Water Science & Technology

Water Science & Technology Vol 89 No 6, 1482 doi: 10.2166/wst.2024.084

Evaluation of sustainable development capacity of water sources: a case study of China

Jingqi Zhang and Shaohua Jiang*

Department of Construction Management, Dalian University of Technology, 2 Lingjiang Road, Ganjingzi District, Dalian, Liaoning, China
*Corresponding author. E-mail: shjiang@dlut.edu.cn

JZ, 0009-0009-4992-9287; SJ, 0000-0001-9646-5205

ABSTRACT

The issue of water scarcity has drawn attention from all over the world. The coordination of the interaction between ecological and environmental development of water sources and socio-economic development is currently an essential issue that needs to be solved in order to safeguard the water resources environment for human survival. In this essay, we suggest a paradigm for assessing the sustainable exploitation of water resources. First, three ecological, economic, and social factors are investigated. Twenty essential evaluation indexes are then constructed using the Delphi approach, along with an index system for assessing the potential of water sources for sustainable development. The weights of each evaluation index were then determined using the combination assignment approach, which was then suggested. The coupled degree evaluation model of the capability for sustainable development of water sources was then developed. In order to confirm the viability and validity of the suggested model, the model was used to assess the Liwu River water source's capacity for sustainable growth in the context of the South-North Water Transfer in Shandong, China. It is believed that the aforementioned study would serve as a helpful resource when evaluating the capacity of water sources for sustainable development.

Key words: coupling coordination degree, sustainable development, water source

HIGHLIGHTS

- Proposes a novel coupled coordination degree evaluation model for water source sustainability, expanding upon traditional methods to offer a comprehensive understanding of sustainable development status, aiding in strategic planning.
- Introduces an improved weight determination method using the coefficient of variation combined with the combination assignment approach, enhancing the precision and reliability of sustainability evaluations by mitigating outlier effects.
- Establishes a comprehensive evaluation index system from ecological, economic, and social perspectives, providing a holistic framework for assessing water source sustainability, serving as a reference for future sustainable development efforts.

1. INTRODUCTION

Water shortage and declining water quality have gained prominence on a global scale since the second part of the 20th century. The academic world has paid close attention to research in the area of water sources (Mosquera-Romero *et al.* 2023). Developed countries started putting up their own frameworks for the preservation of their domestic water supplies in the twenty-first century. Additionally, research has been directed more and more toward the interdisciplinary intersection of environmental geography, environmental planning, and regional sustainable development rather than traditional municipal engineering (Zimmermann *et al.* 2023). At this stage, the situation of water sources in China is very serious. Due to the large-scale implementation of water transfer projects in China, the problems of water environment pollution and serious soil erosion at water sources have become potential hidden dangers for water transfer projects (Wan *et al.* 2022). A schematic diagram of the South-North Water Transfer Project is shown in Figure 1. There are further detrimental effects of the project's operation that will come to light over time. Owing to their unique geographic conditions, water source regions are typically found in less developed socio-economic regions. People in the places where water is found urgently require rapid economic development (Dosu *et al.* 2023). However, while the economy has been developed rapidly, ecological construction and protection have been neglected. The sacrifice of the ecological environment as the price of socio-economic development is obviously contrary to the concept of regional sustainable development. China has implemented many efforts to safeguard

