

STUDY ON OPTIMAL ALLOCATION OF WATER-GRAIN SYSTEM IN IRRIGATION AREAS

ÉTUDE SUR L'ALLOCATION OPTIMALE DU SYSTEME EAU-CEREALES DANS LES ZONES D'IRRIGATION

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ABSTRACT

To address water deficit in irrigation districts and improve the utilization efficiency of water and soil resources, this study takes the Moyiyan Irrigation District in Sichuan Province as a case study and constructs an optimal water resources allocation function with the objectives of minimizing water deficit and maximizing economic benefit. By combining the multi-objective genetic algorithm (NSGA-II) with the entropy-weight TOPSIS evaluation model, this study optimizes water resources and selects preferred schemes under different precipitation guarantee rates. The results show that the optimized schemes save $59.9 \times 10^4 \text{ m}^3$ and $512.7 \times 10^4 \text{ m}^3$ of water resources in the irrigation district under the 50% and 75% precipitation guarantee rates, respectively; economic benefit increases by 3.83% and 6.92%, respectively, compared with the baseline year; and the proportion of rice planting area is optimized to 57.7% and 48.8%, thereby achieving coordination between resource utilization and economic benefit. This study provides a theoretical basis and practical pathway for regional adaptive management and sustainable agricultural development in irrigation districts.

Keywords: irrigation district; optimal water resources allocation; NSGA-II algorithm; entropy-weight TOPSIS evaluation model; planting structure.

RESUME

Pour remédier au déficit hydrique dans les périmètres irrigués et améliorer l'efficacité de l'utilisation des ressources en eau et en sol, cette étude traite le périmètre irrigué de Moyiyan situé dans la province du Sichuan comme une étude de cas et construit une fonction optimale d'allocation des ressources en eau avec les objectifs de minimiser le déficit en eau et de maximiser les avantages économiques. En combinant l'algorithme génétique multi-objectif (NSGA-II) avec le modèle d'évaluation TOPSIS avec pondération par entropie, cette étude optimise les ressources en eau et sélectionne des projets sous différents taux de garantie de précipitation. Les résultats montrent que les projets optimisés économisent $59,9 \times 10^4 \text{ m}^3$ et $512,7 \times 10^4 \text{ m}^3$ de ressources en eau dans le périmètre irrigué, dans le cadre de taux de garantie de précipitations de 50% et 75%, respectivement; les avantages économiques augmentent de 3,83% et 6,92%, respectivement, par rapport à l'année de référence; et la proportion de la superficie consacrées à la riziculture est optimisée à 57,7% et 48,8%, assurant ainsi une coordination entre l'utilisation des ressources et les avantages économiques. Cette étude fournit une base théorique et une voie pratique pour la gestion adaptative régionale et le développement agricole durable au sein des périmètres irrigués.

Mots-clés : Périmètre irrigué; Allocation optimale des ressources en eau; Algorithme NSGA-II; Modèle d'évaluation TOPSIS avec pondération par entropie; Structure des cultures.

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1. Introduction

Climate change is altering precipitation, runoff, and crop evapotranspiration processes. Increases in the frequency and intensity of extreme events such as droughts and heavy precipitation have made the supply-demand process of agricultural irrigation more uncertain⁰. The United Nations World Water Development Report states that water resources security is closely related to agricultural production, regional development, and climate adaptation⁰. Monitoring of water stress by FAO and UN-Water shows that, under pressure on limited freshwater resources, improving agricultural water-use efficiency and irrigation management is an important approach for alleviating supply-demand conflicts⁰. Water resources system planning in irrigation districts emphasizes the establishment of coordinated allocation relationships among water sources, water conveyance and distribution projects, cultivated land, and water users⁰. Therefore, research on optimal water resources allocation at the irrigation district scale is of great significance for improving crop water requirement guarantee capacity and the utilization efficiency of water and soil resources.

