Assessing Sustainable Development in Agricultural Irrigation Areas of Sanjiang Plain, Heilongjiang Province: A TOPSIS Model Approach

Ye Linrui
Southwest Jiaotong University, Chengdu, Sichuan, China

Abstract: Agriculture is crucial for food security, resource sustainability, and socioeconomic stability, yet research on large-scale urban irrigation areas remains limited compared to macro-level studies. Guided by carbon neutrality, this study develops a Multi-tiered Sustainability Assessment framework with 4 primary and 13 secondary indicators, targeting 37 irrigation areas in the Sanjiang Plain, Heilongjiang. A hybrid AHP-Entropy Weight method enhances indicator prioritization, combining subjective and objective approaches. ANN and ARIMA models predict rainfall and runoff, addressing extreme weather anomalies. The TOPSIS model evaluates 2023 sustainability levels, revealing: (1) Significant spatial heterogeneity, with Jianshanzi (0.5246) and Jiangchuan (0.2947) as the highest and lowest performers; (2) Ecological Sustainability and Surface Irrigation Area as dominant indicators, followed by Per Capita Irrigated Area and Groundwater Supply. This study offers theoretical and practical guidance for optimizing resource allocation and supporting sustainable agricultural policy development.

Keywords: Sanjiang Plain; Agricultural Irrigation Areas; ARIMA; Combined Weighting; TOPSIS Model

1. Introduction

Since Lester (1982)[1] introduced sustainable agricultural development, it has become central to agricultural research and practice, reinforced by the United Nations' 1987 sustainable development strategy [3]. China, a major agricultural nation, faces severe sustainability challenges, including water-soil resource depletion, non-point source pollution, and ecosystem degradation. With 71.7 million hectares of irrigated land by 2024, contributing 77% of grain and over 90% of economic crop output [4], irrigation districts are vital for food security but exhibit low sustainability and weakened ecological functions [5]. Constructing ecological irrigation districts is thus a strategic priority.

Foreign research on agricultural sustainability has expanded multidimensionally, often at the macro level. Viana (2022) [6] analyzed 1,151 papers (1992–2022), showing a focus on food security in Asia and Africa, aligned with UN Sustainable Development Goals. Ashraf (2021) [7] proposed nanomaterials for sustainable agriculture, enhancing crop bioavailability. Adefila and Ajayi (2024) [8] integrated traditional culture with modern technology for sustainable practices. Evaluation methods like TOPSIS (Davarpanah, 2016) [9], Life Cycle Assessment (Wowra, 2020) [10], System Dynamics (Janez, 2021) [11], and Analytic Hierarchy Process (Chaudhary, 2022) [12] are widely applied.

Domestic research, building on global scholarship, has developed frameworks like Ecological Priority (Gao, 2023) [13], Agricultural Supply-Side Reform (Zhang, 2024) [14], and Rural Revitalization (Meng, 2024) [15]. Tang (2022) [16] evaluated sustainable development in the Yangtze River Economic Belt using a three-dimensional model. Chang (2024)[17] assessed water-soil resource sustainability in the Laoguan River Basin via ecological footprint and Pearson correlation. Zeng (2024) [18] reviewed climate change impacts on agricultural sustainability. Evaluation methods include TOPSIS with AHP-CRITIC (Cao, 2023) [19], Entropy-weighted TOPSIS (Li, 2023) [20], and DPSIR-based TOPSIS (Huang, 2024) [21]. Fuzzy Comprehensive Evaluation (Chen, 2021)[22] and Coupling Coordination Models (Tian, 2024)[23] are also prevalent. However, micro-level analyses of irrigation districts are limited. Rozita (2019)[24] and Karakus (2020)[25] overlooked integrated agroecosystem factors, while Zhang (2022)[26], Zhao (2024)[27], and Yan (2025)[28] omitted key socioeconomic or ecological indicators.

Focusing on the Sanjiang Plain, a key grain production base, this study evaluates 37 large-scale irrigation districts using a four-dimensional (economy-society-ecology-sustainability) index system with 13 second-level indicators. The AHP-Entropy Weight method integrates subjective and objective weighting, and the TOPSIS model quantifies sustainability. This approach bridges theoretical gaps and provides a framework for optimizing agricultural systems. Practically, it supports resource regulation and ecological security strategies, enhancing national grain production and sustainable black soil use.

2. Research Methodology

2.1 Development of Sustainable Development Evaluation Index System for Agricultural Irrigation Areas

2.1.1 Principles for Index System Construction

This study develops an evaluation index system for sustainable agricultural irrigation areas based on four principles. (1) Systematicity: A four-dimensional framework (economic-society-ecology-sustainability) reflects regional traits like surface water, intelligent water-saving, and agro-tourism coordination. (2) Scientific Rigor: The system integrates theory and empirical methods, using a triple outlier screening (statistical tests, spatial autocorrelation, expert review) and third-party verified processes to ensure data objectivity and repeatability. (3) Operability: Technical implementation ensures data integrity through predictive interpolation for missing or abnormal data. (4) Dynamic Adaptability: The framework enhances flexibility via recalibration mechanisms, capturing dynamic ecological interdependencies (energy flux, resource reciprocity, information transduction) and spatiotemporal variations through multiscale observations.

