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Original Research

Optimization of Planting Structure under the Background of Water-Saving Irrigation in Shiyang River Basin, China

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Abstract

Adjusting the agricultural planting structure is one of the important means to realize agricultural water-saving, especially in arid inland river basin. In this paper, taking Shiyang River Basin as an example, on the basis of determining the crop water production function, a multi-objective optimization model was constructed, which comprehensively considered the maximization of economic benefits, the green water utilization rate and ecological benefits. The optimized planting structure was obtained by using GAMS (General Algebraic Modeling System) model solver. The results showed that: The common features of the three level years after optimization is that the sown area proportion of wheat, tubers, vegetables, fruits and cotton all increased, of which the sown area of fruits increased most by 5.30×10^4 ha. However, the sown area proportion of corn and oil-bearing crops decreased, of which the sown area of corn decreased most by 8.90×10^4 ha. Comparing of three level years, it is found that the impact of climate change on planting structure adjustment was relatively weak. With the decrease of precipitation, it is suggested to slightly decrease the sown area of wheat but slightly increase the sown area of tubers. The optimization results of planting structure were different in different counties. The average contribution rate of planting structure adjustment to total water-saving was 73.32%, indicating that planting structure adjustment was the key to water-saving. The water consumption of the same crop was different in different counties. Oil-bearing crops

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and vegetables were more suitable for planting in lower reaches, while corn and tubers were more suitable for planting in middle reaches.

Keywords: optimization of planting structure, virtual water, nonlinear multi-objective programming model

Introduction

Agricultural water accounts for 70-90% of total global fresh water consumption [1-3], especially in arid and semi-arid areas where water resources are scarce, with agricultural water accounting for 90% [4]. Moreover, with the development of the social economy, the agricultural water consumption is increasing [5]. The increase of agricultural water use will inevitably intensify the water use competition among various departments, thus restricting economic development and damaging ecological health [6-9]. In order to alleviate the increasingly serious shortage of water resources, the integrated management of water and agricultural land is currently considered to be the most important and effective method [10, 11]. However, at present, a mismatch between agricultural planting structures and water resources in different regions still exists. The proportion of drought-tolerant crops is low, while the proportion of high water-consuming crops is high [12]. Therefore, the efficient use of agricultural water resources and land resources in planting structure adjustment (PSA) has become a focus of attention for scholars and managers [13-16].

Over the last few decades, many research works have explored how to make the best use of water resources and land resources in irrigated agricultural areas, and a series of mathematical optimization models have been developed [17-19], such as linear or non-linear programming models [20], dynamic programming models, fractional programming models [21] and single-objective or multi-objective programming models [22-24]. Of these, the single-objective programming model is widely used because of its simple calculation [25, 26]. However, the management of agricultural water resources and land resources is a very complex issue, which requires comprehensive consideration of the impact of planning results on society, economy and the ecological environment, there are obvious limitations in the single-objective planning model [21, 24]. However, a multi-objective programming model can provide the ideal framework for a decision maker to obtain an optimal solution for problems with multiple competing objectives and to optimize resource allocation [24], which plays an increasingly important role in the management of agricultural water resources and land resources and is widely used in the optimization and adjustment process of planting structures. Scholars generally believe that different agro-ecological regions have different planting structures, and it is necessary to select suitable planting structures according to local water and soil resources. Kennedy et al. put forward a multi-objective programming model based on maximizing economic benefits, biodiversity and freshwater quality and on the climatic conditions of the Brazilian Cerrado to optimize the agricultural planting structure in this region [27]. In view of the problem of water resource shortages caused by unreasonable sown area of wheat under dry farming and irrigation conditions in Spain, Galán-Martín et al. put forward a double-objective optimization model which considered both the maximization of crop yield and the minimization of water consumption in the environment to optimize the sown area of wheat in dry land and irrigation area in this region [28]. Yang et al. found that the sown area was decreasing in Jinghui Canal Irrigation District. Considering the food security problem, a multi-objective optimization model based on minimizing the amount of agricultural irrigation water, maximizing economic benefits and ensuring food security was established to optimize the agricultural planting structure in this area [29]. Considering that crops can provide ecosystem services as a part of ecosystem vegetation coverage, Tan et al. established a multi-objective optimization model based on minimizing agricultural irrigation water and maximizing economic and ecological benefits to optimize the planting structure in this area [13]. Previous studies have shown that the optimization of planting structure is of great significance to improve economic, social and ecological benefits. Under the condition of a shortage of water resources, the increase of agricultural production and income urgently calls for the establishment of a regional water-saving planting structure model centered on the efficient use of water [30-32].

For arid and semi-arid areas, the amount of agricultural irrigation water is limited. On the basis of ensuring food security, it is necessary to consider PSA from the perspective of agricultural water-saving. At the same time, it is important to make full use of precipitation resources, improve the utilization rate of green water [33] and avoid the inefficient allocation of irrigation water. In this process, it is necessary to accurately grasp the functional response relationship between water consumption and yield in the crop growth period – that is, the water production function [34] – to rationally control water resources and maximize crop yield. For instance, Li [35] and Ma [36] used crop water production function to optimize the irrigation schedule of single crops and watermelons in sandy land, respectively. Li [37] and Yue [38] considered the field water cycle process and obtained the total optimal allocation irrigation water amounts combined with the crop water production function. The purpose of this kind of research is to make full use of limited water resources for crops, increase the yield as much as possible on the basis of avoiding water loss and truly realize the unity of ecological and economic benefits. To date, there are still few programming models that combine the utilization rate of precipitation resources with economic and ecological benefits to optimize planting structures [39, 40]. In view of this, on the basis of scientifically determining the water production functions of different crops, this paper attempted to construct a multi-objective programming model of planting structure, which consider maximization of economic benefits, green water utilization rate and ecological benefits, in order to provide scientific guidance for the planting structure adjustment and agricultural water-saving in drought and water-scarce areas.

The SRB is located in the arid area of northwest China, and its lower reaches – Minqin Oasis is surrounded by the Tengger Desert and Badain Jaran Desert. It is one of the inland river basins in China with the densest population and the highest degree of development and utilization of water and soil resources, with the most prominent contradiction in terms of water use and the most serious ecological and environmental problems [41]. Rapid population growth and economic development have resulted in an excessive water demand for the SRB under critical ecological conditions [42, 43]. The growing ecological crisis in the region is worsening due to the existing imbalanced distribution of water among the upper, middle and lower reaches [44]. Since 1970s, the amount of water discharged from the upper and middle reaches to the Minqin Oasis has been decreasing, resulting in the increasing exploitation intensity of groundwater, the continuous decline of groundwater level, the death of a large amount of surface vegetation, the intensification of desertification and the danger of the Minqin Oasis disappearing. Therefore, in January 2006, the Chinese central government launched the Key Treatment Program of the Shiyang River Basin (KTPSRB), which was implemented in 2007, with the ultimate objective of curbing ecological degradation and avoiding the disappearance of the Minqin Oasis. In the past 10 years (2007-2017), the comprehensive management of the basin has achieved remarkable results, and the ecological deterioration trend has been restrained. In 2017, although the total water consumption in the basin decreased from 37.62×10^8 m^3 to 22.93×10^8 m^3, the proportion of agricultural water consumption decreased from 88.12% to 86.30%. However, there are still some challenges, such as high agricultural water consumption, a high irrigation quota and an unreasonable planting structure. It is urgent to optimize and adjust the planting structure, reduce irrigation water and realize agricultural water-saving. Based on this, on the basis of determining the water production functions of different crops, this paper used the GAMS model solver to construct a multi-objective optimization model of the planting structure, which takes into account the objectives of minimizing the total irrigation water, maximizing the ecological and economic benefits and maximizing the utilization rate of green water, and optimized and adjusted the planting structure of four counties (districts) in the SRB in 2017. The difference between this plan and the existing PSA plan in the SRB is in the following two points: first, we scientifically determine the water production function of each crop, and specify the water consumption when the crop yield is maximized; secondly, with the objective of minimizing the total irrigation water consumption, the utilization rate of green water is maximized and the scientific allocation of irrigation water is realized, which is an urgent scientific problem to be solved in the study area and the main innovation of this paper.

