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Optimization-Based Agricultural Water-Saving Potential Analysis in Minqin County, Gansu Province China

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Abstract: To deal with the contradictions that are caused by natural conditions and unreasonable water allocations in Minqin County, which are located downstream of the Shiyang River basin in arid northwest China, an optimization-based multi-scale calculation method was proposed for analyzing agricultural water-saving potential. Firstly, an optimization model was developed for allocating water and land resources legitimately with the conjunctive use of surface water and groundwater. Secondly, the groundwater equilibrium was fully considered in developing optimization model to achieve the ecological value of agricultural water savings. Then, multi-scale agricultural water-saving potentials were analyzed based on optimal results under different water-saving levels. These results provide local water managers with satisfactory economic benefit with higher water use efficiency. With reasonable management strategies of water and land resources, the ecosystem of Minqin County could gradually recover in the future. The results of the multi-scale water-saving potential analysis can help decision makers to identify desired water-saving plans that consider the coordinated development of the local economy, society, and ecology.

Keywords: water and land optimal allocation; conjunctive use of surface water and groundwater; multi-scale agricultural water-saving potential analysis

1. Introduction

Due to the rapid urbanization and industrialization in China, the increasing conflict between limited water resources and increased water demands calls for reasonable water allocation schemes. As the biggest consumer in most areas, especially in arid and semi-arid areas that are characterized by low rainfall and high evaporation, irrigation water plays an important role in agriculture production [1,2]. For example, in the arid regions of northwest China, irrigation water accounts for approximately 90% of the total water use [3], while the irrigation water use efficiency is far lower than the advanced regions [4]. That is, enormous potentials exist in the conservation of limited agricultural water resources. The accurate assessment of agricultural water-saving potential can not only help local sustainable development by affecting local food security, ecological security, and water security, but also provide specific water-saving direction to local decision makers. Minqin County, which is located downstream of the Shiyang River Basin, is a typical arid area suffering serious ecological deterioration due to the long-term exploitation of groundwater and unguided water management. It is of great significance to study the water-saving potential of Minqin County as a typical case.

The agricultural water-saving potential was measured using various techniques, engineering projects, and water-saving management, and involved four scales, including crop, field, irrigation area, and regional/basin [5]. Many researchers have tried to measure the agricultural water-saving potential [6–9]. Different measures have been adopted, including efficient irrigation technology, deficit irrigation regulation, and irrigation scheduling improvement [10]. However, comprehensive analysis would be obtained by multiple scales of water-saving measures and considering multiple effects [11]. Although every method has its appropriate applications, according to its advantages and disadvantages, unreasonable results might be obtained when overlooking the important effects that are created by agricultural water and land allocation. Zhang and Guo [12] integrated water management optimization model and agricultural water-saving potential analysis methods to analyze local irrigation water-saving potential based on optimization results. However, how to combine multiple scales of water-saving measures with water and land resource optimal allocation has rarely been considered and needs to be addressed.

Decreasing of available irrigation water and the increasing of water demand call for the reasonable allocation and effective management of agricultural water resources. Additionally, crop planting structure optimization, which allocates the optimum planting proportion to each crop to achieve the goals of increasing agricultural economic benefits and decreasing irrigation water use [13], is equally essential for sustainable agricultural development and to address serious water shortage problems. Therefore, irrigation water and planting structure optimization models were extensively employed to provide theoretical guidance for decision makers [14–16]. The interaction and exchange between surface and groundwater resources were considered throughout the conjunctive use of surface water and groundwater [17,18], in which the available groundwater depths were introduced [12,19]. In addition, some studies tried to combine various optimization models with a water-saving potential analysis, and thus contribute to the optimal management of water and land resources [12,20]. However, with more attention being paid to optimizing agricultural water and land resources separately via different optimization models, the interactions between them were not fully considered and few researchers realized the ecological value in agricultural water savings.

Therefore, to deal with the multiple contradictions that are caused by natural conditions and unreasonable water allocation, which manifest in ecological harm and further affect agricultural water and land resource management, the objectives of this study are to (1) establish an integrated optimization model for water and land resource allocation based on the conjunctive use of surface water and groundwater; (2) introduce the groundwater equilibrium constraint to obtain several irrigation water schemes and planting areas under different water-saving levels; and, (3) conduct the analysis of multi-scale irrigation water-saving potential with water-saving measures. Finally, an optimization-based multi-scale research method for agricultural water-saving potential is developed. The method was applied to Minqin County, which is located downstream of the Shiyang River basin in northwest China, to demonstrate its effectiveness and practicality for agricultural water and land management and agricultural water-saving potential analysis. The results may support local decision makers formulate better allocation schemes, and the study methods should be helpful for managers to identify the desired water and land allocation plans in similar areas.

2. Study System

2.1. Study Area

Minqin County is a typical arid region, located downstream of the Shiyang River basin, northwest China, within the east longitude 102°52′–103°50′ and the north latitude 38°22′–39°6′. As the green barrier of ecological security in northwest China with the title of the desert oasis, Minqin County is surrounded by the Badain Jaran desert and Tengger desert (Figure 1), and is located in an arid climate zone, with an average annual precipitation and potential evaporation of about 110 mm and 2623 mm, respectively. Precipitation varies greatly among different seasons, with precipitation from July to September, accounting for nearly 66% of the whole year's precipitation [2]. The average annual precipitation from 1985–2014 in Minqin County is shown in Figure 2, and the precipitation distribution in 2014 of Minqin County is expressed in Figure 3. Minqin County has three main irrigation areas:

Hongyashan, Huanhe, and Changning, among which Hongyashan's irrigation area occupies 92.8% of the whole Minqin irrigation area [21]. All of the surface water supply for Minqin County comes from the Hongyashan reservoir, and agriculture is the highest water use sector.

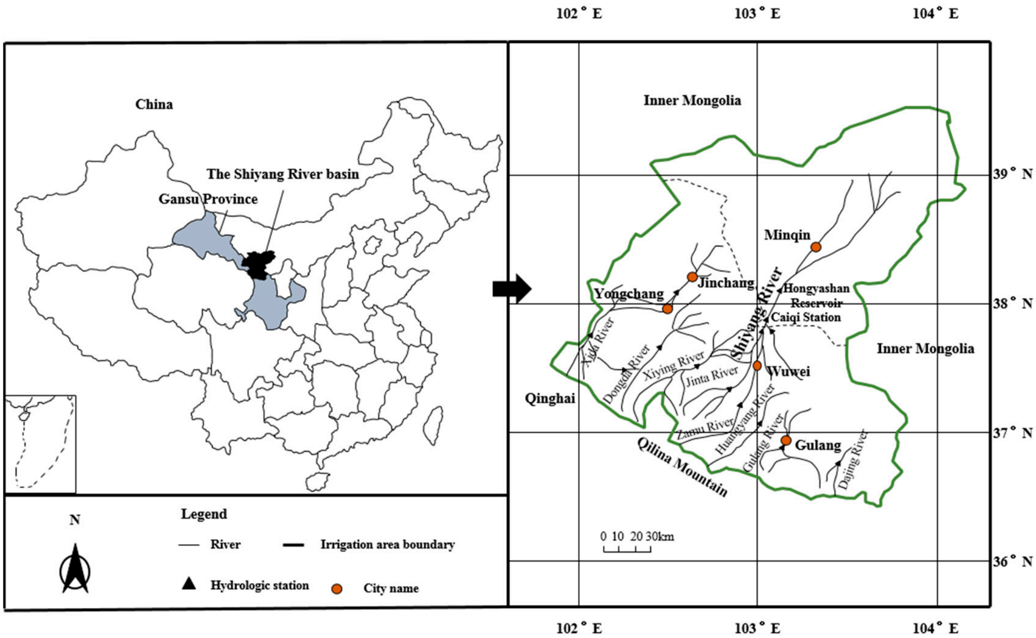

Figure 1. Sketch map of the Shiyang River basin in northwest China.