2.1.2 Construction of the Evaluation Index System

International evaluation systems for agricultural sustainability include the FAO's sustainable development index, the OECD's environmental index, and the World Bank's assessment framework. Recognizing large irrigation areas as complex systems constrained by water-soil resources and driven by human activities [29], this study integrates Sanjiang Plain's characteristics and resource endowments, adhering to principles of representativeness, scientificity, systematicness, and operability, and drawing on prior research [5, 9, 26, 29-35]. Thirteen indicators across society-economy-ecology-sustainability dimensions are selected: (1) Social: Indicators like total population, planned population, and per capita irrigation area quantify resource allocation efficiency. (2) Economic: Irrigation quota, water price, and unit yield analyze resource consumption, market regulation, and output benefits. (3) Ecological: Surface/underground irrigation area, rainfall, and runoff volume depict water-soil interactions and groundwater risks. (4) Sustainable Development: Crop evapotranspiration (ET0) and water supply volume inform climate-responsive water demand and resource scheduling, forming a Multi-element Collaborative Evaluation framework (Table 1).

Table 1. Sustainable Development Evaluation Index System for Agricultural Irrigation Areas

Objective Level	Criterion Level	Indicator Level	Criterion Attribute	Indicator Interpretation	Unit
Evaluation System of Agricultural Sustainable Development in Sanjiang Plain	Social (A)	Total Population (A1)	-	Resident population within the irrigation district	million
		Planned Population Capacity (A2)	+	Indicator of future development intensity	million
		Per Capita Irrigated Area (A3)	+	Total irrigated area / Total population	hm^2/person
	Economic (B)	Irrigation Quota (B1)	-	Water consumption efficiency index	m^3/hm^2
		Water Pricing (B2)	-	Implemented water tariff policy	CNY/m^3

		Crop Yield Per Unit Area (B3)	+	Total crop production / Irrigated area	kg/hm2
	Ecological (C)	Surface-Irrigated Area (C1)	+	Cropland irrigated directly by surface water	million hm²
		Groundwater-Irrigated Area (C2)	-	Cropland dependent on groundwater extraction	million hm²
		Annual Rainfall (C3)	Moderate	Natural water replenishment capacity	mm
		Annual Surface Runoff (C4)	Moderate	Total regulatable surface water resources	million m³
	Sustainability (D)	ET0 (D1)	-	Reference Evapotranspiration	mm
		Surface Water Supply (D2)	+	Actual surface water delivered through irrigation infrastructure	million m³
		Underground Water Supply (D3)	-	Volume of groundwater pumped for agricultural use	million m³

It is hereby explained that the calculation of the ET_0 index in Table 1: Based on the influence mechanism of crop type differences on evapotranspiration, this study adopts a two-step method of zoning and integration to calculate ET_0. The ET_0 of paddy fields and dry fields at each station is sorted and statistically analyzed. The calculation formula is shown in formula 1. The reference crop evapotranspiration ET_0^p of paddy field and the reference crop evapotranspiration ET_0^d of dry field are obtained by multiplying the crop coefficient K_c of paddy field and dry field respectively. Finally, the comprehensive reference crop evapotranspiration ET_0^c of each irrigated area is obtained according to formula 2.

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)} \quad (1)$$

$$ET_0^c = ET_0^p + ET_0^d \quad (2)$$

Where: R_n is the net radiation at the surface; G is the soil heat flux; T is the daily average air temperature; u_2 is the wind speed at 2m height; e_s is the saturated vapor pressure; e_a is the actual vapor pressure; Δ is the slope of the saturated vapor pressure-temperature curve; γ is the psychrometer constant.

2.2 Weight Determination

2.2.1 Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP) was proposed by American operations research scientist Thomas (1977) [36] to solve the problem of power distribution. Through structural decomposition, the method is refined into a variety of key factors, and then the hierarchical model (target layer, criterion layer, scheme layer) and pair comparison matrix are constructed, and the weight is determined by combining expert experience, so that the decision is made in the way of system synthesis thinking. AHP has been applied to a variety of evaluation studies, such as operation management evaluation [37], undergraduate major evaluation [38], university library website user satisfaction evaluation [39], groundwater potential zone evaluation [40], etc. It is still feasible and reasonable to apply AHP model in the evaluation of sustainable development level of agricultural irrigation areas, and the specific process is as follows:

1. Construct Pairwise Comparison Matrix

The judgment matrix is constructed as shown in formula 3:

$$A = \begin{pmatrix} a_{11} & \cdots & a_{1m} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nm} \end{pmatrix} \quad (3)$$

Where: a_{ij} represents the importance of index i relative to j (using the 1-5 scale method).

2. Calculate Weight Vector

The weight vector is calculated according to formula 4:

$$AW = \lambda_{\max} W \quad (4)$$

Where: $\lambda_{\max}$ is the largest feature root.

3. Consistency Verification

Consistency test is based on formula 5:

$$CR = \frac{CI}{RI} \quad (5)$$

Where: CI is the consistency index, RI is the random consistency index, CR is the consistency ratio, and CR is much less than 0.1, indicating that the degree of inconsistency of the judgment matrix A is within the allowable range, and the weight obtained is valid.

2.2.2 Entropy Weight Method

The Entropy Weight method is an objective weighting method based on information entropy theory, developed from the concept of information entropy proposed by American mathematician Claude in information theory in 1948. The core idea is derived from the generalized application of thermodynamic entropy. Shannon introduced entropy into information science to quantify the degree of uncertainty and dispersion of system information and reflect the importance of indicators through the degree of variation. This method can better reflect the utility value of information, overcome the overlap of information among indicators, and eliminate the influence of subjective factors on the determination of indicator weights, thus improving the objectivity and scientific nature of evaluation results [41, 42]. Specific steps are as follows:

1. Standardization

In order to ensure the comparability of indicators, the extreme value method is adopted to standardize the data of each evaluation indicator and eliminate the influence of dimensions and orders of magnitude between indicators. The formula is shown in formula 6:

$$
\begin{aligned}
y_{ij} &= \frac{x_{ij}-x_{\min}}{x_{\max}-x_{\min}} \quad \text{(Positive index)} \\
y_{ij} &= \frac{x_{\max}-x_{ij}}{x_{\max}-x_{\min}} \quad \text{(Negative index)} \\
y_{ij} &= \frac{|x_{ij}-x_0|}{\max(|x_{ij}-x_0|)} \quad \text{(Moderate index)}
\end{aligned} \tag{6}
$$

Where: y_{ij} is the standardized value of item j of the research unit i ($i=1,2,...,n$, n is the number of research units; $j=1,2,\ldots,m$, m is the number of indicators); x_{ij} is the original value of the j index of the i research unit; $x_{\min}$ is the minimum value of the index; $x_{\max}$ is the maximum value of index j; x_0 is the ideal value of the index.

