it can be conducted, continue trade until it stops.

(4) Calculate the total benefits for all agents after all trade transactions have been completed.

In this case, the water allocation objective of the basin is no longer the maximization of gross benefits for all agents in the system; rather, it is the outcome of competitive trade among all water users in the free water market.

3.3. Model Solution

The numerical processes for the two models can be calculated using the software MATLAB. By substituting known conditions, including water resource parameters, economic agent equations for each agent (fitted by using actual data from 2007 to 2012), pollutant emission equations, and economic social parameters, into the model, optimization calculations for multivariable high equations for multiple objectives can be realized with the help of genetic algorithms [23], thus, obtaining the industrial water price, the water consumption of each agent, the number of water rights traded, and the economic outcome under the two systems.

4. Results

Using the base year 2010, the water supply of and the water demand for the Shiyang River Basin in 2020 were forecasted and analyzed to facilitate optimal allocation planning. The optimization results obtained by using the two water rights trade models were also compared to facilitate further discussions.

4.1. Water Supply Forecast

The available water supply includes surface water, groundwater, and water supply from other sources. The available surface water supply is derived from water storage, diversion, lifting, and inter-basin transfer projects. The groundwater supply is mainly derived from water lifting projects, such as electro-mechanical wells. Other sources of water supply include wastewater re-usage and rainfall utilization.

According to the Water Resources Development Planning of the Shiyang River Basin, there will be no additional surface water supply projects, such as water storage and water lifting, in the next decade. Therefore, in accordance with the historical water supply curve, the exponential smoothing method has been adopted to predict that the surface water supply will be 1.77 billion m^3 in 2020. As the utilization rate of canal water in the irrigation area increases, the recharge amount of water infiltration will correspondingly decrease, and the total supply of groundwater will become relatively small. The groundwater supply volume is predicted to reach 570 million m^3 in 2020. According to the policy requirements of Jinchang City, the sewage treatment rate should reach 60% on average, and the amount of reused sewage treatment is likely to increase to 65 million m^3 in 2020. The amount of available rainwater is roughly estimated to reach 12 million m^3 in 2020 (Table 5).

Table 5. Total forecasted water supply of the Shiyang River Basin in 2020 (million m^3).

Planning Year	Surface Supply	Ground Supply	Waste Reuse	Rainfall	Total Supply
2020	1770	570	65	12	2417

4.2. Water Demand Forecast

The norm method and analytic hierarchy process were adopted to predict the water demand (Table 6) and initial water rights allocation (Table 7) for each industry in 2020 [22].

Table 6. Forecasted water demand for the Shiyang River Basin in 2020 (million m^3).

Planning Year	Domestic	Production				Ecological	Total
		Agriculture	Industry	Construction	Tertiary		
2020	86.98	1944.65	271.78	2.23	10.18	150.48	2466.30

Table 7. Forecasted initial water rights allocation for the primary and secondary industries of the Shiyang River Basin in 2020 (million m^3).

Year	Total Amount	Initial Water Rights			
		W-Agriculture	W-Industry	J-Agriculture	J-Industry
2020	2169.6	1462.8	125.2	438.9	142.7
	Percentage	0.674	0.058	0.202	0.066

Note: W and J represent Wuwei city and Jinchang city, respectively. Water demand for the tertiary industry was previously satisfied and did not involve initial water rights allocation.

Domestic water demand was divided into urban water demand and rural water demand. The population was predicted by using the exponential smoothing method and then multiplied by the water quota. The estimated agricultural water needs included farmland irrigation and water needs for forestry, animal husbandry, fishing, and livestock. Three different types of irrigation were considered, namely canal irrigation, well irrigation, and combined well and canal irrigation. The water demands of forestry, animal husbandry, fishing, and livestock included two items: irrigation of forest fruit fields and water for livestock. The predictions for agricultural water demand were required to consider these four factors: (1) variations in the irrigation area, (2) irrigation regulations, (3) crop composition and irrigation norms, and (4) canal water utilization efficiency.

$$Q_{at} = W_{nt} \cdot A_t / \eta_t \tag{13}$$

where Q_{at} is the gross irrigation quota in planning year t, and W_{nt},A_t, and η_t represent the net irrigation quota, irrigation area, and the utilization coefficient of canal water, respectively.