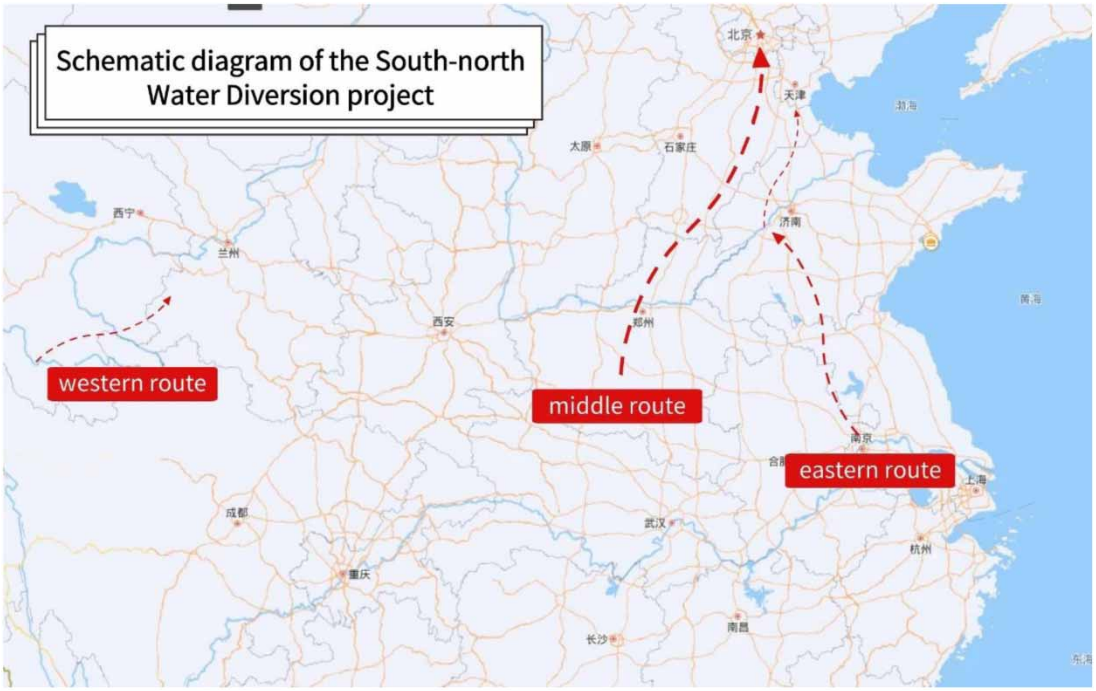

Figure 1 | Schematic diagram of the South-to-North Water Diversion Project.

its key water supplies, including creating forests to preserve water sources, regulating local pollution sources, and establishing protected areas at all levels. It has not, however, been able to completely and successfully reduce the environmental strain on the water supplies (Zhang *et al.* 2023). Examining the sustainability of water sources is crucial in light of the aforementioned considerations. The goal is to be able to completely comprehend the state of regional development, and the issues that are now facing it, and to serve as a resource for decisions made about regional planning and development. On the basis of this, the regional ecological environment and socio-economic control can be regulated through effective measures. The final realization of the regional ecological, social, and economic benefits maximizes the process of sustainable development of water sources. At the same time will also provide a strong guarantee for the safe operation of the water transfer project.

Currently, most of the research on water sources focuses on the control of pollution, innovative management models, and adjustment of incentives (Xu *et al.* 2022). For the study of the sustainability of water sources, a perfect evaluation system has not been established. The current methods for determining the index weights are subjective assignment method, objective assignment method, and combined assignment method. However, the weight of the subjective assignment method is given by experts based on their own experience. The results of the calculation are limited by human experience. The objective assignment method does not take into account the subjective consciousness of people, and the determined weight may not be consistent with the subjective desires of people. Therefore, in order to improve the accuracy and credibility of the evaluation results, this paper will use the combined assignment method to determine the weight coefficients. Based on the extensive analysis of previous studies, this paper adopts the hierarchical analysis method and the entropy method of variation coefficient improvement to assign weights. A coupled coordination degree evaluation model of water source sustainable development ability is established. The research significance of this paper is as follows.

- In this paper, a coupled coordination degree evaluation model for the sustainability of water sources is proposed. It is an innovation and expansion of the traditional evaluation method. Through this model, we can understand the sustainable development status of water sources in a more comprehensive and in-depth way and provide a scientific basis for formulating corresponding protection and management strategies.
- Since the index weights obtained by the entropy method are too equalized, this paper introduces the coefficient of variation method to improve it. It can weaken the influence of outliers and make the evaluation results more accurate and

reasonable. In order to make the evaluation results more scientific and objective, this paper adopts the combination assignment method to determine the weights of each evaluation index. It enables to reflect more accurately the importance of each index in the evaluation and improves the accuracy and credibility of the evaluation.
- There is no complete evaluation index system for the study of the sustainable development capacity of water sources. From three aspects, ecological, economic, and social, this paper assesses the sustainable development capacity of water sources with a view to providing useful references for the sustainable development of water sources.

The rest of this study is organized as follows. Section 2 introduces the current status of research on water sources and the evaluation method of water source sustainability. The third section discusses the research methodology of this paper. Results and discussion are in the fourth part. Finally, conclusions and further work are given in Section 5.