Materials and Methods

Study Area

The SRB (101°41′-104°16′E, 36°29′-39°27′N) is located at the edge of the monsoon region in China, at the intersection of the Qinghai-Tibet Plateau, Inner Mongolia Plateau and Loess Plateau, and is one of the three inland river basins in Hexi Corridor of China. Its upper reaches originate from the northern slope of the eastern Qilian Mountains and flows through the middle corridor plain area, and its lower reaches ends at the Minqin Oasis between Tengger Desert and Badain Jaran Desert, with a total area of 4.16 × 104 km^2. The upper reaches have a humid climate with an annual precipitation of 300-600 mm and annual potential evapotranspiration of 700-1200 mm, which is the runoff forming area. The average annual runoff from 1980 to 2017 was 13.40×10^8 m^3. The middle and lower reaches have a dry climate, and the annual potential evapotranspiration (1300~2000 mm and 2000~2600 mm, respectively) is much larger than the annual precipitation (150~300 mm and <150 mm, respectively), which is a runoff dissipation area and an important irrigated agricultural area. In 2017, the total amount of water resources in the whole basin was 18.78×10^8 m^3, and the annual total water consumption was 22.93×10^8 m^3, of which 86.30% was used for planting, and the utilization rate of water resources was as high as 122.1%, which caused serious water shortages. Due to excessive water use in the middle reaches, the lakes in the lower reaches are dried up, the ecological deterioration and desertification is serious and the planting structure in the basin is unreasonable; furthermore, the irrigation methods are backward, with mainly flood irrigation used, with a high irrigation quota. Therefore, the study area needs to strictly control the expansion of cultivated land, scientifically determine irrigation quotas, increase ecological water consumption and protect the ecological environment.

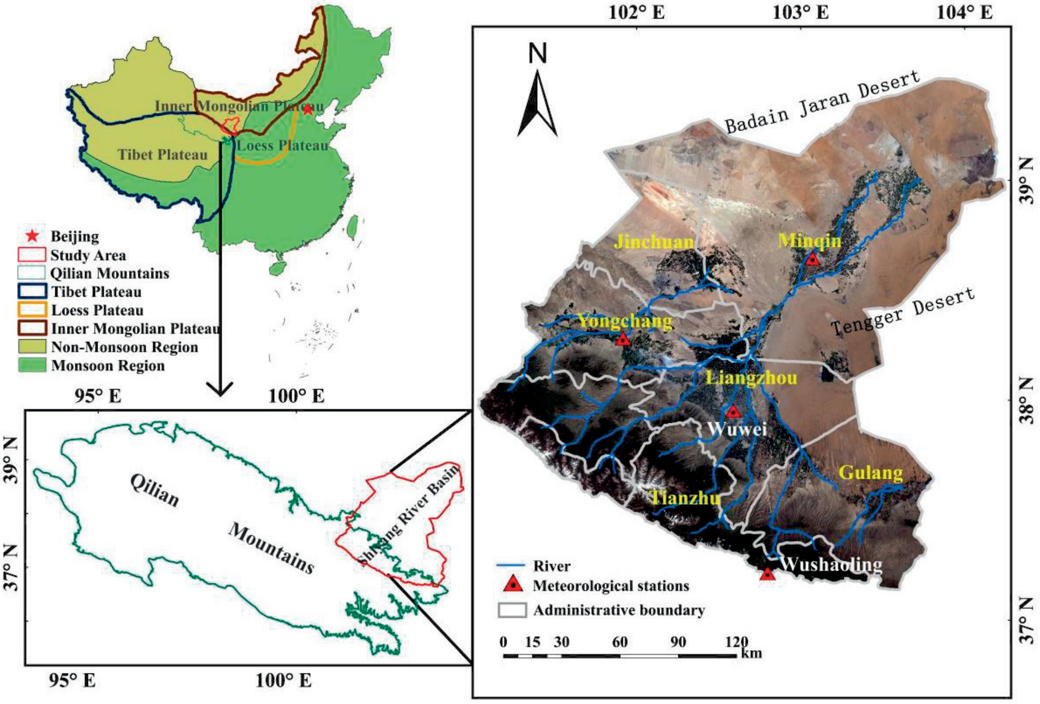

Fig. 1. Study area.

Table 1. Data contents and source.

Data types		Data contents	Data sources
Meteorology data	Wuwei, Minqin, Yongchang, and Wushaoling stations data	Daily maximum temperature, Daily minimum temperature, Daily average relative humidity, Daily average wind speed, and sunshine hours from 1980 to 2017	China Meteorological Data Network
	0.5°× 0.5° grid data in Gulang County and Wushaoling station	Daily maximum temperature, Daily minimum temperature, and Daily average temperature from 1980 to 2017	
Main crops data (wheat, corn, tubers, oil-bearing crops, vegetables, fruits, and cotton)		Areas and yields of Gulang County and Minqin County from 1980 to 2008	Compilation of Statistics on National Economy and Social Development
		Areas and yields in Yongchang County from 1980 to 1995	
		Areas and yields in Liangzhou District from 1980 to 2008	Wuwei Statistical Yearbook
		Areas and yields in Yongchang County from 1996 to 2008	Yongchang Statistical Yearbook
		Areas and yields in Yongchang County, Liangzhou District, Gulang County, and Minqin County from 2009 to 2017	Statistics Bureau of Gansu Province
		Irrigation quota data of different crops per unit area (Table 2)	Water Resources Bureau in Shiyang River Basin of Gansu Province
		Minimum demands of main crops (Table 3)	Balanced diet pagoda of the Chinese Dietary Guidelines (2016)
		Production costs	Su, 2007
		Crop unit price	Gansu Development Yearbook 2017
Other data in Yongchang County, Liangzhou District, Gulang County, and Minqin County		Population data	
		Data of agricultural water consumption	Water resources bulletin of the Shiyang River Basin

The administrative divisions of the SRB mainly include Gulang County, Liangzhou District, Minqin County and parts of Tianzhu County in Wuwei City, and Jinchang City includes Yongchang County and Jinchuan District. Among them, Tianzhu County is in the upper reaches of the river basin, mainly dominated by animal husbandry; Jinchuan District is dominated by non-ferrous heavy metals and chemical industry, and agriculture accounts for a relatively small proportion; while Gulang County, Liangzhou District, Minqin County and Yongchang County are mainly agricultural, and the cultivated land area accounts for 85.75% of the total cultivated land area in the basin. Therefore, this study mainly optimizes and adjusts the planting structure of the above four counties (districts). Food crops mainly include wheat, corn and tubers, while economic crops mainly include oil-bearing crops, vegetables, fruits and cotton. Of these, cotton is mainly planted in Minqin County.

Material

The data sets used in this paper include meteorology data, the areas, yields, crop unit price, production costs, the minimum demands and the irrigation quota data of wheat, corn, tubers, oil-bearing crops, vegetables, fruits, and cotton and the populations, agricultural water resources data in SRB. The specific data contents and sources are shown in Table 1.

The four meteorological stations (Wuwei, Minqin, Yongchang and Wushaoling) have not migrated in the past 38 years, and all the observed data have been strictly controlled in quality [45], such that the data integrity and continuity are good, and the data have high credibility [46], which have been widely used in related studies [47-51].

Method

Based on multi-objective programming, this study optimized and adjusted the planting structure and irrigation quota in the SRB, and the method flow chart is shown in Fig. 2.

Calculation of Crop Water Consumption

(1) Reference crop water consumption

Reference crop evapotranspiration (ET_0) was calculated by the modified Penman–Monteith model (abbreviated as the P-M model) recommended by the United Nations Food and Agriculture Organization (FAO) [52]. Comparative studies of the European Union and the United States have shown that the P-M

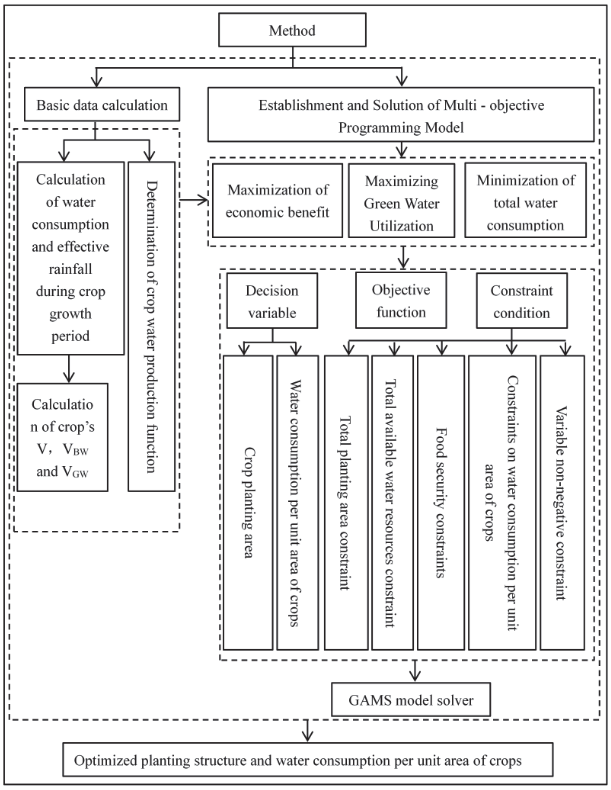

Fig. 2. Method flow chart.