The core of optimal water resources allocation in irrigation districts is to coordinate crop water requirement, available water supply, cultivated land area, and agricultural economic benefit under limited inflow conditions. Existing studies on water-use performance evaluation, crop water productivity, and regional planting structure optimization have shown that improving the irrigation water-use indicator system, increasing output per unit water volume, and optimizing crop layout can effectively alleviate water resources constraints and improve comprehensive agricultural benefit⁰. When both inflow and water requirement are uncertain, multi-objective irrigation water resources allocation models can simultaneously consider objectives such as economic benefit, water-deficit control, and water-use efficiency, thereby providing quantitative support for water allocation and planting structure adjustment in irrigation districts⁰. To address mutual constraints among multiple objectives, the genetic algorithm (NSGA-II), which features fast non-dominated sorting, crowding-distance preservation, and elitist retention mechanisms, has become a commonly used method for solving complex nonlinear multi-objective optimization problems⁰. The TOPSIS method ranks schemes by measuring their distances from the positive and negative ideal solutions⁰, whereas the entropy-weight method uses information entropy to reflect the dispersion degree of indicators and determine objective weights⁰. Combining NSGA-II with the entropy-weight TOPSIS method helps retain multi-objective trade-off information while reducing subjectivity in scheme evaluation. At the irrigation district scale, existing studies have introduced methods such as effective precipitation, inflow uncertainty, cross entropy, maximum entropy, and entropy-weight TOPSIS into agricultural water resources allocation and carrying-capacity evaluation, providing useful modeling ideas for multi-scenario irrigation district water allocation optimization⁰. These studies indicate that, under tightening constraints on agricultural water use, water resources allocation in irrigation districts needs to shift from single water allocation scheduling toward collaborative optimization of “crop water requirement-water source process-planting structure-economic benefit.” This study overcomes the limitations of traditional single-objective programming and conducts an in-depth analysis of the joint allocation of multiple elements within the irrigation district, including water, crops, and the economy, with the aim of providing a theoretical reference for irrigation district water-use management and planting structure adjustment.

2 Model Construction and Solution

2.1 Objective Functions

(1) Minimize total water deficit

The primary objective of the irrigation district is to ensure the normal growth of crops. Crop water demand should be satisfied as much as possible under allowable conditions. In the model, the objective is to minimize the difference between crop water requirement and actual water allocation. The formula is as follows.

$$\min W_q = \sum_{j=1}^j \sum_{i=1}^n p_{i,j} x_j - 0.565 \times \sum_{i=1}^n y_i \quad (1)$$

where W_q is the total water deficit of the irrigation district, m^3 ; $p_{i,j}$ is the irrigation quota of crop j in month i ($j = 1, 2$, and 3 correspond to maize, wheat, and rice, respectively), m^3/m^2 ; y_i is the water supply in month i , m^3 ; and x_j is the planting area of crop j , m^2 .

(2) Maximize economic benefit

The economic benefit of the irrigation district mainly depends on crop planting area, cost, yield, and output value, namely the net output value of crops, which is equal to the difference between total output value and total cost. The formula is as follows.

$$\max K = \sum_{i=1}^n \sum_{j=1}^j 0.565 \times \frac{y_i}{p_{i,j}} \times a_j \times b_j (c_j - d_j) - 0.07 \times \sum_{i=1}^n y_i \quad (2)$$

where K is the net output value of grain crops in the irrigation district, CNY; a_j is the yield per unit area of crop j , kg/m^2 ; b_j is the selling price per kilogram of crop j , CNY/kg; c_j is the total cost per kilogram of crop j , CNY/kg; and d_j is the government subsidy for crop j .

2.2 Constraints

(1) Water requirement

The water supply at different crop growth stages should be greater than the minimum water requirement to prevent crops from wilting due to water deficit. Based on crop growth data, the minimum water requirement is set as 50% of the irrigation quota.

$$M_{i,min} \leq 0.56 \times y_i \quad (3)$$

where y_i is the water supply in month i , m^3 ;

(2) Available water supply

The maximum water volume that the irrigation district can provide is determined according to the actual data from the water intake of the irrigation district, and the maximum water supply under the 50% and 75% frequencies is adopted.

$$y_i \leq N_{i,max} \quad (4)$$

where y_i is the water supply in month i , m^3 ;

(3) Planting area

The total grain crop planting area should be less than the maximum cultivated area in the irrigation district and greater than the minimum cultivated area.

$$S_{min} \leq x_1 + x_3 \leq S_{max} \quad (5)$$

$$S'_{min} \leq x_2 \leq S'_{max} \quad (6)$$

where S_{min} is the maximum cultivated area in the irrigation district, m^2 ; S_{max} is the minimum cultivated area in the irrigation district, m^2 ; and x_j is the planting area of crop j , m^2 .

(4) Non-negativity constraint: all decision variables are non-negative.

2.3 Solution Using the NSGA-II Multi-Objective Optimization Algorithm

In view of the conflicting objectives in optimal water resources allocation in irrigation districts, such as maximizing economic benefit and minimizing water deficit (or maximizing ecological water use), traditional single-objective programming cannot meet practical management requirements. This study introduces the Non-dominated Sorting Genetic Algorithm II (NSGA-II) with an elitist retention strategy for solution.