2. Proportion Calculation

The proportion of indicators is calculated according to formula 7:

$$p_{ij} = \frac{y_{ij}}{\sum_{i=1}^{n} y_{ij}} \tag{7}$$

3. Entropy Determination

The specific gravity of the index is calculated according to formula 8:

$$e_j = -\frac{1}{\ln n}\sum_{i=1}^{n} p_{ij} \ln p_{ij} \tag{8}$$

The smaller the entropy value e_j, the greater the degree of variation of the index, the richer the information, and the higher the weight. Otherwise, the lower the weight [43].

4.Weight Assignment

The index weight w_j of Entropy Weight method is calculated according to formula 9 as follows:

$$w_j = \frac{1-e_j}{\sum_{i=1}^{m}(1-e_j)} \quad (j=1,2,...,m) \tag{9}$$

Where: w_j is the entropy weight of the j index; e_j is the entropy of index j, $e_j \geq 0$.

2.2.3 Combined Weighting

This study employs a combined AHP-Entropy Weight method to determine index weights. AHP, blending subjective judgment with systematic analysis, effectively handles multi-factor hierarchies but is limited by subjective bias and computational complexity. Conversely, the Entropy Weight method, grounded in information entropy, assigns weights objectively, ensuring theoretical rigor but potentially overlooking indicator correlations. By integrating AHP's systematic analysis and expert experience with the Entropy Weight method's objective data mining, this study constructs a comprehensive weighting model through dual quantitative-qualitative verification. This approach enhances scientific credibility, balances subjective and objective strengths, and provides a robust basis for evaluation [44-47]. The formula is shown in formula 10:

$$w_j^C = \alpha w_j^A + \beta w_j^E \quad (\alpha+\beta=1) \tag{10}$$

Where: w_j^C represents the weight of the combination, w_j^A represents the supervisor weight obtained by AHP method, and w_j^E

represents the objective weight obtained by entropy method.

2.3 Hydrological Data Prediction Methods

2.3.1 ARIMA-Based Rainfall Forecasting

The Autoregressive Integral Moving Average Model (ARIMA) is a classical time series prediction method, which eliminates the non-stationarity of data through differential operation [48]. Since rainfall usually shows seasonal variations and is measured on a daily basis, the ARIMA model can be used to obtain predictions with relative accuracy. ARIMA model consists of three important parameters (p,d,g) decision: p the regression coefficient (Auto - Regressive), representing the number of lagged observations included in the model; d corresponds to "I" in the ARIMA model, which means that the time series data needs at least d difference to become stationary series. q is the Moving Average coefficient, indicating that the error term lags q order[49]. The formula of the autoregression-moving average model (ARMA) is shown in formula 11:

$$y_t = \mu + \sum_{i=1}^{p} \gamma_i y_{l-i} + \varepsilon_t + \sum_{i=1}^{q} \theta_i \varepsilon_{t-i} \quad (11)$$

Determination of parameter d : The autocorrelogram stationary test was performed on the time series data, and the truncation of ACF and PACF plots was checked respectively. The two were either trailing or truncated, otherwise they were non-stationary sequences. The non-stationary sequence is tested for stationarity after difference, and the value of d is determined until the stationarity condition is satisfied.

The determination of parameters p and q : After the sequence is stable, the determination of parameters p , q and the model is shown in Table 2:

Table 2. Parameters p , q and Determination Conditions of Model

Model	ACF	PACF
AR(p)	Trailing off	pth order cutoff
MA(q)	qth order cutoff	Trailing off
ARMA(p,q)	qth trailing off	qth trailing off

2.3.2 ANN-Based Runoff Prediction

Runoff in the Sanjiang Plain, affected by extreme weather like rainstorms and snowmelt, shows outliers challenging traditional linear models. ARIMA, though used in hydrology, struggles with nonlinear runoff interactions [50]. This study employs Artificial Neural Networks (ANN), leveraging multi-layer nonlinear transformations to capture spatio-temporal correlations. ANN robustly handles non-linear, non-stationary data and outliers, improving daily runoff predictions under extreme weather compared to ARIMA [51].

2.4 TOPSIS-Based Sustainability Evaluation Model

2.4.1 Model Construction

This study employs the TOPSIS model to assess the sustainable development of 37 agricultural irrigation areas in the Sanjiang Plain, Heilongjiang. Proposed by Hwang and Yoon in 1981 [52], TOPSIS addresses multi-criteria decision analysis by quantifying a closeness coefficient, measuring the geometric distance from alternatives to ideal and negative ideal solutions. It ranks alternatives based on proximity to the ideal and distance from the negative ideal, normalizing scores [53]. TOPSIS offers computational efficiency, high discriminability, and objective assessment, utilizing raw data without distribution constraints. It effectively handles multi-criteria ranking in complex systems, proving valid and practical for irrigation area sustainability evaluations [19, 21, 54].

