Postprint: Effectiveness Evaluation of Water Resources Allocation in the Water Receiving Area of the Central and Southern Ningxia Water Transfer Project

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Date: 2021-12-14T00:00:00+00:00

Abstract

The South-Central Ningxia Water Transfer Project is the only large-scale water transfer project within Ningxia, and its implementation will inevitably exert a tremendous impact on the water resource allocation pattern in the water-receiving areas. Based on the multi-objective nature and fuzzy incompatibility characteristics of water resource allocation, this study investigates water resource allocation and effect evaluation in the water-receiving areas of the South-Central Ningxia Water Transfer Project to further elucidate the project' s influence on the water resource allocation pattern. From the dual perspectives of domestic water priority and ecological priority, planning level years of 2020 and 2025 are selected, and water resource allocation scheme sets with and without the participation of the South-Central Ningxia Water Transfer Project are established respectively. Evaluation indicators are selected from social, economic, and ecological dimensions to construct a corresponding evaluation indicator system. The principal component analysis method and the fuzzy matter-element comprehensive evaluation method are employed respectively to assess the water resource allocation outcomes, with the final score values of the two methods sorted by merit for comparative analysis. Both evaluation methods indicate that the water resource allocation scheme based on ecological priority with the participation of the South-Central Ningxia Water Transfer Project is optimal. Specifically, the fuzzy matter-element evaluation results demonstrate that all schemes incorporating the South-Central Ningxia Water Transfer Project are superior to those without it, whereas the principal component analysis evaluation results exhibit more pronounced quality differentials. Beyond confirming that schemes employing the South-Central Ningxia Water Transfer Project outperform those without it, the principal component analysis also reveals that the greater the volume of water resources allocated to the water-receiving areas, the more optimal the scheme. These findings concurrently substantiate the rationality of both evaluation methods for water resource allocation effect assessment, while demonstrating that the participation of the South-Central Ningxia Water Transfer Project has significantly propelled economic development in the water-receiving regions and concurrently enhanced regional ecological and environmental benefits.

Full Text

Evaluation of Water Resources Allocation Effect in the Receiving Area of the Central and Southern Ningxia Water Transfer Project

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Abstract

The water transfer project in central and southern Ningxia represents the only large-scale water transfer initiative within the autonomous region, and its implementation will inevitably exert substantial influence on water resources allocation patterns in the receiving area. Given the multi-objective and fuzzy incompatibility characteristics inherent to water resources allocation, this study investigates water resources allocation and effect evaluation in the receiving area of the central and southern Ningxia water transfer project to clarify the project' s impact on regional water allocation frameworks. From the dual perspectives of domestic water priority and ecological water priority, a set of water allocation schemes with and without the central-southern water transfer project were developed for the 2020 and 2025 planning horizons. An evaluation index system was constructed encompassing social, economic, and ecological dimensions. Principal component analysis and fuzzy matter-element comprehensive evaluation methods were employed to assess the allocation outcomes, with final scores from both approaches ranked and comparatively analyzed. Both evaluation methods consistently identified the ecological-priority scheme with central-southern water transfer project participation as optimal. Fuzzy matter-element evaluation demonstrated that all schemes incorporating the water transfer project outperformed those without it, while principal component analysis revealed more pronounced performance differentials, confirming not only the superiority of transfer-project-inclusive schemes but also establishing that greater water allocation volumes in receiving areas yield superior outcomes. These findings validate the rationality of both methods for water resources allocation effect evaluation and underscore that the central-southern water transfer project significantly promotes economic development in receiving areas while enhancing regional ecological and environmental benefits.

Keywords: central and southern Ningxia water transfer project; water resources allocation; evaluation of water resources allocation effect; principal component analysis; fuzzy matter-element comprehensive evaluation

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1 Water Resources Optimization Allocation Model

The evaluation indices for water resources allocation effect assessment are indirect metrics requiring quantification through optimization allocation results as intermediate indicators. Therefore, regional water resources must first be optimally allocated. The process is described below.