(1) NSGA-II genetic algorithm

The NSGA-II genetic algorithm can effectively solve nonlinear optimization problems and identify the Pareto optimal solution set of two mutually restrictive objective functions. Genetic algorithms are widely applied and, compared with other algorithms, are more mature. Their solution process is fast and convenient, they can quantitatively represent changes in water volume with high accuracy, and they require short computation time. Therefore, they have been widely applied to provide a scientific basis for optimization adjustment under dynamic changes in water resources. The calculation flowchart is shown in Figure 1. The NSGA-II genetic algorithm was implemented by programming in MATLAB R2022b. Because the genetic algorithm randomly generates the initial population and selects regenerated individuals according to fitness, the model optimization results consist of multiple optimized schemes in the Pareto optimal solution set.

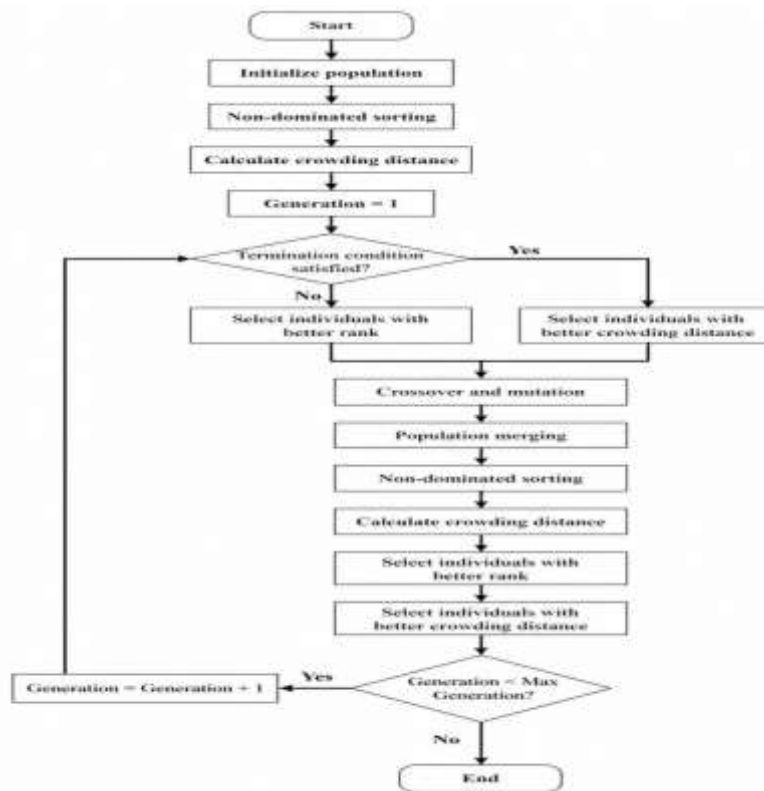


Figure 1. Schematic diagram of the NSGA-II algorithm calculation process

(2) Scheme comparison and selection

The optimization algorithm is used to solve the multi-objective water resources allocation model. Because the objectives mutually constrain each other, a unique optimal solution cannot be obtained; instead, multiple Pareto non-inferior solution sets are generated, corresponding to different allocation schemes. During the selection of preferred schemes from the Pareto solution set, subjective judgment may easily be introduced when determining the weights of different objectives. Therefore, an evaluation model must be constructed for scheme comparison and selection. The entropy-weight method assigns objective weights according to the dispersion degree of indicators, thereby eliminating interference from subjective factors. The distance-to-ideal-solution method ranks schemes by measuring their relative closeness to the ideal solution. To fully exploit the advantages of both methods, this study constructs an entropy-weight TOPSIS comprehensive evaluation model to select preferred schemes from the solution set. This model combines the advantages of objective weight determination by the entropy-weight method and scheme ranking by TOPSIS, forming a systematic evaluation framework. The calculation steps are as follows.

1) Data preprocessing

① Construct the initial decision matrix

$$X = \begin{pmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{m1} & \cdots & x_{mn} \end{pmatrix} \quad (7)$$

where m is the number of schemes; n is the number of evaluation indicators; and x_{ij} is the value of evaluation indicator j in scheme i .

