agronomy

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# An Evaluation System of the Modernization Level of Irrigation Districts with an Analysis of Obstacle Factors: A Case Study for North China

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**Abstract:** Irrigation districts are a pivotal infrastructure of agricultural water conservancy engineering. Implementing modernization will be the main task of large-scale irrigation districts for a considerable amount of time in the future. In this study, four typical large-scale irrigation districts in North China were investigated: the Renmin Shengliqu, Weishan, Shijin, and Zuncun irrigation districts. The concept of a modern irrigation district was deconstructed to establish an evaluation index system which includes four second-level indicators, twelve third-level indicators, and thirty fourth-level indicators. A hybrid approach based on AHP and OWA was used to quantify indicator weights used in group decision making. TOPSIS was introduced to measure the modernization level of the four irrigation districts. An obstacle factor diagnosis model was applied to search for key obstacle factors that will affect the modernization and improvement of the irrigation districts. The results showed that (1) the modernization levels of the Renmin Shengliqu, Weishan, Shijin, and Zuncun irrigation districts in 2020 and 2025 were 0.3916 and 0.5755, 0.3748 and 0.5396, 0.4493 and 0.6012, and 0.2343 and 0.6166, respectively. The evaluation results indicate that the four irrigation districts are still in the beginning phase (or even preparation phase) of the modernization process. (2) Eight indicators were identified as the main common obstacle factors for the four evaluated irrigation districts, including the irrigation water-use efficiency factor, the coverage proportion of information technology, the proportion of efficient water conservation irrigation areas, and so on. (3) There are two effective methods to enhance the modernization level of the four irrigation districts: improving water resource utilization efficiency and strengthening the management system with an emphasis on informatization. The present study can enrich the theoretical evaluation of irrigation districts and provide a scientific basis for the modernized construction and management of irrigation districts in China.

**Keywords:** irrigation district; comprehensive evaluation; index system; modernization level; TOPSIS; obstacle diagnosis model; OWA; North China



**Citation:** Fan, X.; Qin, J.; Lv, M.; Jiang, M. An Evaluation System of the Modernization Level of Irrigation Districts with an Analysis of Obstacle Factors: A Case Study for North China. *Agronomy* **2024**, *14*, 538. https://doi.org/10.3390/agronomy14030538

Academic Editor: Maria do Rosário Cameira

Received: 23 January 2024
Revised: 29 February 2024
Accepted: 4 March 2024
Published: 5 March 2024



## 1. Introduction

Agriculture is the main industry of the national economy of China. As a significant infrastructure, irrigation districts provide water resources for agricultural production through water diversion, conveyance, and distribution. There were more than 7800 large-scale (≥20,000 ha) and medium-scale (667 to 20,000 ha) irrigation districts in China in 2022; the total grain yield of these irrigation districts accounted for 50% of the national grain production while its water consumption was 215 billion m$^3$, accounting for 39.10% of the total water consumption in China. In particular, large-scale irrigation districts play an important role in mass food production and the intensive utilization of water resources. With the rapid development of the economy and society, constructing modern irrigation districts is the main task for the future. The Ministry of Water Resources of China planned to take fifteen years to improve the backbone irrigation and drainage infrastructure, upgrade the management processes, ameliorate the ecological environment, enhance water resource utilization efficiency, and, finally, build a group of modern irrigation districts that can be adapted to the demand of the times. Since 2020, some large-scale irrigation districts have begun their modernization; for example, through canal lining and digital twin irrigation district platform design, the Renmin Shengliqu Irrigation District is building new infrastructure and strengthening its management as a modern irrigation district.

Comprehensive evaluation, as an effective tool for quantitative management and decision making, can describe the complex system of an irrigation district and measure its overall development level.

Some studies on the comprehensive evaluation of irrigation districts have been conducted. Early related studies mainlyconcentrated on improving the utilization efficiency of limited soil and water resources [1], maintaining a stable socioeconomic system [2], and promoting coordinated development balancing economic benefits and the ecological environment [3]. In the 2000s, the Rehabilitation and Water-Saving Reform of Large-Scale Irrigation Districts Project was carried out all over China, and the research focus switched to project assessment and its subsequent effects, such as comprehensive benefits [4], water conservation effects [5,6], ecological environment impact [7,8], and so on. Meanwhile, a new concept called a water-saving irrigation district was proposed. During the 2010s, the construction of ecological civilization became a national strategy, and the research on irrigation districts shifted towards a focus on the ecological environment, with topics such as ecological health [9], ecological systems [10], and ecological irrigation districts [11]. In 2020, the Ministry of Water Resources of China formulated and implemented a nationwide modernization construction plan for large-scale irrigation districts, with a 15-year plan to comprehensively and systematically improve the development level of large-scale irrigation districts. However, as an emerging concept, there are few studies on the comprehensive evaluation system.

An indicator system involves the decomposition and quantification of different evaluation objects and systems [12]. Gu [13] developed an index system for the comprehensive evaluation of irrigation districts' sustainable development, including four second-level indicators and sixteen third-level indicators. Based on a comparative evaluation of seven indicators before and after rehabilitation, Wang [14] and Zhang [15] analyzed the integrated benefit of large-scale irrigation districts. Sun [16] constructed a four-layer, 35-indicator evaluation system to evaluate the agricultural water management in irrigation districts of North China. Zhang [17] established an evaluation index system for the water resource carrying capacity of ecological irrigation districts and applied it to the Dagong Yellow River Diversion Irrigation District. Zhang [9] designed a health evaluation index system to effectively evaluate an ecological irrigation district. Liu [18] proposed an index system targeted at ecological civilization irrigated districts that included 18 indicators. Chai [19] extracted 35 indicators from a 112-indicator base to accomplish dynamic ecological environment evaluation. It can be concluded that the research on indicator systems roughly follows the changes in the study subjects in different time periods.

An irrigation district is a complex system that includes economic factors, social factors, ecological environmental factors, etc. Thus, a methodology for the comprehensive evaluation of irrigation districts is a multi-criteria decision-making (MCDM) problem. There are various mathematical techniques that can be classified as MCDM methods and used for irrigation district evaluation, such as the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) [20], Bayesian Network (BN) models [21], Data Envelopment Analysis (DEA) [22], the Variable Fuzzy Set (VFS) [23], the Weighted Average Method [24], the Project Pursuit Model [25], VIse Kriterijumski Optimizacioni Racun (VIKOR) [26], and the Best–Worst Method (BWM) [27]. Among these methods, TOPSIS is a decision-making technique for multiple-objective decision analysis that was proposed by Hwang and Yoon [28,29] and has been successfully applied in many fields, including, but not limited to, electrical network management [30], assessments [31,32], human resource management [33], supplier selection [34], and carbon regulation [35,36]. Here, an emphasis is placed on the quantifiable difference between the evaluation object's state at a specific time and the ideal state, which can be effectively handled by TOPSIS [37,38]. TOPSIS can systematically deal with the difference through the geometric distance of multidimensional vectors. In addition, compared to VIKOR, TOPSIS measures an object by utilizing its relative distance between the positive ideal solution (PIS) and the negative ideal solution (NIS), while VIKOR only considers the distance from the positive solution [39]. Thus, TOPSIS provides PIS-based guidance and an NIS-based rectifying role. As a note, since the data constituting the positive ideal solution and negative ideal solution are obtained from inside of each evaluation object, conventional TOPSIS methods can only calculate the relative ranking among various schemes, and the evaluation results can only be used for internal comparisons [40–42]. Therefore, in this study, the target value of irrigation district modernization will be introduced to constitute the ideal solution for modernization in order to achieve an absolute measurement of the level of irrigation district modernization.

Weighting is a quantitative process that indicates the relative importance of each indicator and is also a key link in the entire evaluation system. The existing weighting methods can be classified into two categories: subjective-based methods and objective-based methods. The former calculates indicator weights according to the subjective will of experts, such as the Analytic Hierarchy Process (AHP) [43,44], the Delphi Method [45], etc.; the latter determines weights based only on the indicator values, not subjective judgments, and includes the Entropy Method [46], the CRITIC Method [47], the Variance Coefficient Method [48], Principle Component Analysis (PCA) [49], etc. As a management institution of water supplies, multiple stakeholders construct irrigation districts based on their respective cognition, so the weighting process should take the subjective willingness of all parties into account. In view of its clear structure and simple process, the AHP is regarded as the representative of the subjective method; it has been widely applied and has been proven to be effective and scientific [50–52].

To sum up, as a newly emerging concept, there are few evaluation systems for modern irrigation districts; these include a comprehensive evaluation index system, an adoptable evaluation method, reasonable weight allocation, and evaluation result-based key factor analysis. In brief, it is difficult to support the evaluation of irrigation district modernization by only relying on the existing research. In order to fill the research gaps mentioned above and provide countermeasures and suggestions on a decision-making basis and management reference for the ongoing modernization construction and management practices, this study was conducted specifically. In the present study, a complete evaluation system including an index system, an evaluation method, a weighting method, and problem extraction was constructed. In addition, an empirical analysis was conducted of four representative large-scale irrigation districts (the Renmin Shengliqu, Weishan, Shijin, and Zuncun irrigation districts) located in four agricultural provinces in North China. This study consisted of the following four parts: (1) establishing an evaluation index system with a hierarchical structure based on the attributes and objectives of modern irrigation districts; (2) designing a subjective weighting method including four categories of agricultural water industry stakeholders; (3) applying the improved TOPSIS method to comprehensively evaluate the modernization level of the four irrigation districts; (4) exploring eight key obstacle factors that limit the modernization progress of irrigation districts using the indicator system based on the Obstacle Factor Diagnostic Model. The main aim of this paper is to fill the research gap in the field of comprehensive evaluation and guide the medium-long-term planning of irrigation districts. So, we will summarize the main conclusions, limitations, and future research directions for the evaluation of irrigation district modernization and provide some policy recommendations for the modernization of the four irrigation districts in North China. A detailed flow chart is shown in Figure 1.