1.1 Objective Functions

1) Social objective: Minimizing water shortage was selected as the social objective, denoted by $f_1(x)$, calculated as:

$$f_1(x) = \min \sum_{k=1}^{K} \left(D_t - \sum_{i=1}^{I} \sum_{j=1}^{J} x_{ij}^k \right)$$

where D_t represents urban water demand in the planning year (10^4 m^3); t denotes the planning year; x_{ij}^k is water withdrawal from source i for user j in subregion k (10^4 m^3); I is the number of water sources; J is the number of water users; and K is the number of subregions.

2) Economic objective: Maximizing gross domestic product was selected as the primary economic objective, denoted by $f_2(x)$, calculated as:

$$f_2(x) = \max \sum_{k=1}^{K} \sum_{j=1}^{J} x_{ij}^k \times \mathrm{gdp}_j$$

where gdp_j represents GDP generated per unit water by user j.

3) Ecological-environmental objective: The ecological objective for the receiving area minimizes pollutant discharge, represented by f_3 and calculated as:

$$f_3 = \min \sum_{k=1}^{K} \sum_{j=1}^{J} 0.01 \times d_j \times p_j \times x_{ij}^k$$

where d_j is the concentration of major pollutants in wastewater discharged by user j (mg/L), typically using COD as the primary pollutant indicator; and p_j is the wastewater discharge coefficient for user j, representing the ratio of wastewater discharge to water consumption over a given period.

1.2 Constraint Conditions

1) Water source availability constraint: The total water allocated to all user sectors in each subregion must not exceed available water supply:

$$\sum_{c=1}^{C} x_{cj}^{k} + \sum_{i=1}^{I} x_{ij}^{k} \leq W_c^k + W_i^k$$

where x_{cj}^{k} is water supply from public source c to user j in subregion k (10^4 m^3); W_c^k is water allocated to subregion k from public source c (10^4 m^3); x_{ij}^{k} is water supply from independent source i to user j in subregion k (10^4 m^3); W_i^k is water allocated to subregion k from independent source i (10^4 m^3); J is the number of users; K is the number of subregions; C is the number of public water sources; and I is the number of independent water sources.

2) User water demand constraint: Direct water acquisition by users must not exceed planned demand:

$$\sum_{c=1}^{C} x_{cj}^{k} + \sum_{i=1}^{I} x_{ij}^{k} \leq D_j$$

where D_j is the planned water demand for user j (10^4 m^3).

3) Water source conveyance capacity constraint: For each subregion, water allocated to each sector must be less than or equal to the maximum conveyance capacity of water supply projects:

$$\sum_{j=1}^{J} x_{cj}^{k} \leq Q_c^k, \quad \sum_{j=1}^{J} x_{ij}^{k} \leq Q_i^k$$

where Q_c^k is the maximum conveyance capacity of public source c in subregion k (10^4 m^3); and Q_i^k is the maximum conveyance capacity of independent source i in subregion k (10^4 m^3).

4) Major pollutant discharge constraint:

$$\sum_{k=1}^{K} \sum_{j=1}^{J} 0.01 \times d_j \times p_j \times x_{ij}^{k} \leq P$$

where P is the maximum allowable pollutant discharge in subregion k (10^4 m^3).

For this multi-objective nonlinear model, optimization was implemented using the MATLAB function optimization toolbox `fgoalattain`.

2 Water Resources Allocation Effect Evaluation

Water resources allocation effect evaluation specifically assesses the comprehensive benefits of each allocation scheme to identify the optimal alternative. Various methods exist, including grey correlation analysis, evidence theory, probabilistic neural networks, TOPSIS, fuzzy entropy models, and principal component analysis, each with distinct advantages and limitations. This study selected fuzzy matter-element evaluation and principal component analysis to achieve complementary strengths, with scheme ranking comparisons clarifying the impact of the central-southern water transfer project on receiving areas and determining optimal allocation patterns.