② Data standardization

This study adopts the Min-Max standardization method to transform the data into decimals between 0 and 1. Formula (8) is used when an indicator is positively correlated with the evaluation result, and Formula (9) is used when an indicator is negatively correlated with the evaluation result.

$$Y_{ij} = \frac{X_{ij} - \min(X_{ij})}{\max(X_{ij}) - \min(X_{ij})} \quad (8)$$

$$Y_{ij} = \frac{\max(X_{ij}) - X_{ij}}{\max(X_{ij}) - \min(X_{ij})} \quad (9)$$

where Y_{ij} is the dimensionless value obtained after standardizing the original indicator. 2) Determine weights using the entropy-weight method

① Calculate the indicator proportion

$$\rho_{ij} = \frac{x_{ij}}{\sum_{i=1}^m x_{ij}} \quad (10)$$

where p_{ij} is the proportion value of evaluation scheme i under indicator j .

② Calculate information entropy and the difference coefficient

$$E_j = -\frac{1}{\ln(m)} \sum_{i=1}^m \rho_{ij} \ln(\rho_{ij}) \quad (11)$$

$$D_j = 1 - E_j \quad (12)$$

where E_j is the information differentiation degree or effective information content of indicator j .

- ③ Determine the weight

$$w_j = \frac{1 - E_j}{\sum_{j=1}^n (1 - E_j)} \quad (13)$$

- 3) TOPSIS comprehensive evaluation

- ① Construct the weighted evaluation matrix $Z_{ij} = Y_{ij} \times W_j$ (14)

where Z_{ij} is the weighted standardized data, representing the comprehensive influence of indicator j on evaluation object i .

- ② Identify the optimal scheme and the worst scheme

$$Z_j^+ = \max(Z_{1j}, Z_{2j}, \dots, Z_{mj}) \quad (15)$$

$$Z_j^- = \min(Z_{1j}, Z_{2j}, \dots, Z_{mj}) \quad (16)$$

where: Z_j^+ is the positive ideal value of evaluation indicator j among all solution sets;

Z_j^- is the negative ideal value of evaluation indicator j among all solution sets.

- ③ Calculate the positive ideal distance and negative ideal distance

$$D_i^+ = \sqrt{\sum_j (Z_{ij} - Z_j^+)^2} \quad (17)$$

$$D_i^- = \sqrt{\sum_j (Z_{ij} - Z_j^-)^2} \quad (18)$$

- ④ Calculate the relative closeness of each evaluation indicator to the optimal value

$$C_i = \frac{D_i^-}{D_i^+ + D_i^-} \quad (19)$$

where: $0 < C_i < 1$; the larger the relative closeness value, the closer the scheme is to the ideal solution and the higher the evaluation level.

The schemes are ranked in ascending order according to the value of relative closeness C_i , and the scheme with the largest value is selected as the optimal scheme.

3. Case Study

3.1 Overview of the Study Area

3.1.1 eographical location

The Moyiyan Irrigation District in Sichuan Province, China, was selected as the case study area, as shown in Figure 2. The irrigation area is $4.61 \times 10^7 \text{ m}^2$. The irrigation district has a subtropical humid climate, with a multi-year average temperature of 17°C , an annual average precipitation of 1152.7 mm, and an annual average evaporation of 965.0 mm. The water source is mainly diversion from the Min River. In the baseline year (2023), the irrigation district mainly planted three major grain crops: rice,

wheat, and maize. The proportion of rice planting area was excessively high, and water consumption during the peak rice water requirement period from June to August accounted for 63.15%, resulting in an extremely uneven spatiotemporal distribution of water use. Under the 50% and 75% precipitation guarantee rates, the actual water diversion volumes were $3174 \times 10^4 \text{ m}^3$ and $2949 \times 10^4 \text{ m}^3$, respectively; the water deficits were $6 \times 10^4 \text{ m}^3$ and $507 \times 10^4 \text{ m}^3$, respectively; and the water-deficit rates were 0.19% and 24.82%, respectively. Water deficit in dry years is significant, and the above contradictions urgently need to be addressed through optimal water resources allocation. The current water supply of the Moyiyan Irrigation District is mainly provided by diverting water from the Min River through the Moyiyan water intake.