The industrial water demand forecast was based on historical industrial water consumption, the Key Management Plan Report of the Shiyang River Basin, and the research results of Industry Water Quota in Gansu Province.

The water demand of the construction industry was predicted by using the exponential smoothing method in accordance with Industry Water Quota in Gansu Province and the growth curve of the actual water quota for construction industries in the Shiyang River Basin.

Water demand in the tertiary industries was predicted according to trends in economic development and water consumption per unit of output value.

The ecological water demand forecast was calculated based on the forest-grass irrigation area, irrigation quota, and utilization coefficient of irrigation water.

4.3. Water Allocation Results for 2020

4.3.1. Under the Administered System

In 2020, the amount of water saved for agriculture in Wuwei is expected to reach 823 million m^3, while the figure for Jinchang is 356 million m^3, with corresponding investment amounts of up to 1632.8 and 317.8 million yuan (a total of USD 46.91 million; USD 1 is roughly equal to 6.77 yuan), respectively [24]. The impact of variations in water prices and water-saving behaviors on water rights trade is undoubtedly non-negligible; this impact should be measured by introducing the water-saving amount and cost coefficient into the model. Because it was the dominant water-saving measure in Wuwei and Jinchang, only agricultural water saving was considered for calculations in the model (Table 8). To determine the water-saving cost coefficient k for the two cities, the relationship of water-saving cost K_i and water-saving amount Q_i was simplified linearly with a slope of k_i as follows:

$$K_i = k_i Q_i \tag{14}$$

Table 8. Expected water-saving costs and amounts for Wuwei and Jinchang in 2020.

City	Water-Saving Amount (million m^3)					Agricultural Water-Saving Cost (million yuan)	Cost Coefficient k
	Agriculture	Industry	Domestic Use	C and T Industry	Total		
Wuwei	823.1	13.7	2.6	3.0	842.4	1632.8	1.984
Jinchang	355.6	92.1	0.6	1.8	450.1	317.8	0.893

Note: "C&T industry" refers to the construction and tertiary industry.

Tables 9–11 show the optimized water price and corresponding industrial benefits in 2020; these factors reveal that the key influential factor is transaction price and not the industrial water price. A relatively low transaction price (0.793 yuan/m^3 in 2020) is necessary to achieve the optimal social benefit of the entire basin and increase the profits of the corresponding agents (Tables 9 and 10). For this transaction, the sellers are two agents from Jinchang, while the buyers are two agents from Wuwei, who both succeeded in obtaining water rights in the market (compare data in the second and fourth rows of Table 11). Simultaneously, Wuwei and Jinchang will not need to save as much water as possible, as both cities show strong capacities to cut down on cost and save water; this enables them to satisfy the water demand of the whole basin without reaching their full water-saving capacities (Table 11).

Table 9. Actual water price for base year 2010.

Water Price	Wuwei-Agriculture	Wuwei-Industry	Jinchang-Agriculture	Jinchang-Industry	Domestic Use & Tertiary Industry
yuan/m^3	$p_1 = 0.2$	$p_2 = 3$	$p_3 = 0.1$	$p_4 = 0.67$	$p_0 = 2.2$

Table 10. Optimized water price for planning year 2020.

Year	Water Price	Wuwei-Agriculture	Wuwei-Industry	Jinchang-Agriculture	Jinchang-Industry	Water Market	Tax	Social Benefit
2020	yuan/m^3	$p_1 = 0.207$	$p_2 = 3$, $t_2 = 0.2$	$p_3 = 0.1$	$p_4 = 0.67$, $t_4 = 0.1$	$p_h = 0.793$	$c = 0.06$	$r = 1.0003$

Table 11. Optimized water consumption and benefits for planning year 2020 (million m^3).