2.1 AHP-Coefficient of Variation Combined Weight Calculation

Understanding indicator importance in water resources allocation scheme evaluation requires weight calculation. Method selection is critical, as approaches emphasizing solely subjective or objective perspectives may influence decision outcomes. To maximize avoidance of bias from unilateral subjective or objective weighting, this study employed an AHP-coefficient of variation combined weighting method to eliminate unilateral errors and enhance result objectivity. The calculation formula is:

$$w_i = \frac{\alpha_i \phi_i}{\sum_{i=1}^{n} \alpha_i \phi_i}$$

where w_i is the combined weight of the ith evaluation indicator; n is the number of evaluation indicators; α_i is the weight of the ith indicator determined by the coefficient of variation method; and ϕ_i is the weight of the ith indicator determined by the analytic hierarchy process.

2.2 Fuzzy Matter-Element Comprehensive Evaluation Method

In 1983, Professor Cai Wen introduced matter-element analysis, which first described object states using the three elements of "matter, characteristics, and values." Fuzzy matter-element comprehensive evaluation incorporates fuzzy theory into matter-element analysis by processing related problems through analyzing parameter variation patterns, effectively resolving incompatibility issues between objects. Water resources allocation effect evaluation using this method exhibits strong fuzziness and subjectivity. The approach establishes membership functions for evaluation indicator sets, calculates standard fuzzy matter-elements and difference-square compound fuzzy matter-elements, and solves for comprehensive evaluation scores using indicator weights through Euclidean approach degree, enabling final allocation effect analysis. Specific methods and steps are as follows:

1) Optimal membership degree calculation:

For larger-the-better indicators:

$$u_{ij} = \frac{x_{ij} - \min x_{ij}}{\max x_{ij} - \min x_{ij}}$$

For smaller-the-better indicators:

$$u_{ij} = \frac{\max x_{ij} - x_{ij}}{\max x_{ij} - \min x_{ij}}$$

where u_{ij} is the optimal membership degree value; x_{ij} is the value corresponding to the ith evaluation indicator in the jth scheme ($i = 1, 2, \dots, n$; $j = 1, 2, \dots, m$); and $\max x_{ij}$ and $\min x_{ij}$ are the maximum and minimum values of a given evaluation indicator across all allocation schemes.

2) Construct standard scheme n-dimensional fuzzy matter-element R_{0n}:

$$R_{0n} = \begin{bmatrix} M_0 & C_1 & u_1 \\ & C_2 & u_2 \\ & \vdots & \vdots \\ & C_n & u_n \end{bmatrix}$$

where M_0 is the standard configuration scheme; C_n is the nth evaluation indicator; and u_n is the fuzzy value corresponding to indicator C_n.

3) Construct difference-square fuzzy matter-element R_Δ: Calculate the squared differences between each term of standard fuzzy matter-element R_{0n} and compound fuzzy matter-element R_{mn}, represented by Δ_{ij} ($i = 1, 2, \dots, n$; $j = 1, 2, \dots, m$), to construct:

$$R_\Delta = \begin{bmatrix} M_1 & C_1 & \Delta_{11} & C_2 & \Delta_{12} & \cdots & C_n & \Delta_{1n} \\ M_2 & C_1 & \Delta_{21} & C_2 & \Delta_{22} & \cdots & C_n & \Delta_{2n} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ M_m & C_1 & \Delta_{m1} & C_2 & \Delta_{m2} & \cdots & C_n & \Delta_{mn} \end{bmatrix}$$

4) Euclidean approach degree and comprehensive evaluation: Construct the weight compound matter-element R_w using combined indicator weights:

$$R_w = [w_1, w_2, \dots, w_n]$$

where $w_1, w_2, \dots, w_n$ are the combined weights corresponding to evaluation indicators $C_1, C_2, \dots, C_n$.

