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An Optimisation–Evaluation Framework for the Sustainable Management of the Water–Energy–Food Nexus for an Irrigation District under Uncertainty

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Abstract: The synergistic regulation of the water–energy–food nexus in irrigation districts is important for promoting the sustainable management of agricultural resources in irrigation districts. In this paper, a new integrated optimization–evaluation modelling framework for the water–energy–food nexus in agricultural irrigation areas is developed. It can measure the synergistic effects of economic, social and environmental multidimensional objectives on the sustainable management of agricultural resources in irrigation areas. The model couples an optimisation module and an evaluation module, combines a multiobjective nonlinear planning model with an opportunity-constrained planning model and uses an entropy-weighted TOPSIS assessment approach to sustainably assess the multidimensional indicators of the water–energy–food nexus in irrigation districts, with full consideration given to the effects of uncertainty in agricultural water and soil resources and social systems. The feasibility of the constructed model is verified through a study of the Jinxi irrigation district. The results show that compared to the actual area, the optimised surface water and groundwater availability increased by 23.5% and 22.7%; the optimised total area increased by 4%, whereas corn decreased by 40%, rice increased by 34.6% and soybean decreased by 33.8%; the energy consumption decreased by 17.6% and the total recycled resources amounted to 8.97×10^9 kg, with a combined net economic benefit of CNY 1.25×10^9 more than the actual current amount. The synergistic development of the water–energy–food nexus (WEFN) in the district is relatively harmonious, suggesting that the district should focus on developing agricultural mechanisation and balancing economic benefits with environmental and ecological protection; furthermore, the model constructed should provide decision-making support for the efficient use of agricultural resources in the irrigation district.

Keywords: water–energy–food nexus (WEFN); optimisation–evaluation framework; high uncertainty; sustainability

Citation: Zhou, Y.; Zhang, X.; Chen, Y.; Li, H. An Optimisation–Evaluation Framework for the Sustainable Management of the Water–Energy–Food Nexus for an Irrigation District under Uncertainty. *Agronomy* **2023**, *13*, 1714. https://doi.org/10.3390/agronomy13071714

Academic Editor: Junliang Fan

Received: 25 April 2023
Revised: 18 June 2023
Accepted: 23 June 2023
Published: 26 June 2023

1. Introduction

Agriculture is the largest consumer of surface water and groundwater resources in developing countries, and approximately 90% of the available water resources are used for irrigation in Northeast China. Water, energy and food are the basis for human survival [1]. However, with the presence of rapid economic development and population growth, the demand for water from different water sectors (such as agriculture, industry and municipalities) is increasing dramatically. The demand for energy and food is also increasing, and together with pollution and the irrational use of resources, the availability of fresh water for agriculture has been decreasing at an accelerating rate in recent years.

These problems constrain the sustainable development of Chinese society and highlight the need to optimise the limited irrigation water and energy resources, especially from the point of view of sustainable management [2]. In recent years, the already limited irrigation water resources have become increasingly scarcer, energy supplies have become more unstable and food security has become insecure. These three conflicts make water, energy and food closely interlinked, affecting each other [3]. Therefore, there is a need for a comprehensive and optimal evaluation approach to the sustainable management of the three systems—water, energy and food—which can contribute to the sustainable development of agricultural systems and food security at a global and regional scale and provide some reference value for other similar countries and regions.

Water, energy and food form the material basis for stable regional development [3]. In 2011, the Bonn Conference (The Water–Energy–Food Security Nexus) was held in Germany. At the conference, water, energy and food were initially outlined as the "WEF Nexus" [4]. In 2015, a new WEF nexus modelling tool (WEF Nexus Tool 2.0) was designed with the ability to define the linkages between the interrelated resources of water, energy and food; it can assess scenarios and identify sustainable national resource allocation strategies [5]. In turn, a number of crises have arisen that require a reassessment of the WEF nexus. The long-term impacts of COVID-19 will likely require the prioritization of cross-linkages between subsystems within the WEF nexus, presenting different experiences of short-term adaptation at the sectoral level and reassessing the impact on the WEF nexus [6]. Moreover, the sustainability crisis in the water, energy and food sectors in the context of social and economic influences requires maximising synergies between the water sector and other sectors [7]. In the context of water-related relationships and frameworks, case studies of the water–employment–migration (WEM) nexus framework, a system approach that encompasses complex and multifaceted issues related to water resources and weighs and synergises its various sectors, have recently been presented [8]. Without compromising resource sustainability, efforts that address competition between different resource uses and overall resource shortages are needed [9]. Water scarcity can be a direct threat to energy needs and food security. Agriculture is the largest user of water, with irrigation accounting for 70% of total water use [10], because management decisions about the allocation of water for agricultural irrigation are often onerous tasks.

The optimisation of irrigation water resources based on sustainable development is not only about economic efficiency, but also about energy consumption effects and the potential for recoverable biomass energy [11]. The irrigation water resources optimisation problem can, therefore, be described as a multiobjective problem, i.e., maximising economic benefits for farmers/crop yields versus minimising energy consumption and maximising renewable energy [12]. These objectives are synergistic with each other and can be used to solve water allocation problems in irrigation water systems based on economic, social and environmental sustainability [13]. Many scholars are working on sustainable irrigation water resource management issues using multiobjective programming in their research [14]. The Copula-based stochastic multiobjective programming (C-SMP) model for improving irrigation water use efficiency can help to develop more efficient and sustainable irrigation strategies [15]. However, in agricultural systems, there are limited examples of the use of multiobjective planning in the sustainable management of the WFEN, taking into account irrigation water and renewable energy sources.

Research has mainly focused on the optimal allocation or assessment of agricultural resources in specific regions, but rarely have the agricultural resources of the region been reassessed on the basis of the optimal allocation. In existing studies, each subsystem of the agricultural water–energy–food nexus (WEFN) system is often assessed separately. Dai et al. assessed the impact of water management on the water cycle in small watershed irrigation systems (SWISs) through a scenario analysis using RIS-SWAT [16]. However, the construction associated with these research frameworks considers only the integrated assessment of soil and water resources within agricultural systems, with few studies integrating optimisation and assessment models into a single framework for the management of agricultural resources, which is expected to gradually become an important direction in this research area. Another important issue for the regional sustainability assessment of an optimised agricultural WEFN system is the assignment of weights to each indicator and the objective evaluation of each indicator according to the degree of influence of the subsystems and external influencing sectors of the WEFN system [17]. Generally, there are two main categories of comprehensive multi-indicator evaluation methods: subjective and objective weighting evaluation methods [18]. The former is mostly a qualitative approach, where weights are obtained through the subjective judgement of experts based on experience, such as the analysis hierarchical analysis (AHP) and fuzzy comprehensive judgement; the latter determines weights based on the correlation between indicators or the coefficient of the variation of each indicator, such as the grey correlation method and the technique for the order of preference by similarity (TOPSIS) method. The AHP model subjective weighting method can focus on the assessment objectives and is very effective; however, it lacks an objective basis [19]. Therefore, a more objective method, such as the TOPSIS method, can be used. This method is intended for the optimal and inferior solutions identified by the original matrix, then calculating the distance between the evaluation object and the optimal and inferior solutions using the relative proximity as the final score. The advantage is that the information from the original data can be used objectively to accurately reflect the gap between the evaluation objects. However, the disadvantage is that the weights are somewhat arbitrary [20]. Therefore, the entropy weight method can be considered to objectively assign weights to the indicators of the WEFN system, and the TOPSIS comprehensive evaluation method, which combines the entropy weight method, can adequately solve this problem and provide a more flexible solution for uncertain indicator information [21]. However, studies involving the construction of a comprehensive multiattribute evaluation framework for pre-existing optimisation scenarios based on the theme of optimisation evaluation in the context of the entire agricultural WEFN system are limited. Therefore, to address the above challenges, there is a need to develop a realistic approach to the sustainability optimisation evaluation of agricultural WEFN systems that incorporates the complexity of precision irrigation uncertainty in different contexts into a framework for the overall assessment and optimal management of multiattribute decision making.

In addition, when actually managing agricultural resource systems, decisionmakers are faced with unavoidable uncertainties in the face of changing natural conditions and social policies. For example, fluctuations in available surface irrigation water and available groundwater irrigation water and changes in available land in different use scenarios can cause fluctuations in the size of cultivated area for food and consequent changes in energy consumption and recovery. At the same time, food production in the region can affect agricultural economic efficiency and social change, and recoverable energy can have an impact on the environmental ecology of the region [22]. These uncertainties are common and unavoidable, and can have positive or negative effects. These uncertainties are always represented in optimisation models by parameters with stochastic characteristics. Many authors have chosen various approaches to address these issues. However, given the uncertainties associated with irrigation water availability, few studies have been reported on balancing energy consumption and maximising the recovery of renewable energy by limiting the area available for irrigated surface and groundwater water use and cultivation in a multiobjective planning framework.