2020	Wuwei-Agriculture	Wuwei-Industry	Jinchang-Agriculture	Jinchang-Industry	Total Water Consumption	Social Benefit
Initial water rights	1462.8	125.2	438.9	142.5	2169.4	$R = 1.0003$
Percentage	0.674	0.058	0.202	0.066	1	
Actual Consumption	1468.4	260.8	349.7	90.5	2169.4	
Percentage	0.677	0.120	0.161	0.042	1	
Maximum water-saving amount	823.1	0	355.6	0		
Actual water-saving amount	0	0	84	0		
Percentage of water-saving	0	0	23.61%	0		
Optimized benefits (million yuan)	4867	22,893	774.1	19,905.4	48,439.5	

In addition, cost accounting was utilized to analyze whether each agent took real action to save water in the trading process. Under the condition that the water demand of the ith consumption agent x_i is less than its initial water rights w_i, the water use cost before saving water is $\int_0^{x_i}(p_0 + t_i x)dx$, where t_i is the slope of ladder water prices for the ith agent. With effective water-saving behaviors, a volume equaling $a_i x_i$ (α_i is the water-saving coefficient) is saved, which decreases the cost to $\int_0^{(1-\alpha_i)x_i}(p_0 + t_i x)dx - \alpha_i x_i p_h + E_i(\alpha_i x_i)$. The system reaches its critical state when the values of the two costs are equal. As the linear function is used to depict the water-saving cost (Equation (14)), if the slope of ladder water prices t_i is omitted, the equation under critical state can be simplified as

$$p_h + p_0 = k_i \tag{15}$$

where p_h is the transaction price, p_0 is the basic industrial water price for the ith agent, and k_i is the water-saving coefficient of the ith agent.

When the transaction price $p_h > k_i - p_i$, p_i represents the optimized water price of the ith agent in the administrated model, while p_h is fixed in the water market. The agent is likely to demonstrate water-saving behavior until the full capacity of water saving is reached. Otherwise, the agent will reach the opposite conclusion, as more profits can be obtained through water rights trade than through water saving. When Equation (14) holds, the amount of water that should be saved is determined by the comprehensive optimization objective (Table 12).

Table 12. Relationship between critical water transaction price and water-saving cost coefficient in 2020.

Year	Water Price	Wuwei-Agriculture	Water-Saving Coefficient	Critical Price	Jinchang-Agriculture	Water-Saving Coefficient	Critical Price
2020	yuan/m^3	p_1 = 0.2	k_1 = 1.984	p_h = 1.784	p_3 = 0.1	k_3 = 0.893	p_h = 0.793

Figure 3 illustrates how transaction price p_h influences the water-saving behavior of each agent under the condition of fixed industrial water price. When $p_h = 1.5$,

$$p_h < k_i - p_i = 1.784 \tag{16}$$

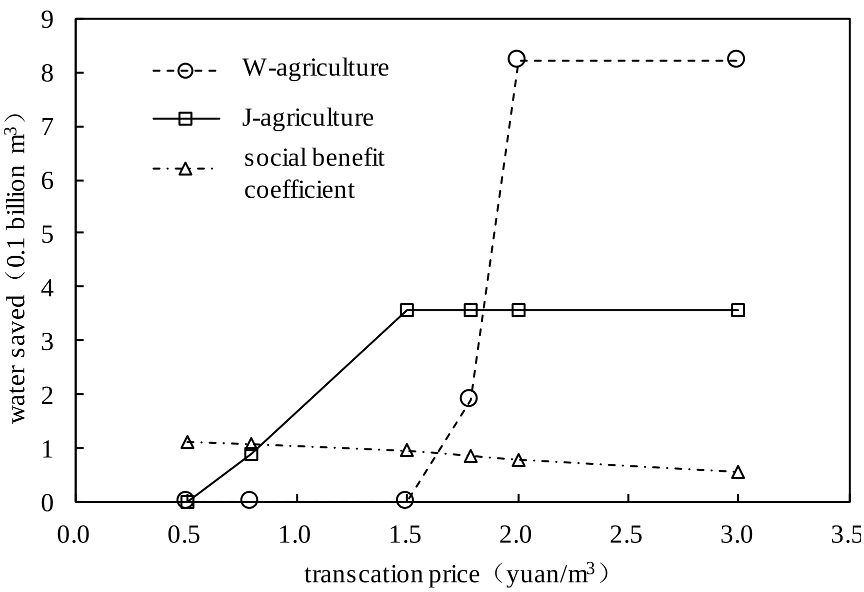

Figure 3. Relationship between water transaction price and water-saving amount of each agent in 2020.