Table 2. Irrigation quotas of main crops in the middle and lower reaches of the SRB (m^3/ha).

	Wheat	Corn	Tubers	Oil-bearing crops	Vegetables	Fruits	Cotton
Yongchang	5850	6600	4500	4350	6000	5100	/
Liangzhou	5400	6700	4275	4200	5550	5100	/
Gulang	4900	5730	4200	3450	5550	5100	/
Minqin	5700	5700	4200	5250	6900	5700	4500

Table3. The minimum demands of main crops in the middle and lower reaches of the SRB (kg/(person·year)).

	Grain crops			Oil-bearing crops	Vegetables	Fruits	Cotton
Crops	Wheat	Corn	Other crops				
Demands	200	100	100	7.3	292	73	40

model is relatively accurate when calculating ET_0 in both humid and arid regions. However, using the P-M model to calculate potential evaporation requires daily meteorological data from meteorological stations (daily maximum temperature, daily minimum temperature, daily average relative humidity, daily average wind speed and sunshine hours). When there is no meteorological station in the study area and the above daily data cannot be obtained, the potential evaporation can be calculated by using the Hargreaves formula (abbreviated as the H formula), another model recommended by the FAO. The Hargreaves formula only needs meteorological data of daily grid points (daily maximum, minimum and average temperature). However, many studies have shown that the calculation results of the H model have large errors and need to be corrected [53-55]. Therefore, for Yongchang, Liangzhou and Minqin, which have meteorological stations, the P-M model is directly applied to calculate the ET_0 of the reference crop in growth seasons [56]; that is, the reference crop water consumption. There is no meteorological station in Gulang, while Wushaoling meteorological station is the closest to Gulang. Therefore, $ET_{0\text{-P-M}}$ (calculated by the P-M model) and $ET_{0\text{-H}}$ (calculated by the H formula) can be calculated by using the daily meteorological data of Wushaoling meteorological station and the daily grid data at its location. On this basis, a regression model (formula (1)) between $ET_{0\text{-P-M}}$ and $ET_{0\text{-H}}$ was established, and the $ET_{0\text{-H}}$ of reference crop in Gulang was modified by this regression model to obtain its corresponding $ET_{0\text{-P-M}}$; that is, the reference crop water consumption in Gulang.

$$\mathrm{ET_{0-PM}} = 0.9586\mathrm{ET_{0-H}} - 0.0861 \quad (1)$$

where $ET_{0\text{-PM}}$ is the water consumption (mm) of the reference crop calculated by the P–M model, and $ET_{0\text{-H}}$ is the water consumption (mm) of the reference crop calculated by the H formula.

The correlation coefficient (R) of this regression model is 0.970, which passed the test of significance level at 0.01. F (22.919) is much larger than the value of SigF (0.0001), indicating that the model has higher accuracy, and there is a significant positive linear relationship between $ET_{0\text{-PM}}$ and $ET_{0\text{-H}}$.

(2) Crop water consumption

The actual water consumption of each crop is different from that of the reference crop. Therefore, on the basis of calculating the water consumption of reference crops, it is necessary to calculate the actual water consumption in combination with the crop coefficient (Kc) of each crop at different growth stages. The crop coefficients in this paper adopt the experimental results of Kang et al in the SRB [57]. The specific calculation process is as follows:

$$\mathrm{ET_{nci-x}} = \mathrm{Kc_{ci-x}} \times \mathrm{ET_{0nc-x}} \quad (2)$$

$$\mathrm{W_{nci}} = 10 \times \sum_{x=1}^{m} \mathrm{ET_{nci-x}} \quad (3)$$

where ET_{nci-x} is the water consumption in the xth stage during the growth period of crop i in region c in the nth year (mm), K_{ci-x} is the crop coefficient in the xth stage during the growth period of crop i in region c, ET_{0nc-x} is the water consumption of reference crops in the xth stage during the growth period in region c in the nth year (mm), and W_{nci} is the water consumption per unit area in the growth period of crop i in region c in the nth year (m^3/ha). The function of 10 is used to convert the water consumption depth (mm) into water consumption volume per unit area (m^3/ha), and m is the number of crop growth stages.

Effective rainfall in the crop growth period refers to the rainfall directly utilized by crop growth, which does not include surface runoff and leakage below crop roots [58, 59]. Generally, the effective rainfall is calculated by the empirical rainfall effective utilization coefficient, and the effective rainfall during the crop growth period can be calculated by the following formula [60]:

$$EP_{nci} = \sum_{x=1}^{m} \sigma P_{nci-x} \quad (4)$$

where EP_{nci} is the effective rainfall of crop i in the growth period of region, c in the nth year (mm), P_{nci-x} is the daily rainfall of crop i in the x stage in the growth period of region c in the nth year (mm), and σ is the effective utilization coefficient of daily rainfall (P_{nci-x}<5 mm, $\sigma = 0$; 5 mm≤P_{nci-x}≤50 mm, $\sigma = 1$; P_{nci-x} > 50 mm, $\sigma = 0.8$).

The minimum level of crop water requirement and effective rainfall is the green water consumption of a crop. The blue water consumption is the difference between the crop water requirement and green water. It can be calculated by the following formula [61-63]:

$$\mathrm{WG_{nci}} = \min(\mathrm{W_{nci}}, 10\mathrm{EP_{nci}}) \quad (5)$$

$$\mathrm{WB_{nci}} = \max\left(0, (\mathrm{W_{nci}} - \mathrm{WG_{nci}})\right) \quad (6)$$

(3) Crop virtual water, virtual blue water and virtual green water

The formula for calculating the content of crop virtual water, virtual blue water and virtual green water is as follows [64]:

$$\mathrm{V_{nci}} = \frac{\mathrm{W_{nci}}}{\mathrm{Y_{nci}}} \quad (7)$$

$$\mathrm{VB_{nci}} = \frac{\mathrm{WB_{nci}}}{\mathrm{Y_{nci}}} \quad (8)$$

$$\mathrm{VG_{nci}} = \frac{\mathrm{WG_{nci}}}{\mathrm{Y_{nci}}} \quad (9)$$

where V_{nci}, VB_{nci} and VG_{nci}, are the content of virtual water, virtual blue water and virtual green water of crop i in region c in the nth year (m^3/kg), respexctively; Y_{nci} is the yield per unit area of crop i in regional c in the nth year (kg/ha); W_{nci} is the water consumption per unit area in the growth period of crop i in region c in the nth year (m^3/ha); WB_{nci} is the amount of blue water consumed by crop i in region c in the growth period of the nth year (m^3/ha); and WG_{nci} is the amount of green water consumed by crop i in region c in the growth period of the nth year (m^3/ha).

Determination of the Crop Water Production Function

In this study, the crop water production function takes the total water consumption per unit area (W_{ci}) as an independent variable and the yield (Y_{ci}) as a dependent variable, reflecting the functional relationship between the total water consumption per unit area and the yield in the whole growth period. A large number of studies show that, with the improvement of water source conditions and the management level [57, 65, 66], the relationship between Y_{ci} and W_{ci} changes in a non-linear form. The initial Y_{ci} increases with the increase of W_{ci} and reaches its maximum when W_{ci} reaches a certain value, and then Y_{ci} decreases with the increase of W_{ci}, showing a quadratic parabolic relationship:

$$Y_{ci} = a_{ci}W_{ci}^2 + b_{ci}W_{ci} + d_{ci} \tag{10}$$

where Y_{ci} is the yield of crop i in region c (kg/ha), W_{ci} is the total water consumption per unit area of crop i in regional c in the whole growth period (m^3/ha), and a_{ci}, b_{ci} and d_{ci} are empirical coefficients and constant terms of water production function of crop i in region c.