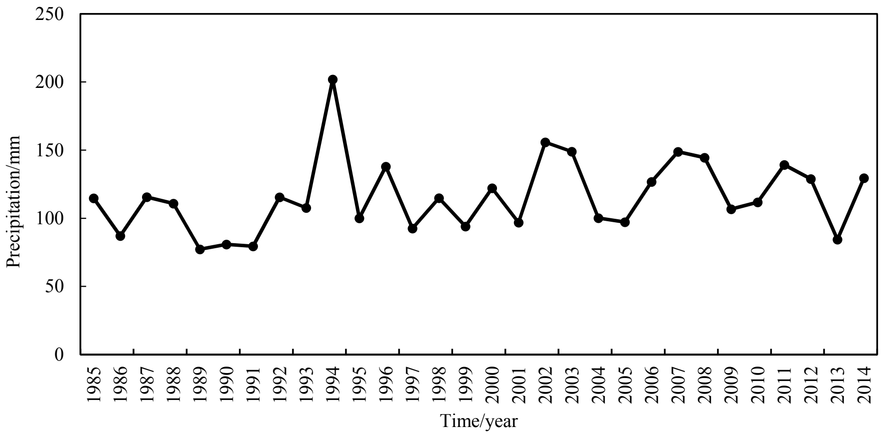

Figure 2. Precipitation from 1985–2014 in Minqin County.

Because of economic development and population growth in the upper and middle reaches of the Shiyang River, the available surface water in Minqin County is rapidly decreasing. Meanwhile, a more serious problem is the over-exploitation of the groundwater. In the past few decades, the over-exploitation of the groundwater has caused a series of ecological problems, such as the continuous decline of the groundwater level (Figure 4), deterioration of the groundwater environment, and further leads to serious desertification, increased salinity, and oasis shrinking [22]. To restore the ecological system of the Minqin oasis, local water managers limited the groundwater exploitation, and thus led to a corresponding reduction of agricultural production. Although the government has taken action by transferring water from other areas in recent years, the water availability for the study area is far less than the water requirement. Thence, both the water utilization efficiency and water production efficiency need to be improved.

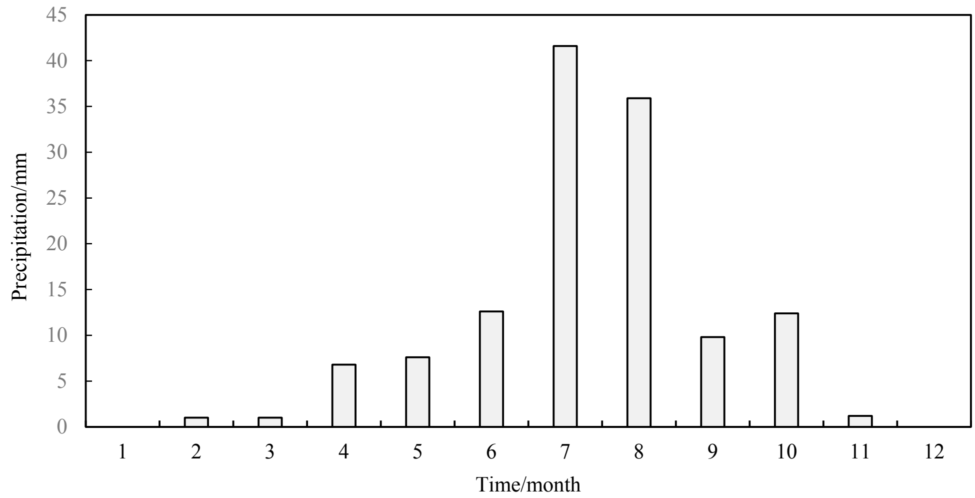

Figure 3. Precipitation distribution for 2014 in Minqin County.

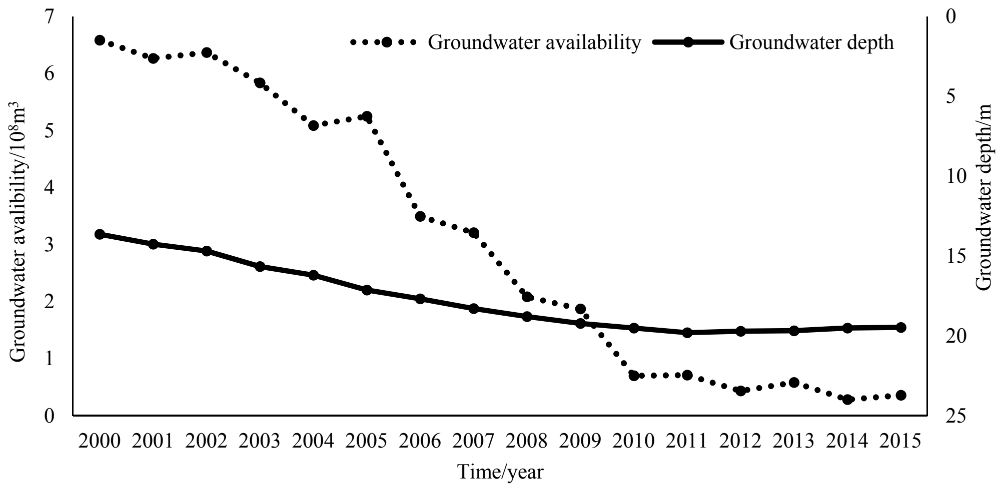

Figure 4. Groundwater availability and groundwater depth from 2000–2015 in Minqin County.

The economic development of Minqin County mainly depends on agricultural production, and the main crops in Minqin include spring wheat, maize, cotton, vegetables, melons, and oil crops. The current irrigation quotas of the typical crops in Minqin County are displayed in Figure 5. The statistical data of Minqin County in recent years can be seen in Table 1, which shows that the proportion of economic crops has increased gradually, and the cultivated areas of water-consuming crops are increasing too, indicating that fierce contradictions exists between the crop planting structure and limited available water. This contradiction is a great challenge faced by local managers in practice.

Table 1. Summary of crop acreage from 2011–2015 in Minqin County (unit: hm^2).