In this situation, Wuwei's agricultural industry does not need to save water. However, for Jinchang, transaction price p_h exceeds its critical value, which will make the water quantity saved by agents reach its maximum amount of 355.6 million m^3 (6th row in Table 11).

Moreover, it is noteworthy that when the transaction price increases, the social benefit coefficient r decreases; this is attributed to the unreasonable utilization of water resources (Figure 3). The transaction price parameter should, thus, be reduced to resolve the problem of supply exceeding demand.

4.3.2. Under the Market-Based System

The trading procedures of the MS model are as follows:

(1) The total water supply, water demand, and water price for each industry, initial water rights, and economic agent equations are the same as those under AS.
(2) Based on the economic agent equation of each industry, the optimal water consumption of each agent is calculated while considering the current water price. An agent whose optimal water consumption is less than its initial water rights is considered a seller. Thus, the surplus water resources for selling constitute the total water supply in the market, which will be purchased by the buyers whose optimal water consumption has not yet been satisfied.
(3) In a certain period, there are M sellers and N buyers in the market. Calculate the upper limit of the critical bid quotation and the corresponding water demand of each buyer.
(4) Rank the buyers' quotations from high to low and the sellers' quotations from low to high, thus, determining their prioritization. Check whether there are any role changes for the agents (for example, from buyer to seller).
(5) On the basis of each buyer's quotation, compare the buyer's water-saving cost with the cost of buying water, while simultaneously comparing each seller's water-saving cost with the potential benefit of selling water. If more profit can be gained through saving water, the agent will participate in water-saving behavior. Otherwise, the agent will choose to directly trade with other agents in the market.
(6) Taking all current quotations into account, trade transactions should be conducted until the entire water supply is sold out or the water demands of all the buyers are satisfied. Next, calculate the purchasing price, purchasing amount, actual water consumption, and corresponding economic benefit for each agent.

Substitute all relevant parameters for the Shiyang River Basin into MS and define the termination as "all buyers' water demands have been met" or "all sellers' tradable water rights have been sold." Accounting for the use of agricultural water-saving techniques, calculate the ultimate water consumption amount and corresponding benefit for each industry in the planning year by using the bulletin-board trading mechanism.

Table 13 shows the maximum purchasing amount for each buyer and its maximum affordable purchasing quotation. From high to low, the quotation ranks are as follows: Wuwei-Industry, Wuwei-Agriculture, and Jinchang-Agriculture. However, Jinchang-Industry rarely needs to purchase water rights from the market. The allocation results for MS under different sets of purchasing quotations can be calculated and compared with the corresponding results for AS to further analyze the differences between the two systems in terms of water allocation.

Table 13. Range of quotations and purchasing amounts of each agent in 2020.

Agent	Range of Transaction Prices p_h (yuan/m^3)	Critical Water Prices (yuan/m^3)	Range of Purchasing Amounts b (million m^3)
Wuwei-Agriculture	(0, 1.784] (1.784, +∞)	1.784	[0, 307) 0
Wuwei-Industry	(0, 197.97]		[0, 284)
Jinchang-Agriculture	(0, 0.793] (0.793, +∞)	0.793	[0, 84.8) 0
Jinchang-Industry	0		0

Note: There is an inverse relationship between the transaction price p_h and the purchasing amount b; as p_h increases, b decreases.