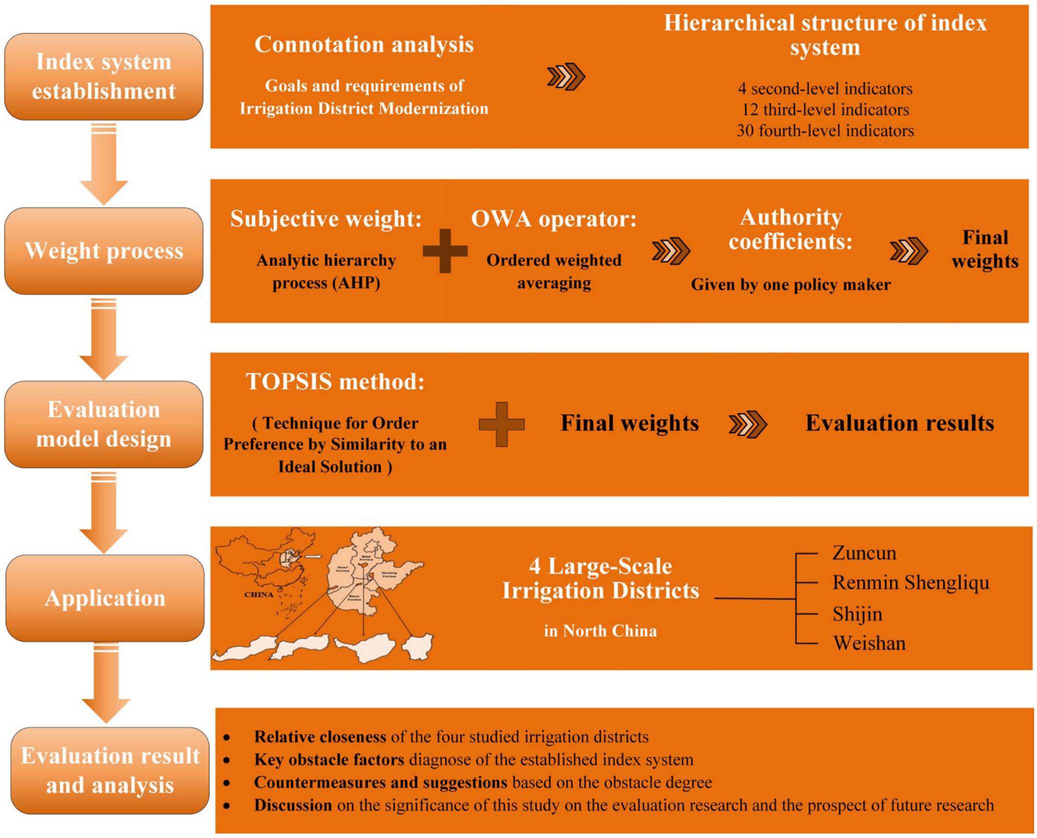


**Figure 1.** The flowchart of this study.

## 2. Materials and Methods

### 2.1. Index System

In 2020, the Ministry of Water Resources of China [53] defined the concept of a modern irrigation district by describing its four attributes: efficient water conservation, perfect infrastructure, scientific management, and good ecology. The present study will follow this definition and treat these attributes as second-level indicators. Based on the principle of scientificity and representativeness, an index system with pertinence and maneuverability will be constructed for the four studied irrigation districts in North China to ensure the reliability and validity of the measurements of the districts' modernization process. The designed evaluation index system includes one first-level indicator, four second-level indicators, twelve third-level indicators, and thirty fourth-level indicators, as shown in Table 1. The detailed explanation of Table 1 is as follows:

(1) There are four third-level indicators for efficient water conservation, including the water conservation project, water resource allocation, planting structure, and the water conservation mechanism. The indicators for the water conservation project include $A_{11}$ and $A_{12}$. They reflect the degree of coverage of irrigation district water sources and the coverage of highly efficient water conservation irrigation techniques. Water resource allocation mainly represents the efficiency and rationality of water resource utilization. It comprehensively considers water resource consumption from water sources to crops and lifts the ecological water supply to be parallel to the agricultural water supply to support the water ecological function of irrigation districts. The indicators in this section are the irrigation water use efficiency factor ($A_{21}$) and the ecological water demand satisfaction rate ($A_{22}$). For $A_{22}$, the ecological water demand volume is measured by each irrigation district's management bureau based on their own situation and mainly includes large-scale greenbelt water demand, river and lake replenishment within the irrigation district, groundwater recharge, and others. The indicator for planting structure is used to express the relative proportion of different

plants. Furthermore, an area comparison between grain crops and cash crops will reveal the balance between grain production and agricultural economic development, which is represented by $A_{31}$. The indicator for the water conservation mechanism includes $A_{41}$ and $A_{42}$, which represent the mechanism's perfection degree in terms of rewards and penalties. For water users whose water consumption does not exceed the water quota in a certain year, the irrigation district management bureau will provide corresponding water conservation bonuses. However, owing to various reasons, these rewards are often difficult to fully implement; this indicator can fully reflect the implementation of water conservation policies in the irrigation district.

(2) Perfect infrastructure includes four third-level indicators: water source engineering, water delivery and distribution engineering, field engineering, and drainage engineering. These indicators were established to measure the infrastructure development level of irrigation district canals and drainage ditches and can be quantified by the intact rate and matching rate during the process of modernization. The ten fourth-level indicators are $B_{11}$ and $B_{12}$ (for water source engineering); $B_{21}$, $B_{22}$, $B_{23}$, and $B_{24}$ (for delivery and distribution engineering); $B_{31}$ and $B_{32}$ (for field engineering); and $B_{41}$ and $B_{42}$ (for drainage engineering). High-Standard Farmland is a construction project supervised by the Chinese Agricultural Department and it has had a significant impact on the water use efficiency at the field scale. Due to limited past investments, some irrigation districts have not yet completed the construction of all drainage facilities; $B_{42}$ is used to measure the ratio of built drainage facilities to all drainage facilities that should be built at a specific time point.

(3) Scientific management includes two third-level indicators: normalization and standardization management and water consumption order. The normalization and standardization management considers dedicated administrators ($C_{11}$, $C_{12}$), funds and support ($C_{14}$, $C_{15}$), and grassroots water user association development ($C_{13}$). The index of water consumption order should reflect water measurements, the collection of water charges, and information technology supporting the above tasks. The corresponding indicators are $C_{21}$, $C_{22}$, and $C_{23}$. Information technology is used to collect water fees through precise measurements, ultimately improving the water management efficiency of irrigation district management bureaus.

(4) The indicators related to good ecology should fully reflect the ecological service function of the irrigation district. There are two third-level indicators: the irrigation district residential environment composed of the forest cover rate ($D_{11}$) and the water area rate ($D_{12}$), and landscape service, which consists of the comfort level near water ($D_{21}$) and is used to evaluate the satisfaction level of residents concerning the leisure and entertainment services provided by the water landscape, which reflects the ecological service function of the irrigation district. The landscape water quality compliance rate ($D_{22}$) and the water ecological monitoring system coverage rate ($D_{23}$) are automatically measured by water quality monitoring systems installed in backbone canal systems and drainage ditches to avoid water pollution.

**Table 1.** The index system for evaluating irrigation district modernization.

| 2nd-Level Indicator | 3rd-Level Indicator | 4th-Level Indicator | Unit | Source(s) | Property |
|---|---|---|---|---|---|
| Efficient water conservation $A$ | Water conservation project $A_1$ | Proportion of efficient water conservation irrigation area $A_{11}$ | % | [16,24] | Positive |
| | | Proportion of effective irrigated area $A_{12}$ | % | MWR | Positive |
| | Water resource allocation $A_2$ | Irrigation water use efficiency factor $A_{21}$ | no unit | MWR | Positive |
| | | Ecological water demand satisfaction rate $A_{22}$ | % | MWR, [18,24] | Positive |

**Table 1.** *Cont.*

| 2nd-Level Indicator | 3rd-Level Indicator | 4th-Level Indicator | Unit | Source(s) | Property |
|---|---|---|---|---|---|
| Efficient water conservation *A* | Planting structure $A_3$ | Area ratio between grain crops and cash crops $A_{31}$ | no unit | [16] | Positive |
| | Water conservation mechanism $A_4$ | Implementation level of water conservation rewards $A_{41}$ | % | MWR, [16] | Positive |
| | | Collection rate of higher water bills $A_{42}$ | % | MWR | Positive |
| Perfect infrastructure *B* | Water source engineering $B_1$ | Matching rate of water source engineering $B_{11}$ | % | MWR | Positive |
| | | Intact rate of water source engineering $B_{12}$ | % | MWR | Positive |
| | Water delivery and distribution engineering $B_2$ | Lining rate of backbone canal system $B_{21}$ | % | MWR, | Positive |
| | | Intact rate of backbone canal system $B_{22}$ | % | MWR | Positive |
| | | Matching rate of backbone canal system structures $B_{23}$ | % | MWR | Positive |
| | | Intact rate backbone canal system structures $B_{24}$ | % | MWR | Positive |
| | Field engineering $B_3$ | Matching rate of field channel facilities $B_{31}$ | % | MWR | Positive |
| | | Proportion of High-Standard Farmland area $B_{32}$ | % | [7,16] | Positive |
| | Drainage engineering $B_4$ | Intact rate of drainage facilities $B_{41}$ | % | MWR | Positive |
| | | Matching rate of drainage facilities $B_{42}$ | % | MWR | Positive |
| Scientific management *C* | Normalization and standardization management $C_1$ | Number of dedicated administrators per 1000 ha $C_{11}$ | 1000 $ha^{-1}$ | MWR | Negative |
| | | Proportion of dedicated administrators with junior college degrees or above $C_{12}$ | % | [16] | Positive |
| | | Coverage proportion of water user associations $C_{13}$ | % | MWR | Positive |
| | | Implementation rate of personnel funds $C_{14}$ | % | MWR, [14,16] | Positive |
| | | Implementation rate of maintenance funds $C_{15}$ | % | MWR, [13,14] | Positive |
| | Water consumption order $C_2$ | Proportion of water charge collection $C_{21}$ | % | MWR | Positive |
| | | Flow rate in lateral canal entrance $C_{22}$ | % | MWR, [12] | Positive |
| | | Coverage proportion of information technology $C_{23}$ | % | MWR | Positive |
| Good ecology *D* | Residential environment $D_1$ | Proportion of forest cover $D_{11}$ | % | [10,11] | Positive |
| | | Proportion of water area $D_{12}$ | % | [9] | Positive |
| | Landscape service $D_2$ | Comfort level near water $D_{21}$ | % | MWR | Positive |
| | | Landscape water quality compliance rate emphD$_{22}$ | % | MWR | Positive |
| | | Water ecological monitoring system coverage rate $D_{23}$ | % | MWR, [9,11] | Positive |

## 2.2. Methods

### 2.2.1. AHP Method

The establishment of an irrigation district must meet the needs of human production and domestic water use; however, the relative importance of the construction content contained in different indicators also varies, which often results in different policy orientations and investment preferences. In this study, the concept of a hierarchical pairwise comparison was introduced by using the AHP method. By using AHP, the weighting process can be divided into several hierarchical levels, and then a pairwise comparison at each level can be made based on the knowledge and experience of the experts surveyed (professional stakeholders). AHP is about breaking a problem down and then aggregating the solutions of all the sub-problems into a conclusion [54]. There are two reasons for using AHP: on the one hand, it is a quantifiable subjective weighting method, and its calculation process is based on the experience of experts in assessing the importance of indicators, so it can systematically address the weight of a large number of indicators; on the other hand, the consistency check step it contains helps avoid the negligence caused by experts when indicators are weighed, which ensures the accuracy of the weighting results. Its successful application in various fields has proved the above two conclusions [55–57]. The weights are applied to all the inter- and intra-hierarchy factors, and here, the AHP method provides a structured framework to set the relative importance on each level of the hierarchy using pairwise comparisons that are quantified using a scale of 1–9 [58].

Let $C_1$, $C_2$, …, $C_m$ be m evaluated indicators and they are at the same level; $W = (w_1, w_2, \ldots, w_m)$ are their normalized relative importance weight vectors which can be calculated by using pairwise comparisons and satisfy the normalization condition:

$$\sum_{j=1}^{m} w_j = 1, \text{with } w_j \geq 0, \text{ and } j = 1, 2, \cdots, m \tag{1}$$

The relative importance comes from pairwise comparisons between the m indicators and can be obtained by surveying industry experts. Each expert's response forms an $m \times m$ pairwise comparison matrix as follows:

$$A_{pairwise} = (a_{ij})_{m\times m} = \begin{matrix} & C_1 & C_2 & \cdots & C_m \\ C_1 & a_{11} & a_{12} & \cdots & a_{1m} \\ C_2 & a_{21} & a_{22} & \cdots & a_{2m} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ C_m & a_{m1} & a_{m2} & \cdots & a_{mm} \end{matrix} \tag{2}$$

where $a_{ij}$ is a quantified judgment on $w_i/w_j$, $a_{ii} = 1$ and $a_{ij} = 1/a_{ji}$ for $i, j = 1, 2, \ldots, m$.