	Spring Wheat	Maize	Cotton	Oil Flex	Seed Melon
2011	7400.04	5386.69	12,826.73	7160.04	2106.68
2012	3853.35	9560.05	11,480.06	7773.37	2173.34
2013	3353.35	9373.38	8880.04	9666.72	2633.35
2014	4473.33	9646.67	7553.33	10,666.67	2320.00
2015	4673.57	9967.17	5000.25	11,513.91	2473.46

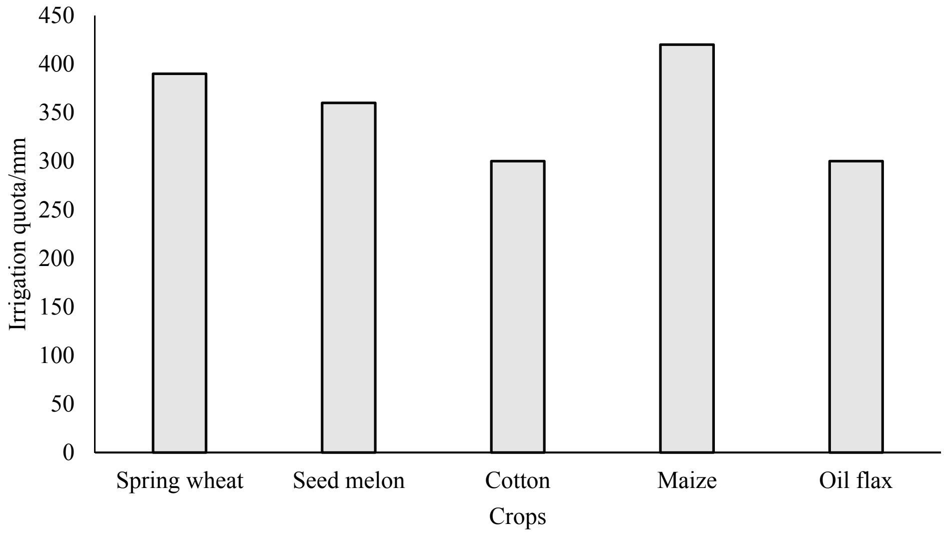

Figure 5. Current irrigation quotas of typical crops in Minqin County.

With the improvement of agriculture water management, great water-saving potentials exist in local irrigation water allocation system. Therefore, it is of great significance to analyze the agricultural water-saving potentials with the efficient utilization of limited water and land resources in order to improve agricultural production, promote socioeconomic development, and help ecological restoration in Minqin County.

2.2. Data Collection

Natural environmental data, socio-economic information, and typical crops data were used in this study. Meteorological data from 1985–2014 in the Minqin County were obtained from the China Meteorological Data Sharing Service System; crops data [23], including the typical crop sensitivity index, crop growth stages division, crop coefficient, and maximum crop yield, were used in this study; crop planting data and population were obtained from *The Statistical Yearbook of Wuwei City*; streamflow data, water supply data, and current irrigation water distributions originated in the survey of Wuwei City; the groundwater management objectives were available in *The Shiyang River Basin Key Governance Projects*; the current irrigation quotas were obtained from *The Wuwei Industry Water Quota*; and finally, the value range of the parameters expressed in Table 2 [24] were references of the coefficient including the regional specific yield, the leakage coefficient of the canal system, the precipitation infiltration coefficient, and the field leakage coefficient. All were used for the optimization model.

Table 2. The range of the main parameters.

	Specific Yield	Precipitation Infiltration Coefficient	Canal Leakage Coefficient	Irrigation Supply Coefficient
Clay	0.02–0.05	0.08–0.15	0.08–0.15	0.08–0.12
Silt	0.05–0.10	0.12–0.18	0.12–0.18	0.12–0.18
Fine sand	0.06–0.20	0.15–0.22	0.15–0.22	0.15–0.20
Sand and gravel	0.12–0.25	0.18–0.25	-	-
Sandstone	0.04–0.10	0.05–0.10	-	-
Basalt	0.05–0.08	0.08–0.15	-	-
Sedimentary rocks	0.03–0.10	0.05–0.08	-	-

3. Study Methods

3.1. System Framework

This paper attempts to combine the optimization model for agricultural water and land resource allocation with agricultural water-saving potential. This section contains two major components (Figure 6): (1) integrated optimization model for agricultural water and land resource allocation and (2) multi-scale agricultural water-saving potentials. The joint connect point between these two parts is the total available water of Minqin County.

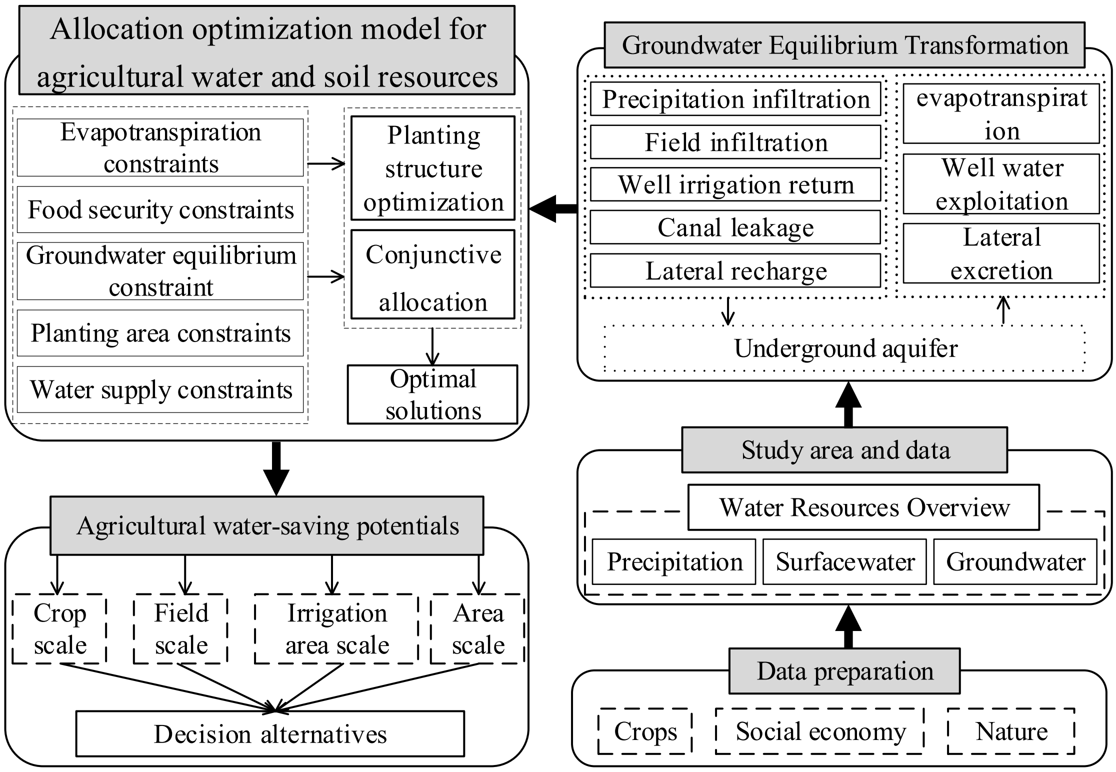

Figure 6. System framework.

The optimization model is developed to achieve the efficient utilization of water resources and optimally allocate the land resources of crops via adjusting the crop planting acreage. The appropriate adjustments of agricultural water resources and cultivated areas are explored to support decision makers for better agricultural water management.

When considering the realities of the study area, analysis with the multi-scale water-saving potentials, which consists of the crop-scale, field-scale, irrigation area-scale, and region-scale, are conducted. The water-saving potentials of different scales are calculated by corresponding water-saving measures. By comparing the results among different scales, a relatively reliable analysis could be obtained to help local managers to alleviate agricultural water shortage.

3.2. Groundwater Equilibrium Analysis

Irrigated groundwater balance refers to the relationships between the total groundwater recharge, the total discharge, and the storage during a period of time. That is, the difference between the groundwater recharge and the discharge in a certain period is equal to the change of the underground reservoir inventory, which can be expressed as follows [25]:

$$\Delta Q = Q_s - Q_e \quad (1)$$

where ΔQ is the change in the amount of groundwater during the certain period; Q_s is the total amount of groundwater recharge during the certain period; and, Q_e is the total amount of groundwater discharge during the certain period.