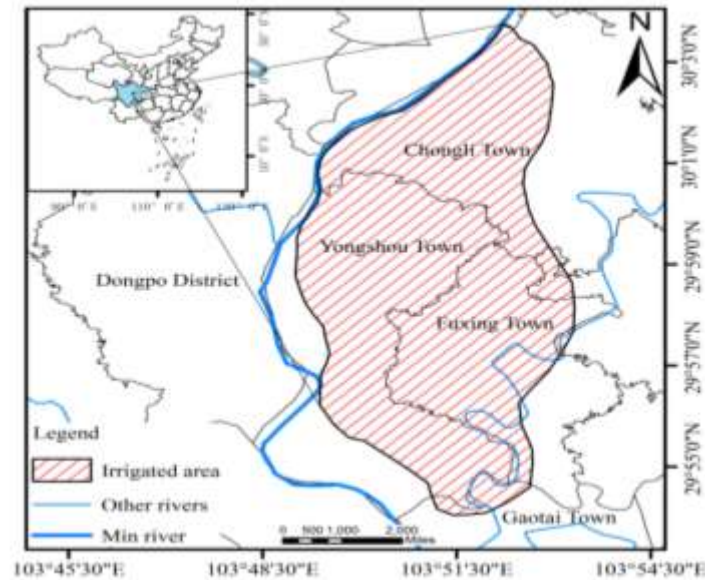
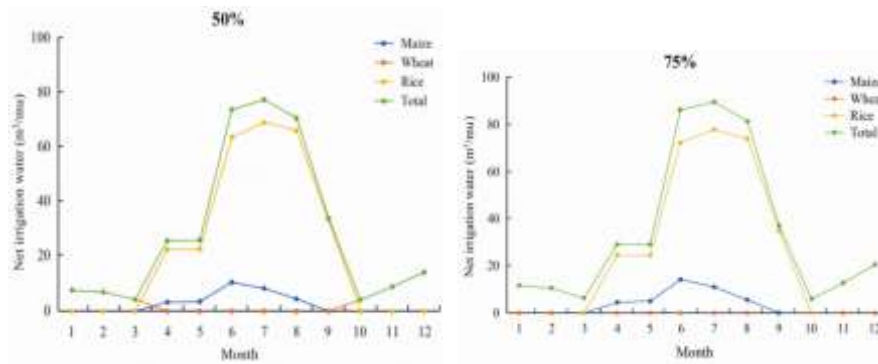


Figure 2. Distribution map of the Moyiyan Irrigation District

3.1.2 Analysis of Irrigation Water Use

Based on irrigation district data (from the Implementation Scheme Report of the Moyiyan Irrigation District Project, Meishan Statistical Yearbook, Sichuan Provincial Water Use Quota, and China Meteorological Data Network, among others), water-use efficiency and water-use structure in the irrigation district were analyzed, and the irrigation district water requirement under different precipitation guarantee rates (50% and 75%) was calculated. In the baseline year (2023), the actual water diversion volumes in the irrigation district under the 50% and 75% precipitation guarantee rates were $3174 \times 10^4 \text{ m}^3$ and $2949 \times 10^4 \text{ m}^3$, respectively, and the canal-system water-use coefficient was 0.565. According to the calculation results of the quota method, the net irrigation water requirements under the different precipitation guarantee rates were $1790 \times 10^4 \text{ m}^3$ and $2080 \times 10^4 \text{ m}^3$, respectively; the gross irrigation water requirements were $3168 \times 10^4 \text{ m}^3$ and $3681 \times 10^4 \text{ m}^3$, respectively; the current water deficits were approximately $6 \times 10^4 \text{ m}^3$ and $507 \times 10^4 \text{ m}^3$, respectively; and the water-deficit rates were 0.19% and 24.82%, respectively. The monthly water requirements of grain crops in the irrigation district are shown in Figure 3(a)-(b). Temporally, the water requirement in the irrigation district is highest from June to August, and the total water requirement during these three months accounts for more than 63.15% of the annual total. This is mainly because rice is in a critical growth stage, and rice is the principal water-consuming grain crop in the irrigation district; therefore, the irrigation water requirement from June to August is relatively large. The water requirement in the irrigation district is lowest in March and October, accounting for approximately 6% of the annual total. According to the planting structure in the irrigation district, this is because the district is in the transition period between harvest and planting of grain crops, resulting in a relatively low total water requirement. During the rice growth period from March to September, rice water use dominates the total water use and rice is the main water-consuming crop in the irrigation district. Wheat water requirement is highest in the early growth stage in November and December and then

gradually decreases in January, February, and March of the following year. The maize growth period basically overlaps with the rice growth period, but its water consumption is only approximately one-tenth that of rice and is mainly concentrated in the early and middle stages, namely June and July; water requirement is relatively low in other months.