The water production functions of wheat, corn, vegetables, fruits and cotton in Minqin, wheat and oil-bearing crops in Gulang and wheat in Liangzhou have been determined by experiments (corresponding experimental years are 1993, 1989, 2007, 1992, 1993, 1987, 1988 and 1985, respectively) [57]. On this basis, according to the historical maximum crop yield of each county and district from 1980 to 2017, the empirical coefficients a_{ci}, b_{ci} and constant term d_{ci} of the determined water production function are modified, and the empirical coefficients a_{ci}, b_{ci} and constant term d_{ci} of the undetermined water production function of crops are solved and calculated to determine the empirical coefficients a_{ci}, b_{ci} and the constant term d_{ci} of the water production function of various crops in different counties (districts) (Table 4).

The correction process of empirical coefficients a_{ci}, b_{ci} and the constant term d_{ci} of existing crop water production functions was as follows:

(i) The actual crop yield (y_{ci-exp}) in the experimental year was obtained by yearbook data, which was brought into the crop water production function determined by Kang et al. [57], and the total water consumption per unit area of crops ($W_{ci-exp-s}$) in the experimental year was obtained without ineffective irrigation. At the same time, the total water consumption per unit area ($W_{ci-exp-s}$) in the growth period of crops in this region in the experimental year was calculated by the part of Calculation of crop water consumption. There is a linear relationship between $W_{ci-exp-s}$ and W_{ci-exp}, and α_i is the coefficient of this linear relationship.

(ii) We selected the historical maximum yield of a crop from 1980 to 2017 to represent the maximum yield that can be achieved during the growth period of the crop in this region ($y_{ci\text{-}m\text{-}38}$), and we calculated the corresponding water consumption per unit area ($W_{ci\text{-}m\text{-}38}$) when the crop reached the maximum yield through the part of Calculation of crop water consumption. Using α_i, the total water consumption per unit area ($W_{ci\text{-}m\text{-}38s}$) when the crop reaches the maximum yield can be calculated and brought into the crop water production function determined by Kang et al. [57]. Comparing the calculated yield $y_{ci\text{-}m\text{-}38s}$ with the historical maximum yield $y_{ci\text{-}m\text{-}38s}$, if the error between the two is less than 5% [65], the crop water production function determined by Kang et al. [57] is not modified and is thus directly used in this study. On the contrary, the empirical coefficients a_{ci}, b_{ci} and the constant term d_{ci} are adjusted until the error between $y_{ci\text{-}m\text{-}38s}$ and $y_{ci\text{-}m\text{-}38}$ is within 5%.

(iii) When the water consumption W_{ci} is 0, there is a linear relationship between the maximum yield $y_{ci\text{-}m\text{-}38}$ and constant term d_{ci}, and β_i is the coefficient of this linear relationship.

The α_i and β_i of a certain crop in a certain county (district) are also applicable to the same crop in other counties (districts). On this basis, the empirical coefficients a_{ci}, b_{ci} and the constant term d_{ci} of the water production function of this crop are determined. The solution process is as follows:

On the basis of calculating α_i and β_i in the above process, according to the historical maximum yield ($y_{ci\text{-}m\text{-}38}$) of a crop and the total water consumption per unit area corresponding to the maximum yield ($W_{ci\text{-}m\text{-}38}$) in each county and district, the empirical coefficients a_{ci}, b_{ci} and the constant term d_{ci} of the crop water production function in four counties (districts) are obtained according to formulas (11), (12) and (13). Among them, the α_i and β_i values of tubers are the average values of the α_i and β_i values of wheat and corn in Minqin. Because Yongchang and Liangzhou are located in the middle reaches, the α_i and β_i values of wheat in Yongchang are the same as those in Liangzhou. The α_i and β_i values of corn, vegetables and fruits in Yongchang, Liangzhou and Gulang are the same as those in Minqin. The α_i and β_i values of oil-bearing crops in Yongchang, Liangzhou and Minqin are the same as those in Gulang. The empirical coefficients a_{ci}, b_{ci} and the constant termd_{ci} of the crop water production function in the four counties (districts) are as follows:

(1) Water consumption per unit area when the crop reaches the maximum yield in the whole growth period:

$$-\frac{b_{ci}}{2a_{ci}} = \alpha_i W_{ci-m-38} \tag{11}$$

(2) Maximum yield:

$$\frac{4a_{ci}d_{ci}-b_{ci}^2}{4a_{ci}} = y_{ci-m-38} \quad (12)$$

(3) Constant term:

$$d_{ci} = \beta_i y_{ci-m-38} \quad (13)$$

In addition, the water production function constructed in this paper is deduced and determined based on existing research [57], while these experimental data are obtained under the background of climate of historical period. Therefore, in order to verify the applicability of the water production function, the crop water consumption and yield data in the past decade (2010-2017) were used for verification. Substitute the theoretically calculated crop water consumption into the water production function of each county (district) in Table 4 to obtain y_{ci-10s}, and compare the calculated y_{ci-10s} with y_{ci-10} in the statistical yearbook. The average yield error of each county (district) in the past ten years is shown in Table 5.

It can be seen from Table 5 that the average error between the actual recorded crop yield (y_{ci-10s}) and the calculated crop yield (y_{ci-10}) in the past ten years is 0.6409-12.8218%, indicating that the water production function determined in this paper has high accuracy.

Table 4. Empirical coefficients a_{ci}, b_{ci} and constant term d_{ci} of the crop water production function in four counties (districts) in the SRB.

Region	Crop	a_{ci}	b_{ci}	d_{ci}
Yongchang	Wheat	-0.000044	4.6646	-5488.2181
	Corn	-0.00447	41.3406	-82675.0022
	Tubers	-0.0039	284051	-41360.5869
	Oil-bearing crops	-0.00032	2.7869	-2314.2197
	Vegetables	-0.00301	31.4167	-3922.941
	Fruits	-0.0099	5.8898	-2619.3133
Liangzhou	Wheat#	-0.0004	5.0751	-5770.5
	Corn	-0.0034	34.7909	-76209.8607
	Tubers	-0.00641	43.8176	-6069.1657
	Oil-bearing crops	-0.00023	2.2130	-1960.0225
	Vegetables	-0.00208	24.4396	-3434.5872
	Fruits	-0.00113	6.7782	-3016.1283
Gulang	Wheat#	-0.0002	2.5352	-2081.6
	Corn	-0.00251	27.2038	-63814.61124
	Tubers	-0.01375	104.6291	-161412.4738
	Oil-bearing crops*	-0.00003	2.6495	-221.15
	Vegetables	-0.00271	31.9630	-4500.4165
	Fruits	-0.00182	10.7016	-4688.9633
Minqin	Wheat*	-0.0007	8.1187	-16064
	Corn^	-0.00205	25.617	-6934.9
	Tubers	-0.00251	21.5327	-37434.4258
	Oil-bearing crops	-0.0014	16.3457	-17413.7155
	Vegetables^	-0.0013	17.351	-43195
	Fruits*	-0.0348	254.51	-41373
	Cotton*	-0.0004	3.7297	-6495.9

Note: * shows that the empirical coefficients a_{ci}, b_{ci} and the constant term d_{ci} of the water production function of this crop have not been modified. # shows that only the constant term d_{ci} of the water production function of this crop has been modified. ^ shows that empirical coefficients a_{ci}, b_{ci} and the constant term d_{ci} of the water production function of this crop have been modified.
The empirical coefficients a_{ci}, b_{ci} and constant term d_{ci} of the water production function of other crops were obtained by deduction.

Table 5. The average yield error of each county (district) in the SRB.