If the matrix $A_{pairwise}$ satisfies $a_{ij} = a_{ik} \times a_{ki}$ for any $i, j, k = 1,2, \ldots, m$, then $A_{pairwise}$ can be identified as completely consistent; otherwise, it is inconsistent. Based on the matrix $A_{pairwise}$, the weight vector $W$ can be calculated by solving the following characteristic equation:

$$A_{pairwise}W = \lambda_{max}W \tag{3}$$

where $\lambda_{max}$ is the maximum eigenvalue of matrix $A_{pairwise}$ and its eigenvector ($X = \{X_1, X_2, \ldots, X_m\}$) can be obtained after normalizing the eigenvector $X$ [59], as shown below.

$$W = \left\{ X_1/\sum_{i=1}^{m} X_i \quad X_2/\sum_{i=1}^{m} X_i \quad \cdots \quad X_i/\sum_{i=1}^{m} X_i \right\} = \left\{ W_1 \quad W_2 \quad \cdots \quad W_m \right\} \tag{4}$$

Then, a consistency check is calculated to ensure that the pairwise comparison matrix evaluation is accurate and effective. Thus, the random consistency ratio ($CR$) is proposed for this verification before the weight vector as follows:

$$CR = \frac{|\lambda_{max} - m|}{m-1} \times \frac{1}{RI} \tag{5}$$

where $RI$ is the average random consistency indicator and its values are shown in Table 2.

**Table 2.** Values of average random consistency ($RI$).

| *m* | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *RI* | 0 | 0 | 0.58 | 0.90 | 1.12 | 1.24 | 1.32 | 1.41 | 1.45 | 1.49 | 1.51 | 1.54 | 1.56 |

According to the AHP method, if $CR \leq 0.1$, the pairwise comparison matrix is acceptable and available; otherwise, the above process must be repeated to ensure consistency.

#### 2.2.2. OWA Operator Based on Stakeholders

Ordered Weighted Averaging (OWA) operators were proposed by Yager [60] and are widely used to measure preference aggregations for group decision making [61–63]. By ranking the information provided by each expert, OWA determines the comprehensive information of the object to be evaluated through weighted averages. The weighting result of a single expert makes it difficult to avoid the contingency, not reflecting the overall opinion of the whole industry. OWA enables the integration and generalization of multiple experts' weighting results; the method assumes that the weighting results of the same indicator obey normal distribution, and the processing of group decision results ensures the integrity of weights information [64].It should be noted that the number of experts met the requirements of OWA and the Delphi method [65].

The OWA process is conducted as follows:

Step 1. For every evaluation indicator, the weight given by each type of stakeholder is $a_1, a_2, \ldots, a_n$. Then, the vector is arranged in descending order and these elements are ranked starting with zero to obtain $b_0 \geq b_1 \geq b_2 \geq \ldots b_j \geq \ldots \geq b_{n-1}$.

Step 2. The newly sorted $b_j$ are weighted according to combination numbers, which are defined as $\sum_{k=0}^{n-1} C_{n-1}^{k} = 2^{n-1}$, and form a weighted vector as follows:

$$w_{j+1} = C_{n-1}^{j} / \sum_{k=0}^{n-1} C_{n-1}^{k} = C_{n-1}^{j} / 2^{n-1} \quad (6)$$

Step 3. The weights given by the experts of the corresponding type are weighted by using the weighted vector, and then the absolute weight of indicator $i$ is calculated:

$$\overline{\omega}_i = \sum_{i=1}^{n} w_j b_j \quad (7)$$

where $w_j \in [0, 1], j \in [1, n]$.

Step 4. The relative weight of indicator $i$ is

$$\omega_i = \overline{\omega}_i / \sum_{i=1}^{m} \overline{\omega}_i \quad (8)$$

where $i = 1, 2, \ldots, n$.

Through the group decision-making process using the OWA operator above, the 3 types of stakeholders' weight preferences are integrated. Then, the policymaker designates the authority coefficient of the 3 stakeholders, and the final weights of each indicator are obtained as follows:

$$\omega_i^{final} = \alpha\omega_i^M + \beta\omega_i^R + \gamma\omega_i^P \quad (9)$$

where $\alpha$, $\beta$, and $\gamma$ are the authority coefficients of the manager, the researcher, and the producer, respectively. $\alpha + \beta + \gamma = 1$. $\omega_i^M$, $\omega_i^R$, and $\omega_i^P$ are the relative weights of indicator $i$ for the manager, the researcher, and the producer, respectively.

#### 2.2.3. TOPSIS Method

TOPSIS is widely used for decision making using multiple criteria. By setting the positive ideal solution and the negative ideal solution, TOPSIS tries to rank evaluated objects based on the relative distance between the positive ideal solution and the negative ideal solution [66–68]. It has the characteristics of a simple principle and calculation process and can be well integrated with indicator weights. At the same time, it can not only reflect the difference between the evaluated object and the ideal solution but also indicate the difference between the evaluated objects. In this study, the TOPSIS method consisted of the following steps:

(1) The determination of the evaluation objects. The panel data for 2020 and 2025 in the 4 irrigation districts were selected as the objects. The 2020 data were from actual investigation while the 2025 data were from planning data based on development predictions.

(2) The establishment of an evaluation matrix. $m$ represents the number of evaluation objects. $m$ is equal to 8, since each irrigation district has two sets of panel data that correspond to the years 2020 and 2025, respectively. Two groups of ideal value are input into the matrix as 2 additional rows. $n$ is the indicator number, and the data matrix is as follows:

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ x_{m+1,1} & x_{m+1,2} & \cdots & x_{m+1,n} \\ x_{m+2,1} & x_{m+2,2} & \cdots & x_{m+2,n} \end{bmatrix} \quad (10)$$

(3) The determination of the positive ideal and negative ideal solutions. For the positive ideal solution,

$$X_{pis} = \begin{bmatrix} x_{m+1,1} & x_{m+1,2} & \cdots & x_{m+1,n} \end{bmatrix} \quad (11)$$

For the negative ideal solution,

$$X_{nis} = \begin{bmatrix} x_{m+2,1} & x_{m+2,2} & \cdots & x_{m+2,n} \end{bmatrix} \quad (12)$$

where $x_{m+2,j}$ is the worst value of the $j$th indicator that was planned for the 4 irrigation districts for 2020.

(4) The standardization of matrix $X$. The standardization process is as follows: For the profitability indicator,

$$r_{ij}^{+} = \left(x_{ij} - x_{m+2,j}\right) / \left(x_{m+1,j} - x_{m+2,j}\right) \quad (13)$$

where $j$ = 1, 2, 3, . . ., $n$. For the cost indicator,

$$r_{ij}^{-} = \left(x_{m+1,j} - x_{ij}\right) / \left(x_{m+1,j} - x_{m+2,j}\right) \quad (14)$$

where $j$ = 1,2,3, . . ., $n$. Then, the standardized matrix is

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ r_{m+1,1} & r_{m+1,2} & \cdots & r_{m+1,n} \\ r_{m+2,1} & r_{m+2,2} & \cdots & r_{m+2,n} \end{bmatrix} \quad (15)$$

(5) The construction of weighted matrix $Y$.

$$Y = \begin{bmatrix} y_{11} & y_{12} & \cdots & y_{1n} \\ y_{21} & y_{22} & \cdots & y_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ y_{m+1,1} & y_{m+1,2} & \cdots & y_{m+1,n} \\ y_{m+2,1} & y_{m+2,2} & \cdots & y_{m+2,n} \end{bmatrix} \quad (16)$$

where $\omega_i^{final}$ represents the final weight of ith indicator and $y_{ij} = r_{ij} \times \omega_i^{final}$.

(6) The establishment of the weighted normalization matrix $Z$.

$$Z = \begin{bmatrix} z_{11} & z_{12} & \cdots & z_{1n} \\ z_{21} & z_{22} & \cdots & z_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ z_{m+1,1} & z_{m+1,2} & \cdots & z_{m+1,n} \\ z_{m+2,1} & z_{m+2,2} & \cdots & z_{m+2,n} \end{bmatrix} \quad (17)$$

where $z_{ij} = y_{ij} / \sqrt{\sum_{i=1}^{m} y_{ij}^2}$.

(7) The calculation of the relative closeness of each irrigation district. The distance of the 4 irrigation districts from the positive ideal and negative ideal solutions can be obtained as follows:

$$D_i^{+} = \sqrt{\sum_{j=1}^{n} \left(Z_{ij} - Z_j^{+}\right)^2}, D_i^{-} = \sqrt{\sum_{j=1}^{n} \left(Z_{ij} - Z_j^{-}\right)^2} \quad (18)$$

where $i$ = 1, 2, . . ., $m$. The relative closeness of the irrigation districts is

$$D_i = D_i^{-} / \left(D_i^{-} + D_i^{+}\right), i = 1, 2, \cdots, m \quad (19)$$

where $D_i$ is between 0 and 1. The larger the value, the better the modernization level of the corresponding evaluation object. Based on previous studies [69,70], the relative closeness can be divided into 5 grades, which are used to represent different phases in the process of modernization (Table 3).

**Table 3.** Modernization phases of irrigation districts.

| Relative Closeness | Modernization Phase |
|---|---|
| (0, 0.3000) | Preparation phase |
| [0.3000, 0.5000) | Beginning phase |
| [0.5000, 0.7000) | Initial implementation phase |
| [0.7000, 0.9000) | Basic realization phase |
| [0.9000, 1.0) | Developed phase |

#### 2.2.4. Obstacle Factor Diagnosis Model

An obstacle factor diagnosis model can enable targeted formulation and the adjustment of investment preferences and policy guidance by analyzing and diagnosing the key obstacles that affect the modernization of irrigation districts. Here, the obstacle diagnosis model [71] was used to determine the degree of obstacles that restrict irrigation district modernization and the specific obstacle factors. The formula for calculating the obstacle degree is as follows:

$$O_{ij} = \omega_j^{final}\left(1 - r_{ij}\right)/\sum_{j=1}^{n} \omega_{j=1}^{final}\left(1 - r_{ij}\right) \quad (20)$$

where $O_{ij}$ is the obstacle degree of irrigation district $i$ based on the $j$th indicator; $\omega_j^{final}$ is the final weight of the $j$th indicator; and $r_{ij}$ is the element of the standardized matrix from Equations (13) and (14).

## 3. Application

### *3.1. Study Areas*

North China (110°04′–122°42′ E, 31°23′–42°40′ N) mainly covers four provinces (Hebei, Henan, Shandong, and Shanxi) and two megacities (Beijing and Tianjin). The prevailing continental semi-humid monsoon climate brings the area cold, dry winters and hot, wet summers, with an average annual precipitation in the region of less than 600 mm. The irrigation districts are densely distributed in North China and have a tillage history of over 2000 years, which makes it a traditional agricultural production area. Since the 21st century, rehabilitation and water conservation reform projects have greatly promoted the construction level of irrigation districts in this area and consolidated the foundation of the water supply. However, as the economic and social needs have changed, the local irrigation districts are facing a series of difficulties and challenges. Some of these are inherent and long-standing, such as the serious aging of engineering facilities, the low support for engineering facilities, the low design standards for irrigation and drainage projects, etc. The other challenges are newly emerged, for instance, low irrigation water prices, unreasonable groundwater exploitation, a worsening environment, a low information level, etc. In 2021, the Ministry of Water Resources of China selected 34 out of the existing 451 large-scale irrigation districts and incorporated them into the 14th Five-Year Plan on large-scale irrigation district rehabilitation and modernization projects. In the following 5 to 15 years, the 34 selected irrigation districts will obtain large-scale investments to improve their development level. Four typical large-scale irrigation districts in North China, including the Shijin Irrigation District in Hebei Province, the Zuncun Irrigation District in Shanxi Province, the Renmin Shengliqu Irrigation District in Henan Province, and the Weishan Irrigation District in Henan Province, are the focus of this study and their locations are shown in Figure 2.