(a) 50% precipitation guarantee rate (b) 75% precipitation guarantee rate

Figure 3. Crop water requirement under different precipitation guarantee rates

3.2 Model Parameter Determination

3.2.1 Irrigation Regime

Based on the irrigation regime and water consumption information of grain crops in the irrigation district, the monthly water consumption ratios during the growth period of grain crops in the irrigation district were determined, as shown in Table 1.

Table 1. Water consumption ratios during the crop growth period

	April	May	June	July	August	September
Maize	12%	13%	31%	27%	14%	2%
Rice	12%	6%	25%	27%	24%	6%
Wheat	9%	19%	30%	17%	15%	10%

3.2.2 Crop Benefit Parameters

The economic benefit of crops in the irrigation district was calculated using cost, price, government subsidy, and water fee, as shown in Table 2.

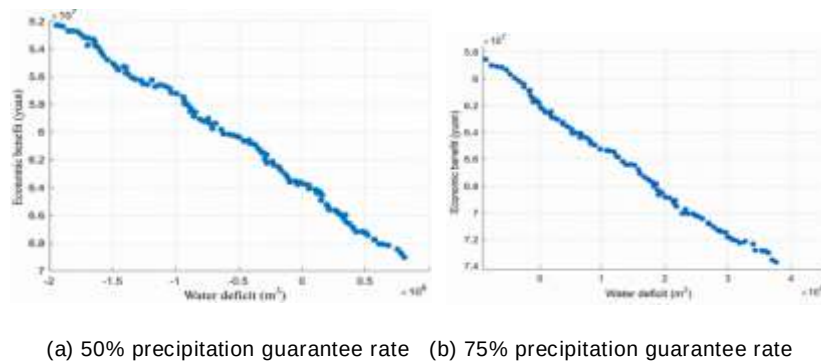
Table 2. Crop yield, output value, and price

	Ideal yield (kg/mu)	Cost (CNY/kg)	Price (CNY/kg)	Government subsidy (CNY/mu)	Water fee (CNY/m ³)
Maize	450	2.42	1.1	110	0.07
Wheat	350	2.62	1.3	105	0.07
Rice	600	2.67	1.5	130	0.07

3.3 Analysis of Optimal Allocation Results

Using the constructed optimal water resources allocation model, the monthly water allocation of the current water sources in the irrigation district during the year was optimized. The NSGA-II optimization algorithm was used to solve the model. The population size was set to 200, and 500 iterations were performed. The Pareto solution sets under different precipitation guarantee rates are shown in Figure

4(a)-(b), where (a) and (b) correspond to the 50% and 75% precipitation guarantee rates, respectively. Because the population size in the optimization algorithm was set to 100, the resulting Pareto solution set was relatively large (approximately 170 groups). To accurately characterize the relationship between the water-deficit objective and the economic-benefit objective in the irrigation district, Pearson correlation analysis was conducted. The results show a significant negative correlation between the two objectives, with a correlation coefficient of -0.92 ($P \leq 0.05$), indicating a competitive relationship during the process of seeking the optimal solution. Under the different precipitation guarantee rates (50% and 75%), the water deficit ranges of the two Pareto solution sets were -193×10^4 to 83×10^4 m³ and -97×10^4 to 394×10^4 m³, respectively, and the corresponding economic benefit ranges were 5200×10^4 to 7000×10^4 CNY and 5800×10^4 to 7400×10^4 CNY, respectively.

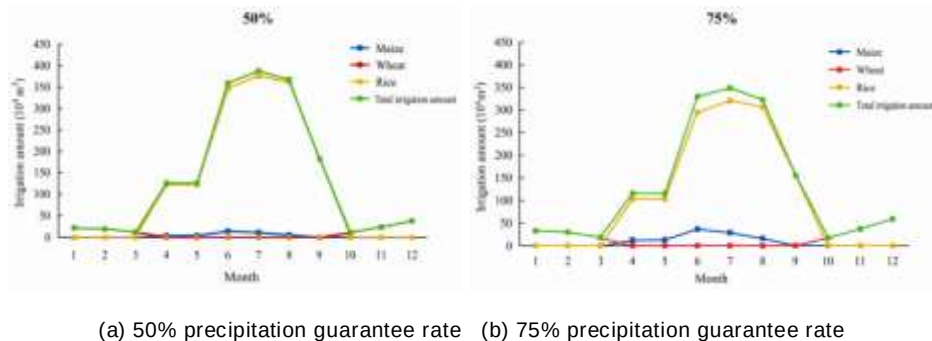


(a) 50% precipitation guarantee rate (b) 75% precipitation guarantee rate

Figure 4. Pareto scatter plots under different precipitation guarantee rates

The constructed entropy-weight TOPSIS comprehensive evaluation model was used to evaluate the obtained multiple non-inferior solution sets, and the weight coefficients determined by the entropy-weight method are shown in Table 3. Under the premise of comprehensively considering the objective of minimizing water deficit and the objective of maximizing economic benefit, the allocation scheme with the largest C_i was selected as the optimal water allocation scheme according to the weight information of different objectives.