Region	Crop	Average error (%)
Yongchang	Wheat	5.3102
	Corn	0.6409
	Tubers	9.5681
	Oil-bearing crops	10.4840
	Vegetables	9.5384
	Fruits	12.7037
Liangzhou	Wheat	0.6358
	Corn	3.4009
	Tubers	2.8078
	Oil-bearing crops	5.7818
	Vegetables	11.8142
	Fruits	7.8145
Gulang	Wheat	5.4023
	Corn	10.4464
	Tubers	9.6018
	Oil-bearing crops	6.4536
	Vegetables	8.0418
	Fruits	9.2474
Minqin	Wheat	1.3968
	Corn	8.3648
	Tubers	5.3650
	Oil-bearing crops	12.8218
	Vegetables	10.5029
	Fruits	5.2855
	Cotton	4.6730

Establishment and Solution of Multi-Objective Programming Model

The programming model established in this paper is a nonlinear multi-objective planning model which aims to maximize economic benefits, the green water utilization rate and ecological benefits. The model takes the regional crop sown area and water consumption per unit area as decision variables. Crops include food crops (wheat, corn and tubers) and economic crops (oil-bearing crops, vegetables, fruits and cotton). The multi-objective programming model was used to optimize the planting structure and water consumption in the crop growth period in four counties (districts) of the SRB in 2017.

(1) Objective function

– Economic benefit objective: the economic objective is to maximize the net income of agriculture.

$$\text{Max}f_1=\sum_{c=1}^{e}\sum_{i=1}^{j}x_{ci}(P_{ci}-p_{ci})(a_{ci}W_{ci}^2+b_{ci}W_{ci}+d_{ci}) \tag{14}$$

where f_1 is the agricultural economic benefit; x_{ci} is the sown area of crop i in region c (ha); P_{ci} is the unit price of crop i in region c (yuan/kg); p_{ci} is the production cost of crop i in region c, including the planting cost and labor cost (yuan/kg); W_{ci} is the water consumption per unit area of crop i in region c (m^3/ha); a_{ci}, b_{ci} and d_{ci} are the coefficients of the water production function; e is the number of administrative districts; and j is the number of crop species.

– Green water utilization rate objective: the objective is to maximize the virtual green water rate of crops.

$$\text{Max}f_2=\frac{\sum_{c=1}^{e}\sum_{i=1}^{j}x_{ci}y_{ci}VG_{ci-1,2,3}}{\sum_{c=1}^{e}\sum_{i=1}^{j}x_{ci}y_{ci}V_{ci-1,2,3}}\times 100\% \tag{15}$$

where f_2 is the green water utilization rate; y_{ci} is the yield of crop i in region c (kg/ha); $VG_{ci-1,2,3}$ and $V_{ci-1,2,3}$ are the virtual green water and virtual water content of crop i in region c in high-water year, flat-water year and dry-water year, respectively. In this paper, the virtual green water and virtual water content of crops corresponding to the most precipitation from 1980 to 2017 were used as the values of high-water year, the average values of the virtual green water and virtual water content of crops from 1980 to 2017 were used as the value of flat-water year, and the virtual green water and virtual water content of crops corresponding to the lowest precipitation from 1980 to 2017 were used as the values of dry-water year. In this way, the planting structure can be optimized under different climatic conditions.

– Ecological benefit objective: the ecological objective is to minimize the total water consumption during the crop growth period.

$$\text{Min}f_3=\sum_{c=1}^{e}\sum_{i=1}^{j}x_{ci}W_{ci} \tag{16}$$

where f_3 is ecological benefit, x_{ci} is the sown area of crop i in region c (ha), and W_{ci} is the water consumption per unit area of crop i in region c (m^3/ha).

(2) Constraint condition

The constraint conditions of the model can be roughly divided into the following two categories: the available land resource constraint and water resource constraint. Specific constraint conditions are as follows:

– Constraints of the total sown area:

According to the basic requirements of KTPSRB, it is not suitable to reclaim cultivated land, and thus the total sown area of a certain area is not larger than the total sown area of seven main crops in the current year, and it is not less than the total crop sown area that meets the minimum cultivated land area per capita of KTPSRB.

$$Aa_c\leq\sum_{c=1}^{e}x_{ci}\leq A_c \tag{17}$$

where A_c is the total sown area of seven main crops in the current year in region c (ha); Aa_c is the total crop sown area in region c after ensuring the minimum cultivated land area per capita.

– Constraints of total available water resources:

Irrigation water is the main type of water used for crops in this study area, which includes the water needed for crop growth and the water lost in the process of water intake, water delivery and water distribution in the irrigation area. The irrigation water demand of main crops is less than that of agriculture.

$$\sum_{c=1}^{e}\left(\sum_{i=1}^{j} x_{ci}\,(W_{ci}-WG_{ci})/re\right) \le W_{sum} \tag{18}$$

where $W_{ci} – WG_{ci}$ is the irrigation water needed by crop i in region c, and re represents the utilization coefficient of agricultural irrigation water, which determined to be 0.68 according to the KTPSRB; W_{sum} is the total agriculture irrigation amount in the basin (10^8m^3).

– Constraints of food security:

$$x_{ci}(a_{ci}W_{ci}^2 + b_{ci}W_{ci} + d_{ci}) \ge t_c L_{ci} \tag{19}$$

where t_c is the year-end resident population in region c (person), and L_{ci} is the minimum per capita demand of crop i in region c (kg/ (person·year)).

– Constraints of water consumption per unit area of crops:

$$0 \le W_{ci} \le \text{-b/2a} \tag{20}$$

– Non-negative constraint of variable:

$$x_{ci} \ge 0 \tag{21}$$

$$W_{ci} \ge 0 \tag{22}$$

(3) Model solution

– Normalization processing: The objective function of multi-objective programming has the problem of non-uniform dimensions, so it is necessary to treat each objective function as dimensionless to eliminate the influence of dimensions on evaluation results. Firstly, the maximum value f_q^M and minimum value f_q^m of each single-objective function under constraint conditions are obtained and then normalized. When the objective function is maximized and minimized, it is converted by formulas (23) and (24), respectively.

$$u_q = \frac{f_q-(f_q^m)}{f_q^M-f_q^m} \tag{23}$$

$$u_q = \frac{(f_p^M)-f_p}{f_q^M-f_q^m} \tag{24}$$

where u_q is the normalized objective value of the qth objective, f_q^m is the minimum value for the qth objective, and f_q^M is the maximum value for the qth objective.

– The auxiliary function is constructed, and the multi-objective function is transformed into a single-objective function by the linear weighting method [39]:

$$F_{(q)} = \sum_{q=1}^{q} w_q u_q \tag{25}$$

where $F_{(q)}$ is an auxiliary function and w_q is the weight coefficient of the qth objective.

– Determination of weight coefficient of each objective function:

The fuzzy binary comparison method [67] is used to determine the importance of different objective functions; one or more sets of weight coefficients are given to the objective functions, and the sum of the weight coefficients is 1 when solving the multi-objective planting structure optimization problem. In this study, the weights of the three objective functions of the economic benefit objective, the green water utilization ratio objective and the ecological benefit objective were 0.3, 0.3 and 0.4, respectively.

– Solving tool

The General Algebraic Modeling System (GAMS) [68] is a tool to deal with linear, nonlinear and mixed integer optimization problems. It can use concise and popular computer language to express large and complex models and solve them, mainly including objective function and constraint conditions. With the passage of time, the GAMS has developed from being able to solve linear programming problems to being able to solve both linear programming problems and nonlinear programming problems, and it is generally recognized as an effective tool for solving large and complex mathematical programming models. Therefore, this study used a GAMS solver to solve the nonlinear multi-objective programming model with the aim of maximizing economic benefit, the green water utilization rate and ecological benefit, and obtaining the optimized planting structure and water consumption of crops in their growth periods in the four counties (districts) of the SRB in 2017.

Calculation of the Contribution of Factors Affecting the Total Water-Saving Amount

Based on the background of agricultural water-saving, this paper adjusted and optimized the planting structure and crop irrigation water requirement in SRB by a multi-objective optimization method. Compared with the result before optimization, there are three factors affecting the change of total water saving amount: total sown area compression (factor 1), c rop irrigation water compression (factor 2) and PSA (factor 3). These three factors have different influences on the total water-saving. Therefore, this study quantified the rate of contribution of these three factors to the total water-saving using the control variable method [69] to determine the main factors affecting the water-saving. The specific process is as follows:

(i) Contribution rate of factor 1: Under the condition that the irrigation water and planting structure of crops are unchanged, only the water-saving amount (SW_1) with the change of the total sown area is considered, and then the contribution rate of factor 1 to the total water-saving is calculated (Con_1).