2.4.2 TOPSIS Implementation Procedure

1. Construct Standardized Evaluation Matrix

According to formula (6), the standardized price matrix of sustainable development of agricultural irrigation areas in Sanjiang Plain is obtained, as shown in formula 12:

$$Y = \begin{pmatrix} y_{11} & \cdots & y_{1m} \\ \vdots & \ddots & \vdots \\ y_{n1} & \cdots & y_{nm} \end{pmatrix} \quad (12)$$

2. Generate Weighted Normalized Matrix

According to the comprehensive index weights calculated by formula 6, the standardized weighted evaluation matrix can be obtained, as shown in formula 13:

$$R = (r_{ij})_{n\times m} = \begin{pmatrix} y_{11}\times w_1 & \cdots & y_{1m}\times w_m \\ \vdots & \ddots & \vdots \\ y_{n1}\times w_1 & \cdots & y_{nm}\times w_m \end{pmatrix} \quad (13)$$

Where: r_{ij} is the standardized value weighted by the evaluation index of item j of research unit i .

3. Determine the Optimal and Worst Vectors

The maximum and minimum values of each column of the normalized weighted evaluation matrix respectively constitute the optimal and the worst vectors as shown in formula 14-15:

$$R^{+} = (r_{\max 1}, r_{\max 1}, \ldots, r_{\max m}) \quad (14)$$

$$R^{-} = (r_{\min 1}, r_{\min 1}, \ldots, r_{\min m}) \quad (15)$$

Where: R^{+} and R^{-} are the optimal and worst vectors respectively; $r_{\max}$ and $r_{\min}$ are the maximum and minimum values of column m of the normalized weighted evaluation matrix respectively.

4. Calculate Separation Distances

The Euclidean distance calculation method is adopted to determine the distance between the evaluation index of item j and the optimal and worst vectors, and the calculation formulas are shown in formula 16-17 respectively:

$$D_i^{+} = \sqrt{\sum_{j=1}^{m} (r_{\max j} - r_{ij})^2} \quad (16)$$

$$D_i^{-} = \sqrt{\sum_{j=1}^{m} (r_{\min j} - r_{ij})^2} \quad (17)$$

Where: D_i^{+} is the distance from the evaluation index of the j item to the optimal and worst vectors respectively.

5. Calculation of Sustainable Development Level Assessment Values

The closeness coefficient T_i was defined as the metric quantifying the proximity between the sustainability level of the i^{-th} study unit and the optimal sustainability benchmark, serves as the assessment value for irrigation district i in the Sanjiang Plain of Heilongjiang Province. The value of T_i ranges from [0,1], where a higher value indicates closer proximity to the optimal sustainability level, reflecting superior sustainable development performance in the irrigation district. The calculation formula is given by formula 18:

$$T_i = \frac{D_i^{-}}{D_i^{+} + D_i^{-}} \quad (18)$$

3. Results and Discussion

3.1 Study Area Overview

The Sanjiang Plain irrigation areas in northeastern Heilongjiang (130°13’–135°05’E, 46°28’–48°27’N) span 12,000 km², formed by Heilongjiang, Ussuri, and Songhua River deposits. With a temperate monsoon climate and 550 mm annual precipitation, mostly from May to September, the region faces groundwater over-extraction due to uneven surface water distribution and reliance on groundwater despite advanced hydraulic infrastructure.

The geographical distribution of the 37 irrigation districts is illustrated in Figure 1.

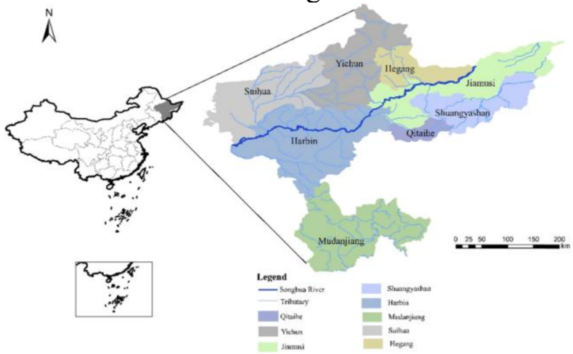

Figure 1. Geographical Distribution of the 37 Irrigation Districts (Image source: Author-Created)

3.2 Forecast Results

The basic data of water resources, soil resources, social economy, ecology and other aspects adopted by the research institute mainly come from Heilongjiang Statistical Yearbook 2023, Water Resources Bulletin of Heilongjiang Province (2023), Planning Report on Key Project of Three River Confluence Water Diversion and Irrigation System in Heilongjiang Province, Groundwater Over-exploitation Control Plan for Sanjiang Plain in Heilongjiang Province, and Research on Water-saving Irrigation Technology for Rice in Sanjiang Plain, etc. All specific indicator values were derived from the aforementioned datasets through systematic collation.

3.3 Weighting Results

Based on the comprehensive review of existing research results, combined with expert consultation and multiple rounds of discussions, this study determined the combination weight coefficients $\alpha = \beta = 0.5$. Through the incorporation formula 10, the scientific integration of subjective and objective weights was achieved, and finally, the comprehensive weighting results as shown in Tab. 3 were obtained. Among them, column 5 presents the subjective weighting results based on AHP, reflecting the expert's experience judgment; column 6 shows the objective weighting results based on the entropy method, representing the difference in data information; column 7 is the comprehensive weight value obtained by using the combination weighting method. Through the weighted harmonic of the subjective and objective weighting results, it effectively overcomes the limitations of a single weighting method and comprehensively considers the subjective and objective factors, improving the scientificity and reliability of weight allocation. This combination weighting result will serve as the basic parameter for subsequent comprehensive evaluation research (Table 3).