Under the 50% precipitation guarantee rate, the actual net water requirement of grain crops in the irrigation district in the optimal scheme was 1849×10^4 m³, the gross water requirement was 3272×10^4 m³, the actual water diversion volume was 3326×10^4 m³, and the surplus water volume in the irrigation district was 53.9×10^4 m³ (because the water deficit of grain crops in the irrigation district after optimal allocation was negative, it is referred to as surplus water). Compared with the pre-optimization condition, the water deficit in the irrigation district decreased by 59.9×10^4 m³. Under the 75% precipitation guarantee rate, the actual net water requirement of grain crops in the irrigation district in the optimal scheme was 1710×10^4 m³, the gross water requirement was 3027×10^4 m³, the actual water diversion volume was 3033×10^4 m³, and the surplus water volume in the irrigation district was 5.7×10^4 m³. Compared with the pre-optimization condition, the water deficit in the irrigation district decreased by 512.7×10^4 m³.



(a) 50% precipitation guarantee rate (b) 75% precipitation guarantee rate

Figure 5. Monthly water allocation results in the irrigation district

Analysis of the irrigation proportions of different crops in the irrigation district shows that, under the 50% precipitation guarantee rate, the annual water allocation volumes for the corresponding grain crops, namely maize, wheat, and rice, were $41.8 \times 10^4 \text{ m}^3$, $129.3 \times 10^4 \text{ m}^3$, and $1707.9 \times 10^4 \text{ m}^3$, respectively. Under the 75% precipitation guarantee rate, the corresponding water allocation volumes for maize, wheat, and rice were $86.2 \times 10^4 \text{ m}^3$, $192.5 \times 10^4 \text{ m}^3$, and $1434.9 \times 10^4 \text{ m}^3$, respectively. The monthly water allocation volumes of each grain crop are shown in Figure 5(a)-(b).

Table 3. Weight coefficients of objective functions under different hydrological frequencies

	50%	75%
F1	0.71	0.78
F2	0.29	0.22
Total	1	1

Table 4. Optimized planting structure in the irrigation district

	Maize (mu)	Wheat (mu)	Rice (mu)	Total (mu)
Baseline year (2023)	15929	26970	51687	94586
50%	13267	26948	54780	94995
75%	21267	27348	46254	94869

Analysis of the total economic benefit of the irrigation district shows that the economic benefit obtained from the 2023 irrigation district data was $5793.8 \times 10^4 \text{ CNY}$, as shown in Figure 6. For the optimal allocation scheme, under the 50% precipitation guarantee rate, the total economic benefit of grain crops in the irrigation district was $6015.7 \times 10^4 \text{ CNY}$, an increase of 3.83% compared with the baseline year. Under the 75% precipitation guarantee rate, the total economic benefit of grain crops in the irrigation district was $6195 \times 10^4 \text{ CNY}$, an increase of 6.92% compared with the baseline year. For the analysis of grain crop planting area, the planting proportions of rice, maize, and wheat in the irrigation district were mainly adjusted, and the adjustment results are shown in Table 4.

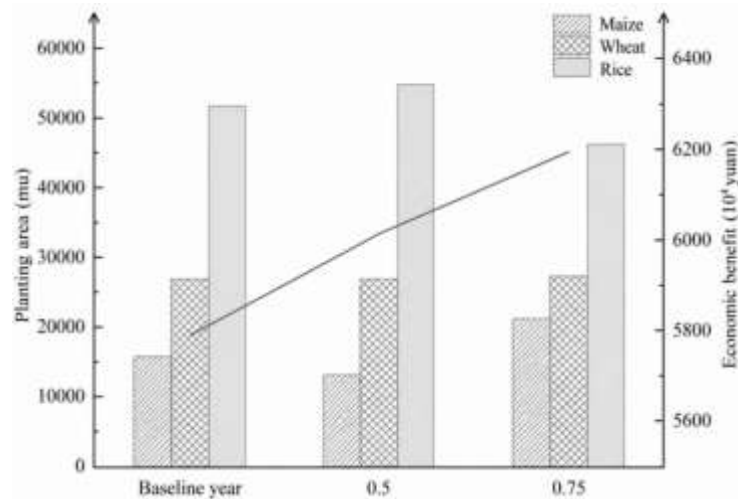


Figure 6. Optimized planting structure and economic benefit in the irrigation district