The main sources of recharge in the study area include precipitation infiltration, field infiltration, canal leakage, well irrigation seepage feedback, and lateral recharge. The main discharges include well water exploitation, evapotranspiration, and lateral discharge. The change of the groundwater level indicates the amount of variation in the stored groundwater. The amount of lateral supply and lateral discharge is so small as to be ignored. The limit depth of groundwater evaporation is 5 m [26]. Minqin's groundwater depth is far more than 5 m, so the evapotranspiration is assumed to be zero in this study. Therefore, the groundwater equilibrium function can be expressed, as follows:

$$\mu A \Delta H = Q_p + Q_c + Q_f + Q_w - Q_o \tag{2}$$

where the μ is the regional specific yield; A (hm^2) is the area; ΔH (m) is the increase of the groundwater level during the certain period; Q_p (10^4 m^3) is the precipitation infiltration during the certain period; Q_c (10^4 m^3) is the canal leakage during the certain period; Q_f (10^4 m^3) is the field infiltration during the certain period; Q_w (10^4 m^3) is well irrigation seepage feedback during the certain period; and, Q_o (10^4 m^3) is the amount of well water exploitation during the certain period.

3.3. Integrated Optimization Model for Water and Land Resource Allocation

When considering the transformation of surface water resource, the Jensen model (which Jensen M.E. first proposed in 1968) is introduced in this study to optimize the farmers' net economic benefit with an objective formulation. The decision variables are the allocation of the surface water and groundwater for each crop in each period, and the crops' cultivated areas. The objective function is expressed as:

$$\max = \sum_{i=1}^{m} A_i B_i Y_{mi} \prod_{j=1}^{n} \left(\frac{SW_{ij} + EP_{ij} + GW_{ij}}{ET_{maxij}} \right)^{\lambda_{ij}} - C_1 \sum_{i=1}^{m} A_i \sum_{t=1}^{T} \left(\frac{SW_{it}}{\eta_1} \right) - C_2 \sum_{i=1}^{m} A_i \sum_{t=1}^{T} \left(\frac{GW_{it}}{\eta_2} \right) - \sum_{i=1}^{m} A_i D_i \tag{3}$$

$$SW_{ij} = \sum_{t=1}^{T} q_{ijt} SW_{it} \tag{4}$$

$$GW_{ij} = \sum_{t=1}^{T} q_{ijt} GW_{it} \tag{5}$$

where i is the crop type; j is the number of crop growth stage; t is the index of time periods; A_i is the crop area of crop i (hm^2); B_i is the price of the crop per unit (CNY/kg); Y_{mi} is the maximum yield of crop i per unit under full irrigation (kg/hm^2); SW_{ij} is the irrigated surface water of crop i during stage j (mm); GW_{ij} is the irrigated groundwater of crop i during stage j (mm); EP_{ij} is the effective precipitation of crop i during stage j (mm); ET_{maxij} is the maximum evapotranspiration of crop i during stage j (mm); λ_{ij} is the water sensitivity index of crop i within stage j; SW_{it} is the irrigated water for surface water of crop i during period t (mm); GW_{it} is the irrigated water from the groundwater of crop i during period t (mm); C_1 is the price of surface water per unit (CNY/m^3); C_2 is the price of groundwater per unit (CNY/m^3); η_1 is the utilization coefficient of surface water; η_2 is the utilization coefficient of groundwater; D_i is the planting cost of crop i (CNY); and, q_{ijt} is the proportion of crop i during stage j in the period t. There are some constraints in this model, as described below.

3.3.1. Groundwater Equilibrium Constraint

In order to prevent land salinization and desertification, respectively, caused by a high groundwater level and low groundwater level, the groundwater equilibrium constraint was introduced into the model. The available upper and lower bounds of the groundwater depth were used to control the groundwater level in a reasonable range in order to protect the groundwater resources. The specific constraint is expressed as follows:

$$H_t = H_{t-1} - \frac{\alpha P_t}{\mu} - \frac{\sum_{i=1}^{m} A_i \left[\beta \frac{SW_{it}}{\eta_1} + \beta' \frac{SW_{it}}{\eta'} + \beta'' GW_{it} - \frac{GW_{it}}{\lambda \eta_2}\right]}{\mu A} + EG_t \quad (6)$$

$$H_{min} \le H_t \le H_{max} \quad (7)$$

where H_t is the groundwater level depth in the period t (mm); H_{t-1} is the groundwater level depth in the period $t-1$ (mm); P_t is the effective precipitation in the period t (mm); α is the precipitation leakage coefficient; β is the canal leakage coefficient; β' is the irrigation return flow coefficient; η' is the field water use coefficient; λ is the ratio of agricultural water consumption to the total amount of well water exploitation; β'' is the well regression coefficient; EG_t is the groundwater evaporation in the period t (m^3); H_{min} is the groundwater level upper limit (m); and, H_{max} is the groundwater level lower limit (m).

3.3.2. Water Supply Constraints

The amount of surface water and groundwater calculated in the model cannot exceed the total available agricultural water supply, thus the following constraints are proposed.

Surface water supply constraint

$$\sum_{i=1}^{m} A_i \sum_{t=1}^{T} SW_{it} \le Q\eta_1 \quad (8)$$

Groundwater availability constraint

$$\sum_{i=1}^{m} A_i \sum_{t=1}^{T} GW_{it} \le G\eta_2 \quad (9)$$

where Q (10^4 m^3) is the surface water supply and G (10^4 m^3) is the groundwater availability.

3.3.3. Evapotranspiration Constraint

In the model, the sum of precipitation and irrigation water during each growth stage should be less than the maximum water requirement, and satisfy the minimum evapotranspiration of crops during the corresponding growth stage. Therefore, the constraint is formed, as follows:

$$ET_{minij} \le SW_{ij} + EP_{ij} + GW_{ij} \le ET_{maxij} \quad (10)$$

where ET_{minij} is the minimum evapotranspiration of crop i during stage j (mm).

3.3.4. Food Security Constraint

In Minqin County, the main grain crops are spring wheat and maize. The sum of the two outputs should meet the minimum food requirements of the total population (420 kg/person) [20]. This constraint can be expressed, as follows:

$$\sum_{i=1}^{k} A_i Y_{mi} \prod_{j=1}^{n} \left(\frac{SW_{ij} + EP_{ij} + GW_{ij}}{ET_{maxij}} \right)^{\lambda_{ij}} \ge \overline{Y} \times S \quad (11)$$

where $\overline{Y}$ is the per capita minimum food weight (kg/person) and S is the local population.

3.3.5. Planting Area Constraints

In the process of optimization, the total acreage of the crops should less than the maximum area. The maximum and minimum planting area constraints are formed to avoid the extreme cultivation adjustment of certain crops. Constraints are expressed, as follows

$$\sum_{i=1}^{m} A_i \leq A_{max} \quad (12)$$

$$A_i \leq A_{i,max} \quad (13)$$

$$A_i \geq A_{i,min} \quad (14)$$

where A_{max} is the total crop acreage (hm^2); $A_{i,max}$ is the maximum acreage of the crop i (hm^2); and, $A_{i,min}$ is the minimum acreage of the crop i (hm^2).