Table 3. Integrated Weighting Results

Objective Level	Criterion Level	Indicator Level	Criterion Attribute	Subjective Weight (AHP)	Objective Weight (Entropy)	Integrated Weight
Evaluation System of Agricultural Sustainable Development in Sanjiang Plain	Social (A)	Total Population (A1)	-	0.026	0.012	0.019
		Planned Population Capacity (A2)	+	0.034	0.013	0.024
		Per Capita Irrigated Area (A3)	+	0.103	0.171	0.137
	Economic (B)	Irrigation Quota (B1)	-	0.048	0.071	0.060
		Water Pricing (B2)	-	0.063	0.009	0.036
		Crop Yield Per Unit Area (B3)	+	0.152	0.085	0.119
	Ecological (C)	Surface-Irrigated Area (C1)	+	0.018	0.261	0.140
		Groundwater-Irrigated Area (C2)	-	0.049	0.017	0.033
		Annual Rainfall (C3)	Moderate	0.042	0.098	0.070
		Annual Surface Runoff (C4)	Moderate	0.074	0.082	0.078
	Sustainability (D)	ET0 (D1)	-	0.053	0.020	0.037
		Surface Water Supply (D2)	+	0.120	0.126	0.123
		Underground Water Supply (D3)	-	0.219	0.035	0.127

3.4 Forecast Results

3.4.1 Model Pre-validation

Based on the 2015 Special Report and 2016–2020 Water-saving Plan, 45 years of rainfall/runoff data (1976–2020) were analyzed. Pre-2000 data trained the model, with 2001–2020 data validating predictions. The 2023 runoff forecast assessed sustainability. At Baoqing station, 1976–2000 runoff training yielded a 2001–2020 prediction with R-square 0.90 (Figure 2). This method predicted runoff for nine sites in 2021–2023.

3.4.2 Irrigation District Data Allocation

1. Runoff Allocation

Based on *the Special Report on Irrigation Districts (2015)*, this study proportionally allocated predicted runoff to 37 districts according to their historical contributions (Table 1). Annual runoff projections for 2023 are detailed in Table 4.

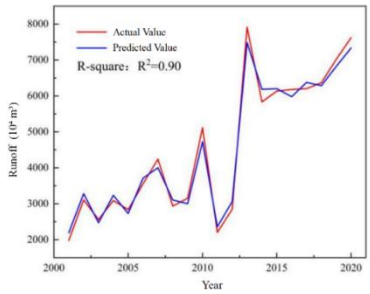

Figure 2. Forecast Results of Runoff of Baoqing Railway Station from 2001 to 2020

Table 4. Annual Runoff Statistics by Hydrological Station

No.	Hydrometric Station	Mean	Cv	Runoff (10^8 m³)				
				P=50%	P=75%	P=85%	P=90%	P=95%
1	Baoqing	5.40	0.70	4.57	2.64	1.88	1.47	0.98
2	Baoquanling	7.88	0.52	7.19	4.87	3.88	3.30	2.54
3	Baoan	1.97	0.73	1.63	0.92	0.64	0.49	0.32
4	Caizui	17.32	0.75	14.20	7.84	5.37	4.07	2.64
5	Fulitun	0.92	0.63	0.81	0.49	0.37	0.30	0.22
6	Heli	1.19	0.60	1.06	0.66	0.51	0.42	0.31
7	Hongqiling	2.57	0.49	2.38	1.65	1.34	1.14	0.90
8	Huaxing	0.56	0.47	0.52	0.37	0.30	0.26	0.21
9	Yadan River	0.77	0.75	0.63	0.35	0.24	0.18	0.12

2. Rainfall Estimation

Using data and conditions of Heilongjiang's irrigation districts, annual rainfall and total water resources were analyzed. The rainfall-to-runoff ratio was calculated, and by applying this to predicted runoff, rainfall for 37 irrigation areas from 2021–2023 was estimated. Results are presented in Table 5.

Table 5. Rainfall Data for Irrigation Districts (2021–2023)

No.	Irrigation District	Rainfall (mm)		
		2021	2022	2023
1	Yanjun Farm	3570	3027	2288
2	Tuanjie	2303	2107	1566
3	Wutong River	18338	13715	10238
4	Baoquanling Lingnan	3570	3027	2288
5	Gongqing	3570	3027	2288
6	Fengxiang	3570	3027	2288
7	Jian	32836	27440	22851
8	Jixian Jibi	32721	27164	22733
9	Southern No. 291	34266	28870	24281
10	Jixian Small Yellow River	32721	27164	22733
11	Dongxie General	32721	27164	22733
12	Youyi Western	7614	7529	7575
13	Xinghuo	20641	15822	11804
14	Yuelai	20641	15822	11804
15	Jiangchuan	20641	15822	11804
16	Xinhegong	20641	15822	11804
17	Jinjiang	35024	29271	24299
18	Jinjiang	35024	29271	24299
19	Xingfu	2188	1831	1448
20	Hongqi	2188	1831	1448
21	Jindong	35024	29271	24299
22	Jinxi	2188	1831	1448
23	Lianhua River	32836	27440	22851
24	Songjiang	2303	2107	1566
25	Suisong	2303	2107	1566
26	Puyang	3570	3027	2288
27	Qunying	35024	29271	24299
28	Zhenxing	2303	2107	1566
29	Jinnan	2188	1831	1448
30	Daxing	2188	1831	1448
31	No. 597	30533	25333	21285
32	Sanhuanpao	30533	25333	21285
33	Longtou Bridge	30533	25333	21285
34	Jianshanzi	30533	25333	21285
35	Hamatong	30533	25333	21285
36	No. 853	30533	25333	21285
37	Qiliqin	9923	9161	9547

3.5 Evaluation Results

The evaluation results of sustainable development levels for agricultural irrigation areas based on the TOPSIS model are presented in Table 6.