2. BACKGROUND

2.1. Studies on water sources

The environmental conditions of water sources have an important impact on regional water supply security and sustainable economic development and are also closely related to people's life and health safety. Wu *et al.* (2019) concluded that organic micropollutants in the water environment have potential impacts on ecological safety and human health. By analyzing four drinking water sources in Henan Province, China, water contaminants were found to be of high risk to algae and invertebrates (Wu *et al.* 2019). Cao *et al.* (2019) collected long-term monitoring data of conventional physicochemical parameters and metal elements in water bodies from 2005 to 2017. Multivariate statistical techniques were also used to evaluate the elements' sources. It was discovered that the presence of trace elements was significantly impacted by both endogenous releases and human activity (Cao *et al.* 2019). Yang *et al.* (2020) analyzed the current status of ecological compensation in the Yellow River Basin in China and discussed the types and key areas of ecological compensation in the Yellow River Basin. After a series of analyses, it was suggested to strengthen basic research and key case studies on ecological compensation mechanisms in the Yellow River basin (Yang *et al.* 2020). Sun *et al.* (2020) realized that the main cause of nonpoint source pollution in drinking water sources is unreasonable management of commercial forests in upstream areas. The relationship between soil factors and surface runoff pollutants was studied using redundancy analysis. It was concluded that effective measures were to increase vegetation cover and improve the soil environment (Sun *et al.* 2020). Yu *et al.* (2021) used a questionnaire survey method to statistically analyze the sustainable development of the Sun Moon Lake Reservoir in Taiwan. The study found that the development of the reservoir has brought a large amount of waste. This caused the disappearance of culture and architecture (Yu *et al.* 2021). Wang *et al.* (2021) found that the main cause of water source pollution is eutrophication of water bodies. Realizing the importance of implementing clean agricultural production to protect the environment of water sources, a series of feasible measures were proposed (Wang *et al.* 2021). Leya *et al.* (2022) used key information interviews to assess the status of water source security in six areas with urban fringe characteristics in Bangladesh. The study showed that partnership among key stakeholders can enhance water source security in similar urban peripheral environments (Leya *et al.* 2022). In summary, scholars have conducted a large number of studies on contaminants and environmental safety of water sources. A foundation has been laid for the study of the sustainability of water sources.

2.2. Research on water source evaluation system

In recent years, significant results have been achieved in the application of water source evaluation index weighting, ranking of evaluation objects, and correction of evaluation results. In order to improve the accuracy of water source evaluation and reduce the influence caused by subjective factors, water source evaluation systems are usually combined with statistical methods. Ding *et al.* (2019) used a two-dimensional water quality detection model to generate a computational network. A safety platform for drinking water sources in the Three Gorges Reservoir area of China was developed (Ding *et al.* 2019). Wang *et al.* (2020) realized that identifying the spatial and temporal variability of nonpoint source pollution is a prerequisite for improving water quality. A combined model based on land use types was used to simulate pollution loads. And the spatial and temporal characteristics of pollution sources in typical urbanized areas were identified by assessing the pollution loads in typical urbanized areas (Wang *et al.* 2020). Zhang *et al.* (2020) used a cloud model to analyze the ecological environmental vulnerability of water sources. The ecological environmental vulnerability evaluation index system of water sources was constructed by studying the water sources of the South-North Water Diversion Central project in China (Zhang *et al.* 2020). Qin *et al.* (2021) combined multiple linear regression models with Bayesian networks to identify and assess contaminants in water sources (Qin *et al.* 2021). Liu *et al.* (2021) combined the water quality index (WQI) and entropy weighting method to evaluate the environmental quality of groundwater in the Dawu water source. Full index method, Delphi method, and multivariate statistical analysis were used to analyze the evaluation results. The conclusion of overall good water quality was drawn (Liu *et al.* 2021). Xiao *et al.* (2022) proposed a combined assignment method for the comprehensive evaluation of coastal water quality. The study showed that riverine input is the main source of pollutants in the study area (Xiao *et al.* 2022). Zhang *et al.* (2022) proposed an evaluation method that combines the intrinsic vulnerability of aquifers with pollution source loads. The contamination risk of groundwater in the Guanzhong Basin, China, was evaluated from a macroscopic perspective (Zhang *et al.* 2022). Hou *et al.* (2022) considered that controlling nonpoint source pollution is crucial. It is necessary to estimate the nonpoint source pollution export and identify the pollution sources. After studying rainfall and topography and investigating the characteristics of pollution sources and surface sources, an improved output coefficient model was developed (Hou *et al.* 2022). From the existing literature, it can be seen that scholars have focused on qualitative studies and a few scholars have conducted quantitative analyses. However, the single evaluation method is too subjective and has poor evaluation results.