3.3.6. Non-Negative Constraints

The total amount of irrigation water in each crop growth period must be greater than zero, and the expression of these constraints are as follows:

$$SW_{it} \geq 0, GW_{it} \geq 0 \quad (15)$$

Spring wheat, maize, cotton, seed melon, and oil flax are selected for model optimization in this study. The number of crop growth stages is five, and the number of time periods is 12. The average prices of spring wheat, seed melon, cotton, maize, and oil flax are 2.5 CNY/kg, 1.6 CNY/kg, 14.5 CNY/kg, 1.6 CNY/kg, and 6.5 CNY/kg, respectively. The precipitation meteorological data multiplied by the effective utilization factor is calculated as the effective precipitation. The values of ET_0 and ET_{max} are obtained from the FAO-56 (Food and Agriculture Organization) Penman-Monteith method. The available water supply is calculated when considering the proportion of planting and the irrigation water use coefficient based on the total agricultural irrigation water consumption in 2014. Other relevant parameters are shown in Tables 3–5. The optimization model is programmed by LINGO mathematical optimization software (LINDO Systems Inc., Chicago, IL, America), and the results are the optimization schemes of the comprehensive model of water and land resource allocation.

Table 3. Typical crops' water product function parameters.

Growth Stage		1	2	3	4	5
Spring wheat	Date	3.21–4.29	4.30–5.12	5.13–6.1	6.2–6.13	6.14–7.16
	EP (mm)	5.55	2.72	4.39	4.03	22.72
	ET_{ma_x} (mm)	72.69	61.04	113.49	78.76	233.29
	λ	−0.223	0.330	0.094	0.590	0.329
Seed melon	Date	5.1–6.20	6.21–7.5	7.6–7.31	8.1–8.20	8.21–9.17
	EP (mm)	12.79	8.67	27.64	18.52	14.63
	ET_{max} (mm)	97.14	40.02	115.60	42.77	50.35
	λ	0.108	0.062	0.256	0.200	−0.038
Cotton	Date	4.21–6.22	6.23–7.16	7.17–9.14	9.15–10.20	
	EP (mm)	15.28	19.69	48.32	10.58	
	ET_{max} (mm)	55.63	89.08	170.12	16.59	
	λ	0.245	0.172	0.469	0.063	
maize	Date	4.14–5.20	5.21–6.28	6.29–7.26	7.27–9.13	
	EP (mm)	7.01	11.56	28.32	37.44	
	ET_{max} (mm)	71.13	139.54	151.58	209.26	
	λ	0.193	0.115	0.005	0.100	
Oil flex	Date	4.17–6.9	6.10–6.18	6.19–7.5	7.6–8.27	
	EP (mm)	11.64	3.02	9.34	52.65	
	ET_{max} (mm)	176.99	49.06	95.16	196.99	
	λ	0.172	0.084	0.102	0.011	

Table 4. Growth stage-time period transformation variable (q_{ijt}).

		January	February	March	April	May	June	July	August	September	October	November	December
Spring wheat	1	0.00	0.00	0.35	0.97	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	2	0.00	0.00	0.00	0.03	0.39	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	3	0.00	0.00	0.00	0.00	0.61	0.03	0.00	0.00	0.00	0.00	0.00	0.00
	4	0.00	0.00	0.00	0.00	0.00	0.40	0.00	0.00	0.00	0.00	0.00	0.00
	5	0.00	0.00	0.00	0.00	0.00	0.57	0.52	0.00	0.00	0.00	0.00	0.00
maize	1	0.00	0.00	0.00	0.57	0.65	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	2	0.00	0.00	0.00	0.00	0.35	0.93	0.00	0.00	0.00	0.00	0.00	0.00
	3	0.00	0.00	0.00	0.00	0.00	0.07	0.84	0.00	0.00	0.00	0.00	0.00
	4	0.00	0.00	0.00	0.00	0.00	0.00	0.16	1.00	0.42	0.00	0.00	0.00
	5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cotton	1	0.00	0.00	0.00	0.33	1.00	0.73	0.00	0.00	0.00	0.00	0.00	0.00
	2	0.00	0.00	0.00	0.00	0.00	0.27	0.52	0.00	0.00	0.00	0.00	0.00
	3	0.00	0.00	0.00	0.00	0.00	0.00	0.48	1.00	0.47	0.00	0.00	0.00
	4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.53	0.65	0.00	0.00
	5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Seed melon	1	0.00	0.00	0.00	0.00	1.00	0.67	0.00	0.00	0.00	0.00	0.00	0.00
	2	0.00	0.00	0.00	0.00	0.00	0.33	0.16	0.00	0.00	0.00	0.00	0.00
	3	0.00	0.00	0.00	0.00	0.00	0.00	0.84	0.00	0.00	0.00	0.00	0.00
	4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.65	0.00	0.00	0.00	0.00
	5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.35	0.57	0.00	0.00	0.00
Oil flex	1	0.00	0.00	0.00	0.47	1.00	0.30	0.00	0.00	0.00	0.00	0.00	0.00
	2	0.00	0.00	0.00	0.00	0.00	0.30	0.00	0.00	0.00	0.00	0.00	0.00
	3	0.00	0.00	0.00	0.00	0.00	0.40	0.16	0.00	0.00	0.00	0.00	0.00
	4	0.00	0.00	0.00	0.00	0.00	0.00	0.84	0.87	0.00	0.00	0.00	0.00
	5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 5. Variable declaration.

Variable	Variable Meaning Description	Value
η_1	Surface water irrigation utilization coefficient	0.61
η_2	Groundwater irrigation utilization coefficient	0.85
C_1	Surface water price, CNY/m^3	0.24
C_2	Groundwater price, CNY/m^3	0.26
α	Precipitation leakage coefficient	0.20
β	Canal leakage coefficient	0.16
β'	Irrigation backflow coefficient	0.20
β''	Well irrigation compensation coefficient	0.20
η'	Field water delivery efficiency	0.85
λ	Agricultural water consumption ratio	0.44
EG_t	Evapotranspiration, mm	0.00
μ	Specific yield	0.16
A	Area, 10^6 hm^2	1.59
H_1	Initial value of groundwater depth, m	18.75
Q	Surface water supply, 10^4 m^3	8511.39
G	Groundwater availability, 10^4 m^3	2794.85
$\overline{Y}$	Per capita minimum food weight, kg/person	420.00
S	Population, 10^4	24.11

3.4. Multi-Scale Agricultural Water-Saving Potential Analysis Method

The agricultural water-saving potentials mainly include four scales: crop, field, irrigation area, and region/basin. There are notable differences in the agricultural water-saving potential in each scale, and the implementation of water-saving measures in the corresponding scales inevitably affects the others [5]. The researches on the multi-scale agricultural water-saving potentials are as follows:

1. The crop physiological process is taken into account in the process of the crop-scale agricultural water-saving potential calculation. To obtain satisfactory crop yields, the irrigation mode of water deficit is applied to save irrigation water. Different degrees (5%, 10%, 15%, 20%, 25%, and 30%) of water deficit are divided and implementation proportions of 10%, 20%, and 40% are set up, from which the most advisable scheme can be picked out. The difference between the previous irrigation water value and the current irrigation water value is calculated accordingly as the crop-scale water-saving potential.
2. The field-scale water-saving potentials are obtained by calculating the differences between the previous irrigation water consumption and the optimized irrigation water allocation with crop planting structure adjustments. As displayed in Figure 5, the irrigation water consumption of spring wheat and maize is larger than the other crops. Thus, reducing the planting area of these two crops and increasing the area of cotton and oil flax appropriately could save more irrigation water. However, to ensure regional food security, the area of spring wheat and maize cannot be reduced too much.
3. The irrigation area-scale water-saving potentials are reflected by the leakage and the loss of water in the process of irrigation water delivery, which relate to engineering measures, including canal system seepage, pipeline water supply, sprinkler irrigation, and drip irrigation. Currently, in Minqin County, the surface water irrigation utilization coefficient, and the groundwater irrigation utilization coefficient reach 0.61 and 0.85, respectively, and could be further enhanced. Assuming that the head flow is constant, the irrigation water delivered to the field is increased, while the water utilization coefficient is improved. The increased amount of water is calculated as the water-saving potential in the irrigation area.
4. The optimal combination of water-saving measures in crop, field, and irrigation areas is considered in the calculation of the region-scale water-saving potential. The detailed calculation steps (Figure 7) are as follows: (1) the optimization scheme of the integrated optimization

model for agricultural water and land resource allocation is used as the optimal combination of crop-scale and field-scale water-saving measures; (2) the agricultural net irrigation water is calculated; (3) water savings with different water utilization coefficient improvements are calculated with engineering water-saving measures applied; (4) the amount of gross irrigation water is calculated; and, (5) the calculation results are compared to the current irrigation water consumption, and the reduction of the headwater diversion is calculated as the region-scale agricultural water-saving potential.