This study, therefore, aims to develop a sustainability-oriented optimisation–evaluation framework that combines an optimisation module and an evaluation module for the allocation and evaluation of resources for agricultural production under uncertain conditions. The main function of the framework is to determine a scientific irrigation water use structure under different conditions to balance the development of the objectives of economic efficiency, energy consumption and renewable energy use in regional irrigation areas. Based on the optimisation framework developed, not only can sustainable water use solutions for precision irrigation under different scenarios be obtained, but it is also possible to evaluate the level of sustainability in different areas based on the WEFN system estimated for each area under the best sustainable optimisation scenario. In addition, the optimisation evaluation framework is applied to a practical case study in the Jinxi irrigation district, located in Heilongjiang province, China, to demonstrate its feasibility. The improved optimisation evaluation framework can help managers identify more rational and optimal agricultural resource allocation options under uncertainty and promote the sustainable development of regional irrigation districts.

2. Methods

Agricultural WEFN systems are established in irrigated agricultural regions. By optimally regulating and evaluating important irrigation resources within the agricultural WEFN system, the sustainable development of the region can be promoted [23]. Figure 1 shows the relationship between the individual resources and the optimisation evaluation objectives in the WEFN system.

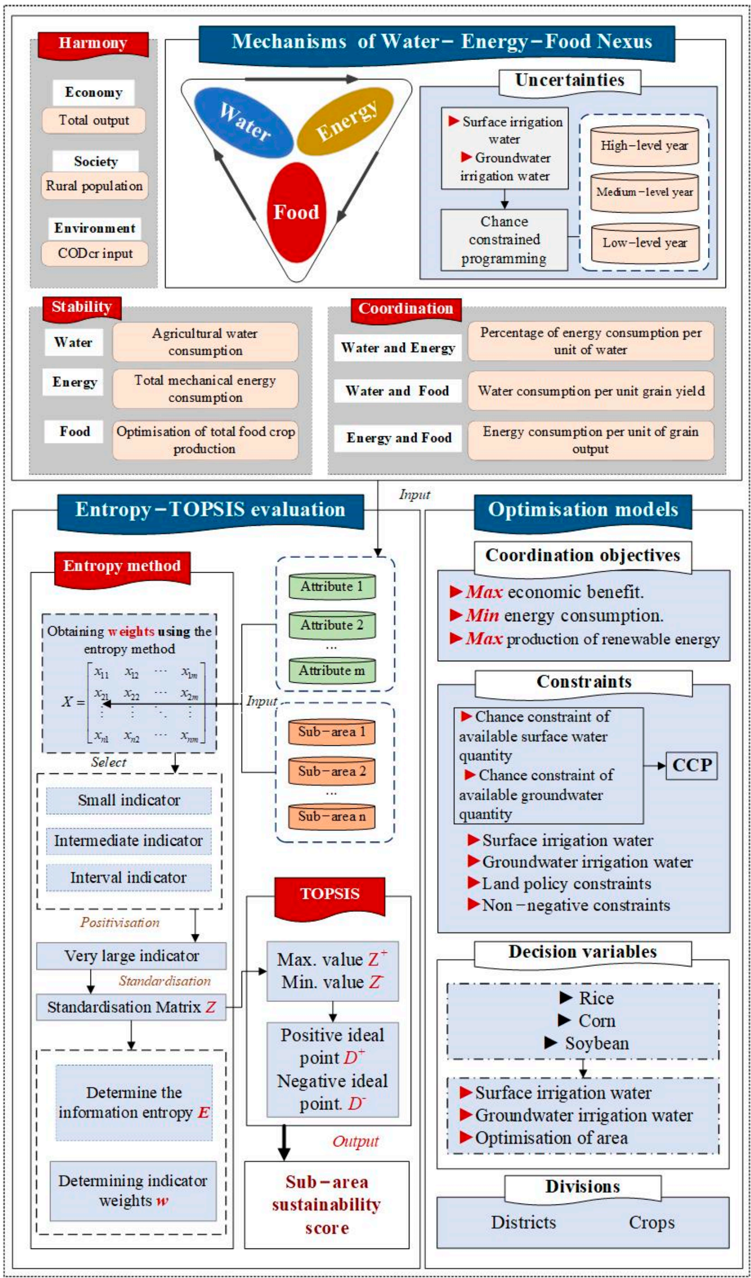


Figure 1. Framework for optimisation and evaluation methods (note: CCP: chance−constrained programming; TOPSIS: technique for order of preference by similarity to ideal solution).

The optimisation and evaluation approach proposed in this section consists of four main modules: the agricultural WEFN system module, the evaluation module, the optimisation module and the uncertainty module. First, the WEFN system includes subsystems and impact sectors, involving water systems, energy systems, food systems and their coupled systems, as well as economic, social and environmental aspects. The optimisation model was constructed considering three factors: the objective function, the constraints and the decision variables. The objective function starts with the renewable energy in the area and involves maximising economic efficiency and energy recovery, as well as maximising renewable energy. The constraints include irrigation water use and acreage. The decision variables include surface water irrigation water, groundwater irrigation water, optimised area, surface water use and groundwater use. The evaluation module is mainly based on the entropy-weighted TOPSIS method, where weights were obtained using the entropy-weighted method and the scores for each subregion were calculated and normalised based on the weights using the TOPSIS method. For the uncertainty module, chance-constrained programming (CCP) was chosen to address the uncertainties in the module.

2.1. Framework Development

2.1.1. Multiobjectives in Optimisation Module

A multiobjective programming model was developed for optimising irrigation water allocation to achieve different specific targets based on sustainable development.

The first objective was the total economic benefits of the irrigation system, which maximise linear programming. The economic objective was to maximise the agricultural revenue of farmers by optimising irrigation water allocation.

$$\max F = Ben\_CA - \mathrm{Cos}\_WA \tag{1}$$

$$Ben\_CA = \sum_{i=1}^{I}\sum_{k=1}^{K}(\beta \cdot Y_{ik} \cdot PC_k + \chi \cdot BF_k \cdot Y_{ik} - FCA_{ik}) \cdot A_{ik} \tag{2}$$

$$\mathrm{Cos}\_WA = \sum_{i=1}^{I}\sum_{k=1}^{K}\left(IQ_{ik}^{sur} \cdot WP_{ik}^{sur} + IQ_{ik}^{gro} \cdot WP_{ik}^{gro}\right) \cdot A_{ik} \tag{3}$$

where F is the economic benefit (CNY); Ben_CA is the net crop benefit (CNY); Cos_WA is the cost of water for the crop (CNY); i is zone, $i = 1 \ldots I$; k is the crop type, $k = 1 \ldots K$; Y_{ik} is zone i crop k of production (kg/hm^2); PC_{ik} is division i crop k selling price (CNY/kg), β is the proportion of the primary produce sold 0.67; χ is the proportion of crop byproducts sold; PBF_{ik} is the price of byproducts for subzone i crop k (CNY/kg); FCA_{ik} is the fixed cost (including planting, harvesting and transport) for subzone i crop k (CNY/hm^2); A_{ik} is the area irrigated for subzone i crop k (hm^2); is the amount of surface water irrigation for subzone i crop k (m^3/hm^2); IQ_{ik}^{gro} is the amount of groundwater irrigation for subzone i crop k (m^3/hm^2); WP_{ik}^{sur} is the price of surface water for subzone i crop k (CNY/m^3); WP_{ik}^{gro} is the price of groundwater irrigation for subzone i crop k (CNY/m^3).

The second objective is the energy consumption objective, i.e., to minimise the amount of energy consumed in the growth process. The study considered mechanical energy consumption, manual energy consumption, planting energy consumption, fuel energy consumption and water energy consumption.

$$\min R = ME + El + Es + Ep + Ew \tag{4}$$

$$ME = \sum_{i=1}^{I}\sum_{k=1}^{K}\frac{E_i}{T_i} \cdot Q_h \cdot A_{ik} \tag{5}$$

where ME is the mechanical energy (MJ), E_{ik} is the productive energy of the machine in the subzone i crop k, 93.61 (MJ/hm^2) for tractors and 116 MJ/kg for combines, T_{ik} is the economic life of the machine (h), and Q_h is the total working time of the machine in a season.

$$El = \sum_{i=1}^{I}\sum_{k=1}^{K} Wl_{ik} \cdot Ei_{ik} \cdot A_{ik} \quad (6)$$

where El is the energy of human labour (MJ), Wl_{ik} is the number of workers per hectare in subzone i crop k (n), and Ei_{ik} is the energy consumption per worker in subzone i crop k (MJ/n). For a human being, the equivalent energy for one hour of work should be 1.96 MJ.

$$Es = \sum_{i=1}^{I}\sum_{k=1}^{K} Wi_k \cdot Ez_k \cdot A_{ik} \quad (7)$$

where Es is the energy of the seed (MJ), Wi_{ik} is the amount of seed used in subzone i crop k (kg/hm^2) and Ez_{ik} is the energy per kg of seed in subzone i crop k (MJ/kg).

$$Ep = \sum_{i=1}^{I}\sum_{k=1}^{K} Qi_i \cdot Er_i \cdot A_{ik} \quad (8)$$

where Ep is the fuel energy (MJ), Qi_{ik} is the amount of fuel consumed in subzone i crop k (L/hm^2) and Er_{ik} is the energy equivalent per fuel unit in subzone i crop k (MJ/L).

$$Ew = \sum_{i=1}^{I}\sum_{k=1}^{K} (WF_{ik}) \cdot A_{ik} \quad (9)$$

where Ew is the energy consumed by water (MJ) and WF_{ik} is the energy consumed by water per unit area of irrigation (MJ/ hm^2) in subzone i crop k.