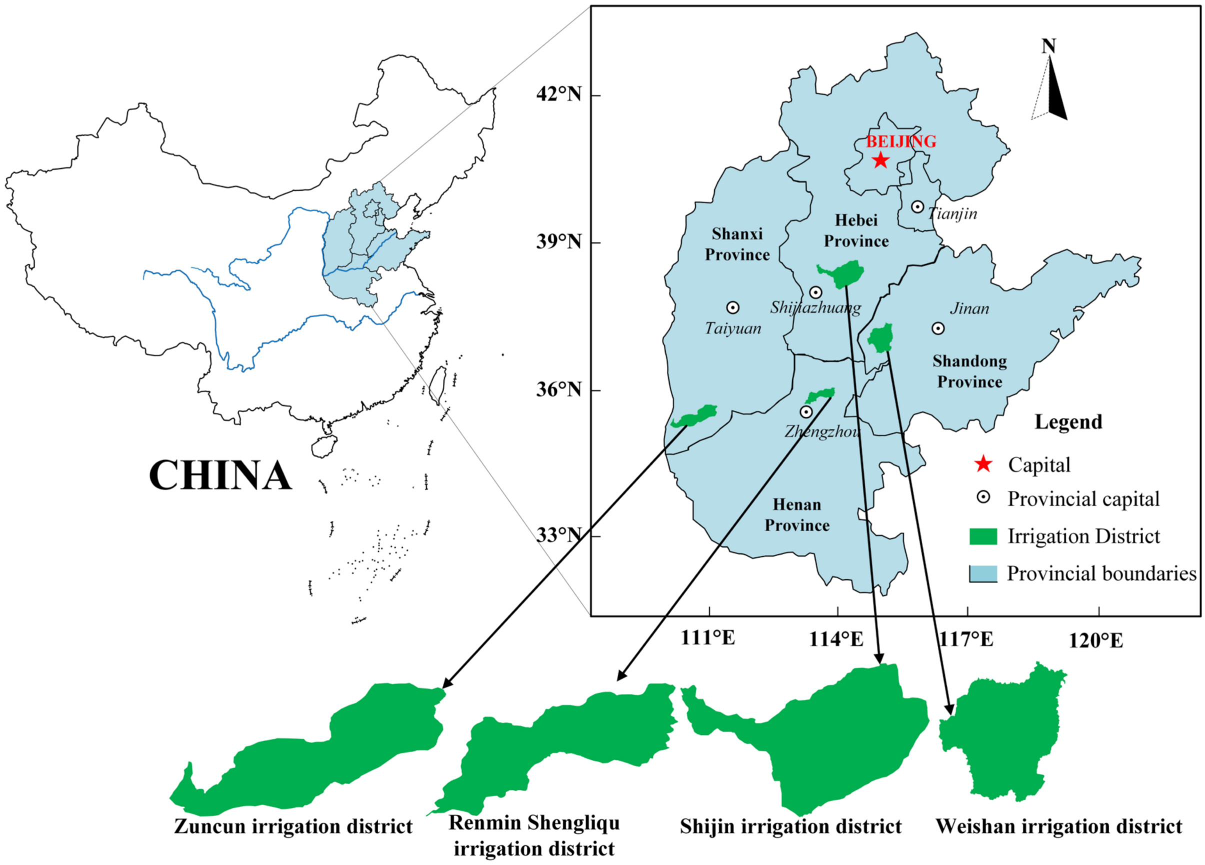


**Figure 2.** The location of studied irrigation districts.

The reasons why these irrigation districts were chosen are as follows: (1) they are well known locally and even nationally, and have a significant influence on the industry; (2) long-term national policy support and construction investment from all levels of government made them more representative for modernization processes; (3) the problems they face have both commonalities and differences, but they basically cover all the weaknesses of all large-scale irrigation districts in North China; and (4) they have relatively good archival management systems which facilitated the process of data collection and collation.

To provide a more detailed description of the four irrigation districts, some important background parameters are given in Table 4. The crop patterns of the four irrigation districts are presented in Table 5, and the agricultural irrigation water consumption amounts from 2016 to 2020 of the four districts are provided in Figure 3. Lastly, the digital elevation information of the four districts is demonstrated in Figures A1–A4.

**Table 4.** Basic information on the four irrigation districts.

| District | Designed Irrigation Area ($10^4$ Hectares) | Water Source(s) | Intake Type(s) | Water Carriage Mode | Main Soil Type |
|---|---|---|---|---|---|
| Renmin Shengliqu | 99,200 | Yellow River | Artesian diversion | Canal system | Loam, sandy soli |
| Zuncun | 110,667 | Yellow River | Electric pumping | Canal system | Clay loam, sandy loam |
| Shijin | 162,667 | Gangnan Reservoir, groundwater | Water storage irrigation, well irrigation | Canal system | Loam, sandy loam |
| Weishan | 338,667 | Yellow River | Artesian diversion | Canal system | Loam, sandy loam |

**Table 5.** The crop patterns of the four irrigation districts in 2020.

| District | Wheat | Maize | Rice | Peanut | Cotton | Fruit | Vegetable |
|---|---|---|---|---|---|---|---|
| Renmin Shengliqu | 69% | 61% | 12% | 10% | 9% | 8% | 12% |
| Shijin | 70% | 70% | 0% | 21% | 9% | 0% | 0% |
| Zuncun | 45% | 30% | 0% | 0% | 20% | 30% | 5% |
| Weishan | 75% | 66% | 0% | 5% | 5% | 0% | 0% |

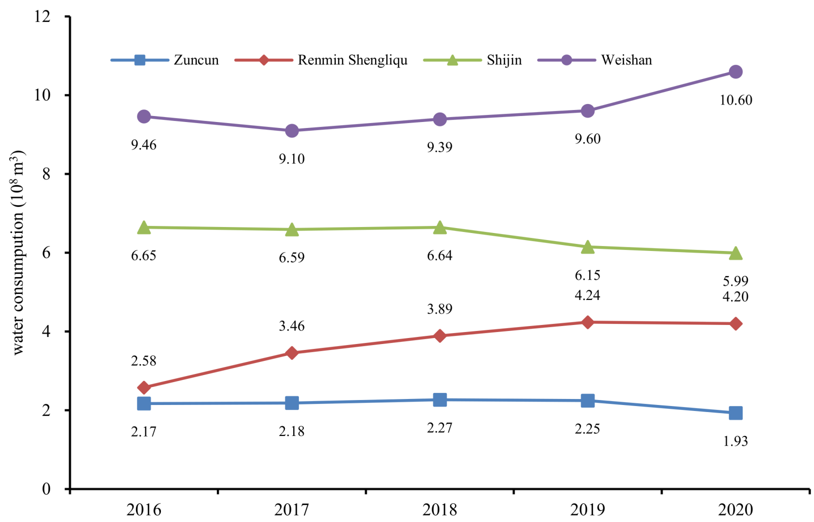


**Figure 3.** The irrigation water consumption of the four irrigation districts from 2016 to 2020.

### *3.2. Data Collection*

In the present study, 2020, 2025, and 2035 were selected as the time points for research. The data and target values of the evaluation indicators were mainly from the 14th Five Year Plan on large-scale irrigation district rehabilitation and the implementation of modernizing transformation designed by the corresponding irrigation district management bureau, while some water management data in 2020 came from grassroots local WUAs which are affiliated with local management bureaus. It should be noted that most planning values for the Shijin Irrigation District for 2035 are unavailable, so this irrigation district was excluded from structuring the positive ideal solution in the TOPSIS method in Section 2.2.3.

In the present study, the experts in the irrigation district field were classified into four types of professional stakeholders: policymaker, manager, researcher, and producer; their affiliations and positions are shown in Table 6. An AHP questionnaire was sent to every expert by e-mail or by post. Then, the OWA operator was used to integrate the weights given by each expert through AHP. It should be noted that the policymakers did not directly take part in the AHP questionnaire about indicator weights; instead, they quantified the authority degree of the three other stakeholders, which was called the expert's weight coefficient. The number of experts met the requirements of OWA and the Delphi method [48].

**Table 6.** Information on the four types of professional stakeholders.

| Stakeholder Type | No. | Department Type | Current Role | Years of Experience |
|---|---|---|---|---|
| Policymaker | 1 | Official water administrative department | Chief engineer | 24 |
| Manager | 2 | Specialized management organization | Head of organization | 21 |
| | 3 | Specialized management organization | Head of organization | 20 |
| | 4 | Specialized management organization | Project manager | 16 |
| | 5 | Specialized management organization | Project manager | 23 |
| | 6 | Contracting company | Construction manager | 17 |
| | 7 | Contracting company | Construction manager | 13 |

**Table 6.** *Cont.*

| Stakeholder Type | No. | Department Type | Current Role | Years of Experience |
|---|---|---|---|---|
| Researcher | 8 | University | Professor | 18 |
| | 9 | University | Professor | 17 |
| | 10 | University | Associate professor | 9 |
| | 11 | Research institute | Senior researcher | 28 |
| | 12 | Research institute | Senior researcher | 22 |
| | 13 | Research institute | Associate researcher | 9 |
| | 14 | Research institute | Senior researcher | 12 |
| | 15 | Research institute | Senior researcher | 13 |
| Producer | 16 | Water user association | Head of WUA | 10 |
| | 17 | Water user association | Head of WUA | 13 |
| | 18 | Water user association | Head of WUA | 8 |
| | 19 | Water user association | Head of WUA | 15 |
| | 20 | Water user association | Member of WUA | 14 |
| | 21 | Water user association | Member of WUA | 9 |
| | 22 | Water user association | Member of WUA | 11 |

## 4. Results

### *4.1. Weighting Results*

The weights of the second-level indicators given by the proposed AHP-OWA weighting method for the three types of stakeholders are displayed in Figure 4. The weights obtained from different panels presented some discrepancies. For instance, indicators *B* (perfect infrastructure) and *C* (scientific management) were regarded as the two most important indicators by the managers, and this result was also supported by the producers. In contrast, the researchers believed that indicators *A* (efficient water conservation) and *C* are the two indicators with the greatest significance for the modernization of irrigation districts. The commonality among these three types of stakeholders is that indicator *D* (good ecology) received the lowest rating. Thus, the weighting results indicate that all three types of stakeholders were unanimous in setting improvements to management as a top priority, while promoting the ecology function was not the most significant issue to be considered for solutions in the future.