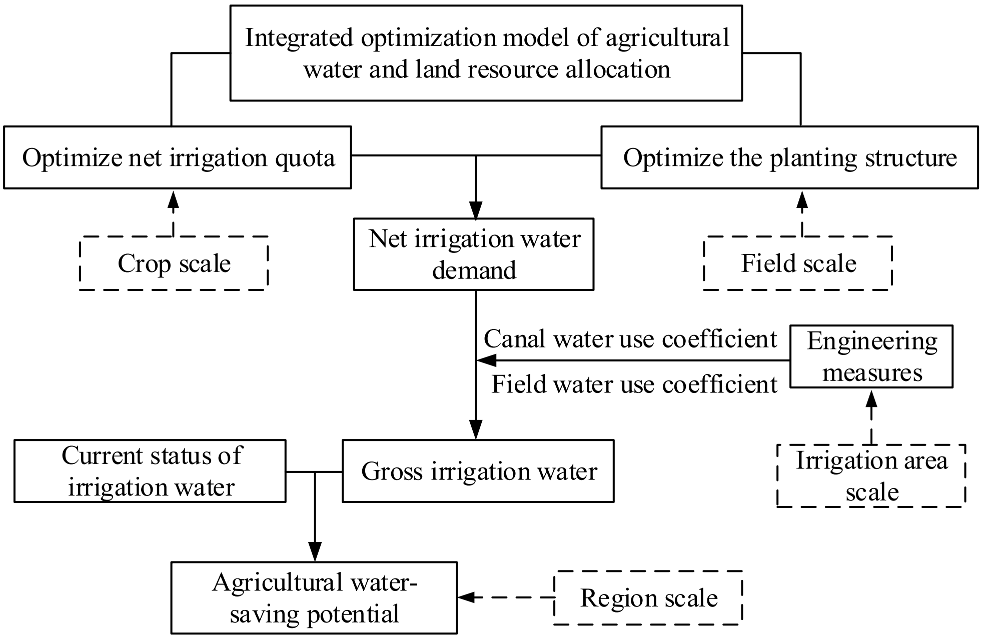

Figure 7. Region water-saving potential calculation flow chart.

4. Results Analysis and Discussion

4.1. Integrated Optimization Model for Agricultural Water and Land Resource Allocation

The integrated optimization model for agricultural water and land resource allocation is used in order to obtain the distribution of water and crop area during the crop growth period (Table 6, Figure 8). As expressed in Table 6, the optimization results increase the water that is allocated to maize because the maize has the highest water productivity among five crops. Simultaneously, the irrigation water of other four crops is reduced when compared with the current scheme. After optimization, 8.66×10^4 m^3 irrigation water can be saved. As shown in Figure 8, excessive groundwater exploitation in the peak period of water supply can be effectively avoided by the conjunctive allocation of surface water and groundwater. Thence, the groundwater depth can maintain a safe level with a slight degree of lifting, which contributes positively to regional ecological restoration. The optimal total net benefit is 0.4 billion CNY, and the net benefit per unit water is 3.3 CNY. When considering maximum economic benefit, land resources are allocated to the crops with high yield and low water demand to make full use of limited resources. For local water managers, adjusting the local crop irrigation quota and crop acreage could promote water savings, production increases, and expanded revenue. For local farmers, reducing the cultivation of spring wheat and oil flax, and replacing them with maize, cotton, and seed melon, may be a better choice and bring greater benefits.

Table 6. Comparison of the indicators before and after optimization.

		Spring Wheat	Seed Melon	Cotton	Maize	Oil Flax
Irrigation (mm)	Present	390	360	300	420	300
	Optimization	366	237	238	473	286
Crop area (hm^2)	Present	4473	2320	7553	9647	10,667
	Optimization	3353	2633	8880	9970	9823
Yield (kg/hm^2)	Present	7321	2250	1476	10,143	2200
	Optimization	7201	2809	1530	14,614	3150
Water productivity (kg/m^3)	Present	2.08	0.61	0.44	2.41	0.69
	Optimization	1.78	0.88	0.46	2.62	0.87
Water benefit (CNY/m^3)	Present	5.00	4.86	6.41	5.56	4.52
	Optimization	4.27	7.04	6.69	6.03	5.65

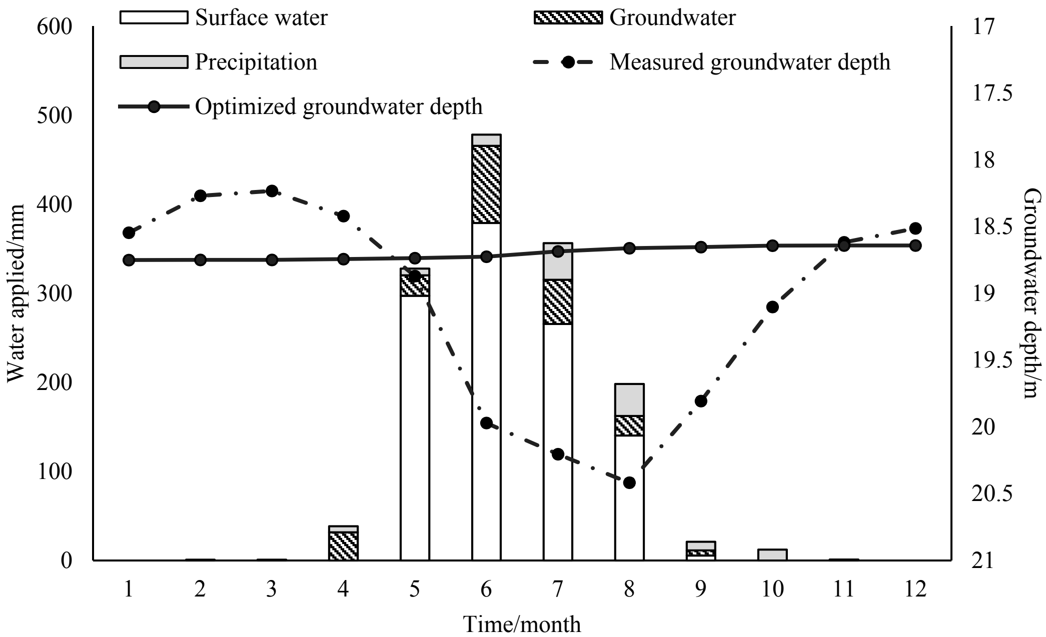

Figure 8. Water distribution and groundwater level changes in each month of 2014.