Since this study employs comprehensive evaluation, the $\mathrm{M}(\cdot, +)$ algorithm is introduced:

$$\rho H_j = 1 - \sqrt{\sum_{i=1}^{n} w_i \Delta_{ij}} \quad (j = 1, 2, \dots, m)$$

where ρH_j is the Euclidean approach degree of the jth scheme. In water resources allocation evaluation, Euclidean approach degree reflects the proximity between allocation schemes and the standard optimal scheme, with larger values indicating closer similarity. The Euclidean approach degree compound fuzzy matter-element can be expressed as:

$$R_{\rho H} = \begin{bmatrix} M_1 & M_2 & \cdots & M_m & \\ \rho H_j & \rho H_1 & \rho H_2 & \cdots & \rho H_m \end{bmatrix}$$

where $R_{\rho H}$ is the Euclidean approach degree compound fuzzy matter-element; m is the number of configuration schemes; and M_m is the mth configuration scheme.

Larger-the-better indicators are positive metrics where higher values indicate better evaluation results, while smaller-the-better indicators are inverse metrics where lower values indicate better results.

2.3 Principal Component Analysis Effect Evaluation Method

Principal component analysis was employed for water resources allocation effect evaluation due to its ability to quantify numerous social, economic, and ecological factors into dimensionless indicators, effectively resolving conflicts arising from different indicator dimensions. This method significantly reduces computational dimensions while enabling robust analysis and yielding comprehensive evaluation results for water resources allocation in receiving areas. The methodology proceeds as follows:

1) Evaluation indicator standardization:

$$X'_{ij} = \frac{X_{ij} - \bar{X}_j}{S_j} \quad (i = 1, 2, \dots, n; j = 1, 2, \dots, p)$$

where X'_{ij} is the standardized value of the original indicator; X_{ij} is the original value of the ith sample' s jth evaluation indicator; $\bar{X}_j$ is the sample mean of the jth indicator; and S_j is the sample standard deviation of the jth indicator.

2) Correlation coefficient matrix calculation:

$$r_{ij} = \frac{\sum_{k=1}^{n}(x_{ki} - \bar{x}_i)(x_{kj} - \bar{x}_j)}{\sqrt{\sum_{k=1}^{n}(x_{ki} - \bar{x}_i)^2 \sum_{k=1}^{n}(x_{kj} - \bar{x}_j)^2}}$$

where R is the sample matrix comprising n samples and p evaluation indicators; r_{ij} is the correlation coefficient between original variables x_i and x_j; x_{ki} is the standardized value of the ith indicator for the kth sample; and $\bar{x}_i$ and $\bar{x}_j$ are sample mean data after standardization.

3) Eigenvalue and eigenvector calculation: Solve the characteristic equation:

$$|R - \lambda I| = 0$$

where λ represents eigenvalues and I is the identity matrix. The Jacobi method is typically used to solve for eigenvalues λ_i $(i = 1, 2, \dots, p)$, which are then arranged in descending order. Corresponding eigenvectors a_i $(i = 1, 2, \ldots, p)$ are subsequently determined, requiring $\sum_{j=1}^{p} a_{ij}^2 = 1$.

4) Contribution rate calculation: The contribution rate of principal components is:

$$p_i = \frac{\lambda_i}{\sum_{k=1}^{p} \lambda_k} \quad (i = 1, 2, \ldots, p)$$

The cumulative contribution rate is:

$$\sum_{i=1}^{m} p_i = \frac{\sum_{i=1}^{m} \lambda_i}{\sum_{k=1}^{p} \lambda_k}$$

Typically, eigenvalues $\lambda_1, \lambda_2, \ldots, \lambda_m$ with cumulative contribution rates exceeding 85% are retained.

5) Principal component loading calculation:

$$l_{ij} = a_{ij}\sqrt{\lambda_j} \quad (i = 1, 2, \ldots, p; j = 1, 2, \ldots, m)$$

where l_{ij} is the loading of the jth principal component corresponding to the ith eigenvalue; λ_j is the eigenvalue of the jth principal component; and a_{ij} is the eigenvector.