Table 14 displays the optimal allocation results for different sets of purchasing quotations. Define the benefit ratio of AS as 100% and calculate the ratio of the gross economic benefit under MS to that of AS. For instance, a quotation set for the four agents is [1.5, 2, seller, seller]; this means that Wuwei-Agriculture and Wuwei-Industry are planning to purchase water rights at the price of 1.5 yuan/m^3 and 2 yuan/m^3, respectively, but Jinchang-Agriculture and Jinchang-Industry are selling their surplus water rights. According to trading procedure nos. (2) and (4)–(6), with the highest transaction price of 2 yuan/m^3, Wuwei-Agriculture is prone to agricultural water-saving behavior, as the transaction price is higher than the critical water-saving price. In this situation, Wuwei-Agriculture, whose maximum water-saving reaches 823 million m^3, is converted from the buyer to the seller and becomes the first agent to trade with Wuwei-Industry in accordance with trading procedure no. (5). This result reveals that the water demand of Wuwei Industry, whose maximum purchasing amount is 284 million m^3, can be fully satisfied by Wuwei-Agriculture; thus, the two agents can finalize the trade transaction with an amount of 281.8 million m^3. Jinchang-Agriculture and Jinchang-Industry will no longer participate in the trade, and their water consumption will be determined by the economic agent equations in accordance with the limits of the initial water rights. Now, the potential tradable water rights exceed the water demand in the market; thus, the water resources in the basin are not fully utilized and hold a benefit ratio of 99.7%. The corresponding optimal gross economic benefit will be 48,303 million yuan (less than the figure obtained under AS), which is 48,439.5 million yuan.

Table 14. Comparison of the results obtained from the two systems in 2020 (million m^3, yuan/m^3, million yuan).

Model	2020	Wuwei-Agriculture	Wuwei-Industry	Jinchang-Agriculture	Jinchang-Industry	Total	Benefit Ratio
AS	Initial water rights	1462.8	125.2	438.9	142.5	2169.4	100%
	Actual consumption	1468.4	260.8	349.7	90.5	2169.4	
	Water-saving amount	0	0	84.0	0		
	Role	buyer	buyer	seller	seller		
	Transaction price	0.793	0.793	0.793	0.793		
	Optimal benefit	4867.0	22,893.0	774.1	19,905.4	48,439.5	
MS	Purchasing quotation	0.7	0.793	seller	seller		99.0%
	Purchasing amount	0	142.7	−89.4	−53.4		
	Actual consumption	1462.8	267.9	349.5	89.2	2169.4	
	Water-saving amount	0	0	89.4	0		
	Optimal benefit	4387.5	22,986.7	774.1	19,823.1	47,971.4	
	Purchasing quotation	1.5	2	seller	seller		99.7%
	Purchasing amount	−281.8	281.8	0	0		
	Actual consumption	1181.0	406.9	438.9	90.5	2117.3	
	Water-saving amount	281.8	0	0	0		
	Optimal benefit	4477.9	23,185.4	822.7	19,817.0	48,303.0	

Note: AS represents administered system, and MS represents market-based system; Negative purchasing amount implies the sale of water rights.

When the quotation set is [0.7, 0.793, seller, seller], according to Equation (14), only Jinchang-Agriculture shows the tendency to save water, with the maximum amount reaching 356 million m^3. The tradable water rights of Jinchang-Agriculture and Jinchang-Industry are 89.4 and 53.4 million m^3, respectively; both are purchased by Wuwei-Industry, with none left for Wuwei-Agriculture. The benefit ratio under this condition is 99%, with a total economic benefit of 47,971.4 million yuan, which is still less than that obtained under AS.

The results above demonstrate that, as the basis of the decision to save water and participate in trade, the highest bid in the quotation set has a dominant influence over how the trade is conducted. This case includes an occasion where the benefit ratio improves with the increase in transaction price; this results from the use of cost-benefit accounting in agricultural water-saving. Only when the quotation is higher than the critical value does the agent become stimulated to adopt water-saving behavior to save as much water as possible and to introduce surplus water rights into the market.

Note that the economic benefits of MS are lower than that of AS because the water prices of industries in AS are obtained through optimization calculation to reap economic, social, and environmental benefits (Table 10). In MS, the water prices of industries cannot be obtained through optimization calculation. Moreover, it cannot use the 2010 initial water prices; it can only use the predicted industry water price for 2020. Wuwei's predicted agricultural water price is 0.28 yuan/m^3, which is higher than that of AS in the model optimization numerical (0.207 yuan/m^3). Thus, the water fee increases, while economic benefits decrease. The total benefit value is also smaller than the result in the AS model. For example, when the predicted water price is reduced in 2020, the agricultural water price in Wuwei is reduced to 0.22 yuan/m^3. Recalculation shows that the benefit value of MS exceeds that of AS. This result is due to the introduction of water-saving technology, which is similar to the emergence of additional water resource supplies. If water-saving measures are not introduced, and trading is conducted on the basis of existing total water resources, the benefit value of MS will not exceed that of AS.