4. Discussion

Traditional agricultural water resources management is often limited to extreme-value solutions for a single objective and has difficulty balancing economic benefit with ecological water saving. This study found a significant negative correlation between the water-deficit objective and the economic-benefit objective (correlation coefficient = -0.92), indicating an obvious competitive relationship. In the baseline year, the proportion of rice planting area in the irrigation district was excessively high, causing water consumption during the peak water requirement period from June to August to account

for 63.15%, with an extremely uneven spatiotemporal distribution of water use. After model optimization, the planting structure was reasonably adjusted, and the proportions of rice planting area under the 50% and 75% precipitation guarantee rates were optimized to 57.7% and 48.8%, respectively. The structural adjustment not only substantially reduced water requirement pressure during the peak period but also increased the overall economic benefit of the irrigation district by 3.83% and 6.92%, respectively, compared with the 2023 baseline condition. This fully confirms that scientific planting structure adjustment is a key pathway for achieving coordinated development between efficient resource utilization and steady agricultural economic growth.

In multi-objective optimization, previous studies often relied on subjective weighting methods to transform multiple objectives into a single objective when handling objective conflicts, which may easily overlook decision objectivity and solution-set diversity. This study introduced the Non-dominated Sorting Genetic Algorithm II (NSGA-II) with an elitist retention strategy, which can effectively solve nonlinear optimization problems and output multiple uniformly distributed Pareto non-inferior solution sets. For optimization within the non-inferior solution sets, this study innovatively constructed an entropy-weight TOPSIS comprehensive evaluation model. The entropy-weight method was used for objective weighting to eliminate interference from subjective factors, and the distance-to-ideal-solution method (TOPSIS) was combined to comprehensively measure and rank the schemes. This “intelligent algorithm + objective evaluation” combined mode provides a more scientific and systematic decision-making framework for dynamic water resources allocation under multidimensional mutual constraints.

Although this study achieved significant results in the allocation of water and soil resources at the micro scale of the irrigation district, the discussion of the optimal allocation results mainly focused on the dual-objective coordination of water resources allocation and economic benefit. Driven by China’s macrostrategic goals of “carbon peaking and carbon neutrality,” agricultural systems also bear the responsibility of energy conservation and emission reduction. Future research can further quantify ecological factors such as carbon sinks (crop photosynthesis), carbon emissions (fertilizer application and agricultural machinery energy consumption), and non-point source pollution mentioned in system dynamics models as constraints or optimization objectives in the allocation model. In addition, scenario analysis combined with future Shared Socioeconomic Pathways (such as SSP126 and SSP585) will provide more comprehensive and far-reaching mathematical support for the high-quality, green, and low-carbon transformation of modern agriculture.

Conclusions

Taking the Moyiyan Irrigation District in Sichuan Province as the study area, this study constructed a multi-objective optimal water resources allocation model with the objectives of minimizing water deficit and maximizing economic benefit. The NSGA-II algorithm and entropy-weight TOPSIS evaluation model were combined to solve the Pareto solution set and select the preferred scheme, providing a quantitative decision-making method for irrigation district water resources allocation and planting structure adjustment.

Optimal allocation can significantly improve water-deficit conditions in the irrigation district. Under the 50% and 75% precipitation guarantee rates, the optimized schemes saved $59.9 \times 10^4 \text{ m}^3$ and $512.7 \times 10^4 \text{ m}^3$ of water resources in the irrigation district, respectively. Through refined monthly water allocation scheduling, water resources waste can be effectively reduced, and the drought-adaptation capacity and water-use efficiency of the agricultural system can be improved.

The optimized planting structure accounts for both water saving and benefit improvement. Under the 50% and 75% precipitation guarantee rates, the proportions of rice planting area were optimized to 57.7% and 48.8%, respectively, and the economic benefits of the irrigation district reached $6015.7 \times 10^4 \text{ CNY}$ and $6195 \times 10^4 \text{ CNY}$, respectively, representing increases of 3.83% and 6.92% compared with $5793.8 \times 10^4 \text{ CNY}$ in the 2023 baseline condition. This indicates that planting structure optimization and water allocation optimization have good synergistic effects.

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