(ii) Contribution rate of factor 2: Under the condition that the irrigation water and planting structure of crops are unchanged, only the water-saving amount (SW_2) with the change of the crop irrigation water is considered, and then the contribution rate of factor 2 to the total water-saving is calculated (Con_2).

(iii) Contribution rate of factor 3: Under the condition that the irrigation water and the total sown area of crops are unchanged, only the water-saving amount (SW_3) with the change of the planting structure is considered, and then the contribution rate of factor 3 to the total water-saving is calculated (Con_3).

$$\mathrm{Con}_1 = \frac{SW_0 - SW_1}{SW_0} \times 100\% \tag{26}$$

$$\mathrm{Con}_2 = \frac{SW_0 - SW_2}{SW_0} \times 100\% \tag{27}$$

$$\mathrm{Con}_3 = \frac{SW_0 - SW_3}{SW_0} \times 100\% \tag{28}$$

where SW_0 represents the actual total water-saving amount; SW_1 represents the water-saving amount against the background of the change of total sown area; SW_2 represents the water-saving amount against the background of the crop irrigation water change; SW_3 represents the water-saving amount against the background of the change of planting structure; Con_1 represents the contribution rate against the change of total sown area; Con_2 represents the contribution rate of the crop irrigation water change; Con_3 represents the contribution rate of the change of planting structure.

Results

Optimization Results of Planting Structure

Optimization Results of Total Planting Structure in the Basin

The planting structure of high-water year, flat-water year and dry-water year was optimized respectively. Compared with before optimization, the total sown area of the optimized crops in three level years all decreased by 1.07 × 10^4 ha. After analysis, it was found that the cultivated land area per capita about 0.1751 ha before optimization and about 0.1680 ha after optimization in three level years, which both meet the basic requirement of 0.166 ha of KTPSRB.

By comparing the sown area proportion of each crop, comparison of optimization results in the high-water years, flat-water years and dry-water year with before optimization. It was found that the sown area of wheat, tubers, vegetables, fruits and cotton all increased. The sown area proportion of wheat increased by 5.46%, 5.26% and 5.25%, respectively, and increased most in the high-water year, by 1.19 × 10^4ha. The sown area proportion of tubers increased by 8.29%, 8.32% and 8.36%, respectively, and increased most in dry-water year, by 2.04 × 10^4 ha. The sown area proportion of vegetables increased by 6.35%, 6.55% and 6.52%, respectively, and increased most in flat-water year, by 1.56×10^4ha. The sown area proportion of fruits all increased by 21.38%; and the sown area proportion of cotton all increased by 0.52%. The sown area proportion of corn and oil-bearing crops all decreased.

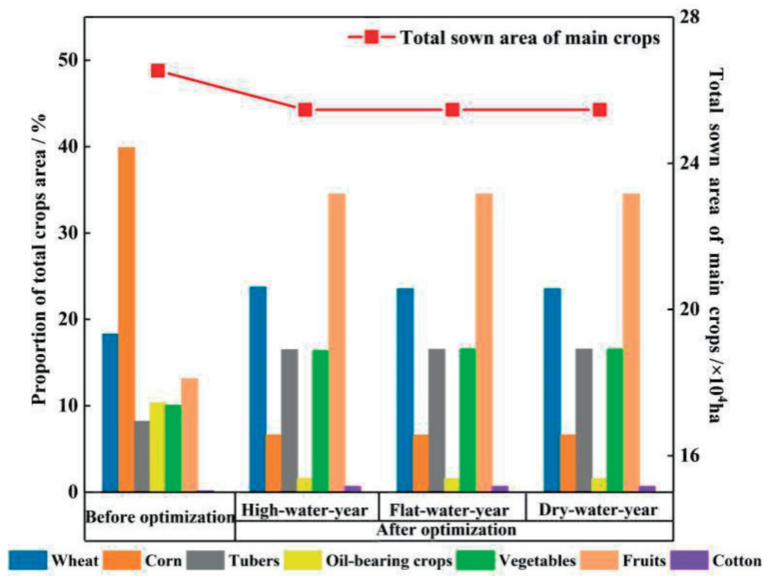

Fig. 3. Comparison of planting structure before and after optimization in the SRB.

The sown area proportion of corn decreased by 33.25%, 33.26% and 33.26%, respectively, and decreased most in flat-water and dry-water year, both by 8.90 × 10^4 ha. The sown area proportion of oil-bearing crops decreased by 8.75%, 8.77% and 8.77%, and decreased most in flat-water and dry-water year, both by 2.34 × 10^4 ha.

The above data show that the influence of climate change on planting structure adjustment is relatively weak. It is suggested to slightly decrease the sown area of wheat but increase the sown area of tubers with the decrease of precipitation.

Optimization Results of Planting Structure in Each County and District

Compared with the situation before optimization, it can be seen from Fig. 4 that the total sown area of crops after optimization all showed a decreasing trend in Yongchang, Liangzhou and Minqin, while Gulang remained unchanged.

In Yongchang, the comparison of optimization results in the high-water years, flat-water years and dry-water year with data before optimization. The sown area proportion of vegetables and fruits all increased. The sown area proportion of vegetables increased by 21.12%, 21.15% and 20.59%, respectively, and increased most in flat-water year, by 1.067 × 10^4 ha, and the sown area proportion of fruits all increased by 42.87%. The sown area proportion of wheat, corn, tubers and oil-bearing crops all decreased. The sown area proportion of wheat decreased by 23.95%, 23.98% and 23.48%, respectively, and decreased most in flat-water year, by 1.347 × 10^4 ha. The sown area proportion of corn decreased by 26.83%, 26.83% and 26.81%, respectively, and decreased most in high-water year and flat-water year, both by 1.475 × 10^4 ha. The sown area proportion of tubers all decreased by 6.93%. The sown area proportion of oil-bearing crops decreased by 6.27%, 6.27% and 6.24% respectively, and decreased most in high-water year and flat-water year, both by 3.345× 10^4 ha. Comparison of three level year, from high-water year to dry-water year, the sown area proportion of vegetables decreased by 0.53%, while the sown area proportion of wheat, corn and oil-bearing crops all increased by 0.47%, 0.02% and 0.03%, respectively.

In Liangzhou, the comparison of optimization results in the high-water years, flat-water years and dry-water year with data before optimization. The sown area proportion of wheat, tubers, vegetables and fruits increased. The sown area proportion of wheat increased by 23.44%, 23.16% and 22.84%, respectively, and increased most in high-water year, by 2.396 × 10^4 ha. The sown area proportion of tubers all increased by 1.83%. The sown area proportion of vegetables increased by 3.79%, 4.11% and 4.48%, respectively, and increased most in dry-water year, by 0.436× 10^4 ha. The sown area proportion of fruits all increased by 20.93%. The sown area proportion of corn and oil-bearing crops both decreased. The sown area proportion of corn decreased by 47.19%, 47.20% and 47.22%, respectively, and decreased most in dry-water year, by 5.208 × 10^4 ha.