6) Principal component comprehensive score calculation:

$$Z_i = \sum_{p=1}^{m} a_{pi} x_{pi} \quad (i = 1, 2, \ldots, n)$$

where Z_i is the sum of products between each eigenvector and corresponding standardized indicator values; a_{pi} is the eigenvector corresponding to the pth eigenvalue for principal components with cumulative contribution exceeding 85%; x_{pi} is the standardized value corresponding to the pth eigenvalue; and D is the sum of products between principal component contribution rates p_i and corresponding Z_i values.

3 Water Resources Allocation and Effect Evaluation in the Receiving Area of Central and Southern Ningxia Water Transfer Project

3.1 Water Resources Allocation Scheme Set Configuration

Given the fragile ecological environment in arid regions, reasonable ecological water use must be ensured during water resources optimization allocation in receiving areas. While most current water allocation practices consider ecological water demand, few prioritize it. This study configured water resources following two approaches: domestic water priority and ecological water priority, allocating water preferentially to domestic and ecological uses while meeting minimum water requirements for domestic, industrial, agricultural, and ecological sectors to determine optimal allocation patterns.

To specifically examine the water resources allocation effects of the central-southern water transfer project on receiving areas and maximize elimination of interference from other factors, this study employed direct comparative analysis of "with versus without" the water transfer project. The scheme set was configured based on water source composition and allocation sequence, totaling eight allocation alternatives (Table 1).

3.2 Water Resources Optimization Allocation Calculation

The receiving area' s planned water sources include Yellow River water, Jing River water, local surface water, and groundwater (four types, denoted as i). Water users are categorized into domestic, industrial, ecological, and agricultural sectors (four types, denoted as j). Corresponding decision variables were determined based on water sources and users. Using the goal attainment method with the `fgoalattain` function and 500 iterations, the optimal allocation results for the planning year under 75% hydrological year guarantee rate are presented in Table 2.

3.3 Indicator and Weight Calculation Results

Evaluation indicator values for each scheme were calculated based on the water resources optimization allocation results (Table 3). The analytic hierarchy process was used to calculate weights (Table 4). Coefficient of variation method weights were calculated as: $w_1 = 0.040$, $w_2 = 0.110$, $w_3 = 0.025$, $w_4 = 0.103$, $w_5 = 0.113$, $w_6 = 0.096$, $w_7 = 0.480$, $w_8 = 0.026$, $w_9 = 0.007$. Combined weights were then calculated using formula (11): $w_1 = 0.171$, $w_2 = 0.188$, $w_3 = 0.017$, $w_4 = 0.131$, $w_5 = 0.079$, $w_6 = 0.036$, $w_7 = 0.368$, $w_8 = 0.009$, $w_9 = 0.001$.

3.4 Fuzzy Matter-Element Comprehensive Evaluation Calculation

1) Construct standard scheme fuzzy matter-element R_{0n}:
2) Construct difference-square fuzzy matter-element R_{Δ}:
3) Construct indicator weight compound matter-element R_w based on combined weight results:

$$R_w = [w_i] = [0.171, 0.188, 0.017, 0.131, 0.079, 0.036, 0.368, 0.009, 0.001]$$

4) Calculate Euclidean approach degree compound fuzzy matter-element $R_{\rho Hj}$:

$$R_{\rho Hj} = [\rho H_j] = [0.713, 0.551, 0.719, 0.584, 0.962, 0.749, 0.987, 0.792]$$

Euclidean approach degree calculations yielded the following results: Scheme 7 is optimal. In pairwise comparisons where the water transfer project serves as the sole variable factor (Schemes 2 vs. 1, 4 vs. 3, 6 vs. 5, 8 vs. 7), schemes with the central-southern water transfer project (2, 4, 6, 8) achieved higher Euclidean approach degree scores than their counterparts without the project (1, 3, 5, 7). In comparisons with identical allocation volumes (Schemes 3 vs. 1, 4 vs. 2, 7 vs. 5, 8 vs. 6), ecological-priority schemes (3, 4, 7, 8) outperformed domestic-priority schemes (1, 2, 5, 6), demonstrating that ecological-priority allocation yields superior results. This indicates that ecological factors have become an indispensable component in water resources allocation processes.