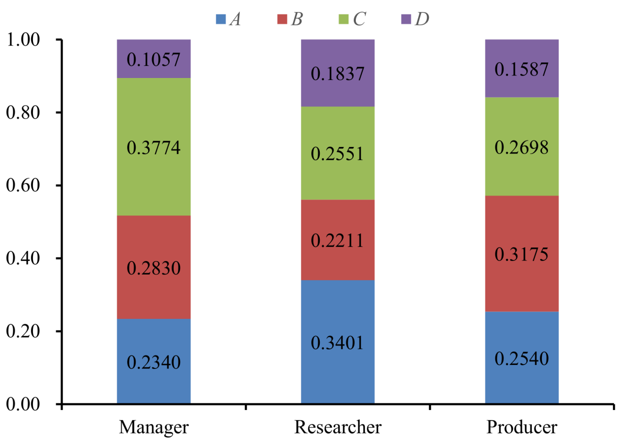


**Figure 4.** The weights of 4 second-level indicators.

The third-level indicators are shown in Figure 5. It shows that the managers believe that the indicators of $C_1$, $B_2$, and $C_2$ should be fully emphasized and it indicates that they focused more on their ability to operate and maintain their irrigation district and improve the water transmission and distribution network under their own management to ensure the appropriate water use at the grassroots level. The weights from the researchers were different from those of the managers, and they paid considerable attention to $C_1$ and $A_2$ while underlining the importance of $D_2$. This illustrates that the researchers focused their attention more on irrigation water efficiency and ecological function recovery. The weights integrated from the producers showed a high similarity with those of the managers, but the producers selected $D_2$ instead of $C_1$ as a critical third-level indicator. The top three indicators selected by the three types of stakeholders accounted for 52.13% (managers), 41.70% (researchers), and 42.88% (producers) of the third-level indicators.

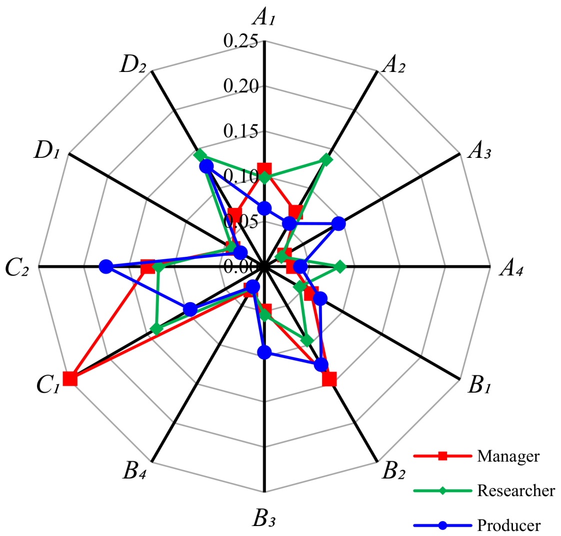


**Figure 5.** The weights of 12 third-level indicators.

The weights of the fourth-level evaluation indicators are shown in Table 7. In the water conservation project indicator, all three types of respondents believed that the proportion of effectively irrigated area was more important than the proportion of efficient water conservation irrigation area but to varying degrees. That is probably because efficient water-conserving irrigation technology represented by drip irrigation, sprinkling irrigation, and micro-irrigation is mainly used for cash crops with high added value, which are grown on a small scale in planting areas compared with grain crops in irrigation districts. By contrast, an effective irrigated area is the area that can be covered by the water source of the irrigation district in normal years. Indicator $A_{12}$ reflects the gap between the current status and the designed standards, and it has significance for irrigation district evaluation. Similarly, in water resource allocation, the weight of $A_{21}$ and $A_{22}$ differed by threefold to fivefold in the opinions of the three types of stakeholders. This can also be attributed to large differences between agricultural water use and ecological water use. An irrigation district is still a production institution with the provision of an agricultural water supply as its core function, even though its ecological function has been emphasized in recent years. It should be noted that the researchers endow these two indicators with more importance compared to the other stakeholders. For the planting structure at the third level, there was only one corresponding fourth-level indicator, the area ratio between grain crops and cash crops, which reflects the production orientation of the irrigation district. An appropriate ratio may balance food security and water users' economic benefits, which is also reflected in the indicator weight given by the producers. In the water conservation mechanism indicator, the collection rate of higher water bills had a higher weight than the implementation level of water conservation rewards in the opinion of the managers and researchers, which is contrary to the producers' viewpoint. Moreover, the researchers emphasized $A_{41}$ and $A_{42}$ much more than the managers (0.0345 vs. 0.0114 and 0.0490 vs. 0.0206, respectively).

**Table 7.** The indicator weights of the 4 levels.

| 2nd-Level Indicator | 3rd-Level Indicator | 4th-Level Indicator | Managers | Researchers | Producers | Final Weight |
|---|---|---|---|---|---|---|
| $A$ | $A_1$ | $A_{11}$ | 0.0295 | 0.0357 | 0.0254 | 0.0306 |
| | | $A_{12}$ | 0.0773 | 0.0626 | 0.0391 | 0.0652 |
| | $A_2$ | $A_{21}$ | 0.0579 | 0.1012 | 0.0466 | 0.0686 |
| | | $A_{22}$ | 0.0116 | 0.0354 | 0.0084 | 0.0181 |
| | $A_3$ | $A_{31}$ | 0.0256 | 0.0216 | 0.0948 | 0.0383 |
| | $A_4$ | $A_{41}$ | 0.0114 | 0.0345 | 0.0280 | 0.0217 |
| | | $A_{42}$ | 0.0206 | 0.0490 | 0.0118 | 0.0274 |
| $B$ | $B_1$ | $B_{11}$ | 0.0370 | 0.0250 | 0.0410 | 0.0342 |
| | | $B_{12}$ | 0.0229 | 0.0200 | 0.0303 | 0.0235 |
| | $B_2$ | $B_{21}$ | 0.0421 | 0.0276 | 0.0342 | 0.0362 |
| | | $B_{22}$ | 0.0303 | 0.0221 | 0.0205 | 0.0259 |
| | | $B_{23}$ | 0.0454 | 0.0254 | 0.0410 | 0.0385 |
| | | $B_{24}$ | 0.0261 | 0.0193 | 0.0297 | 0.0248 |
| | $B_3$ | $B_{31}$ | 0.0207 | 0.0210 | 0.0569 | 0.0280 |
| | | $B_{32}$ | 0.0285 | 0.0329 | 0.0381 | 0.0318 |
| | $B_4$ | $B_{41}$ | 0.0126 | 0.0090 | 0.0156 | 0.0121 |
| | | $B_{42}$ | 0.0173 | 0.0188 | 0.0101 | 0.0163 |
| $C$ | $C_1$ | $C_{11}$ | 0.0173 | 0.0112 | 0.0112 | 0.0143 |
| | | $C_{12}$ | 0.0312 | 0.0262 | 0.0141 | 0.0263 |
| | | $C_{13}$ | 0.0610 | 0.0242 | 0.0415 | 0.0461 |
| | | $C_{14}$ | 0.0728 | 0.0408 | 0.0095 | 0.0506 |
| | | $C_{15}$ | 0.0659 | 0.0356 | 0.0184 | 0.0473 |
| | $C_2$ | $C_{21}$ | 0.0549 | 0.0389 | 0.0512 | 0.0494 |
| | | $C_{22}$ | 0.0247 | 0.0144 | 0.0343 | 0.0235 |
| | | $C_{23}$ | 0.0494 | 0.0639 | 0.0896 | 0.0618 |
| $D$ | $D_1$ | $D_{11}$ | 0.0280 | 0.0248 | 0.0164 | 0.0247 |
| | | $D_{12}$ | 0.0120 | 0.0164 | 0.0141 | 0.0138 |
| | $D_2$ | $D_{21}$ | 0.0205 | 0.0412 | 0.0733 | 0.0373 |
| | | $D_{22}$ | 0.0308 | 0.0346 | 0.0308 | 0.0319 |
| | | $D_{23}$ | 0.0144 | 0.0667 | 0.0242 | 0.0320 |

Note: The final weight was calculated using Equation (9), where the three authority coefficients assigned by the policymakers were $\alpha = 0.5000$, $\beta = 0.3000$, and $\gamma = 0.2000$.

Regarding the water source engineering indicator, all the experts agreed that the matching rate of water source engineering is more important than the intact rate of water source engineering; the former's weight varied from 0.0250 (researchers) to 0.0410 (producers), while the latter's weight was greater than 0.0200 (researchers) or less than 0.0303 (researchers). This result indicates that new construction or expanding water source engineering is the priority task for modernization rather than repairing the existing engineering facilities, which were mostly constructed at the beginning of the 2000s. As for field engineering, the producers held an opposite opinion to the other two types of stakeholders, and the producers believed that the matching rate of field channel facilities was more critical than the area proportion of High-Standard Farmland; the weight value of the former was 0.0569, while the latter was 0.0381. This could be due to High-Standard Farmland being focused on improving comprehensive agricultural production capacity, but water user associations only perform a function of grassroots water management (water charge collection, etc.). In drainage engineering, $B_{41}$ and $B_{42}$ were both given relatively low weights (all less than 0.02) by the three types of stakeholders, probably because the utilization ratio of water resources in North China had remained relatively high for a long time, which led to insufficient attention to drainage facilities.

As regards the third-level indicator of normalization and standardization management, it was vigorously advocated and promoted by all the relevant departments from the upper layer to the base layer, and it was also regarded as the core aspect of the annual performance evaluation of the specific departments of the irrigation districts. The third-level indicators cover a wide range of content; here, only five relatively important subordinate indicators were selected for evaluation, mainly including personnel composition and funding guarantees. It can be seen that $C_{13}$, $C_{14}$, and $C_{15}$ were listed as the three most important indicators by the managers, with corresponding weights of 0.0610, 0.0728, and 0.0659, respectively. At the same time, the managers were not very sensitive to the number of personnel and their educational background, which is illustrated by the weights of $C_{11}$ and $C_{12}$ given by the managers. The researchers largely upheld the managers' weighting conclusions in terms of rankings. The producers gave the indicator coverage proportion of water user associations ($C_{13}$) a weight of 0.0415, but the other indicators' weights ranged from 0.0095 ($C_{14}$) to 0.0184 ($C_{15}$), which were significantly lower than the weight for $C_{13}$. In water consumption, the flow rate in the later canal entrance had a weight ranging from 0.0144 (researchers) to 0.0343 (producers), which was lower than the weight for $C_{21}$ (from 0.0389 to 0.0549) and $C_{23}$ (from 0.0494 to 0.0896) given by all three types of experts. The reason why $C_{21}$ and $C_{23}$ were weighted with large values could be attributed to their respective connotations. $C_{21}$ is a core indicator that measures the implementation of price reforms for water used for agriculture and is of great significance for promoting agricultural water conservation. $C_{23}$ is an effective means to improve the irrigation district's management efficiency by transforming the traditional human-driven management method and using integrated information technology.

In the residential environment, the percentage of forest cover and the proportion of water area reflect the climate-adjusting ability of the residential environment in the irrigation district. Under the premise of a limited water resource, the water area is unlikely to increase significantly in the foreseeable future, and the three types of stakeholders all valued $D_{21}$ more than $D_{22}$. As the last third-level indicator, landscape service is divided into $D_{21}$, $D_{22}$, and $D_{23}$, and they cause quite scattered opinions from the three types of experts. $D_{22}$, $D_{23}$, and $D_{21}$ were each ranked as the most important by the managers, researchers, and producers, respectively. Furthermore, water quality is an assessment indicator issued by the superior department, and that is the reason why the managers gave it sufficient weight. Producers, usually hailing from local residents, pay more attention to the subjective enjoyment brought by the water environment in an irrigation district. As for researchers, sufficient data information brought by comprehensive water ecological monitoring systems would drive the overall improvement of the water landscape service in irrigation districts, which is reflected by the three indicators valued by the researchers.

### 4.2. Evaluation Results

The evaluation results using the final weights and TOPSIS method are shown in Figure 6. In 2020, the modernization phases of Renmin Shengliqu, Weishan, and Shijin were classified as the beginning phase because the relative closeness (0.3290, 0.3748, and 0.4573, respectively) of the three irrigation districts was higher than 0.3000. In comparison, the relative closeness of Zuncun in 2020 was only 0.2379, corresponding to the lowest development state, the preparation phase. By 2025, as planned, the four irrigation districts' relative closeness will increase to different extents, with the relative closeness reaching 0.5755, 0.5396, 0.6012, and 0.6169 for Renmin Shengliqu, Weishan, Shijin, and Zuncun, respectively, with corresponding growth rates of 46.97%, 44.04%, 31.67%, and 157.83%. Thus, the four irrigation districts will enter into the initial implementation phase together.