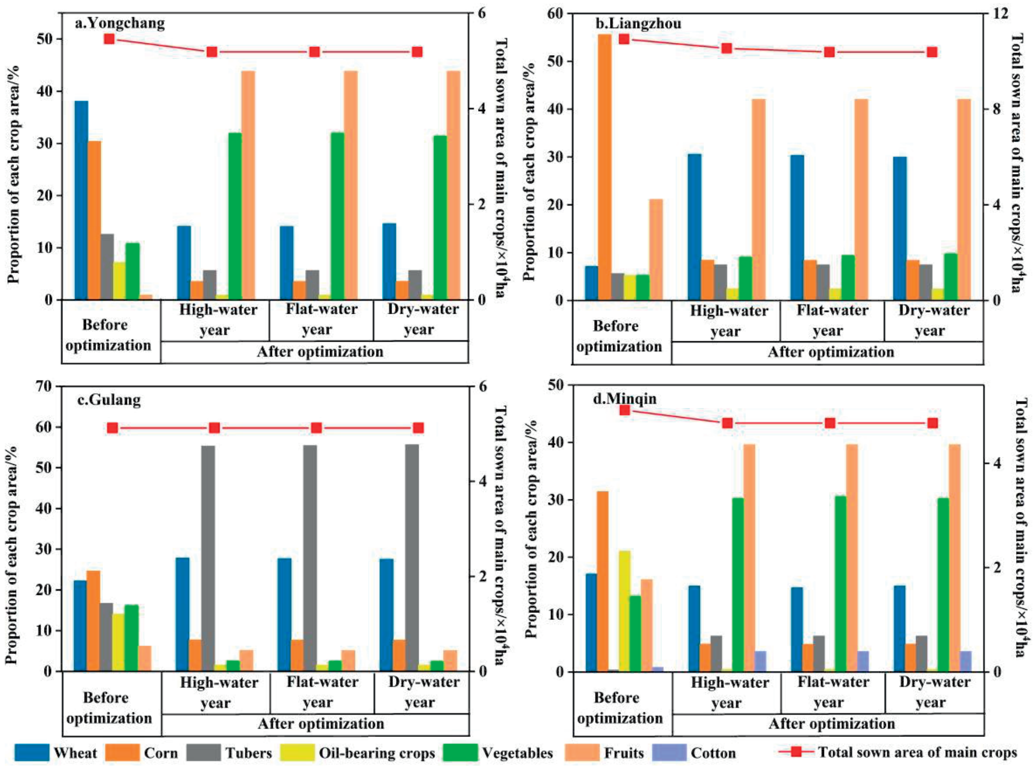

Fig. 4. Comparison of planting structure before and after optimization in each county and district.

The sown area proportion of oil-bearing crops decreased by 2.80%, 2.82% and 2.85%, respectively, and decreased most in dry-water year, by 0.325 × 10^4 ha.

In Gulang, the comparison of optimization results in the high-water years, flat-water years and dry-water year with data before optimization. The sown area proportion of wheat and tubers increased. The sown area proportion of wheat increased by 5.59%, 5.48% and 5.31%, respectively, and increased most in high-water year, by 0.287 × 10^4 ha. The sown area proportion of tubers increased by 38.58%, 38.73% and 38.95%, respectively, and increased moat in dry-water year, by 1.995 × 10^4 ha. The sown area proportion of corn, oil-bearing crops, vegetables and fruits all decreased. The sown area proportion of corn and oil-bearing crops all decreased by 16.96% and 12.50%, respectively. The sown area proportion of vegetables decreased by 13.64%, 13.65% and 13.67%, respectively, and decreased most in dry-water year, by 0.700 × 10^4 ha. The sown area proportion of fruits decreased by 1.09%, 1.10% and 1.12%, respectively, and decreased most in dry-water year, by 0.057 × 10^4 ha.

In Minqin, the comparison of optimization results in the high-water years, flat-water years and dry-water year with data before optimization. The sown area proportion of tubers, vegetables, fruits and cotton increased. The sown area proportion of tubers all increased by 5.91%. The sown area proportion of vegetables increased by 17.03%, 17.38% and 17.03%, respectively, and increased most in flat-water year, by 0.796 × 10^4 ha. The sown area proportion of fruits and cotton all increased by 23.52% and 2.78%, respectively. The sown area proportion of wheat, corn and oil-bearing crops all decreased. The sown area proportion of wheat decreased by 2.08%, 2.39% and 2.08%, respectively, and decreased most in flat-water year, by 0.157 × 10^4 ha. The sown area proportion of corn decreased by 26.54%, 26.57% and 26.54%, respectively, and decreased most in flat-water year, by 1.346 × 10^4 ha. The sown area proportion of oil-bearing crops decreased by 20.61%, 20.62% and 20.61%, respectively, and decreased most in flat-water year, by 1.036 × 10^4 ha.

In summary, the planting structures of the four counties (districts) in the three level years have the flowing similarities and differences: the common feature is that the sown area of corn and oil-bearing crops should be greatly reduced. The differences are that the sown area of wheat should be decreased in Yongchang and Minqin, while it should be increased in Liangzhou and Gulang, and the sown area of vegetables and fruits should be increased in the other three counties (districts) except Gulang, and the sown area of tubers should be increased in the other three counties (districts) except Yongchang. Comparing the optimized structure of each county (district) in the three level years, it is found that the impact of climate change on planting structure is relatively weak. In view of this, this paper will select the optimized result of flat-water year to conduct further analysis.

Optimization Benefit Analysis

Benefit Analysis of Optimization of Total Planting Structure in Basin

The comparison of the optimization results of the multi-objective model with those of each single-objective model is shown in Table 6. The results show that each single-objective model can obtain the optimal value of the objective under a certain index, but other important factors cannot be considered at the same time. However, the multi-objective model can coordinate three different single objectives and obtain a reasonable planting structure. With regard to the overall benefit of the basin, compared with the situation before optimization, the crop green water utilization rate increased by 14.21%, the economic benefit increased by 72.62 hundred million yuan, and a total water consumption of 6.85×10^8 m^3 was saved.

Benefit Analysis of Optimization of Total Planting Structure in Each County and District

It can be seen from Table 7 that the benefits after optimization vary greatly among counties (districts). Compared with the situation before optimization, in Yongchang, the crop green water utilization rate increased by 1.66%, the economic benefit increased by 45.13 hundred million yuan, and a total water consumption of 1.62 × 10^8 m^3 was saved. In Liangzhou, the crop green water utilization rate increased by 2.09%, the economic benefit increased by 11.08 hundred

Table 6. List of overall economic benefits, green water utilization rate and ecological benefits of the basin before and after optimization.

	Before optimization	After optimization			
		Single economic objective	Single green water objective	Single water-saving objective	Multi-objective (Flat-water-year)
Economic benefits (hundred million yuan)	107.71	286.11	81.62	50.42	180.33
Green water utilization rate (%)	22.49	30.77	39.11	19.28	36.70
Ecological benefits (10^8 m^3)	14.04	12.03	8.22	5.10	7.19

Note: The smaller the total water consumption during the growth period of crops, the better the ecological benefits.

Table 7. List of overall economic benefits, green water utilization rate and ecological benefits of the basin before and after optimization in four counties (districts).

		Before optimization	After optimization
Economic benefits (hundred million yuan)	Yongchang	23.06	68.19
	Liangzhou	27.71	38.79
	Gulang	23.90	39.30
	Minqin	33.04	34.04
Green water utilization rate (%)	Yongchang	17.98	19.64
	Liangzhou	9.54	11.63
	Gulang	38.68	49.35
	Minqin	7.93	8.75
Ecological benefits ($10^8 m^3$)	Yongchang	2.88	1.26
	Liangzhou	5.42	2.63
	Gulang	2.63	2.13
	Minqin	3.11	1.16

Note: The smaller the total water consumption during the growth period of crops, the better the ecological benefits.

Table 8. Contribution rate of three factors to total water-saving amount after optimization in each county and district (%).

	Yongchang	Liangzhou	Gulang	Minqin
Factor 1	5.37	6.27	-	5.16
Factor 2	24.18	22.36	30.15	13.25
Factor 3	70.45	71.37	69.85	81.59

million yuan, and the total water consumption saved was 2.79×10^8 m^3. In Gulang, the crop green water utilization rate increased by 10.67%, the economic benefit increased by 15.40 hundred million yuan, and the total water consumption saved was 0.50×10^8 m^3. In Minqin, the crop green water utilization rate increased by 0.82%, the economic benefit increased by 1.00 hundred million yuan, and the total water consumption saved was 1.95×10^8 m^3. Of these, the saved agricultural water consumption was the most in Liangzhou, and the economic benefits increased the most in Yongchang.

Discussions

PSA is the Key to Water-Saving

After analyzing the results of the multi-objective optimization in counties (districts), it is found that there are three factors that affect the total water-saving: total sown area compression (factor 1), crop irrigation water compression (factor 2) and PSA (factor 3). But these three factors have different influences on the total water-saving. Therefore, the key factor that affect total water-saving amount has further identified in this paper.

The results are shown in Table 8. The total sown area in Gulang did not change before and after optimization, so only the contribution rates of factors 2 and 3 to the water-saving amount of the planting industry in Gulang were explored.