In general, there exists a significant disparity between China and developed countries concerning both theoretical research and practical approaches to water source protection. Many efforts fall short in addressing the driving mechanisms behind changes in water quality, and only a few delve into the effective safeguarding of water sources from the perspective of watershed or catchment land use. The rights and interests of various stakeholders in water sources have not received adequate attention. The absence of operational and promotional mechanisms for water source protection hampers the effectiveness of implemented measures. Research on the evaluation of water sources remains limited, and the existing evaluation system cannot be fully applied to assess water sources. Moreover, the current evaluation methods lack scientific rigor, highlighting the need to identify a suitable evaluation approach. These constitute the primary focus areas of this paper.

3. METHODS

3.1. Establishing an index system for evaluating the sustainability of water sources

Having comprehensively reviewed the existing studies on water sources and the methodologies employed in assessing their sustainability, the next crucial step is to establish a robust index system for evaluating the sustainability of water sources. With the increasing improvement of sustainable development theory, sustainable development is defined as development in three areas. That is, sustainable economic development, sustainable social development, and sustainable ecological development. Only by achieving the harmonization of the three areas can sustainable development be realized (Ji and Zhang). For the establishment of evaluation indicators, mainstream methods mainly include the checklist method, Delphi method, scenario analysis method, flow chart method, etc. (Wang & Tian 2021). Given the sizable number of projects studying water sources in recent years, it is not difficult to bring together experts and scholars in related fields. The advantage of the Delphi method is that experts do not have to be gathered in one place. The views are anonymous and have the same weight (Loges & Tiberius 2022). Due to COVID-19, the Delphi method is adopted in this paper for safety reasons. Combined with relevant research results on water sources, the principles of evaluation index system construction are followed. In this paper, three aspects of ecology, economy, and society are studied and each evaluation index is re-screened. Ten experts were selected from the expert database of National Development and Reform Commission and Ministry of Finance, see S1. Finally, a water source sustainability evaluation index system containing 3 primary indicators and 20 secondary indicators was established. The established index system for evaluating the sustainability of water sources is shown in Figure 2.

3.2. Research process

Water source sustainability evaluation is a multi-attribute decision problem. With only a single method, it is difficult for decision-makers to make accurate decisions (Li & Hu 2022). Therefore, after establishing the index system for evaluating the sustainable development capacity of water sources, the entropy value method and the coefficient of variation method are used to determine the weights of each evaluation index. Finally, the coupled coordination degree evaluation model of the sustainable development capacity of water sources is established. The establishment process of the model is shown in Figure 3.