The third objective was to maximise renewable energy, as biomass, such as straw, contains an enormous amount of energy, and recycling this biomass would reduce energy consumption.

$$\max F_{REP} = \sum_{k=1}^{K}\sum_{i=1}^{I} \sigma_{sgr\_k} \cdot \sigma_{sc\_k} \cdot \sigma_{LHV\_k} \cdot A_{ik} \cdot Y_{ik} \quad (10)$$

where F_{REP} is the energy recovery (MJ); σ_{sgr_k} is the straw to grain ratio of crop k; σ_{sc_k} is the collectible straw coefficient of crop k; and σ_{LHV_k} is the lower calorific value of bioenergy for crop k (MJ/kg).

2.1.2. Constraints in the Optimisation Module

The constraints that the above multiobjective functions were subjected to are shown. Furthermore, random phenomena, such as the surface and groundwater supply amount in this study, commonly exist as uncertainty and random factors in irrigation water allocation systems; these random factors are always represented by the right-handed parameters, with stochastic features in the constraints of the optimising model. To address this uncertain phenomenon, CCP was selected in this study to solve the random phenomena in terms of the constraints of the optimisation module. CCP is an effective method used to address the random phenomena that exist on the right-hand side of the constraint through probability distribution.

The chance constraint of available surface water quantity: the amount of utilised surface water had to be less than the total available quantity of surface water (canal water) for irrigation in the research period.

$$\frac{\sum\limits_{j=1}^{J}\left(IQ_{ik}^{sur} \cdot A_{ik}\right)}{\tau^{sur}} \leq SWA_i \quad (11)$$

$$Pr\left\{\sum_{i=1}^{I} SWA_i \leq Q_R\right\} \leq 1 - p_d \tag{12}$$

where SWA_i is the amount of surface water available in area i (m^3), Q_R is the runoff volume in the area (m^3), and τ^{sur} is the surface water use efficiency.

The chance constraint of available groundwater quantity: Groundwater is always considered an important water supply source for water users, because the available surface water is limited and not abundant enough to meet the water demand. The amount of groundwater utilised for irrigation and natural vegetation had to be less than the total quantity of groundwater in the research period.

$$\frac{\sum_{j=1}^{J}\left(IQ_{ik}^{\mathrm{gro}} \cdot A_{ik}\right)}{\tau^{gro}} \leq GWS_i \tag{13}$$

$$Pr\left\{\sum_{i=1}^{I} GWS_i \leq \sigma \times TGW\right\} \leq 1 - p_d \tag{14}$$

where GWS_i is the groundwater supply for irrigated agriculture in subzone i (m^3), τ^{gro} is the groundwater use efficiency, TGW is the total groundwater volume (m^3), and σ is the percentage of total groundwater volume used for irrigated agriculture.

The amount of surface water irrigation needed to be within a reasonable range; therefore, the surface water constraints were as follows:

$$IQ_{ik}^{sur\_\min} \leq IQ_{ik}^{sur} \leq IQ_{ik}^{sur\_\max} \tag{15}$$

where $IQ_{ik}^{sur\_\min}$ is the minimum value of surface water irrigation per unit area (m^3/hm^2) for subzone i crop k; $IQ_{ik}^{sur\_\max}$ is the maximum value of surface water irrigation per unit area (m^3/hm^2) for subzone i crop k.

The amount of groundwater irrigation needed to be within a reasonable range; therefore, the groundwater constraints were as follows:

$$IQ_{ik}^{gro\_\min} \leq IQ_{ik}^{gro} \leq IQ_{ik}^{gro\_\max} \tag{16}$$

where $IQ_{ik}^{gro\_\min}$ is the minimum value of groundwater irrigation per unit area (m^3/hm^2) for subzone i crop k; $IQ_{ik}^{gro\_\max}$ is the maximum value of groundwater irrigation per unit area (m^3/hm^2) for subzone i crop k.

Land policy constraints: There needed to be a lower and upper limit on the area to be planted in each irrigation area. The constraint was expressed as:

$$A_{ik}^{\min} \leq A_{ik} \leq A_{ik}^{\max} \tag{17}$$

where $A_{ik}^{\min}$ and $A_{ik}^{\max}$ are the minimum and maximum permissible planting areas (hm^2), respectively.

The non-negative constraint: The decision variable was not negative, and the constraint was expressed as:

$$A_{ik} \geq 0 \tag{18}$$

$$IQ_{ik}^{sur} \geq 0 \tag{19}$$

$$IQ_{ik}^{gro} \geq 0 \tag{20}$$

2.1.3. Model Solutions

The study used a fuzzy algorithm to solve this multiobjective model by introducing a satisfaction variable λ, and the above multiobjective model was transformed into the following single-objective model:

$$\max = \lambda \tag{21}$$

$$\begin{cases} F_{\max}(x) - F(x) \geq \lambda[F_{\max}(x) - F_{\min}(x)] \\ R(x) - R_{\min}(x) \geq \lambda[R_{\max}(x) - R_{\min}(x)] \\ F_{REP\_\max}(x) - F_{REP}(x) \geq \lambda[F_{REP\_\max}(x) - F_{REP\_\min}(x)] \\ G(x) \leq h \\ x \geq 0 \\ 0 \leq \lambda \leq 1 \end{cases} \tag{22}$$

where λ is the satisfaction level of the affiliation function; the greater the satisfaction level, the better the optimisation result; $F(x)$, $R(x)$ and $F_{REP}(x)$ are the economic efficiency, energy consumption and energy availability objective functions, respectively; $\{\}_{\max}(x)$ and $\{\}_{\min}(x)$ are, respectively, the maximum and minimum acceptable levels of the corresponding functions to find the maximum and minimum values of each single objective and to bring them into the affiliation function to find the optimal solution for the model.

$G(x) \leq h$ includes the surface water availability constraint, groundwater availability constraint, irrigation water constraint, land policy constraint and non-negative constraint.

2.2. Development of the Evaluation Module

Based on the optimisation module, a range of optimal irrigation water allocation schemes could be obtained. However, the sustainable evaluation of the Jinxi irrigation district using this optimal set of irrigation water use scenarios was also an issue of concern to agricultural decisionmakers. The evaluation module consisted of three main areas: (1) the parameter characterisation module: the selection of key indicators for the agricultural WEFN system in the Jinxi irrigation district and their quantitative representation in relation to the optimisation scheme; (2) Comprehensive evaluation module: the comprehensive evaluation of the agricultural WEFN system based on the entropy-weighting TOPSIS evaluation; and (3) the output module: the evaluation of scores and ranking of the subregions in the target area.

As a result, a sustainable assessment framework for the regional agricultural WEFN system was developed and used to meet the main tasks of the subregional assessment scores within the region.

2.2.1. Index System of the Agricultural WEFN System

A scientific and reasonable indicator system is the basis for studying and evaluating the synergistic security of the WEFN in agricultural regions [24]. The security status and development of the agricultural WEFN system is influenced by all subsystems, so a comprehensive evaluation system for the agricultural WEFN system should be constructed with all aspects in mind. Taking into account the characteristics of each subsystem of the agricultural WEFN system, the stability, harmony and coordination of the WEFN as the criteria for selecting indicators, and the development of resources in the Jinxi irrigation district, the indicators representative and accessible for each subsystem were selected by integrating various factors.

Thus, under the stability criterion (S), the water resources system (WS), energy system (ES) and food system (FS) constituted the subsystem level selection indicators. Under the coordination criterion (C), the water–energy system (WE), the water–food system (WF) and the energy–food system (EF) constituted the subsystems. Under the harmony criterion (H), the economic system (ECOT), the social system (ST) and the environmental system (ENT) formed the subsystems and were selected as the indicators. In summary, for the three criteria, we selected nine indicators based on the three subsystems, covering the symbiotic units, symbiotic relationships and symbiotic environment of the system to build a sustainability evaluation indicator system for the agricultural water–energy–food nexus system in the Jinxi irrigation district of Heilongjiang province (Table 1)

Table 1. Indicator system for the agricultural WEFN system.

Target	Criterion	Subsystem	Index	Significance	Unit	Attribute
Water–energy–food sustainability	Stability (S)	Water Resources (WS)	Agricultural water consumption (WS1)	Agricultural water-carrying capacity	10,000 m^3/a	–
		Energy (ES)	Total mechanical energy consumption (ES1)	Agricultural machinery supply	MJ	–
		Food (FS)	Optimisation of total food crop production (FS1)	Level of food availability	kg	+
	Harmony (H)	Economic (ECOT)	Total output (ECOT1)	Total value of output	Million	+
		Social (ST)	Rural population (ST1)		10,000 people	*
		Environmental (ENT)	CODcr input (ENT1)		t	–
	Coordination (C)	Water–energy (WE)	Percentage of energy consumption per unit of water (WE1)	Energy water production efficiency	MJ/(million m^3/a)	#
		Water–food (WF)	Water consumption per unit grain yield (WF1)	Water efficiency in food production	m^3/a/kg	–
		Energy–food (EF)	Energy consumption per unit of grain output (EF1)	Energy efficiency of grain production	MJ/kg	–

Note: "+" stands for very large indicators; "−" stands for very small indicators; "*" stands for intermediate indicators; "#" stands for interval indicators.

