Optimization of agricultural planting structure under multi-objective regulation of water resources

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Abstract. Focusing on the problems such as adjustment of planting structure, imbalance of water supply and serious over-extraction of groundwater in Jinghui Canal Irrigation District, a multi-objective water regulation model was established for finding coordinate development among ecological benefits, social benefits and economic benefits to seek the reasonable program of water resource utilization and agricultural planting. When the ecological benefit was optimal, the total area of crop planting was 6.105 × 10^4 hm², the area of grain crops, fruit trees and vegetables planting was 3.073 × 10^4 hm², 1.444 × 10^4 hm² and 1.592 × 10^4 hm² respectively. Under this scenario, the irrigation water requirement was 35986.87 × 10^4 m³/a. The surface water supply was 32268.42 × 10^4 m³/a and the compensation of groundwater supply was 3718.45 × 10^4 m³/a. Therefore, when the social benefit was optimal, the total area of crop planting was 6.57 × 10^4 hm², the area of grain crops, fruit trees and vegetables planting was 3.684 × 10^4 hm², 1.214 × 10^4 hm² and 1.673 × 10^4 hm² respectively. Under this scenario, the irrigation water requirement was 39571.20 × 10^4 m³/a. The surface water supply was 33438.65 × 10^4 m³/a and the compensation of groundwater supply was 6132.54 × 10^4 m³/a. The agricultural planting structure between the two can serve as a reasonable control interval, and provide a reasonable resource utilization and agricultural planting scheme for the future development of Jinghui Canal Irrigation District.

1. Introduction

The rapid development of urbanization and agricultural planting in irrigation district are competing for water and soil resources. Land utilization types, water utilization structure and agricultural planting structure have been changed, as a result, the imbalance of water supply in drainage canal and well is further aggravated. Therefore, it is of great significance for ensuring water security, grain production safety and significant economic benefits of irrigation district through clarifying the change characteristics of agricultural planting structure, regulating water resources distribution efficiently, and fully utilizing the spatial and temporal complementarity action of surface water and groundwater.

At present, many scholars have carried out researches on the change of agricultural planting structure and regulating of water resources in irrigation district. Zhang et al [1] analyzed the land utilization, the change of crop planting structure in spatial and temporal and their influence on irrigation water demand in Jinghui Canal Irrigation District. Bai et al [2] analyzed the temporal and spatial variation characteristics of crop planting structure in Hetao Irrigation District and its correlation with groundwater environment. Fu et al [3] analyzed the influence of planting structure changes on
water balance factors of farmland irrigation system from multiple time scales. Li et al [4] systematically calculated the impact of the utilization of water and soil resources due to the “ten years consecutive increases” of crops in China, and in which they focused on the played roles in the adjustment of grain planting structure. In the aspects of optimal utilization of water resources in irrigation district, Ramireddygari et al [5] evaluated the effects of irrigation water on runoff and groundwater level through setting different irrigation water scenarios for different hydrological years, and setting the comprehensive utilization of surface flow model (POTYLD) and groundwater flow model (MODFLOW). Laura e. Condon and Reed m. Maxwell [6] proposed a water allocation module (WAM) hydrological model, which was applied to the management decision of the coupling of groundwater and surface water system. Lin et al [7] studied and got the optimal water supply ratio of canal and well as well as the crop planting ratio by using groundwater simulation and linear programming model. Dai et al [8] analyzed the appropriate proportion of canal and well in irrigation district by the software of ArcGIS and PMWIN. Liu [9] took surface water supply and groundwater exploitation as coupling variables to study the best mode of water resources regulation in irrigation district by using the combination of optimization and simulation.

This article, taking Jinghui Canal Irrigation District of Shaanxi Province as an example, established a multi-objective regulation model with coordinated development of water safety, food security and economic benefits, taking the planting area of crops as variables and the availability of surface water resources and exploitable amount of groundwater resources as constraints. The model was solved by a combination of optimization, scheduling and simulation. Crops were coordinated with each other, water resource was distributed properly to crops, water resources were compensated for each other. The results of planting structure optimization and water resource scheduling were continuously transmitted and simulated to research the appropriate utilization space of water resources in the Jinghui Canal Irrigation District. The following questions “How to allocate water for different irrigation sources, how to distribute water resources between crops in different time periods, and what was the reasonable planting area of each crop in the irrigation area” were answered, which could provide reasonable solutions of water resource utilization and agricultural planting plan for the future development of Jinghui Canal Irrigation District.