Table 6. Evaluation Results of Sustainable Development Levels for Agricultural Irrigation Areas

Rank	Irrigation District	Closeness Degree (T_i)	Rank	Irrigation District	Closeness Degree (T_i)
1	Jianshanzi	0.52464	20	Jinxi	0.40196
2	Sanhuanpao	0.50646	21	Jibi	0.40024
3	Hamatong	0.47796	22	New Tuanjie	0.40018
4	Jinjiang	0.47502	23	Wutong River	0.39260
5	Lianhua River	0.46168	24	Daxing	0.39196

6	No. 853	0.46007	25	Hongwei	0.39167
7	Dongxie General	0.45939	26	Jian	0.37450
8	Fengxiang	0.44755	27	Jindong	0.37138
9	Xingfu	0.44353	28	Baoquanling Lingnan	0.36308
10	Gongqing	0.43936	29	Yanjun	0.36045
11	Longtou Bridge	0.43857	30	Youyi Western	0.35194
12	Puyang	0.42856	31	Hongqi	0.35175
13	Jinnan	0.41405	32	Zhenxing	0.34856
14	No. 597	0.41165	33	Songjiang	0.34818
15	Southern No. 291	0.40873	34	Xinghuo	0.34641
16	Qunying	0.40713	35	Suisong	0.34579
17	Qiliqin	0.40446	36	Xinhegong	0.33182
18	Yuelai	0.40320	37	Jiangchuan	0.29467
19	Jixian small Yellow River	0.40244			

The evaluation reveals significant spatial heterogeneity and gradient differentiation in the sustainable development of 37 irrigation areas in the Sanjiang Plain. Only 7 areas (18.9%) have closeness coefficients above 0.45, classified as high-level sustainable; 15 (40.5%) range from 0.40–0.45, deemed benign; 9 (24.3%), including Wutonghe and Daxing, score 0.35–0.40, rated low-level; and 6, like Jiangchuan and Xinhegong, fall below 0.35, labeled disadvantaged. The 43.8% index gap between Jianshanzi and Jiangchuan reflects influences of geography, resources, and policy. Low-level and disadvantaged areas require cross-regional resource integration and policy coordination to bridge gaps.

High-level areas, located along the Songhua and Naoli Rivers, benefit from stable water sources, reduced groundwater reliance, and policy support from modern agricultural reforms, including intelligent water gates. Conversely, low-level and disadvantaged areas, distant from major water systems, rely heavily on groundwater, leading to water level declines and wetland shrinkage. Issues like silted channels, aging equipment, and cavitation in areas like Jiangchuan and Xinhegong reduce irrigation efficiency. Yanjun and Western Youyi face additional challenges from water competition and soil salinization.

3.6 Results and Discussion

The combined weighting results (Tab. 3) prioritize indicators for sustainable development in Sanjiang Plain irrigation areas. At the criterion level, Ecological > Sustainable Development > Economic > Social dimensions; at the indicator level, C1 (Surface Irrigation Area), A3 (Per Capita Irrigated Area), and D3 (Underground Water Supply) are key constraints. TOPSIS and weighting analyses show high-level areas have a C1 value of 8897 hm^2 versus 1703 hm^2 in disadvantaged areas, indicating less groundwater reliance. High-level areas use 7381 m^3 less D3 and have a fourfold higher A3 (47.92 hm^2/person), reflecting better land allocation and reduced overexploitation risks.

Optimization paths include: (1) A "surface water priority" mechanism with cross-basin water diversion, energy-saving upgrades, and pipeline irrigation to reduce losses, alongside wetland restoration standards. (2) A "water efficiency-capacity" incentive combining subsidies and rewards based on water-saving and yield metrics, supported by an integrated water price reform platform. (3) A "blockchain + public participation" platform with a management app, automated water quality alerts, farmer reporting channels, and training to enhance governance participation.

4. Conclusions

To advance carbon neutrality and sustainability, this study developed a Social-Economic-Ecological-Sustainable Development Four-Dimensional Evaluation framework. Using an enhanced TOPSIS model with AHP-Entropy Weight methods, it assessed 37 Sanjiang Plain irrigation districts, overcoming administrative boundaries. Findings show: (1) Significant spatial heterogeneity in sustainability, with proximity indices from 0.2947 (Jiangchuan) to 0.5246 (Jianshanzi); (2) Ecological (32.05%) and Sustainable Development (28.65%) dimensions drive evaluation, with Surface Irrigation Area (14.0%), Per Capita Irrigation Area (13.7%), and Underground Water Supply (12.7%) as key factors, while Total Population (1.9%) has minimal impact. Water use efficiency and ecological resilience are critical constraints. The results guide modern irrigation management and resource allocation. Future research will focus on policy response indicators, water-carbon-food dynamic models, and agricultural big data integration.