2.2.2. Entropy- TOPSIS Evaluation

The entropy- TOPSIS method constructed in this study first addressed the problem of qualitative evaluation indicators in regional agriculture that could not be quantitatively evaluated with the traditional TOPSIS method, coupling the intuitionistic fuzzy theory to complete the quantitative transformation of the qualitative indicators and the construction of a decision matrix set; then, for the data of each indicator transformed into intuitionistic fuzzy numbers, the intuitionistic fuzzy entropy method was introduced for the objective weighting, and, finally, the final ranking of the sustainability of the agricultural WEFN system in the study area was obtained. The specific steps were as follows:

Obtaining Weights Using the Entropy-Weighted Method:

1. Step 1: Obtain the original matrix X_{ij} for the original value of indicator j for year i; m is the evaluation indicator; n is the study area partition (i (i = 1, 2, 3, ..., n); j (j = 1, 2, ..., m)).

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1m} \\ x_{21} & x_{22} & \cdots & x_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ x_{n1} & x_{n2} & \cdots & x_{nm} \end{bmatrix} \tag{23}$$

2. Step 2: Normalise the original matrix.

The different indicators of the evaluation object have different types and characteristics (Table 2).

Table 2. Types of indicators and their characteristics.

Indicator Name	Indicator Characteristics	Attribute
Very large indicator	The bigger the better	+
Very small indicator	The smaller the better	–
Intermediate indicator	The closer to a value in the interval, the better	*
Interval indicator	Falling within a certain range is best	#

Note: "+" stands for very large indicators; "−" stands for very small indicators; "*" stands for intermediate indicators; "#" stands for interval indicators.

To normalise the original matrix was to uniformly transform all the indicators in the agricultural WEFN system of indicators into very large indicators.

Positivising very small indicators:

$$X_p = X_{\max} - X \tag{24}$$

Positivizing intermediate indicators: $\{x_i\}$ is a set of intermediate indicators, with the best value being x_{best}. Then, the formula for positivity was as follows:

$$M = \max\{|x_i - x_{best}|\}, \widetilde{x}_i = 1 - \frac{|x_i - x_{best}|}{M} \tag{25}$$

Interval-type indicator normalisation: Intermediate indicator normalisation: $\{x_i\}$ is a set of interval-type indicators, with the optimal interval being $[a,b]$. Then, the formula for normalisation was as follows:

$$M = \max\{a - \min\{x_i\}, \max\{x_i\} - b\}, \widetilde{x}_i = \begin{cases} 1 - \frac{a-x}{M}, x < a \\ 1 \\ 1 - \frac{x-b}{M}, x > b \end{cases} \tag{26}$$

3. Step 3: Standardization of the normalisation matrix.

Standardisation could eliminate the influence of different indicators in the agricultural WEFN system. In this paper, the entropy-weighted method was used for the standardisation. There were n objects to be evaluated, and m evaluation indicators (already normalised) constituted the normalisation matrix as follows:

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1m} \\ x_{21} & x_{22} & \cdots & x_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ x_{n1} & x_{n2} & \cdots & x_{nm} \end{bmatrix} \tag{27}$$

Then, the matrix normalised to it was denoted as Z and each element in Z was as follows:

$$z_{ij} = x_{ij} / \sqrt{\sum_{i=1}^{n} x_{ij}^2} \tag{28}$$

4. Step 4: Entropy-weighted method used to determine the weights of evaluation indicators.

The entropy-weighted method is a relatively objective method of determining weights, and is more accurate than the hierarchical analysis method, which is more subjective in determining weights. Based on the known data, the confidence entropy of each indicator was calculated, and then the weight of each indicator was derived from the information entropy [25].

Determining information entropy E_j:

$$E_j = -\frac{1}{\ln n}\left(\sum_{i}^{n} p_{ij} \ln p_{ij}\right) \tag{29}$$

$$P_{ij} = \frac{1 + b_{ij}}{\sum_{i}^{n}(1 + b_{ij})} \tag{30}$$

Determining indicator weights w_j:

$$w_j = \frac{1 - e_{ij}}{m - \sum_{i}^{n} e_{ij}} \tag{31}$$

TOPSIS Calculated and Normalised Scores

Suppose there were n objects to be evaluated and the standardised matrix of m evaluation indicators was $Z = \begin{bmatrix} z_{11} & z_{12} & \cdots & z_{1m} \\ z_{21} & z_{22} & \cdots & z_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ z_{n1} & z_{n2} & \cdots & z_{nm} \end{bmatrix}$:

Then, the maximum value could be defined as:

$$\begin{aligned} Z^+ &= \left(Z_1^+, Z_2^+, \cdots, Z_m^+\right) \\ &= \left(\max\{z_{11}, z_{21}, \cdots, z_{n1}\}, \max\{z_{12}, z_{22}, \cdots, z_{n2}\}, \cdots, \max\{z_{1m}, z_{2m}, \cdots, z_{nm}\}\right) \end{aligned} \tag{32}$$

Then, the minimum value could be defined as:

$$\begin{aligned} Z^- &= \left(Z_1^-, Z_2^-, \cdots, Z_m^-\right) \\ &= \left(\min\{z_{11}, z_{21}, \cdots, z_{n1}\}, \min\{z_{12}, z_{22}, \cdots, z_{n2}\}, \cdots, \min\{z_{1m}, z_{2m}, \cdots, z_{nm}\}\right) \end{aligned} \tag{33}$$

The distance of the $i(i = 1, 2, \cdots, n)$ evaluation object from the maximum value could be defined as:

$$D_i^+ = \sqrt{\sum_{j=1}^{m} \left(Z_j^+ - z_{ij}\right)^2} \tag{34}$$

The distance of the $i(i = 1, 2, \cdots, n)$ evaluation object from the minimum value could be defined as:

$$D_i^- = \sqrt{\sum_{j=1}^{m} \left(Z_j^- - z_{ij}\right)^2} \tag{35}$$

Then, we could calculate the un-normalised score of the i ($i = 1, 2, \ldots, n$) evaluation object:

$$S_i = \frac{D_i^-}{D_i^+ + D_i^-} \tag{36}$$

2.3. Uncertainty

This section used chance-constrained programming (CCP) to quantify the uncertainty associated with the environmental and management systems for agricultural land and water resources.

Chance-constrained programming quantified the relationship between the optimal value of the objective function and the optimal set of solutions to the decision variables and the random coefficients in the model for which random optimal values of the objective function and the optimal set of solutions to the decision variables could be estimated at some confidence level interval. Chance-constrained programming is widely used to allow decisions to be determined that do not satisfy the constraints to some extent, and the decision outcome holds with no less than a certain confidence level a probability of satisfying the constraints so that problems with ambiguous information on random variables can be solved effectively.

Chance-constrained programming can handle random parameters present in the left-end term, right-end term and left and right double-end terms of the constraint. A linear programming problem with random variables in the constraints could be ex-pressed as:

$$\max f = \sum_{r=1}^{R} c_r x_r \tag{37}$$

Constraints:

$$\Pr\left\{\sum_{r=1}^{R} a_{pr}x_r \le b_p(\xi)\right\} \ge 1-q \qquad p = 1,2,\ldots,P \tag{38}$$

$$x_r \ge 0 \quad r = 1,2,\ldots R \tag{39}$$

where f is the objective function; x_q is the decision variable; a_{pr} and $b_p(\xi)$ are the input parameters, where $b_p(\xi)$ is a random parameter. To simplify the model transformation process, it was assumed that $b_p(\xi)$ followed a normal distribution: $b_p(\xi) \sim N\left(\mu_{b,p}, \sigma^2_{b,p}\right)$, $1-q(q \in [0,1])$ is the predetermined confidence level for the corresponding random constraint and q represents the violation probability of the corresponding random constraint. The larger the confidence level was, the smaller the probability of violation.

2.4. Solution Process of the Optimisation–Evaluation Framework

The optimisation–evaluation framework for sustainable irrigation water allocation contained an optimisation module that integrated the CCP and weight minimisation deviation models into multiobjective programming and the evaluation module, which was based on the entropy-weighted method. The detailed solution process of this framework could be summarised as follows.

1. Step 1: Construct multiobjectives of the optimisation module;
2. Step 2: Detail the chance constraints of the optimisation module;
3. Step 3: Transfer the multiobjective programming into multiple single-objective subprogramming, all of which have the same chance constraints as that of the multiobjective programming;
4. Step 4: Calculate the maximum and minimum values of each single-objective subprogram;
5. Step 5: Solve the multiobjective programming problem based on Steps 5 and 6 with Formula (2);
6. Step 6: Repeat Step 6 with different weight matrices under the same default probability level of the water supply (P);
7. Step 7: Repeat Steps 3 to 8 with different default probability levels of the water supply (P);
8. Step 8: Establish the WEFN system indicator system;
9. Step 9: Select the corresponding values as the data source for some of the indicators of the agricultural WEFN system indicator system according to the optimisation results and establish the initial decision matrix;
10. Step 10: Determine the weights of different indicators for each subregion through the entropy-weighted method;
11. Step 11: Calculate the overall score of each subregion through the TOPSIS evaluation method;
12. Step 12: Evaluate and manage the degree of sustainable development of the region.