2. General situation of the research area and data sources

2.1. General situation of the research area

Jinghui Canal Irrigation District, located in the middle of Guan Zhong Plain, is a large scale (Ⅱ) irrigation district of artesian diversion from Jinghe River, irrigation with well and canal, combination of irrigation and drainage. It is 70 km long from east to west, 20 km wide from south to north and with a total area of 1180 km², which irrigates 1.453 million mu of farmland. The average annual temperature is about 15°C. The average annual precipitation is 538.9 mm. The average annual evaporation is 1212 mm. There are three water supply projects, including Zhang Jiashan Reservoir, Xijiao Reservoir and Zhang Jiashan canal head diversion junction. There are 5 main canals with a total length of 81.4 km, 24 branch canals with a length of 335.1 km, 593 lateral canal with a length of 1481 km, 5203 distributing canal with a length of 2145 km. The grain crops are mainly wheat and maize. The economic crops are mainly vegetables and fruits. The proportion of grain crops and economic crops is 6:4, and the multiple cropping index is above 1.85 [10].

2.2. Data sources

Agricultural data from 1988 to 2014 was collected that mainly derived from survey data of Shaanxi Jinghui Canal Irrigation Administration, Agricultural Statistical Yearbook, Statistical Bulletin on National Economic and Social Development and relevant literature. The hydrological data from 1956 to 2016 including rainfall, runoff, sediment and other data was collected that mainly derived from Hydrological Station, Bulletin of Water Resources, Water Statistical Yearbook, etc.
3. Trend analysis of plant structure changes
Since 1986, China's agricultural planting structure has been constantly adjusting. The crop planting area that is directly related to urban consumption has been growing rapidly while the acreage of grain crops has been decreasing [11].

Jinghui Canal Irrigation District is known as the cabbage heart of Guan Zhong in Shaanxi Province, which is one of the main grain producing areas in Shaanxi and also is the main supply place of agricultural and sideline products in Xi'an and Xian Yang City. Under the background of changes in agricultural planting structure in China, the trend of agricultural planting structure in the Jinghui Canal Irrigation District shows that the total planting area has been decreasing, and the planting structure has been transiting gradually from grain crops to fruits, vegetables and other economic crops because of rapid urbanization and changes in market demand. The specific performance is that the planting area of wheat, corn and cotton has been decreasing, especially cotton planting has been out of scale. However, the planting area of fruit trees, vegetables, seedlings, flowers and other economic crops keeps increasing, in which the vegetables' planting area increases fastest that mostly use greenhouse facilities. The changes of planting structure were shown in figure 1.

![Figure 1. Land use type and crop area in different periods of Jinghui Canal Irrigation District.](image)

4. Regulation model and method
4.1. Model establishment
The change in planting structure directly led to the change of crops’ water consumption and water-using processes. The inadaptability of facility agriculture to the way of canal irrigation and its imbalance of seasonal water supply increased the water consumption of well irrigation, aggravating the contradiction of the imbalance of canal and well water supply. Therefore, under the constraints of water resources, this study sought the reasonable agricultural planting structure under the optimal scene that ecological benefit (water security), social benefit (food security) and economic benefit were relatively optimal. The multi-objective optimization model was established as below.

\[ G(x) = \max \{ f_1(x), f_2(x), f_3(x) \} \]  

(1)
4.1.1. Ecological benefits. Take the minimum water demand for crop irrigation in Jinghui Canal Irrigation District as the ecological benefit objective function $f_1(x)$.

$$f_1(x) = \min \sum_{i=1}^{n} (x_i, m_i)$$

where $f_i(x)$ was the water requirement for irrigation. $x_i$ ($i=1,2,3,\ldots,n$) was the planting area of the $i$ crop. $n$ was the number of crop species. $m_i$ was the irrigation quota of the $i$ crop, which was determined according to the current irrigation system of Jinghui Canal Irrigation District and fully considering the water-saving facilities and measures.

4.1.2. Social benefit. Urbanization brought some problems such as reduction of total agricultural planting area and grain planting area. Therefore, food security was regarded as the index to measure social benefits, taking the maximum of the minimum per capita cultivated area [12] as the social benefit objective function $f_2(x)$.

The minimum per capita cultivated land area refers to the cultivated land area required to meet the food consumption of the normal life of the population under the conditions of a certain region and grain self-sufficiency and land productivity, which gives the bottom line of the amount of cultivated land to be protected in order to ensure food safety [13].

$$f_2(x) = \max \sum_{i=1}^{n} \left( \beta_i \frac{Gr_i}{p_i \cdot q_i \cdot k} \right)$$

$$q_i = \frac{x_i}{\sum_{i=1}^{n} x_i} \quad (4)$$

where $f_2(x)$ was the minimum per capita cultivated area. $\beta_i$ was the self-sufficiency in food production of the $i$ crop. $Gr_i$ was the per capita demand of the $i$ crop. $p_i$ was the production of the $i$ crop. $q_i$ was the ratio of the planting area of the $i$ crop to the total planting area. $k$ was the multiple crop index. Food self-sufficiency and per capita demand refers to the literature [14].