References

[1] Brown, LR. Building A Sustainable Society[J]. Society. 1982, 19(2): 75-85.
[2] Miao Jianqun, Zhao Mei, HUANG Guoqin. Comprehensive evaluation and empirical analysis of agricultural sustainable development in Southern hilly areas[J]. China Agricultural Resources and Regional Planning, 2021, 42(08): 163-172..
[3] Brundtland, GH. Our Common Future-Call For Action[J]. Environmental Conservation. 1987, 14(4): 291-294.
[4] Wang Renhong. The irrigated area of arable land in our country has reached 1.075 billion mu[M]. 2025.
[5] Ma Tao, Chi Daocai, Wang Dianwu, et al. Evaluation of sustainable development of irrigation areas based on set pair analysis[J]. Journal of Shenyang Agricultural University, 2007, (06): 841-844.
[6] Viana C., Freire D., Abrantes P., et al. Agricultural land systems importance for supporting food security and sustainable development goals: A systematic review[J]. Science of the total environment, 2022, 806: 150718.
[7] Ashraf S., Siddiqui A., Abd Elmoneim O., et al. Innovations in nanoscience for the sustainable development of food and agriculture with implications on health and environment[J]. Science of the Total Environment, 2021, 768: 144990.
[8] Adefila A., Ajayi O., Toromade A., et al. Integrating traditional knowledge with modern agricultural practices: A sociocultural framework for sustainable development[J]. Journal of Sustainable Agriculture and Development, 2024.
[9] Davarpanah S., Bonab S., Khodaverdizadeh M.. Assessment and comparison of sustainable agriculture approach using a combination of AHP and TOPSIS[J]. International Academic Journal of Economics, 2016, 3(9): 7-18.
[10] Wowra K., Zeller V., Schebek L. Nitrogen in Life Cycle Assessment (LCA) of agricultural crop production systems: Comparative analysis of regionalization approaches[J]. Science of the Total Environment, 2021, 763: 143009.
[11] Sušnik J., Masia S., Indriksone D., et al. System dynamics modelling to explore the impacts of policies on the water-energy-food-land-climate nexus in Latvia[J]. Science of The Total Environment, 2021, 775: 145827.
[12] Chaudhary S., Kumar A., Pramanik M., et al. Land evaluation and sustainable development of ecotourism in the Garhwal Himalayan region using geospatial technology and analytical hierarchy process[J]. Environment, development and sustainability, 2022: 1-42.
[13] Gao Honggui, He Meixuan. Theoretical logic, connotation characteristics and practical dimensions of ecological priority and green low-carbon development[J]. Ecological Economy, 2023, 39(08): 13-18.
[14] Zhang Zhongjun, Xu Lipeng. Study on the coordinated development of agricultural supply-side structural reform and the strategy of expanding domestic demand[J]. Agricultural Economy, 2024, (06): 133-135.
[15] Meng Zhigang, Wang Jian. Path innovation of agricultural sustainable development under the implementation of rural revitalization strategy[J]. Agricultural Economy, 2024, (10): 15-17.
[16] Tang Jianfei, Liu Jianling. Evaluation of provincial agricultural sustainable development level and its coupling coordination analysis-taking 11 provinces and cities in the Yangtze River Economic Belt as an example[J]. Economic Geography, 2022, 42(12): 179-185.
[17] Chang Quangen. Evaluation of sustainable utilization of water resources and regulation of soil and water conservation in Laoguan River Basin[J]. Henan Water Conservancy and South-to-North Water Transfer Project, 2024, 53(01): 9-11.
[18] Zeng Chen, Zhou Zhanhang, Ke Xinli, et al. Research status and interdisciplinary analysis of agricultural sustainable development under global climate change[J]. Journal of Huazhong Agricultural University, 2024, 43(06): 6-16+2.

[19] Cao Lianhai, Xiaobo Liu, Zhang Zhiqiang, et al. Evaluation of agricultural water and soil resources in Xuchang City based on CRITIC-TOPSIS[J]. Journal of North China University of Water Resources and Hydropower (Natural Science Edition), 2023, 44(01): 56-61.
[20] Li Li, Yu Guanghu, Guan Wei, et al. Evaluation of carrying capacity of agricultural water and soil resources in coastal areas and analysis of obstacles[J]. Journal of Irrigation and Drainage, 2023, 42(S1): 117-122.
[21] Huang Yan, Xu Cong, Si Zhenjiang. Study on evaluation of sustainable utilization of water and soil resources in cold black soil region based on DPSIR-TOPSIS model[J]. Water-Saving Irrigation, 2024, (12): 26-31+40.
[22] Chen Li, Zhou Hong. Evaluation of water resources carrying capacity in karst basin based on fuzzy comprehensive evaluation and principal component analysis[J]. Safety and Environmental Engineering, 2021, 28(06): 159-173.
[23]Tian Pei, Fan Jingkun, Jin Gui, et al. Evaluation of coupling coordination degree of "water-energy-food" system in Hubei Province[J]. Resources and Environment in the Yangtze River Basin, 2025, 34(01): 100-110.
[24] Rozita E., Sutjiningsih D.. The evaluation of irrigation water requirement under climate change phenomenon in the urban area (a literature study)[C]//IOP Conference Series: Earth and Environmental Science. IOP Publishing, 2019, 311(1): 012005.
[25] Karakuş C., Yıldız S.. Evaluation for irrigation water purposes of groundwater quality in the vicinity of Sivas City Centre (Turkey) by using GIS and an irrigation water quality index[J]. Irrigation and Drainage, 2020, 69(1): 121-137.
[26] Zhang Y., Yang P.. Agricultural Water Optimal Allocation Using Minimum Cross-Entropy and Entropy-Weight-Based TOPSIS Method in Hetao Irrigation District, Northwest China[J]. Agriculture, 2022, 12(6): 853.
[27] Zhao Shixiang, Li Yihan, Li Fei. Comprehensive evaluation of nitrogen non-point source pollution control technology in maize field in Hetao irrigation area based on hierarchical-gray correlation method[J]. China Soil and Fertilizer, 2024, (04): 26-34.
[28] Yan Jingyao, Pei Long. Based on AHP-fuzzy comprehensive evaluation method to evaluate the comprehensive reform performance of agricultural water price-taking Jingdian Irrigation District in Gansu Province as an example[J]. Shanxi Agricultural Economics, 2025, (02): 133-137+174.
[29] Qu Shenhao, Yao Huaizhu, Wang Yandong, et al. Matching status of agricultural water and soil resources in typical irrigation areas in Jiangsu and its carrying capacity characteristics[J]. Soil and water conservation research, 2023, 30(06): 452-457+467.
[30] Han F., Alkhawaji R., Shafieezadeh M.. Evaluating sustainable water management strategies using TOPSIS and fuzzy TOPSIS methods[J]. Applied Water Science, 2025, 15(1): 1-13.
[31] Gugulothu S., Subbarao N., Das R., et al. Geochemical evaluation of groundwater and suitability of groundwater quality for irrigation purpose in an agricultural region of South India[J]. Applied Water Science, 2022, 12(6): 142.
[32] Zou Quancheng, Wu Haoyang, Ye Wei, et al. Comprehensive evaluation of water and soil resources carrying capacity in Ningxia Yangshui Irrigation Area based on PSO-PPE model [J]. Journal of Water Resources and Water Engineering, 2019, 30(04): 250-256.
[33] Sohail M., Mustafa S., Ali M., et al. Agricultural communities' risk assessment and the effects of climate change: A pathway toward green productivity and sustainable development[J]. Frontiers in Environmental Science, 2022, 10: 948016.
[34] Aslan V.. Evaluation of Sanliurfa Karakopru basin groundwater potential for sustainability with GIS-based AHP and TOPSIS methods[J]. Sustainable Water Resources Management, 2023, 9(3): 77.
[35] Chen Yu, Liu Yan, Zhao Zhiqiang. Evaluation of agricultural water and soil resources carrying capacity and diagnosis of obstacle factors in Jiaokou irrigation area [J]. Journal of Irrigation and Drainage, 2024, 43(07): 98-105.
[36] Saaty,Thomas. A scaling method for priorities in hierarchical structures[J].Journal of Mathematical