3. Case Study

The research application consisted of two steps: the selection of the study area and data collection.

3.1. Study Area

The Jinxi irrigation district in Heilongjiang province is located in the western part of Fujin City, Heilongjiang province, China, as shown in Figure 2. The Jinxi irrigation district is part of three townships in Fujin City and has four subdistricts, namely, Song Hua district, Jinshan district, Hua Ma district and Toulin district [26]. The geographical coordinates are 131°30′–132°37′ east longitude and 46°48′–47°14′ north latitude. The irrigation area is bordered by the Songhua River to the north, the Happy Irrigation District to the east, the Friendship Farm to the south and the Erjiuyi Farm to the west, with an area of 1.01×10^5 hm^2 of cultivated land. Much of the irrigation area is a vast plain with low, flat terrain. Agriculture is the major user of water, accounting for more than 95% of total water consumption. Over the last few decades, over 90% of the available water in the area (i.e., surface water and groundwater) was consumed by agricultural irrigation, with surface water sourced from the Songhua River. Fujin City's industry is based on food and food processing, with agricultural machinery manufacturing being the main industrial system, an agricultural population of 71,400 and a total machinery count of 47,600 units, including 21,200 tractors and 26,400 agricultural machines. The Jinxi irrigation district is a key production area for quality crops in China, with rice, soybean and corn as the main crops. To ensure the continued production of food, the security of the water supply needs to be safeguarded, focusing on food production, while taking into account economic development, social stability and environmental protection, and achieving a sustainable allocation of water and energy resources. The random and uncertain nature of water supply and demand makes management more difficult. Therefore, the developed model was applied to the Jinxi irrigation district to solve the problem.

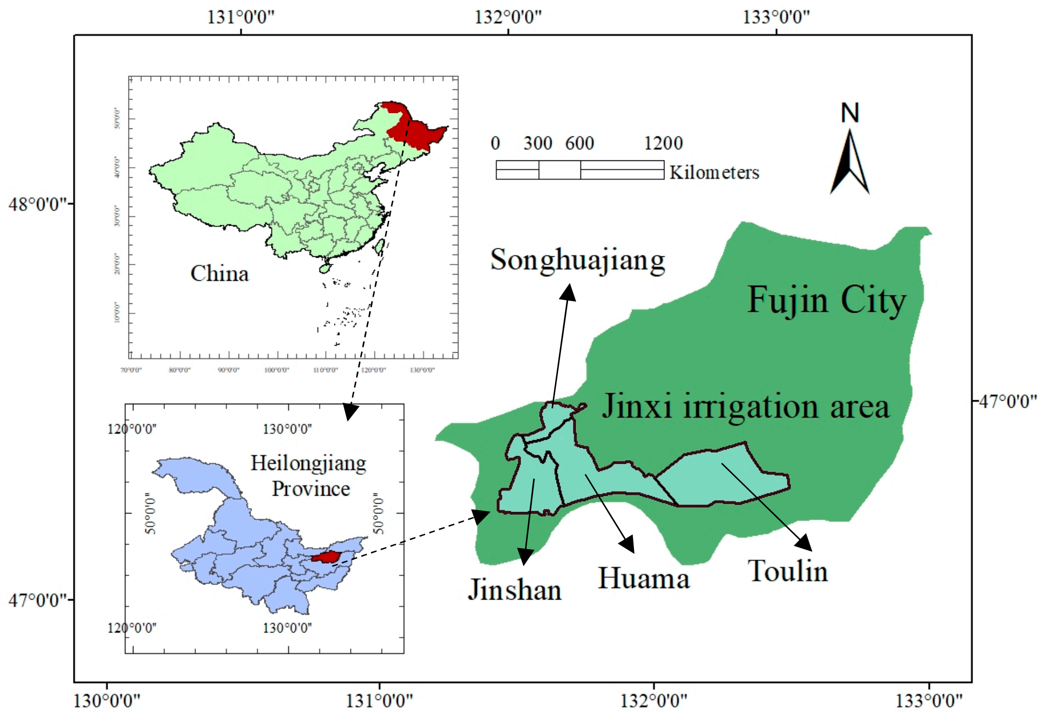


Figure 2. Study area.

In recent years, as the needs of different water users have increased, there has been greater concern about the sustainable management of the limited water resources in the Jinxi irrigation district to balance the local economy, society and the ecological environment [27]. Water for the irrigation of natural vegetation in the Jinxi irrigation district came from groundwater, i.e., the amount of surface water utilised for natural vegetation in the Jinxi irrigation district was equal to zero. As there was no pasture in the Jinxi irrigation district, the water allocation index for natural vegetation was zero. The coefficients of surface water and groundwater utilisation in the Jinxi irrigation district were 0.55 and 0.85, respectively.

3.2. Data Collection

The construction of models for the optimisation and evaluation of agricultural WEFN systems requires the establishment of parameters and coefficients for hydrological and agricultural crop production and the associated external environment. The data were mainly taken from the Fujin City Statistical Bulletin, Fujin County Statistical Yearbook, government reports and published references. Agricultural hydrological data included agricultural water use and hydrological data, including the crop water demand and water supply. Economic, social and environmental data mainly included the gross production value, crop unit prices, rural population, CODcr inputs, quantity, quality and operating parameters related to agricultural machinery, energy use information and irrigation water efficiency data. These could be used to determine the share of energy consumption per unit of water, the share of water consumption per unit of food production and the share of energy consumption per unit of food production within the coupled system, as well as the efficiency of surface water use, the efficiency of groundwater use and the quantity of seed consumed per unit area. The required bioenergy data included the straw pellet ratio, straw collection factor, bioenergy calorific value, seed energy, machinery energy consumption, farm machinery energy consumption and personnel energy consumption. The prices of the agricultural parameters were taken from the Heilongjiang Agricultural Products Price Information Network and the Fujin City Statistical Yearbook. Drainage parameters were taken from the Jinxi Irrigation District Project Feasibility Study Report. See Appendix A for the results of the relevant data.

4. Results Analysis and Discussion

4.1. Optimised Solution of Crop Planting Structure and Agricultural System Benefits

As shown in Figure 3, the agricultural water allocation for surface water was higher than the agricultural allocation for groundwater, with an irrigation ratio of approximately 3:1. The allocation of surface water and groundwater was cofrequent, meaning that areas with high surface water allocations also had high groundwater allocations. Of the various subregions, the largest water allocation was in Jinshan district, where surface water irrigation was 3301.75 m^3/hm^2 and groundwater irrigation was 1100.58 m^3/hm^2. The smallest water allocation was in Toulin district, where surface water irrigation was 3059.74 m^3/hm^2 and groundwater irrigation was 1019.92 m^3/hm^2. Yields per unit area were also greatest in areas with high water allocations, which meant that within the appropriate irrigation range, yields increased proportionally as the amount of water increased, and there was a positive correlation between the yield and irrigation water. Appropriate increases in irrigation water have positive implications for promoting crop yields and increasing economic benefits for managers [28].

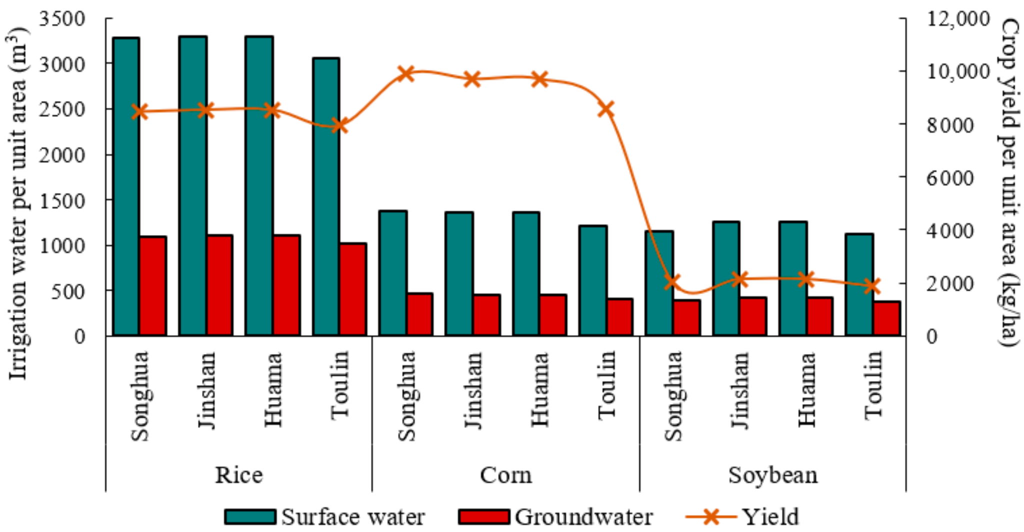


Figure 3. Irrigation water and yield per unit area in each irrigation district.