5. Discussion and Conclusions

Based on previous studies, this study further explored the optimal allocation of regional water resources. Because they are centered on ideal economic agent equations, this study assumed that the behaviors of water use agents will only comply with the objective of achieving maximum economic benefit; therefore, the influence of market variation, environmental controls, development strategy, and so on were excluded. Additionally, the study demonstrates the important role of water-saving techniques and cost in water allocation; thus, a high transaction price in the market is considered as the incentive for agents to adopt water-saving behaviors.

The allocation results for both AS and MS were calculated and discussed. The AS model conceptually focuses on a top-down comprehensive transparent control facilitated by the government and builds an entirely ideal environment for conducting water rights transactions without the impacts of competition and game. However, for the MS model, which is better suited to real-world trade scenarios, the study introduced a bulletin-board approach to facilitate the calculation of allocation plans under different sets of quotations. In MS, as a basis for judging a given agent's tendency to save water and participate in the trade transactions, the highest bid in the quotation set wields dominant influence over how the trade is conducted. The higher the transaction price is, the better the benefit ratio of MS will be. Therefore, a relatively low transaction price will result in inactivity in terms of water rights trade, and this will have a significant impact on the economic benefit of the basin.

With many influential factors and complex structures, the regional water resource management system is still underdeveloped and needs to be improved so that appropriate trading rules can be formulated in the water rights transaction market. Therefore, the discussion of the following questions in future research is of great scientific value:

(1) The oversimplification of water agents is a problem in this area. For example, all agricultural industries were assumed to have the same marginal value for water; however, different industries

tend to have different values, and some even have negative marginal benefits. To determine the accuracy of the results, it is necessary to focus on the problem of how to choose and decide typical industry needs. In this study, we considered only one agricultural agent for convenience reasons.

(2) It is important for future research to analyze the influence of different policies and trading systems on trading results to elevate the results of the selected model to the level of macroscopic operability and suggestion.

(3) This study considered only agricultural water-saving techniques, but wider attention should be paid to the influence of industrial and domestic water-saving behaviors on the transaction price and amount in the market.

(4) The benefit ratio in this study was defined by using economic benefits; thus, it may not reflect the allocation efficiency of water trading systems precisely. Methods to comprehensively evaluate the working effect of water allocation still require more exploration. An evaluation mechanism for assessing the comprehensive utilization efficiency of water resources based on a basin scale should be established in the future.