4.2. Multi-Scale Agricultural Water-Saving Potential

4.2.1. Crop-Scale Water-Saving Potential

The Jensen model was introduced to calculate the yield of crops in each scenario (Table 7). The highest yields minus the actual yields are regarded as the reduction of the crop yields. The relationships between the reduction of crop yields and the degree of water deficit are expressed in Figure 9. As shown in Figure 9, 15% is a desirable degree of water deficit while considering both the water-saving potential and crop yields. Based on the water-saving schemes, water-saving potentials were obtained by reducing the irrigated water by in different implementation proportion of 10%, 20%, and 40% (Figure 10). In this study, 100% represents totally applying water-saving measures to save water in the region. Although more water has been saved with 40% implementation, assurance in technology and high cost jointly hinder its application. Thus, a scheme of 20% implementation with a 15% water deficit seems more recommendable for local managers, in which the water-saving potential reaches 9.68×10^5 m^3. In addition, as shown in Figure 9, reducing the irrigation water of oil flax and seed melon firstly contribute to minimizing farmers' losses.

Table 7. Summary of typical crop yields at different levels of water deficit.

Water Deficit	Yield (kg/hm^2)				
	Spring Wheat	Seed Melon	Cotton	Maize	Oil Flax
5%	7158.1	2676.5	1457.3	14,045.5	3322.1
10%	6738.0	2592.7	1384.4	13,319.8	3256.7
15%	6320.6	2507.0	1311.3	12,593.3	3188.9
20%	5906.1	2419.3	1238.0	11,866.0	3118.5
25%	5494.7	2329.2	1164.4	11,137.9	3045.3
30%	5086.5	2236.6	1090.6	10,408.9	2968.9

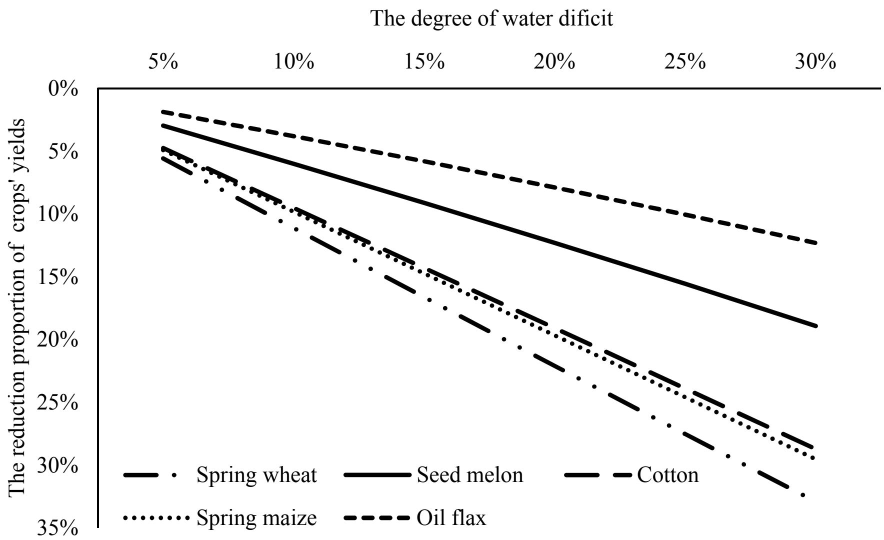

Figure 9. The relations between the reduction of crop yields and the degree of water deficit.

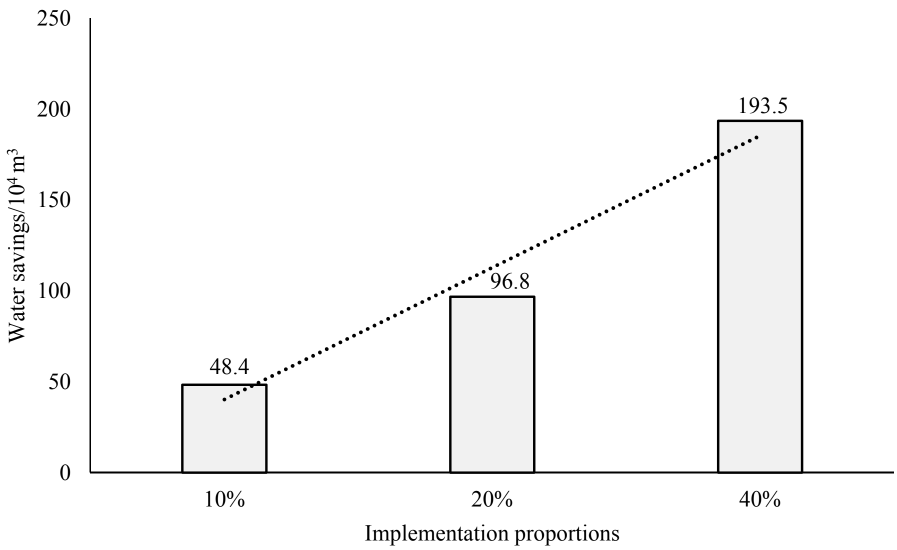

Figure 10. The water savings by different implementation proportions.

4.2.2. Field-Scale Water-Saving Potential

In this section, it is assumed that water quantity in the typical crop growth period is constant with the change of planting area. The saved water consumption was calculated, and the results were shown in Figure 11, where 100% represents that the planting structure is totally adjusted. Although the water consumption of grain crops is high, it is inadvisable to decrease grain crops' acreage too much, due to the restriction of regional food security. From the data in Table 1, the current proportion of grain crops, including spring wheat and maize is 41%. Therefore, it can be concluded that 15% is a proper adjustment proportion, with the field-scale water-saving potential reaching 2.34×10^6 m^3.

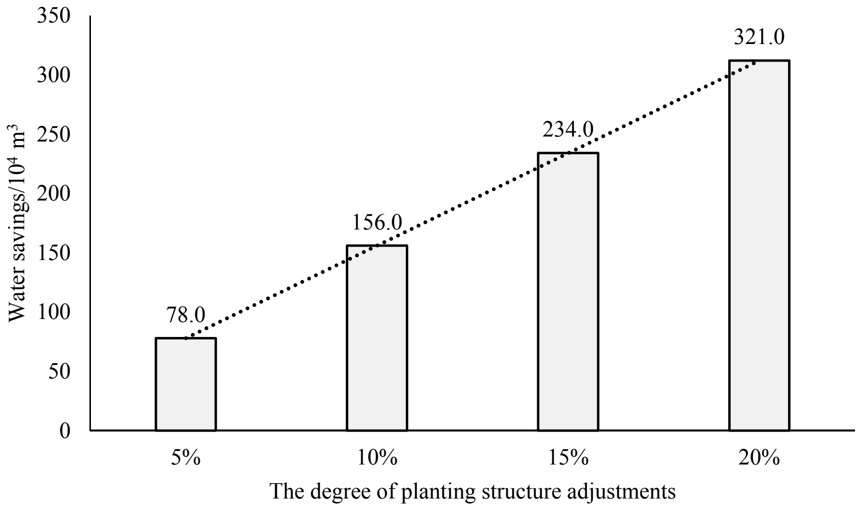

Figure 11. Water savings of different planting structure adjustments.

4.2.3. Irrigation Area-Scale Water-Saving Potential

From the data of water consumption of different industries in 2014, the current surface irrigation water is 1.40×10^8 m^3, and the gross ground irrigation water is 3.49×10^7 m^3. In this study, the available irrigation water is 1.74×10^8 m^3, which is the calculation result of the total agricultural water supply multiplied by the planting proportion (70%). Although plenty of leakage water could be saved by irrigation area-scale water-saving engineering measures, it is difficult to substantially improve the water use coefficient of the canal system and field water use coefficient. Based on previous researches [5], reasonable targets are set up, and the water-saving potentials under different water use efficiency levels are calculated (Figure 12). When the surface water utilization coefficient is 0.66 and the groundwater utilization is 0.90, the water-saving potential of the irrigation area-scale is 8.62×10^6 m^3. Therefore, it is necessary to choose suitable regional development water-saving targets, when implementing irrigation area-scale water-saving measures in irrigation areas.