4.1.3. Economic benefit. Take the maximum net benefit of agricultural output value in Jinghui Canal Irrigation District as the objective function of economic benefit $f_3(x)$.
\[ f_i(x) = \max \sum_{i=1}^{n} \left( p_i y_i - C_i - d_w \right) x_i \]  

(5)

Where \( f_i(x) \) was the net benefit of agricultural output value. \( y_i \) was the unit price of the of the \( i \) crop. \( d_w \) was the cost price of agricultural irrigation water utilization. \( C_i \) was the cost of one crop per unit area including the cost of seed, labor, machinery, fertilizer and so on.

4.2. Scenarios
Four crops including wheat, corn, apple tree and cucumber were selected as the variates. The research respectively set the reference scenario, initial scenario and optimization scenario to carry out simulation and regulation.

4.2.1. Reference scene. The research selected 2014 as the current year, and calculated the water demand of crops on the basis of the planting structure in this year. Surface water was used firstly and the water supply system was used to calculate the availability of surface water, then groundwater was used to compensate. Calculated the water supply of surface water and underground water respectively. The above process was set as the reference scene.

4.2.2. Initial scene. The cultivated area of Jinghui Canal Irrigation District was regarded as the constraint value of the crop planting area. The surface water availability was used as the water constraint without considering the exploitation of groundwater. Then, the first optimization calculation of planting structure was performed to output the result of reasonable planting structure. The above process was set as the initial scene.

4.2.3. Optimization scene. The initial result was transmitted to the surface water dispatching system of Jinghui Canal Irrigation District to regulate the monthly supply process of surface water, then groundwater was used to compensate. The amount of groundwater exploitation would be gradually adjusted to 10%, 20%, 50%, 70%, 90% and so on of the allowable exploitation of groundwater to constantly transmit, inverse, optimize, calculate and output the reasonable results. The above process was set as the optimization scene.

4.3. Model solving
Taking the crop planting area of Jinghui Canal Irrigation District as the variable, the availability of surface water and the exploitable reserve of groundwater as the main constraints, setting different simulation scenarios, the article built a surface water dispatching system to regulate, calculate and output the result, then used the Multi-objective Genetic Algorithm of MATLAB to calculate and get the planting area results [15], which were transmitted to each other to simulate repeatedly to output the optimization result.

4.3.1. Surface water dispatching system. The surface water supply projects in Jinghui Canal Irrigation District mainly include Zhang Jiashan Canal Head Diversion Junction, Zhang Jiashan Reservoir and Xi Jiao Reservoir. The dispatching principles were as follows. The water inflow from the Zhang Jiashan Canal Head was supplied first, the excess water was used to fill Xi Jiao Reservoir, then stored the water in Zhang Jiashan Reservoir. When the water inflow from the Zhang Jiashan Canal Head could not meet the demand of water supply, XiJiao Reservoir was firstly opened, Zhang Jiashan Reservoir was secondly. The water inflow would preferentially meet the base flow of river ecology, then would be supplied to the users. The operation process of the scheduling system was shown in figure 2.
The simulation schedule was carried out according to the hydrological year cycle, the flood season was from July to September, the non-flood period was from October to the next June. The adjustment calculation series used 61 years of runoff data from 1956 to 2016. The starting time was July 1956, adjusted monthly [16-18].

4.3.2. Solution process and steps. The solving process was shown in figure 3.

- Set relevant parameters, including: crop type, yield, price, irrigation cost, etc.. Set the constraint value, including: total cultivated land area, availability of surface water and the exploitable reserve of groundwater.
- Carry out the simulation calculation under the initial scenario and output the reasonable crop planting structure results as the initial value of the optimization calculation.
- Calculate the irrigation water demand according to the initial value of the crop planting structure, the surface water dispatching system is called for adjustment calculation and the groundwater is used to compensate, then judge the monthly water supply process result, if the result meets the requirement of water demand, end the operation and output the results; if not, continue to step (4).
- Adjust the constraint value of groundwater exploitation amount and continue to optimize the calculation.
- Judge whether the solution of the objective function is optimal. If satisfied, end the operation and output the result; if not, go to step (4).
- Continue to optimize, transmit, simulate repeatedly until the result is satisfactory.