Psychology,1977,15(3):234-281
[37] Subramanian N., Ramanathan R.. A review of applications of Analytic Hierarchy Process in operations management[J]. International Journal of Production Economics, 2012, 138(2): 215-241.
[38] Zhang Yi, Song Chenchen, Song Peng, et al. On the evaluation of science and engineering majors based on AHP model[J/OL]. Chinese Journal of Systems Science, 2025,(03):1-6[2025-04-13].
[39] Liu Jian, Wang Xiaofei. Research on the construction of evaluation index system of user satisfaction of university library websites based on analytic hierarchy process[J]. Information Science, 2022, 40(12): 80-87.
[40] Suryawanshi S., Singh P., Kothari M., et al. Assessment of groundwater potential zones for hard rock area of sabi river basin using an integrated approach of remote sensing, GIS and AHP techniques[J]. Physics and Chemistry of the Earth, Parts A/B/C, 2025, 137: 103820.
[41] Sun Haifeng, Li Lin. Evaluation of water and soil resources carrying capacity and diagnosis of obstacle factors in China [J]. People's Yellow River, 2021, 43(10): 86-92.
[42] Zhang Sui, Zhang Mei, Chi Guotai. Evaluation model of science and technology based on entropy weight method and its empirical study[J]. Journal of Management, 2010, 7(01): 34-42.
[43] Zou Zhihong, Sun Jingnan, Ren Guangping. Entropy weighting of fuzzy evaluation factors and its application in water quality evaluation[J]. Journal of Environmental Science, 2005, (04): 552-556.
[44] Liu Wei, Dong Wanqi. Study on risk assessment method of drainage network based on AHP- entropy weight method[J]. Journal of Safety and Environment, 2021, 21(03): 949-956.
[45] Qu Feifan. Discussion on influencing factors of project cost of data center supporting construction project based on AHP- entropy weight method[J]. Project Cost Management, 2025, 36(01): 38-44.
[46]Wang Qilin. Evaluation of water resources carrying capacity in Guangdong Province based on AHP- entropy weight model[J]. Water Science and Technology and Economy, 2024, 30(12): 89-92.
[47] Jiang Hong, Zeng Sheng, Zhou Tian, et al. Evaluation of fire rescue capability of extra-long highway tunnels based on improved AHP and entropy weight method[J]. Industrial Safety and Environmental Protection, 2025, 51(02): 28-33.
[48] Yan Xiangxiang. Using ARIMA model to predict the area of park green space[J]. Computer Science, 2020, 47(S2): 531-534+556.
[49] Hanchuan D.,Shuang L.,Lili P., et al. A debris-flow forecasting method with infrasound-based variational mode decomposition and ARIMA[J].Journal of Mountain Science,2024,21(12):4019-4032.
[50] Fashae A., Olusola O., Ndubuisi I., et al. Comparing ANN and ARIMA model in predicting the discharge of River Opeki from 2010 to 2020[J]. River Research and Applications, 2019, 35(2): 169-177.
[51] Xie Zibin. Study on the Prediction of Runoff of Hydropower Station and Reservoir Water Level Based on Neural Network[J]. Water Conservancy Science and Cold Region Engineering, 2022, 5(11): 35-39.
[52] HWANG C-L., YOON K., HWANG C-L., et al. Methods for multiple attribute decision making[J]. Multiple attribute decision making: methods and applications a state-of-the-art survey, 1981: 58-191.
[53] Rajput L., Kumar S.. Linguistic interval-valued polytopic fuzzy set and cloud model based technique for order of preference by similarity to ideal solution[J]. Engineering Applications of Artificial Intelligence, 2025, 142: 109872.
[54] Fu Congying, Lai Zhaohao, Guo Xi. Evaluation of Regional Resources and Environmental Carrying Capacity and Diagnosis of Obstacles Based on Entropy TOPSIS Model[J]. Ecological Economy, 2020, 36(01): 198-204.