It can be seen from Table 8 that, in the four counties (districts), the contribution of PSA to the total water-saving amount was the largest, the contribution of irrigation water compression was second, and the contribution of the total sown area compression was the smallest. This characteristic was most obvious in Minqin, followed by Liangzhou, Yongchang and Gulang. Therefore, PSA is the key to saving water.

Scientific Management of Irrigation Water

The total water consumption, blue water consumption and green water consumption of the same crop were quite different in different counties (districts). The overall trend was that blue water consumption was greater than green water consumption, which mainly depended on agricultural irrigation. In addition, the green water consumption of the same crop was different in different counties (districts), which was due to the different effective utilization of rainfall by the same crop in different counties (districts). The optimized irrigation water consumption of crops is shown in Table 9.

Since the implementation of the KTPSRB in 2007, the irrigation water quota of various crops has been further reduced, but there is still a large space for water-saving. Comparing the irrigation quota of different crops (Table 2) with the optimized irrigation quota (Table 9) and analyzing the water-saving potential of PSA, it is possible to see that the larger the difference in the irrigation quota before and after crop optimization, the larger the space for water-saving.

It can be seen from Fig. 5 that different crops after optimization had a larger space for water-saving. Fruits, corn, vegetables and tubers were the crops with a larger water-saving space in Yongchang, and the maximum water-saving amounts were 46.60×10^2 m^3/ha, 33.93×10^2 m^3/ha, 33.45×10^2 m^3/ha and 26.12×10^2 m^3/ha, respectively. Fruits, vegetables, corn and tubers were the crops with a larger water-saving space in Liangzhou, and the maximum water-saving amounts were 50.43×10^2 m^3/ha, 30.15×10^2 m^3/ha, 26.87×10^2 m^3/ha and 20.21×10^2 m^3/ha, respectively. Fruits, vegetables, corn and tubers were the crops with a larger water-saving space in Gulang, and the maximum water-saving amounts were 42.98×10^2 m^3/ha, 30.49×10^2 m^3/ha, 27.15×10^2 m^3/ha and 25.16×10^2 m^3/ha, respectively. Fruits, vegetables, oil-bearing crops and cotton were the crops with a larger water-saving space in Minqin, and the maximum water-saving amounts were

Table 9. List of total water consumption per unit area, green water consumption and irrigation water consumption of main crops in four counties (districts) after optimization of water-saving objective (m^3/ha).

		Yongchang	Liangzhou	Gulang	Minqin
Wheat	W	4393	3935	5173	4897
	WG	675	447	1638	273
	WB	3718	3488	3535	4624
Corn	W	4455	4805	5257	5850
	WG	1248	792	2242	615
	WB	3207	4013	3015	5235
Tubers	W	3178	3016	3673	3779
	WG	1190	762	2089	608
	WB	1988	2254	1584	3171
Oil-bearing crops	W	3659	3526	3848	2743
	WG	1137	711	2103	547
	WB	2522	2815	1745	2196
Vegetables	W	3610	3102	4412	2255
	WG	955	567	1911	440
	WB	2655	2535	2501	1815
Fruits	W	1642	804	2616	888
	WG	1202	747	1814	615
	WB	440	57	802	273
Cotton	W	-	-	-	3913
	WG	-	-	-	970
	WB	-	-	-	2943

Note: W represents the total water consumption during the crop growth period; WG represents the green water consumption during the crop growth period; WB represents the blue water consumption during the crop growth period, that is, irrigation water consumption.

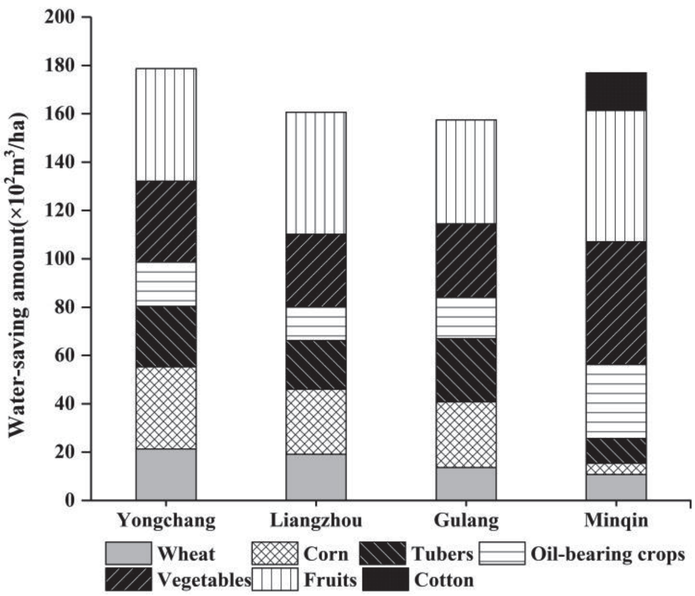

Fig. 5. Irrigation water-saving of main crops after optimization in four counties (districts) in the middle and lower reaches of the SRB.

54.27×10^2 m^3/ha, 50.85×10^2 m^3/ha, 30.54×10^2 m^3/ha, and 15.27×10^2 m^3/ha, respectively. Therefore, in terms of the size of the water-saving space, oil-bearing crops and vegetables are more suitable for planting in the lower reaches, while corn and tubers are more suitable for planting in the middle reaches.

Limitation

The determination of water production function of different crops is one of the important links in the construction of multi-objective planting structure optimization model, and its accuracy has certain influence on the simulation results. However, due to the limitation of the current field experiment conditions, the water production functions of different crops of the study area are obtained by referring to the existing research results, combining with the historical maximum crop yield and the corresponding water consumption per unit area when reaching the maximum yield in each county (district) from 1980 to 2017, and there are certain errors. Therefore, in the follow-up study, field experiment monitoring should be strengthened to obtain a higher precision crop water production function and make the simulation results of the multi-objective programming model more accurate.

Conclusion

PSA is the key to saving agricultural water in the inland river basin of arid areas. On the basis of determining the water production function of different crops, this paper established a multi-objective optimization model of the planting structure with the maximization of economic benefits, the green water utilization rate and ecological benefits to optimize and adjust the planting structure in SRB. The conclusions are as follows:

After PSA, the common features of the three level years after optimization is that the sown area proportion of wheat, tubers, vegetables, fruits and cotton all increased, with the fruits increased most, by 5.30×10^4 ha. However, the sown area proportion of corn and oil-bearing crops decreased, with the corn decreased most, by 8.90×10^4 ha. Comparison of three level years, it is suggested to slightly decrease the sown area of wheat but increase the sown area of tubers with the decrease of precipitation. There were great differences in the adjustment results of planting structures among counties (districts). The common feature is that the sown area of corn and oil-bearing crops should be greatly decreased.

The comprehensive effect of the optimization and adjustment of planting structures is obvious. After the optimization and adjustment of planting structures in the SRB, the crop green water utilization rate increased by 14.21%, the economic benefit increased by 72.62 hundred million yuan, and the total water consumption saved was 6.85×10^8 m^3. Of these, the saved agricultural water consumption was the most in Liangzhou, by 2.79×10^8 m^3, and the economic benefits increased the most in Yongchang, by 45.13 hundred million yuan. The total sown area compression, crop irrigation water compression and PSA are the three major factors affecting water-saving. Of these, PSA is the key to saving water, with an average contribution rate of 73.32%, and PSA in Minqin had the largest contribution rate of 81.59%. Therefore, PSA is the key to the construction of a water-saving society in inland river basins of arid areas.

From the perspective of maximizing irrigation water-saving, tubers are more suitable for planting in Yongchang in the middle reaches, corn is more suitable for planting in Yongchang and Gulang and oil-bearing crops and vegetables are more suitable for planting in Minqin. Therefore, when adjusting the planting structure within counties (districts), it is necessary to comprehensively consider the spatial allocation of different crops in the upper, middle and lower reaches of the basin and realize the maximization of water-saving without reducing economic benefits.

PSA is a very complicated process, especially in arid inland river basins in which water resources are very scarce and the economy is underdeveloped. In this process, the optimization and adjustment of planting structures taking into account "ecological benefits, economic benefits and food security" is foundational; the key is to strengthen the scientific and technological support of agricultural technology and constantly innovate the management system of agricultural water-saving projects, thus guaranteeing the establishment of an agricultural water-saving mechanism with government regulation, market guidance and public participation.

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Conflict of Interest

The authors declare no conflict of interest.

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