Figure 2. Surface water scheduling flow chart of Jinghui Canal Irrigation District.
5. Results and analysis

In 2014, the planting area of wheat, corn, fruit trees and vegetables in Jinghui Canal Irrigation District was 67,400 hm². The research started calculating first according to the above reference scene, and the result was shown in table 1. The water requirement for crop was 40235.60×10⁴ m³/a. The surface water supply was 33528.17×10⁴ m³/a which accounted for 23.38% of the water inflow of Jing Huiqu Head Canal. In order to meet the irrigation requirements of crops, 6707.43×10⁴ m³/a of the groundwater supply was needed which occupied 50.73% of allowable extraction of groundwater. However, the actual amount of surface water taken from Jinghui Canal Irrigation District was 26693.00×10⁴ m³/a accounting for 18.61% of the water inflow of Jing Huiqu Head Canal in 2014, and the monthly water consumption was not matched with the water requirement of crop irrigation. The actual groundwater consumption was 16423.34×10⁴ m³/a which was far exceeded the allowable exploitation amount of groundwater resources in the Jinghui Canal Irrigation District. The agricultural planting structure, the actual water consumption for agricultural irrigation and the water use process were used as the background reference data to verify the optimization of the research results, which could prove that the research results in this paper were more reasonable than the current situation.

The constraint value of the utilizable surface water resources and exploitable groundwater resources respectively was 57371.42×10⁴ m³/a and 13222.67×10⁴ m³/a. The multi-objective genetic algorithm in MATLAB was used to calculate repeatedly. When the number of iteration was 114, the optimization results could be outputted. The schemes with the optimal ecological and social benefits

![Image of Model Solution Flow Chart]
were mainly considered, as shown in table 2.

Table 1. Water requirement and water supply of crop in 2014 of Jinghui Canal Irrigation District. Unit: $10^4$ m$^3$.

| Time     | Crop irrigation requirement | Surface water supply | Groundwater compensation | The actual water intake of surface water |
|----------|----------------------------|-----------------------|--------------------------|----------------------------------------|
| January  | 1976.81                    | 1976.81               | 0.00                     | 2686.00                                |
| February | 1520.77                    | 1520.77               | 0.00                     | 3126.00                                |
| March    | 2534.30                    | 2534.30               | 0.00                     | 3228.00                                |
| April    | 5821.74                    | 4885.25               | 936.49                   | 1472.00                                |
| May      | 4918.65                    | 4217.51               | 701.14                   | 323.00                                 |
| June     | 2383.00                    | 2082.30               | 300.70                   | 1989.00                                |
| July     | 8012.56                    | 5573.45               | 2439.11                  | 3726.00                                |
| August   | 6201.53                    | 4325.03               | 1876.50                  | 1311.00                                |
| September| 2230.34                    | 2230.34               | 0.00                     | 299.00                                 |
| October  | 1153.62                    | 1126.22               | 27.41                    | 4945.00                                |
| November | 1859.10                    | 1859.10               | 0.00                     | 1395.00                                |
| December | 1623.19                    | 1197.10               | 426.09                   | 2193.00                                |
| Total    | 40235.60                   | 33528.17              | 6707.43                  | 26693.00                               |

Table 2. The optimization result.

| Item | Ecological benefits ($10^4$m$^3$/a) | Social benefits (mu) | Economic benefits (One hundred million yuan) | Planting structure ($10^4$ hm$^2$) | Food crops | Fruit trees | Vegetables | Subtotal |
|------|------------------------------------|----------------------|---------------------------------------------|-----------------------------------|------------|-------------|------------|----------|
| I    | 35986.87                           | 0.71                 | 49.18                                       | 3.073                             | 1.440      | 1.592       | 6.105      |
| II   | 39571.20                           | 0.76                 | 46.21                                       | 3.684                             | 1.214      | 1.673       | 6.570      |

Under the condition of optimal ecological benefit, that is, when the irrigation water demand was much smaller, the total crop area in Jinghui Canal Irrigation District was 61050 hm$^2$, of which the planting area of grain crops, fruit trees and vegetables was 30730 hm$^2$, 14400 hm$^2$, and 15920 hm$^2$ respectively.

Under the condition of optimal social benefit, that is, when the minimum cultivated area per capita was much larger, the total area of crops in Jinghui Canal Irrigation District was 65700 hm$^2$, of which the planting area of grain crops, fruit trees and vegetables was 36840 hm$^2$, 12140 hm$^2$, and 16730 hm$^2$ respectively.