The above evaluation results indicate that all four irrigation districts had a certain modernization foundation by 2020 due to the rehabilitation and water-saving reform projects that aimed to raise water resource use efficiency by improving infrastructure and perfecting management mechanisms over the past 20 years. Based on this foundation, the four irrigation districts can set relevant retrofitting programs. It is noteworthy that the degree of increase for Zuncun is markedly higher than the others, which reflects that the planners of Zuncun are determined to catch up with the other districts through modernization transformation projects.

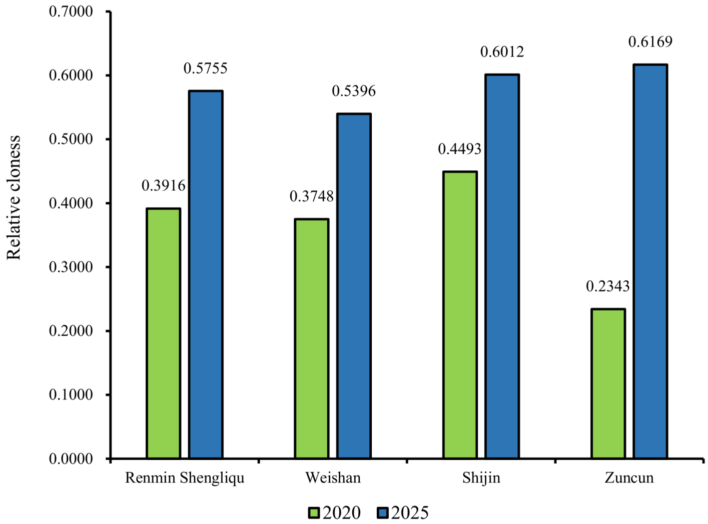


**Figure 6.** The relative closeness of the 4 irrigation districts.

Figure 7 shows the four second-level indicators' relative closeness for the four irrigation districts, and the following conclusions can be drawn.

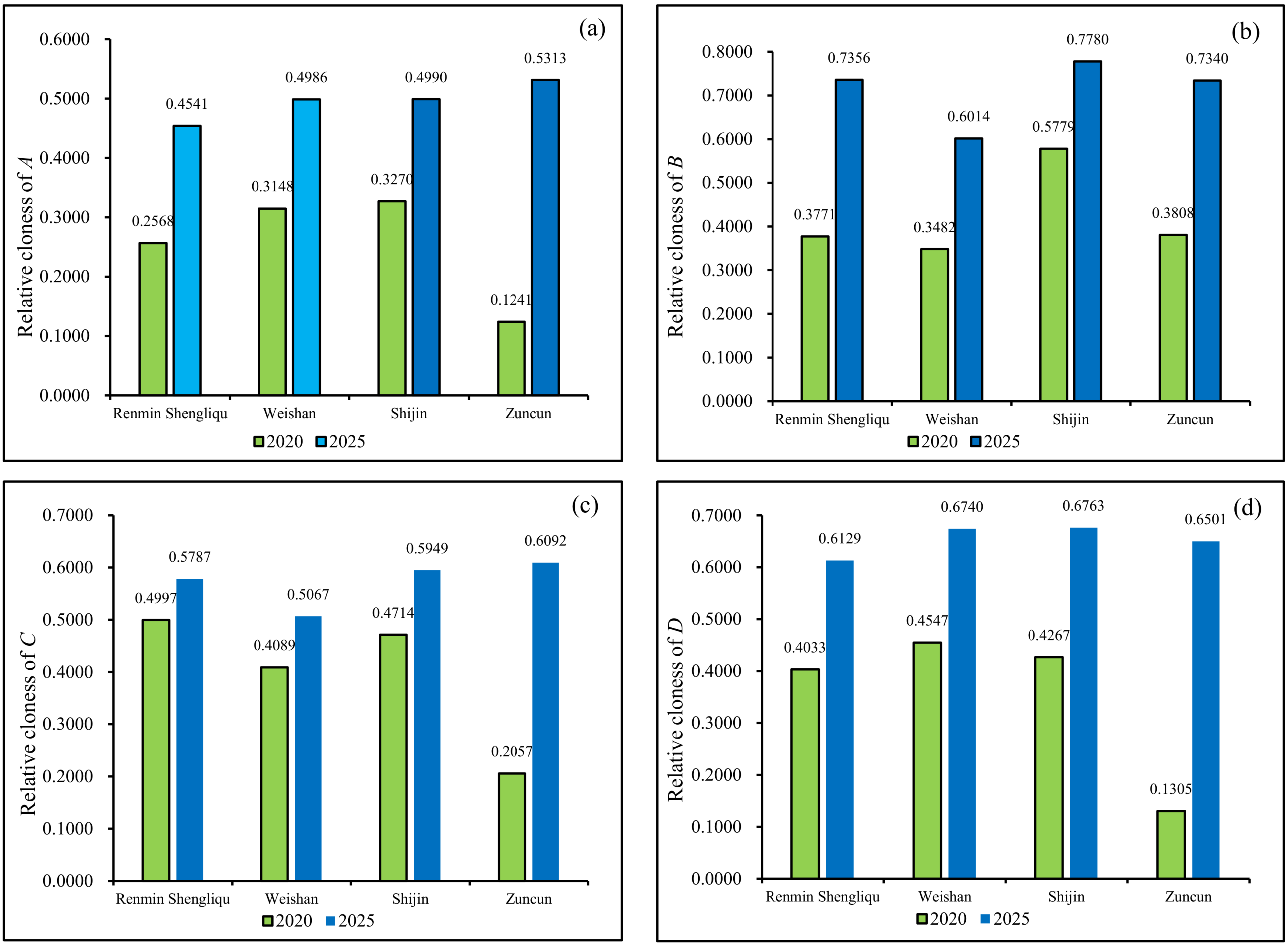


**Figure 7.** The relative closeness of four second-level indicators for the irrigation districts: (**a**) efficient water conservation; (**b**) perfect infrastructure; (**c**) scientific management; and (**d**) good ecology.

Regarding efficient water conservation, the relative closeness of Weishan and Shijin were the highest at 0.3148 and 0.3270, indicating that they were in the beginning phase in

2020. For Renmin Shengliqu and Zuncun, their closeness only reached 0.2568 and 0.1241, which indicates that their efficient water conservation level was still in the preparation phase in 2020. By 2025, the four evaluation objects' closeness will increase significantly, approaching or exceeding 0.5000. Moreover, the most obvious growth will occur in Zuncun, whose closeness will be 0.5225, corresponding to the initial implementation phase. The other three irrigation districts' closeness in efficient water conservation will all be greater than 0.3000 and less than 0.5000, which is considered the beginning phase.

For perfect infrastructure, in 2020, Renmin Shengliqu, Weishan, and Zuncun shared very close values that ranged between 0.3402 and 0.3908 and could be defined as the beginning phase. Meanwhile, the closeness of Shijin was the highest with a value of 0.5779. By 2025, as planned, Renmin Shengliqu, Shijin, and Zuncun's closeness will surpass 0.7000 and reach the basic realization phase. As for Weishan, its closeness will be only 0.6028 and it will be in the initial implementation phase.

Regarding scientific management, Renmin Shengliqu, Weishan, and Shijin were close and they shared the status of the beginning phase in 2020. Zuncun's closeness was lower than the others and only reached 0.2057. In 2025, the four irrigation districts' closeness will be similar, and they will all be in the initial implementation phase.

As for good ecology, the performance of the four irrigation districts was extremely similar to that of scientific management. Zuncun's closeness was obviously lower than the others. However, the four irrigation districts' closeness gaps will be bridged by the year 2025, and they will be in the initial implementation phase with values between 0.6129 and 0.6763.

From the above evaluation results on the four second-level indicators, we can observe that by 2025, the gap in the efficient water conservation level of the four irrigation districts will be minimal compared with the other three second-level indicators, which indicates that each irrigation district has similar expectations for their water conservation level over the following 15 years. Moreover, of the four districts, Zuncun's perfect infrastructure and the other three second-level indicator values were the lowest in 2020, and relevant archives also confirmed this result. In addition, there was no significant difference in investment per unit between Zuncun and the three other irrigation districts, leading to relatively similar closeness values for perfect infrastructure. However, Zuncun has not performed well enough in some indicators of significant weight, such as the proportion of effective irrigated areas, the number of dedicated administrators per 1000 ha, the implementation rate of maintenance funds, etc.

### *4.3. Determination of Obstacle Factors*

Based on the obstacle factor diagnosis method, the obstacle degrees of the irrigation districts were obtained and are shown in Table 8. As a note, only the top eight fourth-level indicators are listed as main obstacle factors in 2020 and 2025. The total obstacle degrees of the eight indicators were almost greater than 40%, confirming that these indicators exert a significant influence among the thirty fourth-level indicators. By analyzing the occurrence frequency and the average obstacle degree of the eight indicators, it can be found that the most common obstacle factors mainly included $A_{21}$ (number of times: 7; average obstacle degree: 14.07%), $C_{23}$ (number of times: 7; average obstacle degree: 9.77%), $A_{11}$ (number of times: 5; average obstacle degree: 7.41%), $B_{32}$ (number of times: 4; average obstacle degree: 7.89%), $D_{21}$ (number of times: 4; average obstacle degree: 7.23%), and $D_{23}$ (number of times: 4; average obstacle degree: 6.27%).

**Table 8.** The main obstacle factors and ranking of the obstacle degree affecting the modernization level.

| District | Year | Obstacle Factors and Ranking of Obstacle Degree | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| Renmin Shengliqu | 2020 | $A_{21}$ (12.48%) | $B_{11}$ (6.22%) | $C_{23}$ (6.15%) | $D_{23}$ (5.82%) | $A_{12}$ (5.59%) | $A_{11}$ (5.56%) | $D_{21}$ (5.26%) | $A_{42}$ (4.98%) |
| | 2025 | $A_{21}$ (23.28%) | $D_{21}$ (9.34%) | $C_{12}$ (9.07%) | $B_{21}$ (8.97%) | $A_{31}$ (8.58%) | $A_{11}$ (7.20%) | $C_{23}$ (7.07%) | $D_{23}$ (6.52%) |
| Weishan | 2020 | $C_{23}$ (10.66%) | $A_{21}$ (8.01%) | $C_{13}$ (7.48%) | $B_{23}$ (6.64%) | $B_{21}$ (6.23%) | $D_{23}$ (5.52%) | $A_{11}$ (5.27%) | $A_{42}$ (4.72%) |
| | 2025 | $C_{23}$ (17.88%) | $A_{21}$ (12.88%) | $B_{21}$ (10.72%) | $C_{13}$ (6.77%) | $B_{23}$ (6.03%) | $D_{22}$ (5.87%) | $B_{32}$ (5.47%) | $A_{12}$ (4.71%) |
| Shijin | 2020 | $C_{23}$ (13.45%) | $A_{21}$ (11.90%) | $D_{21}$ (7.26%) | $D_{23}$ (7.21%) | $B_{32}$ (7.07%) | $A_{42}$ (6.16%) | $A_{11}$ (5.91%) | $B_{31}$ (4.61%) |
| | 2025 | $A_{21}$ (24.49%) | $A_{11}$ (13.10%) | $D_{11}$ (12.26%) | $C_{23}$ (8.20%) | $D_{21}$ (7.06%) | $C_{12}$ (5.95%) | $B_{31}$ (5.90%) | $B_{32}$ (4.30%) |
| Zuncun | 2020 | $A_{12}$ (7.81%) | $C_{14}$ (6.05%) | $C_{21}$ (5.92%) | $C_{15}$ (5.66%) | $C_{13}$ (5.52%) | $A_{21}$ (5.48%) | $C_{23}$ (4.99%) | $A_{31}$ (4.58%) |
| | 2025 | $A_{31}$ (31.24%) | $D_{11}$ (20.12%) | $B_{32}$ (14.72%) | $C_{12}$ (11.49%) | $D_{12}$ (10.77%) | $C_{11}$ (6.93%) | $B_{22}$ (3.02%) | $B_{31}$ (1.73%) |

These results reflect the common problems faced by the irrigation districts in the process of modernization:

(1) Inefficient utilization of water resources. All four irrigation districts have a large coverage area and a long canal network, coupled with perennial heavy load running, which resulted in a low anti-seepage rate and canal system damage; for example, the Renmin Shengliqu Irrigation District's water use efficiency factor merely reached 0.456 in 2020.