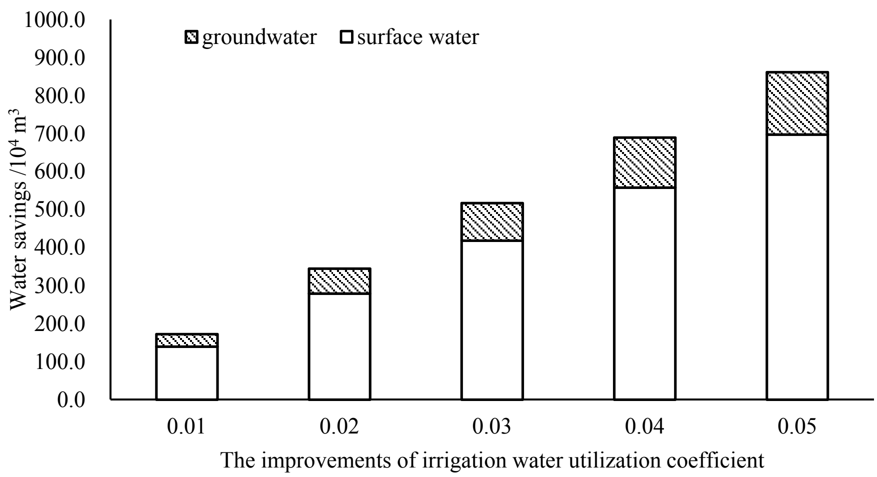

Figure 12. Irrigation area-scale water-saving potentials of different levels.

4.2.4. Region-Scale Water-Saving Potential

From the results of the optimization model, it can be found that the net irrigation water requirement is 9.98×10^7 m^3, of which the surface water is 8.26×10^7 m^3, and the groundwater is 1.71×10^8 m^3. Based on the optimization results, the water-saving potentials under different improvement levels of water use efficiency are calculated (Figure 13). As shown in Figure 13, the possible region-scale water-saving potential can theoretically reach 1.69×10^7 m^3. The region-scale water-saving potential is greater than any other scales, with harmoniously considering the regional ecological, social, and economic stable development. Furthermore, it can be concluded that region-scale water-saving measures can effectively alleviate the contradiction between agricultural water supply and demand and improve the irrigation water use efficiency. For local managers, it is meaningful to execute a suitable water-saving scheme via the optimal combination of water-saving measures in crop, field, and irrigation areas. It is equally important to choose suitable development goals on the basis of local reality.

To sum up, multi-scale agricultural water conservation measures can save considerable irrigation water and ease the regional water pressure. Through saving water intuitively, the water-saving measures at the crop scale have a negative impact on certain crops' yields, while the field-scale water-saving measures can increase crop yields for farmers with saving a large amount of irrigation water. Irrigation area-scale water-saving measures can save a large quantity of water leakage. Finally, the region-scale water-saving measures embody the greatest advantage in saving water to ameliorate the status quo of water shortages. That is, a reasonable scheme can contribute to ecological restoration, effectively alleviating the deterioration of the ecology and groundwater environment in Minqin County. Thus, the preferred choice is to adopt the region-scale water-saving measures for local ecological environment protection and normal agricultural production. Several recommendations are presented, as follows:

1. To ensure the reasonable allocation of limited water resources, an optimal amount of irrigation water for five crops, which not include fallow or non-growing-season periods, should be allocated, with 366 mm for spring wheat, 237 mm for maize, 238 mm for cotton, 473 mm for seed melon, and 286 mm for oil flax.
2. To achieve the efficient utilization of limited land resources, moderate adjustments of crop cultivated areas could be made, including a 25% reduction of spring wheat, 13.5% increase of seed melon, 17.5% increase of cotton, 3.35% reduction of maize, and 7.9% increase of oil flax.
3. To obtain a larger degree of water-saving, stronger financial support should be provided for engineering water-saving renovation measures from the government's investment. The comprehensive promotion of efficient water-saving irrigation technology should be the development target for local agriculture water managers.

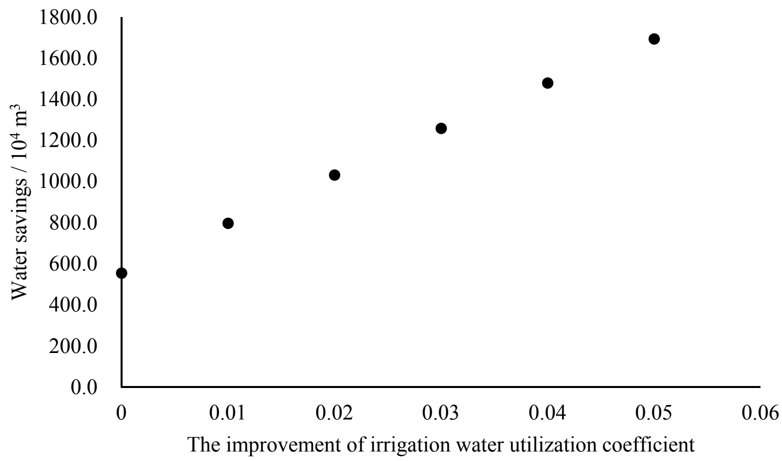

Figure 13. Region-scale water-saving potentials of different levels.

Furthermore, the entire region was considered in the optimization, to deal with the unreasonable water allocation of the Minqin County. These efforts would support local managers to develop more rational water allocation schemes. However, water resource managers face complicated problems in the practice of optimization. For example, China's agricultural land is decentralized. Farmers have the right to choose the growing crops based on individual interests, rather than overall interests, which makes the implementation of the optimization scheme difficult. These factors would be fully considered in future research.

5. Conclusions

This study proposed an integrated optimization model for agricultural water and land resource allocation, and an optimization-based multi-scale water-saving potential analysis framework for support irrigation water management. It can offer alternative water-saving schemes in corresponding conditions for decision makers.

The characteristics of this study are as follows:

1. The integrated optimization model incorporated planting structure optimization and water resource allocation with the conjunctive use of surface water and groundwater, and it was applied to Minqin County in Gansu Province, China. The optimization results provide comprehensive and efficiency water-saving solutions with higher economic benefits.
2. The groundwater equilibrium constraint was used in the model. Taking full advantage of the interaction between surface water and groundwater, this model keeps the groundwater environment a stable and safe condition with a lifting tendency of the groundwater depth. Through balancing agricultural water and ecological water, optimal solutions contribute to both irrigation water saving and ecological restoration.
3. Four scales were chosen in order to analyze the agriculture water-saving potential via adopting water-saving measures, including cutting down the water supply, adjusting the planting structure, improving the utilization coefficient of irrigation water, and the optimal combination of above measures based on integrated optimization model. By analyzing the results of the four scales, it was found that region-scale water-saving scheme not only demonstrates a huge potential of water-saving and agricultural benefit, but also contribute to balancing agricultural prolificacy and ecological restoration.

In addition, the framework, the allocation optimization model and the analysis method in this study can also be applied to other similar regions to help better water-allocation scheme formulation. However, some limitations exist in the proposed method. For example, local policies, year-to-year variability in supply and demand, as well as precise relationships in model formulation could be taken into account in further research.

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