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References

1. Calatrava, J.; Garrido, A. Modelling spot water markets under uncertain water supply. *Soc. Sci. Electr. Publ.* **2002**, *32*, 119–142.
2. Babel, M.S.; Gupta, A.D.; Nayak, D.K. A Model for Optimal Allocation of Water to Competing Demands. *Water Resour. Manag.* **2005**, *19*, 693–712. [CrossRef]
3. Erfani, T.; Binions, O.; Harou, J.J. Simulating water markets with transaction costs. *Water Resour. Res.* **2014**, *50*, 4726–4745. [CrossRef]
4. Wildman, R.A.; Forde, N.A. Management of Water Shortage in the Colorado River Basin: Evaluating Current Policy and the Viability of Interstate Water Trading. *Jawra J. Am. Water Resour. Assoc. (JAWRA)* **2012**, *48*, 411–422. [CrossRef]
5. Zaman, A.M.; Malano, H.M.; Davidson, B. An integrated water trading–allocation model, applied to a water market in Australia. *Agric. Water Manag.* **2009**, *96*, 149–159. [CrossRef]
6. Zhao, J.; Cai, X.; Wang, Z. Comparing administered and market-based water allocation systems through a consistent agent-based modeling framework. *J. Environ. Manag.* **2013**, *123*, 120–130. [CrossRef]
7. Roozbahani, R.; Abbasi, B.; Schreider, S. Optimal allocation of water to competing stakeholders in a shared watershed. *Ann. Oper. Res.* **2015**, *225*, 657–676. [CrossRef]
8. Yu, B.; Tisdell, J.G.; Podger, G.; Salbe, I. A hydrologic and economic model for water trading and reallocation using linear programming techniques. In Proceedings of the MODSIM 2003: International Congress on Modelling and Simulation, Jupiters Hotel and Casino, Townsville, Australia, 14–17 July 2003.
9. Montilla-López, N.M.; Gómez-Limón, J.A.; Gutiérrez-Martín, C. Sharing a river: Potential performance of a water bank for reallocating irrigation water. *Agric. Water Manag.* **2018**, *200*, 47–59.
10. Montilla-López, N.M.; Gutiérrez-Martín, C.; Gómez-Limón, J.A. 2016. Water banks: What have we learnt from the international experience? *Water* **2016**, *8*, 466–484. [CrossRef]
11. Giuliani, M.; Castelletti, A. Assessing the value of cooperation and information exchange in large water resources systems by agent-based optimization. *Water Resour. Res.* **2013**, *49*, 3912–3926. [CrossRef]
12. Hadjigeorgalis, E. A place for water markets: Performance and challenges. *Rev. Agric. Econ.* **2009**, *31*, 50–67. [CrossRef]

13. Bjornlund, H. Efficient water market mechanisms to cope with water scarcity. *Int. Water Resour. Dev.* **2003**, *19*, 553–567. [CrossRef]
14. Howe, C.W.; Schurmeier, D.; Shaw, W.D. *Innovations in Water Management: Lessons from the Colorado-Big Thompson Project and Northern Colorado Water Conservancy District. Scarce Water and Institutional Change*; Resources for the Future Press: Washington, DC, USA, 1986; pp. 171–200.
15. Clifford, P.; Landry, C.; Larsenhayden, A. *Analysis of Water Banks in the Western States*; Washington State Department of Ecology: Olympia, WA, USA, 2004.
16. Draper, S.E. Limits to water privatization. *J. Water Res. Pl-Asce* **2008**, *134*, 493–503. [CrossRef]
17. Souza Filho, F.A.; Lall, U.; Porto, R.L.L. Role of price and enforcement in water allocation: Insights from Game Theory. *Water Resour. Res.* **2008**, *44*, W12420. [CrossRef]
18. Matthews, O.P. Fundamental questions about water rights and market reallocation. *Water Resour. Res.* **2004**, *40*, W09S08. [CrossRef]
19. George, B.; Malano, H.; Davidson, B.; Hellegers, P.; Bharati, L.; Massuel, S. An integrated hydro-economic modelling framework to evaluate water allocation strategies II: Scenario assessment. *Agric. Water Manag.* **2011**, *98*, 747–758. [CrossRef]
20. Berbel, J.; Martin-Ortega, J.; Mesa, P. A Cost-Effectiveness Analysis of Water-Saving Measures for the Water Framework Directive: The Case of the Guadalquivir River Basin in Southern Spain. *Water Resour. Manag.* **2011**, *25*, 623–640. [CrossRef]
21. Maeda, S.; Nagamochi, T.; Kawach, T.; Takeuchi, J. Regional allocation of irrigation water in a rice paddy area with water-saving practices. *Irrig. Drain. Syst.* **2011**, *25*, 81–96. [CrossRef]
22. Wang, L.; Huang, Y.; Zhao, Y.; Li, H.; He, F.; Zhai, J.; Zhu, Y.; Wang, Q.; Jiang, S. Research on Optimal Water Allocation Based on Water Rights Trade under the Principle of Water Demand Management: A Case Study in Bayannur City, China. *Water* **2018**, *10*, 863. [CrossRef]
23. Deb, K. Multi-objective Genetic Algorithms: Problem Difficulties and Construction of Test Problems. *Evol. Comput.* **2014**, *7*, 205–230. [CrossRef]
24. Key Management Plan Report of the Shiyang River Basin. *Gansu Provincial Water Resources Department.* **2007**, 91–93.