In addition to optimising the irrigation water for the crop, this study also optimised the planted area in the study area, as shown in Table 3. The optimisation results showed that, overall, the area of the four subdistricts for rice increased, while the area planted for corn decreased by 40% and 41% in Jinshan and Huama districts, respectively; the area planted for soybeans generally decreased. Overall, the area planted with corn decreased by 40%, the area planted with soybeans decreased by 33.8% and the area planted with rice increased by 34.16%. The reduced area of corn and soybean implied that their combined economic and ecological effects were not high and their net economic benefits were low. The model optimised the area planted with the three crops by weighing the economic benefits against the ecological effects.

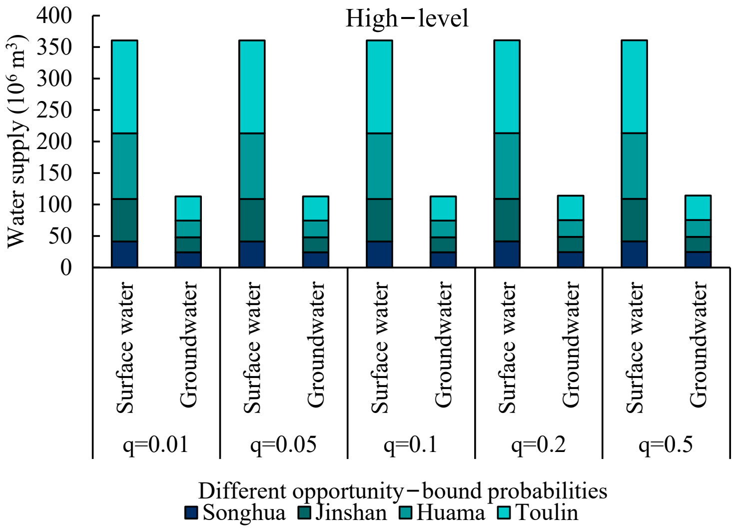
Table 3. Optimal acreage for different crops in different regions.

	Actual Area (hm^2)			Optimised Area (hm^2)		
	Rice	**Corn**	**Soybean**	**Rice**	**Corn**	**Soybean**
Songhua	11,070	3185	911	12,177	1899	865
Jinshan	12,870	17,748	9466	22,780	17,440	4436
Huama	4590	340	42	5300	340	24
Toulin	16,650	6466	1767	18,315	3780	1706

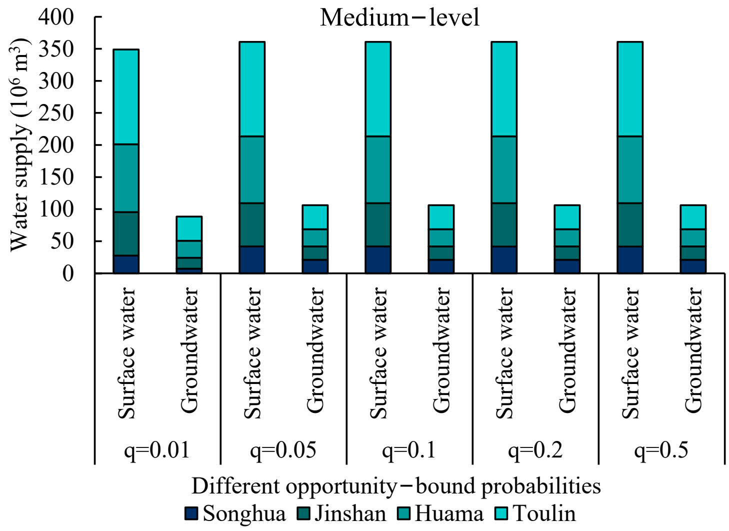
The study considered the renewable resources and energy consumption of the crop. The renewable resources were calculated for renewable resources, such as straw, after the crop was harvested for yield [29], and energy consumption refers to the consumption of energy in the process of growing the crop. The model calculated a total of 8.97×10^9 kg of recycled resources, which would be sold for an RMB (renminbi) benefit of 1.97×10^9. The price of a kilogram of straw was RMB 0.08, and after deducting the cost of recovering the straw, the manager would receive a net economic benefit of RMB 1.25×10^9. The actual energy consumption of the irrigation district was 9.13×10^8 kg. Through the optimisation of the model, the energy consumption was reduced by 17.62%, lowering the energy consumption of the irrigation district and promoting the sustainability of the district.

4.2. Uncertainty of Irrigation Water

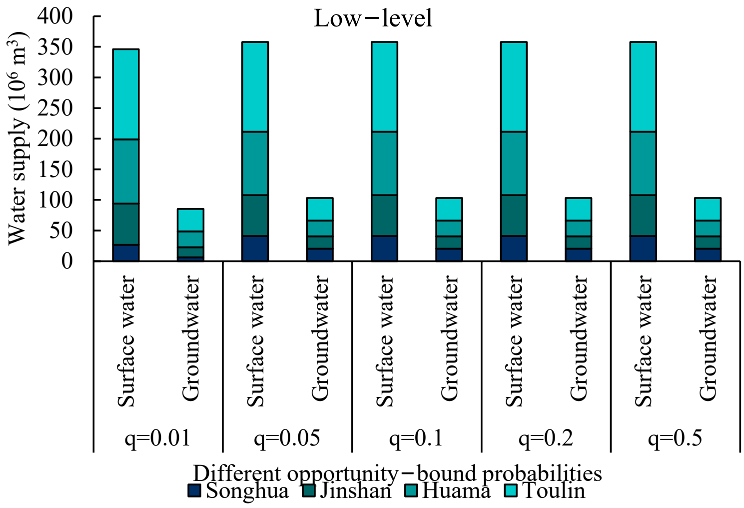
The chance-constrained programming model was used to quantify the amount of surface and groundwater available at three levels, high, medium and low, under different probability conditions, and was brought into the optimisation model to determine the water supply available to the study area under different probability conditions (Figure 4). It was found that in the high-level year, there was no change in water availability in the irrigation area for different violation probabilities because the water availability in the study area in the high-level year was adequate, the crops were irrigated to the maximum and small probability changes did not have a significant impact overall. In the medium-level year, surface and groundwater availability was significantly lower at probability $p = 0.01$ compared to the other probabilities, and there was also a slight reduction in fit at probability $p = 0.05$. In the low-level year, the decrease in water availability was also significant at a probability of $p = 0.01$. At an overall level, the reduction in water availability was more pronounced in the low-level year, followed by the medium-level year. This was because the low-level year was in a state of water scarcity, and there was an insufficient recharge of surface and groundwater, so the amount of water available was also lower, which then required a reduction in the amount of irrigation water available to the crop, thus, saving water.



(**a**)



(**b**)



(**c**)

Figure 4. Surface water and groundwater availability at different chance-constrained probability levels: (**a**) at high level; (**b**) at medium level; (**c**) at low level.

4.3. The Importance of Different Attributes in Different Regions of the Agricultural WEFN

Figure 5 shows the subsystems and coupled systems of the agricultural WEFN system in different regions of the Jinxi irrigation district and the full weight values, including water, energy, food, economic, social, environmental and water–energy coupled systems, water–food coupled systems and energy–food coupled systems. The individual attributes fluctuated considerably and had large standard deviations. The economic indicators for this irrigation area had the largest weighting of 0.25, with the food system following at 0.16. The city of Fujin, where the irrigation area is located, is an important grain production base and commodity grain base, and the city's industry is based on grain and food processing and agricultural machinery manufacturing. This indicates that the irrigation area has conditions for grain production and processing and has developed industrial advantages in agricultural production for grain and food products, with high agricultural economic benefits. However, the coupled systems in the area had a low weighting, of which the lowest was the water–energy coupled system, with a weighting of 0.04, indicating that the degree of integration of agricultural water use and energy consuming machinery within the irrigation area was not high and that some of the irrigation water-saving facilities in the irrigation area had not yet been resolved, which was not compatible with the practical application of the irrigation area and affected the sustainable development of agriculture in the irrigation area.

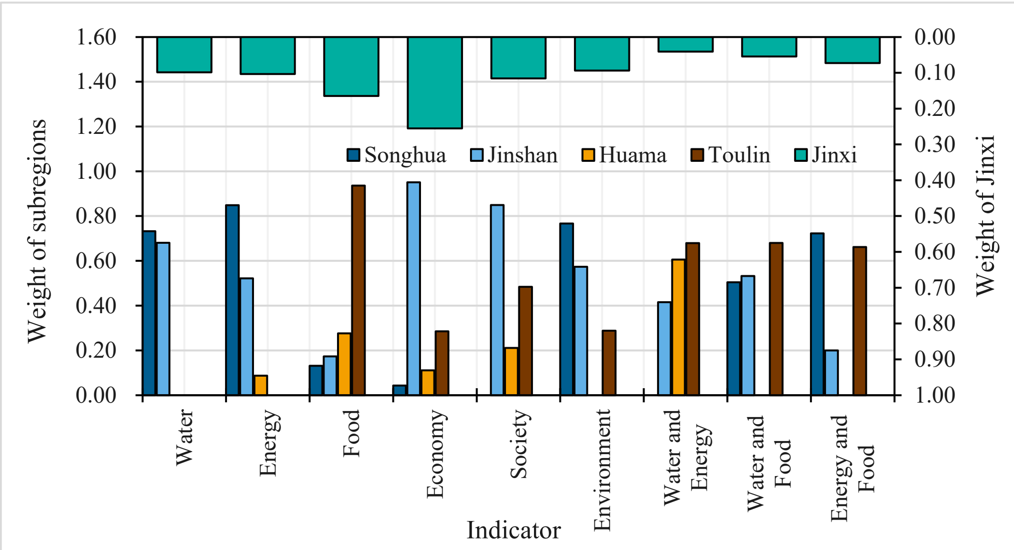


Figure 5. Weighting values for different attributes for different regions of the agricultural WEFN system.