(2) Insufficient informatization support. There have been varying degrees of exploration on informatization construction, but limited investment and an immature mode have resulted in low informatization levels, which appear as fragmented flow measurement systems and poor analysis and decision-making systems. Weishan only established a flow automatic monitoring system at some backbone canal nodes, and its overall informatization coverage rate was only 11% in 2020.

(3) Inadequate application of high-efficiency water conservation irrigation technology. Water resource shortages are the biggest problem faced by irrigation districts in this region, so promoting efficient water conservation irrigation technology is an effective method to alleviate the contradiction between water supply and demand. Groundwater overextraction is a serious problem in Hebei Province, where the Shijin Irrigation District is located, and in view of this, spreading efficient water conservation irrigation technologies plays an important role in the modernization of Shijin, which will also become a key limiting factor affecting the modernization level.

(4) Incomplete fields and matching facilities. The High-Standard Farmland Project can effectively solve the "Last One Kilometer" problem of irrigation districts and improve the overall water efficiency by improving field infrastructure. Typical examples include Zuncun, where, due to the limitations caused by its construction scale and corresponding industrial administration, it is difficult to form an effective connection between High-Standard Farmland and the irrigation district, leading to difficulties in achieving project benefits and reducing water resource waste.

(5) Unsatisfying water ecosystem service functions. In recent years, constructing ecological irrigation districts has been a hot topic in the industry due to the increasing needs of local residents for irrigation districts' ecological service function. Among the four irrigation districts, only Renmin Shengliqu has built a green ecological corridor along both sides of the main canal in the urban section to satisfy the residents' need for entertainment. Moreover, the district has incorporated water ecosystem rehabilitation and water culture protection into its modernization process in order to enhance the ecological service function.

The key obstacle factors differed depending on the district. The top obstacle factor of Renmin Shengliqu was $A_{21}$ in both 2020 and 2025, suggesting that the continuous improvement of water resource utilization efficiency is the primary problem faced by this irrigation district. In addition, the second most important factor undergoes a transformation from $B_{11}$ to $D_{21}$, confirming that the Yellow River channel cutting downwards will make water diversion difficult, which will further lead to the need for headwork reconstruction or modification to improve the matching rate of water source engineering. By 2025, improving the comfort level near the water will become an important influencing factor that restricts the modernization level after the completion of headwork reconstruction. This transformation indicates that giving full play to ecological functions will become increasingly important. As for Weishan, the top two factors remain unchanged ($C_{23}$ and $A_{21}$). This shows that improving management capabilities by enhancing the informatization level, together with continuously improving water resource utilization efficiency, just like in the past twenty years, will still be the top priority for the modernization transformation of Weishan. As for Shijin, the first issue to be addressed is increasing the informatization coverage degree by 2025 and strengthening the management of planning and water conservation with the support of information technology in order to achieve the goal of curbing the expansion of groundwater funnels. Beginning in 2025, the irrigation water use efficiency factor should be elevated to a more important position than before, while efforts are made to promote efficient water conservation irrigation technology. For Zuncun, there are no large gaps between the obstacle degrees of the eight indicators in 2020; this shows that Zuncun is facing multiple problems that need to be solved as soon as possible. One initial problem is increasing the effective irrigated area, a measurement that the water source can cover effectively and can be improved by repairing and expanding the channel network. Other obstacle factors are largely concentrated in management, and therefore, the irrigation district authority should quickly establish and improve management systems. Contrary to 2020, there will be a trend of the centralization of the eight indicators' obstacle degrees beginning in 2025; for instance, the obstacle degrees of $A_{31}$ and $D_{11}$ will reach 31.24% and 20.12%, respectively. However, the types of the eight indicators will show a trend of decentralization because they belong to all four second-level indicators, which proves that the irrigation district authority plans to consolidate the foundation through a 5-year plan and afterwards, they will make comprehensive and organized progress.

## 5. Discussion

Implementing the modernization of irrigation districts is an important decision to realize a healthy and sustainable development of China's agriculture and rural economy, ensure national food security, and achieve an efficient supply of agricultural products. The four large-scale irrigation districts selected for this study all have high industry influence and regional representativeness. In this paper, we evaluated and diagnosed their modernization situation, identified the main problems, and proposed corresponding countermeasures and suggestions, which all have value as a reference for the construction and sustainable development of irrigation districts in North China and even the entire country.

Compared to the empowerment process using individual stakeholders that was adopted by Sun [16] and Yang [11], this study chose a group decision-making method to determine the weights of each indicator; the experts involved in the survey included the three main categories of practitioners in the irrigation district field, so the weighting results are more representative of the industry as a whole. In addition, classical indicator systems are usually established around engineering facilities [24], management level [16], production efficiency [22], and the ecological environment [11], but these systems cannot completely meet the needs of modern irrigation districts; for example, they do not consider the collection rate of higher water bills and water ecological monitoring system coverage rate, which are new aspects of modernization. Thus, this study took into account the indicators that are closely related to the ecological service function and the integrated price reform of water used for agricultural purposes. Moreover, in the existing research results, ecological and environmental indicators are often emphasized excessively, and their weight values often approach or even exceed engineering and management indicators [10]; this can easily lead readers to believe that improving the quality of the ecological environment should be the main priority. It is difficult for the conclusions of this study to be used to support the above views; instead, the results indicate that the current construction is still focusing on engineering facilities and management reform by, for instance, promoting information technology and deepening agricultural water price reform. All of these measures are meant to ensure national food security and achieve the efficient use of water resources. The confirmation of the modernization stage of the four irrigation districts in 2020 and 2025, as well as the identification of the key obstacle factors, all reflect this conclusion.

The modernization of irrigation districts is a complicated concept, which includes agricultural water conservancy projects, institutional construction of specific departments and grassroots water user organization, and the improvement of water landscapes and ecology. In China, both the quantity and types of irrigation districts are largely limited and therefore, there will be an increasing need for in-depth and classification research that not only includes the selection of evaluation indicators and the division of individual indicators, but also the optimization of an evaluation method. In addition, more and more large-scale irrigation districts will be incorporated into the modernization plans and the entire industry will produce an increasing demand for the applicability and accuracy of evaluation systems. How to guide and lead the formulation of relevant industry standards and norms will be a research focus in the future [72].

The modernization of the four irrigation districts will be a long-term process; the results of this study indicate that every irrigation district is facing problems that need to be improved upon or solved, and the importance or urgency of these issues varies. What is certain is that integrating the national policy guidance with the actual situation will be a continuous issue for the irrigation industry.

## 6. Conclusions and Recommendations

### 6.1. Conclusions

In this study, based on the data from four large-scale irrigation districts in North China in 2020, 2025, and 2035, a local suitable modernization index system was designed according to modernization concepts and targets. Here, the AHP-OWA-TOPSIS model was selected to evaluate the modernization level of the irrigation districts. Moreover, the obstacle diagnosis method was used to identify the main obstacle factors that crucially affect the advancement of the modernization level. The main conclusions are as follows:

(1) In 2020, the modernization level of the four irrigation districts ranged from 0.2343 to 0.4493, corresponding to the modernization stage of the preparation phase (Zuncun) and the beginning phase (Renmin Shengliqu, Weishan, and Shijin). By 2025, the modernization level is expected to be in the range of 0.5396 to 0.6169, and the four irrigation districts will enter into the initial implementation phase together.

(2) In North China, low irrigation water efficiency and unsound management systems are the two key obstacle factors that restrict irrigation district development. It is noteworthy that ecological function will become increasingly important with growing obstacle degrees for the four irrigation districts in the future, but it will not be a top priority.

(3) In order to improve the modernization level, Renmin Shengliqu is recommended to continue to increase the irrigation water use efficiency factor, complete the upgrade of headworks before 2025, and promote ecological construction to meet the needs of residents after 2025. Weishan is recommended to prioritize water conservation and improve the management level by strengthening informatization construction. Shijin, similar to Weishan, should promote efficient water-conserving irrigation techniques. For Zuncun, improving the canal network is a precondition to increase the effective irrigation area and consolidate the irrigation foundation. In addition, establishing a complete management system is also essential for Zuncun.

(4) A comprehensive evaluation system for irrigation districts was developed by designing an index system, subjective weighting using group decision-making, TOPSIS-based quantitative evaluation, and diagnosing the main obstacle factors. The present study can aid in irrigation district construction and administration.

(5) With the increased promotion of irrigation district modernization, related evaluation research will inevitably be required to play an increasingly important leading role;

how to guide the development of relevant industry standards and norms is predicted to become a research hotspot in the future.

### 6.2. Recommendations

As China's major grain producing area, how to use limited water resources to support national food security and sustainable economic and social development is an enduring issue for North China's agricultural and water conservancy practitioners. The modernization transformation of irrigation districts provides a good opportunity to solve this problem. Based on the evaluation results, we put forward the following policy recommendations:

(1) We should continuously and deeply promote water conservation construction around irrigation districts. Water resources have always been a rigid constraint on the economic and social development of the region; irrigated districts are major water users for agriculture or even whole sectors, and the modernization of irrigation districts is bound to play an important role in alleviating the contradiction between the supply and demand of water resources in this area. The study results indicate that improving irrigation and drainage facilities and strengthening water use management for the purpose of water conservation are key to improving the modernization level of the irrigation district. More concretely, the water conservation construction is advised to focus on canal lining and management systems supported by information technology.
(2) We should promote ecological construction using scientific evidence. Significant social benefits and hidden economic benefits can lead to long-term investments in irrigated districts, especially in North China. While undertaking heavier production and water conservation tasks, the ecological construction of an irrigation district must be rationally planned in space and time. To be specific, in the near future, ecological construction can be carried out in the form of small-scale pilot programs in eligible irrigation districts, and the suggested ecological construction includes completed channels or water storage projects. From a long-term perspective, the proposed ecological construction needs a mature process before it can be widely promoted.
(3) We should promote the construction of a comprehensive evaluation system which can guide real-world practices. The results of this study show that there are certain differences between the problems faced by the four irrigation districts, which will probably produce differences in the modernization content; therefore, it is necessary to implement corresponding specific assessments. For example, the evaluation of the completeness of irrigation and drainage facilities is advisable for the Zuncun Irrigation District, and an environmental impact assessment of irrigation district modernization concerning groundwater is recommended for the Shijin Irrigation District.