The economic benefit of the result of type I was better than type II, but it didn’t make much difference. The ecological and social benefits of the type II were better than type I. The total planting area of the above two optimization results was lower than the current year 2014, the planting area of food crops declined, and that of fruit trees and vegetables increased in different degree, which was basically consistent with the current change trend of agricultural planting structure. This indicated that there was still some room for adjustment and optimization of agricultural planting structure in Jinghui Canal Irrigation District.

The irrigation water requirement and water supply under the above two agricultural planting structures were shown in table 3.
### Table 3. Optimal water supply of Jing Hui Canal Irrigation District.

| Item | Water requirement ($10^4$ m$^3$/a) | Water supply | Water Percentage of the total(%) | Groundwater compensation ($10^4$ m$^3$/a) | Percentage of permitted extraction(%) |
|------|-----------------------------------|--------------|---------------------------------|------------------------------------------|-------------------------------------|
| I    | 35986.87                          | 32268.42     | 22.50                           | 3718.45                                  | 28.12                               |
| II   | 39571.20                          | 33438.65     | 23.31                           | 6132.54                                  | 46.38                               |

The result of type I shown that, under the condition of that the water requirement for crop was $35986.87 \times 10^4$ m$^3$/a, the surface water supply was $32268.42 \times 10^4$ m$^3$/a which accounted for 22.5% of the water inflow of Jing huiqu Head Canal. In order to meet the water demand, the groundwater should compensate $3718.45 \times 10^4$ m$^3$/a, which covered 28.12% of the allowable exploitation amount of groundwater resource.

The result of type II shown that, the water requirement for crop was $39571.20 \times 10^4$ m$^3$/a, the surface water supply was $33438.65 \times 10^4$ m$^3$/a which accounted for 23.31% of the water inflow of Jing huiqu Head Canal. In order to meet the water demand, the groundwater should compensate $6132.54 \times 10^4$ m$^3$/a, which covered 46.38% of the allowable exploitation amount of groundwater resource.

Analysis of the above two results, the intake of groundwater was lower than the actual groundwater withdrawal in current year 2014. The result of type I could reduce the exploitation of groundwater resource more than type II, which was beneficial to alleviate the situation of serious over-exploitation of groundwater in Jinghui Canal Irrigation District, was good for the protection and restoration of groundwater resource.

### Figure 4. The irrigation water supply process of the I result.

The monthly water demand and water supply process under the two optimization results were shown in figures 4 and 5. In general, the water demand of crop irrigation in the Jinghui Canal Irrigation District was far less than the availability of surface water. There are two peak periods of water demand from April-May and July-August in a year, which were affected by seasonal change of water inflow, sediment concentration, water supply capacity and other factors, the surface water could not meet the requirement for crop irrigation and need the groundwater to compensate jointly. According to the simulation results, the surface water was used first to supply, then groundwater was used to compensate, thus could basically meet the water demand for irrigation.

In conclusion, the planting structure and water resource utilization of the above two results were better than that of the current year. From the perspective of optimal ecological benefit, the agricultural planting structure of the type I was recommended. From the perspective of optimal social benefit, the type II was recommended. The economic benefit of the two schemes was similar, which could play a
positive role in the utilization, protection and restoration of groundwater resource. The agricultural planting structure interval between the two schemes could be defined as a reasonable development interval.

![Diagram of water demand, surface supply, and groundwater compensation over months]

**Figure 5.** The irrigation water supply process of the II result.

### 6. Conclusion

The change of planting structure, crop planting type, farming time and farming method has caused the change in agricultural production activities such as irrigation water demand, irrigation time, and irrigation methods. The change of planting structure in Jinghui Canal Irrigation District mainly reflects in the continuous decreasing of the total planting area, grain-based planting structure has been gradually transforming to the vigorously planting of fruits, vegetables and other economic crops, which causes the food security problem is worthy of attention. The area of facility agriculture has been increasing rapidly that is not adapted to the canal irrigation way and the seasonal uneven water quantity of canal irrigation, which increases the water intake of well irrigation and further aggravates the imbalance of canal well water supply ratio. In this, a multi-objective water regulation model was established for finding coordinate development among ecological benefits (water security), social benefits (food security) and economic benefits, which was solved using the combined method of optimization, scheduling and simulation to output the planting structure optimization configuration results of optimal ecological benefits (minimum irrigation water demand) and optimal social benefits (minimum per capita arable land area was the largest). The water demand and supply process was simulated and verified that were better than the planting structure allocation and water resource utilization of current year, which was beneficial to alleviate the serious over-exploitation of groundwater in Jinghui Canal Irrigation District, and to protect and restore groundwater resource. The agricultural planting structure between the two schemes could be taken as a reasonable regulation interval to provide a reasonable resource utilization and agricultural planting scheme for the future development of Jinghui Canal Irrigation District.

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