The results showed that the industrial structure of the agricultural WEFN system in the study area needed to be further optimised. In terms of the water system indicators, the Song Hua and Jin Shan regions were more dominant, with weights as high as 0.73 and 0.68, respectively, implying that the greatest demand for water allocation in these regions would be directed towards agriculture. However, in the food system, the Song Hua and Jin Shan regions had a relatively low weighting, suggesting that the amount of irrigation water should be kept within appropriate limits so that the benefits of irrigation water can be maximised to ensure food security. In the energy system, the Song Hua and Jinshan regions, with weights of 0.85 and 0.52, respectively, could further harmonise the energy structure of the various regions within the Jinxi irrigation district, promote the use of renewable energy and achieve energy savings and emissions reduction. At the same time, the economic and ecological benefits should be weighed, with the Jinshan region having a greater advantage, with an economic weighting of 0.95 and an environmental weighting of 0.53. Conversely, the Song Hua region had a greater ecosystem weighting and could be considered for building a conservation-oriented society. In the coupled system, the coupled coordination of the Hua-Ma region needs to be further improved. The region had a better water–energy coordination with a weight of 0.61. The region had a higher degree of mechanisation in terms of irrigation water and a poorer degree of water–food and energy–food coupling, and could focus on developing agricultural mechanisation to ensure food security. Therefore, when formulating agricultural management policies, the corresponding policies for different regions could be formulated according to their specific conditions to achieve a sustainable agricultural development.

4.4. Sustainable Development of WEFN Systems in Different Regions

Figure 6 shows a comparison of the combined attributes of the regional agricultural WEFN system in the four subregions of Songhua, Jin Shan, Huama and Toulin in terms of the distance to the ideal solution for the positive and negative scenarios, respectively, i.e., a comparison of the combined sustainable development scenarios. For Huama district, the contrast between the positive and negative cases was very clear, with a wide range of fluctuations in the degree of sustainability in Huama district, indicating that agricultural production activities in the area were vulnerable to various other factors and that there was greater instability in agricultural sustainability. The largest distance for the minimum value in Jinshan district indicated that it was further away from the worst-case scenario, with a better sustainable agricultural development situation and a greater advantage to ensure economic development, while also taking into account social development and environmental protection, and, at the same time, ensure food production, secure water and energy use and sustainable management.

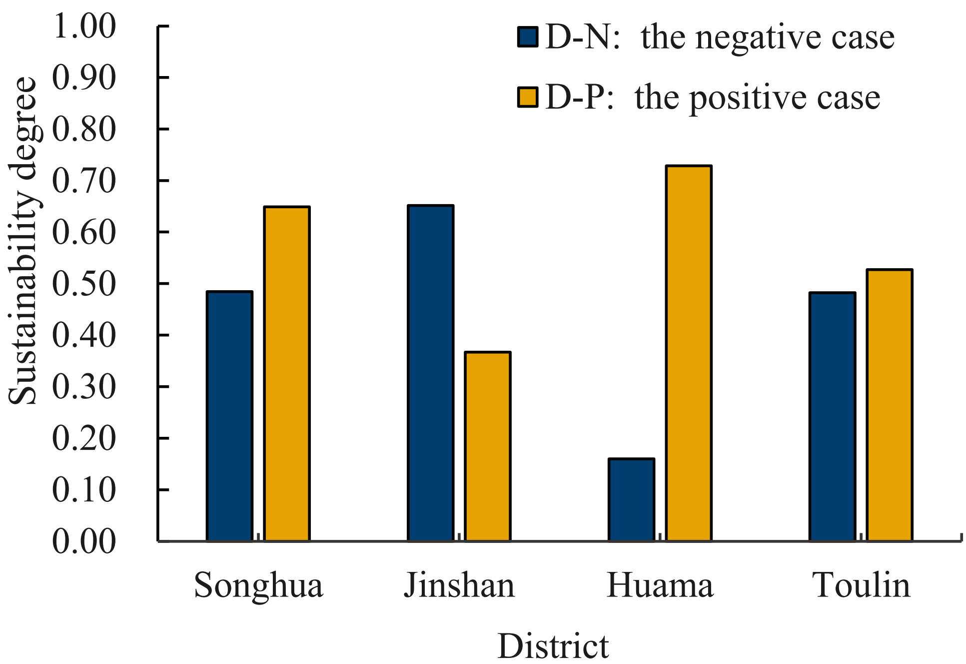


Figure 6. The status of sustainability of WEFN systems in different regions.

Figure 7 shows the normalised scores of the agricultural WEFN system for the four districts in the study area. Therefore, to obtain the greatest benefits from the agricultural system, priority should be given to the management and development of Jinshan district, while further planning should be performed for Huama district to improve the level of sustainable agricultural development in the area, harmonise economic benefits with environmental protection and effectively allocate the region's agricultural resources to achieve sustainable agricultural development [30].

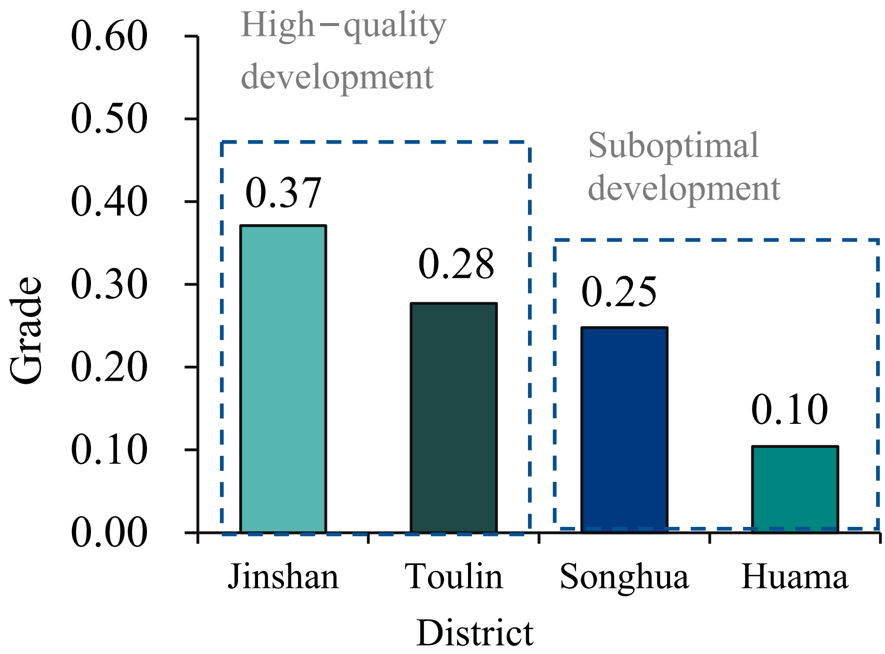


Figure 7. Normalised score scale for different regions.

The case study demonstrated that an optimal evaluation framework for the development of the Jinxi irrigation district achieved sustainable development goals in the agricultural WEFN system by optimising resources and evaluating water resources, energy and food in the study area. The proposed framework could balance social, economic and environmental conflicts and quantify and optimise the linkages, synergies and trade-offs between water, energy and food resources and the social, economic, environmental and ecological spheres of development in the region [31]. These outcome recommendations could help agricultural policymakers evaluate the potential for managing sustainable agricultural development in different areas and subsystems within their management regions [32]. Nevertheless, there were some limitations to the study; for example, the energy consumption determined for the study area only took into account the energy consumption of the farming machinery, but not the energy consumption of people and transport, and renewable energy was not recycled, which could be taken into account in future studies for more in-depth research.

4.5. Discussion

In this study, the optimization–evaluation framework developed aimed at balancing the conflicting economic, social and ecological spheres by optimizing irrigation water use and crop cultivation structures to achieve the sustainable development goals of the WEFN in agriculture. The analysis of the evaluation results and influencing factors showed that the coupling of different subsystems of the WEFN in different study regions should be developed with their corresponding policies, rather than just considering the influencing factors and implicated objectives of a single subsystem. The above conclusions were also evidenced in the published literature, which used fuzzy evaluation methods to evaluate the spatial and temporal variation in the level of synergistic security of the WEFN in China and concluded that different measures should be taken in different areas to improve the level of the synergistic security of water, energy and food [33]; however, there was little optimisation of the allocation of irrigation water in the WEFN. Another study comprehensively quantified the connections and synergies between multiple subsystems, such as water, energy, food, climate change and land; its proposed multi-objective optimisation model could help manage resources in the region in a sustainable manner [34]. This study proposed an optimisation–evaluation method for the WEFN in irrigated agricultural systems. The optimisation module combined CCP and multiobjective planning models for optimising irrigation water allocation and could reduce the uncertainty that prevails in irrigation water allocation in irrigation districts. In previous studies, CCP and multiobjective planning models were used for the determination of optimal land and water allocation schemes, but rarely considered the synergistic development role of energy in farming systems. The optimisation of the model in this study allowed for a reduction in the amount of energy consumed during cultivation, thus, maximising the recovery of renewable energy and the economic benefits associated with sustainable development.