**Author Contributions:** Conceptualization, X.F., J.Q. and M.L.; methodology, X.F. and M.L.; investigation, X.F. and M.L.; writing—original draft preparation, X.F.; writing—review and editing, M.L., J.Q., X.F. and M.J. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the Science and Technology Innovation Project of the Chinese Academy of Agricultural Sciences, Henan Province Key R&D and Promotion Special Science and Technology Tackling Project (NO. 232102320279) and (NO. 222102110022).

**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 no conflicts of interest.

## Appendix A

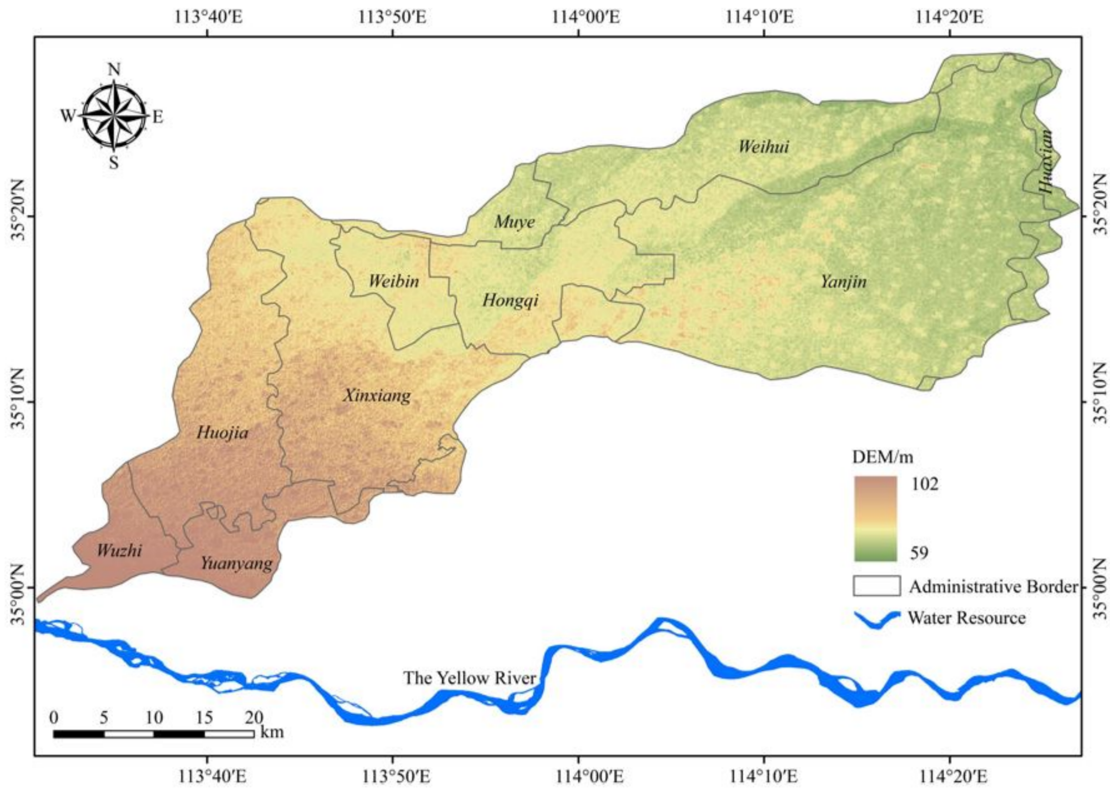


**Figure A1.** Digital elevation map of Renmin Shengliqu Irrigation District.

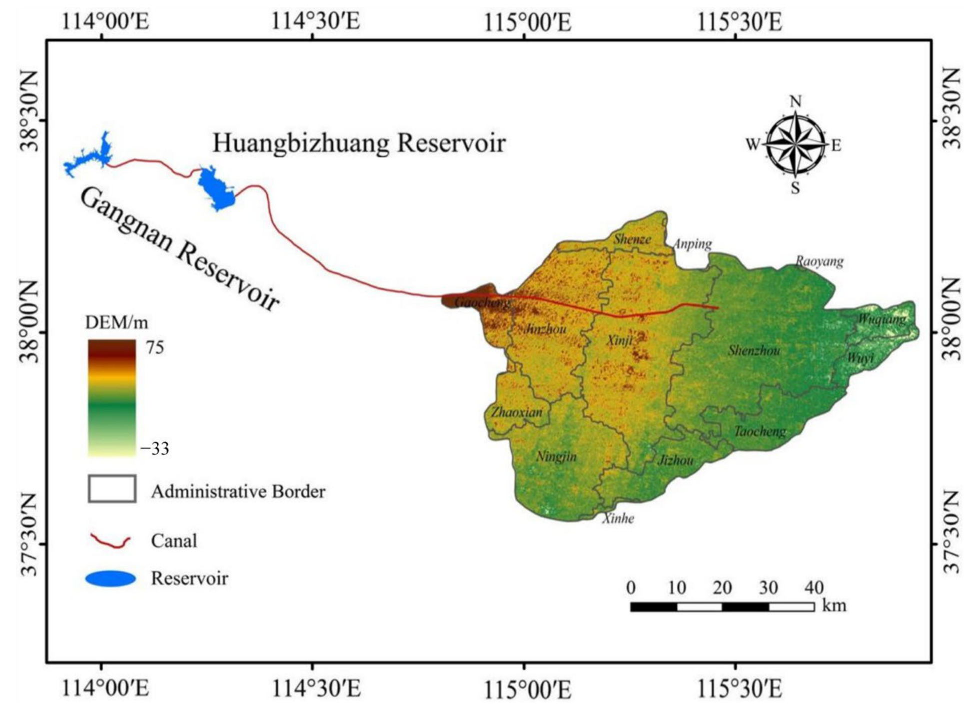


**Figure A2.** Digital elevation map of Shijin Irrigation District.

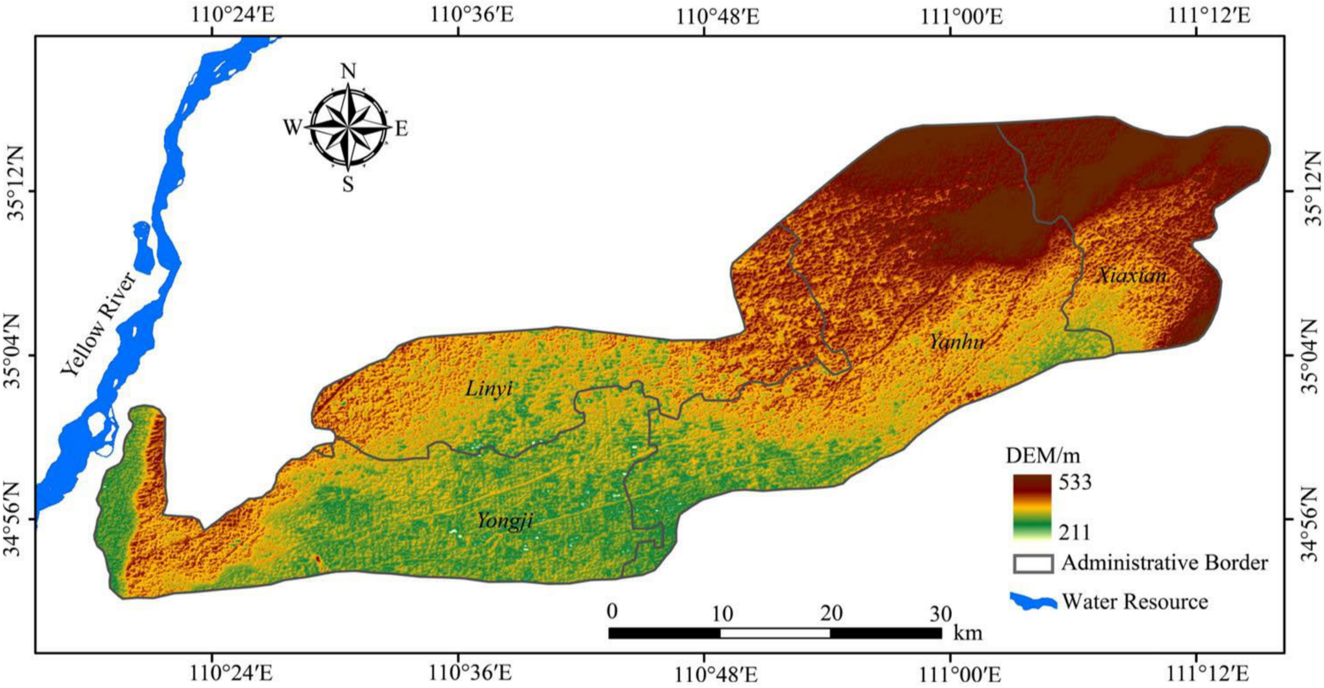


**Figure A3.** Digital elevation map of Zuncun Irrigation District.

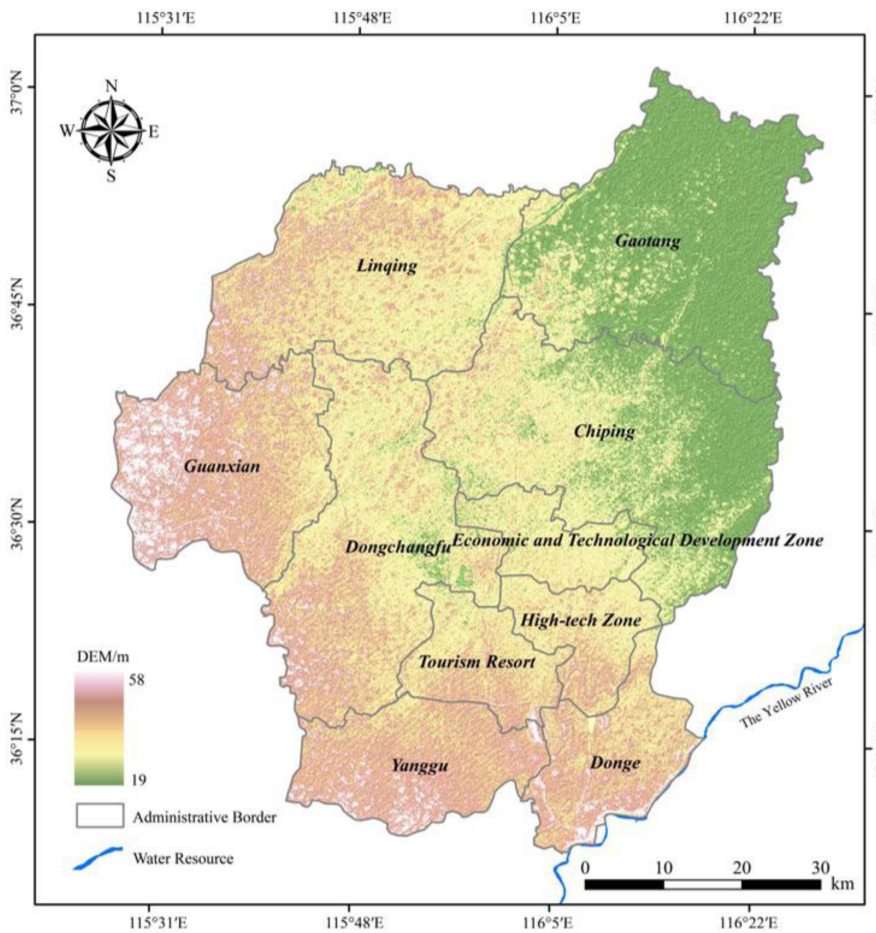


**Figure A4.** Digital elevation map of Weishan Irrigation District.

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