3.5 Principal Component Analysis Effect Evaluation Calculation

Statistical analysis software was used for principal component analysis to perform dimensionality reduction and factor analysis on receiving area indicator results. Effective principal component screening yielded eigenvalues and contribution rates. The cumulative contribution rate of the first two principal components reached 90.249%, indicating these components adequately represent the influence of selected evaluation factors on receiving areas and reflect the importance of the central-southern water transfer project. Therefore, the first two principal components were retained for data analysis (Table 5).

The first principal component shows strong positive correlations with per capita water consumption, water consumption per 10,000 yuan industrial output value, and pollution assimilation capacity, and negative correlation with regional water shortage rate. These indicators encompass socio-economic levels and ecological environmental conditions, demonstrating strong comprehensiveness. The second principal component exhibits positive correlations with urban per capita green area and urbanization rate, reflecting living environmental quality in receiving area towns.

Principal component load matrix results were copied to a newly established Excel file for transformation calculations. After standardizing raw data, principal component variable values were calculated (Table 6). Each principal component was processed by first calculating comprehensive evaluation function F values using the formula coefficients from Table 6. Principal component weights were determined as $\omega_1 = 0.838$ and $\omega_2 = 0.161$ based on contribution rates. Comprehensive scores D were then obtained (Table 7). Scheme 7 achieved the highest score, identifying it as optimal. All schemes with central-southern water transfer project participation outperformed those without the project. Furthermore, across both planning years, ecological-priority schemes consistently scored higher than domestic-priority schemes under identical conditions, confirming that ecological-priority allocation yields superior results.

3.6 Comparative Analysis of Two Evaluation Results

Comparison of principal component analysis and fuzzy matter-element comprehensive evaluation results for eight water resources optimization allocation schemes is presented in Table 8. The eight schemes can be broadly classified into three tiers: Tier 1 includes schemes with central-southern water transfer project participation (Schemes 2, 4, 6, 7, 8); Tier 2 includes schemes without the water transfer project (Schemes 1, 3, 5). In single-factor comparisons considering only water transfer project participation, schemes with the project consistently outperformed those without. Under identical water transfer and other configuration conditions, ecological-priority allocation results surpassed domestic-priority allocation results.

Both evaluation methods identified Scheme 7 as optimal and Scheme 1 as poorest-performing. While the ranking consistency was high, principal component analysis exhibited more pronounced performance differentials, clearly demonstrating that schemes with the water transfer project are superior and that greater water allocation volumes yield better outcomes. Fuzzy matter-element evaluation also showed that all transfer-project-inclusive schemes outperformed those without the project.

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4 Conclusions

The central and southern Ningxia water transfer project not only supplements substantial water resources to receiving areas but also presents both opportunities and challenges. This study systematically investigated evaluation indicator systems and methodologies for water resources allocation effect assessment in water transfer project receiving areas, subsequently applying principal component analysis and fuzzy matter-element comprehensive evaluation methods. Results demonstrate that: (1) The ecological-priority scheme with central-southern water transfer project participation is optimal; (2) Fuzzy matter-element evaluation confirms that all schemes incorporating the water transfer project outperform those without it; (3) Principal component analysis yields consistent results with more pronounced performance differentials, additionally revealing that greater water allocation volumes in receiving areas produce superior schemes. From a water resources optimization allocation perspective, ecological-priority allocation outperforms domestic-priority allocation, indicating that ecological environmental factors must be considered and prioritized in regional water resources allocation to promote virtuous cycles in regional water resources and ecological systems.

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Note: Figure translations are in progress. See original paper for figures.