5. Conclusions

This study developed an optimisation–evaluation framework for the sustainability of water allocation, energy consumption and food production in irrigated agricultural WEFN systems based on a high degree of uncertainty. The study aimed to optimise the allocation of available water resources and promote the coordinated development of economic, social and environmental systems in irrigated areas. The framework had advantages in terms of (1) addressing the complexity of the evolution of the balance between conflicting objectives (i.e., economic, social and environmental objectives) under uncertainty in regional sustainable irrigation water allocation systems for agriculture; (2) considering the impact of subjective factors (e.g., local policy preferences or the views of managers) and objective factors (e.g., uncertainties related to water supply, land use and food production) on the optimisation of irrigation water allocation; and (3) optimising water use construction under conditions of uncertainty and to properly assess its sustainability and manage the potential for sustainable agricultural development in different regions in a coordinated manner. In addition, the developed optimization–evaluation framework was applied to a study of water, energy and food sustainability management within an actual regional agricultural WEFN system in the Jinxi irrigation district of Heilongjiang province in Northeast China. The results showed that the developed framework could be used for the allocation of agricultural land and water within the irrigation area, and that the amount of irrigation water could be increased appropriately. In contrast, in low-level years, the amount of irrigation water for crops should be reduced, helping to improve the efficiency of water use, promoting the increase in crop yields and improving the economic efficiency of the irrigation area. Optimising the structure of food crop cultivation could increase economic and ecological benefits and was conducive to the sustainable development-oriented management of irrigated agricultural resources. The evaluation module could assess the level of sustainability in different areas of the optimised Jinxi irrigation district, which was conducive to further harmonising the industrial structure of the WEFN in the irrigation district and promoting the sustainability of the agricultural system. The optimisation assessment framework could also be used to analyse resource allocation issues for other water users (e.g., industrial or municipal water users) or other resource management issues, achieving a balanced development between the multiple objectives of sustainability. In future research, the preferences of different decision makers should be further investigated using nonlinear planning methods in the evaluation methodology to quantify climate and water–energy–food interrelationships within the irrigation area in the interval dimension. At the same time, more stochastic planning methods, such as interval planning or fuzzy planning, should be incorporated into this optimisation assessment framework to address more complex water management problems.

Author Contributions: Conceptualization, Y.Z.; methodology, Y.Z.; software, Y.C.; validation, Y.C.; formal analysis, X.Z.; data curation, X.Z.; writing—original draft preparation, X.Z.; writing—review and editing, Y.C.; supervision, H.L.; investigation, H.L.; project administration, Y.Z.; funding acquisition, H.L. All authors have read and agreed to the published version of the manuscript.

Funding: This study was supported by the Natural Science Foundation of Heilongjiang province (grant no. LH2020E003) and the Humanity and Social Science general project of the Ministry of Education of China (18YJAZH147).

Data Availability Statement: The data used to support the findings of this study area are available from the corresponding author upon request via email.

Conflicts of Interest: The authors declare that they have no known competing financial interest or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A

Optimisation of model data tables.

Table A1. Optimised base data for rice, corn and soybeans.

	Crop Unit Price (CNY/kg)	Crop Straw-to-Grain Ratio	Coefficient of Crop Straw Collectable	Calorific Value of Bioenergy	Prices of Agricultural and Sideline Products	Seed Energy	Number of Seeds Consumed per Unit Area	Surface Water Use Efficiency	Groundwater Use Efficiency
	CNY/kg			MJ/kg	CNY/kg	MJ/kg	kg		
	PCk	JGk	SJk	RZk	BFk	Wk	Ezk	T(ηsur)	t(ηgro)
Rice	3.14	0.92	0.87	13.71	1.76	20.1	30	0.65	0.85
Corn	1.97	1.16	0.97	19.06	1.10	14.9	37.5		
Soybeans	4.59	1.13	0.77	16.84	2.57	14.9	30		

Table A2. Model data for different crops in different regions.

	Crop Yield per Unit kg/ha			Maximum Area			Lower Area Limit			Planting Costs		
	YAik			Amaxik			Aminik			FCAik		
	Rice	Corn	Soybeans	Rice	Corn	Soybeans	Rice	Corn	Soybeans	Rice	Corn	Soybeans
Jinshan	8538.96	9703.96	2160.08	18500	3184.5	910.52	11070	1727.1	786.6	3774.97089	3513.81635	3475.2008
Toulin	7942.83	8578.96	1887.83	22780	17748	9466	12870	7560.9	4032.9	3774.97089	3513.81635	3475.2008
Songhua	8467.00	9880.29	2037.71	5300	340	42	4590	173.7	21.6	3774.97089	3513.81635	3475.2008
Huama	8538.96	9703.96	2160.08	33420	6465.5	1767.48	16650	3436.2	1550.7	3774.97089	3513.81635	3475.2008
	Surface Water Prices (CNY/m^3)			**Groundwater Prices (CNY/m^3)**			**Surface Water Cap**					
	WPsurik			WPgroik			IQsurmaxik					
	Rice	Corn	Soybeans	Rice	Corn	Soybeans	Rice	Corn	Soybeans			
Jinshan	0.16	0.16	0.16	0.29	0.29	0.29	4402.332	1808.6842	1669.1379			
Toulin	0.16	0.16	0.16	0.29	0.29	0.29	4079.6552	1619.2105	1487.8448			
Songhua	0.16	0.16	0.16	0.29	0.29	0.29	4378.7931	1835.4	1543.0603			
Huama	0.16	0.16	0.16	0.29	0.29	0.29	4402.3276	1808.6842	1669.1379			
	Lower Surface Water Limit			**Groundwater Cap**			**Lower Groundwater Limit**					
	IQsurminik			IQgromaxik			IQgrominik					
	Rice	Corn	Soybeans	Rice	Corn	Soybeans	Rice	Corn	Soybeans			
Jinshan	3301.749	1356.5132	1251.8534	1467.444	602.892	556.38	1100.583	452.169	417.285			
Toulin	3059.7414	1214.4079	1115.8836	1359.888	539.736	495.948	1019.916	404.802	371.961			
Songhua	3284.0948	1376.55	1157.2953	1459.596	611.796	514.356	1094.697	458.847	385.767			
Huama	3301.7457	1356.5132	1251.8534	1467.444	602.892	556.38	1100.583	452.169	417.285			

Table A3. Decision-making variables.

	Surface Water Irrigation Water			Groundwater Irrigation Water			Optimisation of Area			Surface Water Availability	Groundwater Availability
	m^3/ha			m^3/ha			ha			m^3	m^3
	IQsurik			IQgroik			Aik			SWAi	GWIAi
	Rice	Corn	Soybeans	Rice	Corn	Soybeans	Rice	Corn	Soybeans		
Jinshan	3301.749	1356.513	1251.853	1100.583	452.169	417.285	11,070	3184.5	786.6	64,392,132.8	16,413,674.6
Toulin	3059.741	1214.408	1115.884	1019.916	404.802	371.961	12,870	13,728.223	4032.9	93,155,047.7	23,745,426.6
Songhua	3284.095	1376.55	1157.295	1094.697	458.847	385.767	4590	340	21.6	23,949,261.3	6,104,705.62
Huama	3301.746	1356.513	1251.853	1100.583	452.169	417.285	16,650	6465.5	1550.7	101,055,155	25,759,164.1

Evaluation results.

Table A4. Original matrix for the evaluation of WEFN system in different regions.

	Water	Energy	Food	Economy	Society	Environment	Water and Energy	Water and Food	Energy and Food
	Agricultural water consumption	Total mechanical energy consumption	Total food crop optimization	Total industrial output	Rural population	CODcr inputs	Percentage of energy consumption per unit of water	Water consumption per unit of food production as a percentage	Water consumption per unit of food production as a percentage
	10,000 m^3/a	MJ	kg	10,000 CNY	10,000 people	t	MJ/(10,000 m^3/a)	m^3/a/kg	MJ/kg
Jinshan	2618	136,546,600	115,455,747.6	0.64	0.7	765	52,156.84	0.226754	1.182675
Toulin	3243	546,753,000	152,431,527.1	14.25	3.93	1838	168,594.8	0.212751	3.586876
Songhua	11,532	1,093,511,000	242,801,718.9	1.66	1.04	5014	94,824.06	0.474955	4.50372
Huama	11,532	1,202,765,000	822,104,486.8	4.27	1.48	3417	104,298	0.140274	1.463032

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