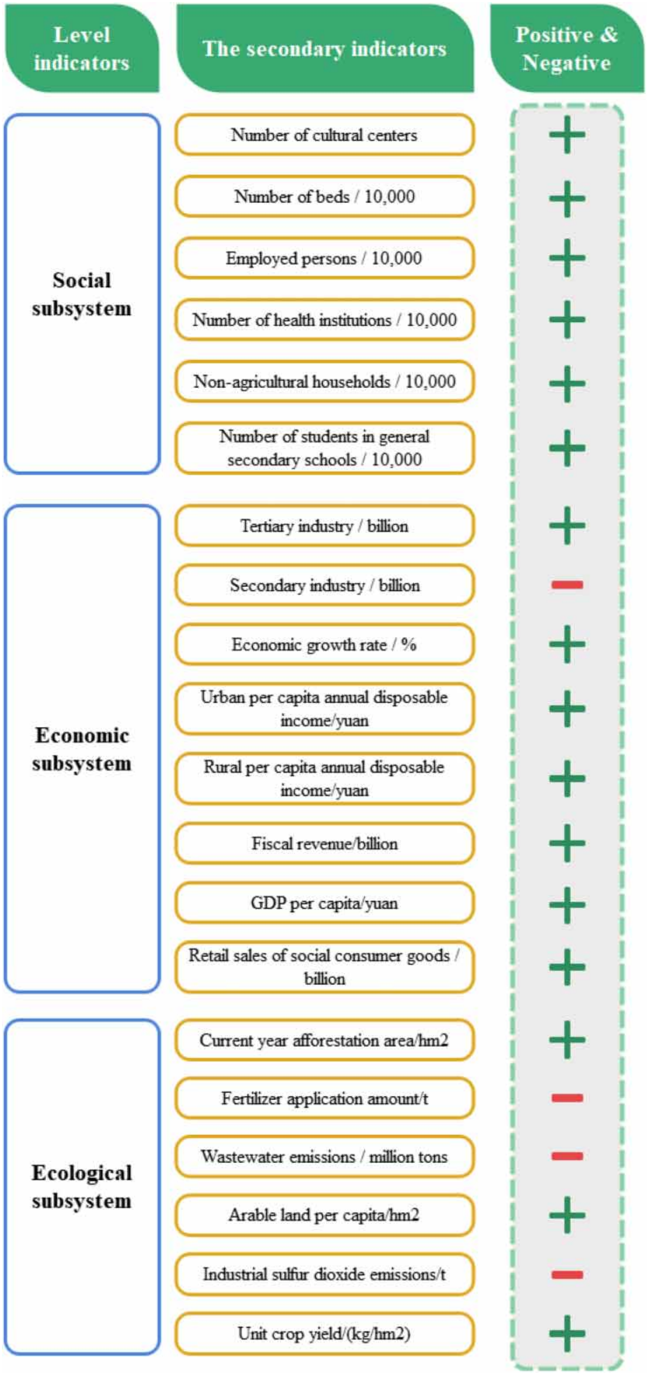

Figure 2 | Evaluation index system of sustainable development capacity of water source.

3.3. Determine the weight of each evaluation index

The significance of each indicator in the evaluation system is gauged through weighting. A judicious distribution of weights is crucial for ensuring the reliability of evaluation results. To attain a balanced weight composition, this paper employs the entropy value method, wherein the utility value of information entropy is utilized to objectively calculate the weights of indicators. Effective information in the original data is fully utilized under the premise of the interference of subjective factors (Liu *et al.* 2022). However, the shortcoming of the method is the equalization of indicator weight. There is no horizontal comparison of the degree of influence of each indicator on the sustainability of water sources. The variation coefficient method

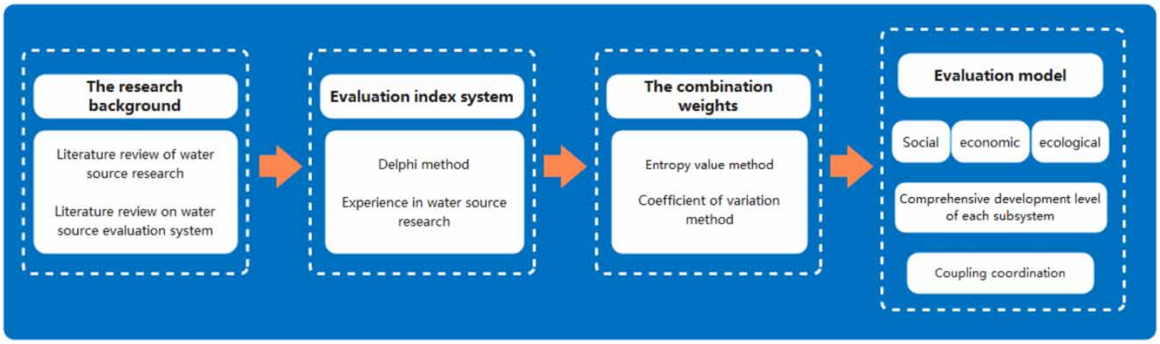

Figure 3 | Flow chart of evaluation model of sustainable development capacity of water source.

directly uses the valid information in the original data, which can better overcome the disadvantage of weight equalization distribution (Jin *et al.* 2022). Therefore, this paper proposes an objective portfolio assignment method based on the coefficient of variation method and the entropy value method.

3.3.1. Entropy method to determine the weight

The entropy method calculates the information utility value based on the information entropy provided in the raw data of each indicator. It is an objective weighting method to determine the weight of each index (Lee & Lee 2022). The steps to determine the index weight by using the entropy method are as follows:

Step 1. The evaluation matrix $A_{m\times n}$ consists of 20 indicators in three main categories. Raw data $\boldsymbol{X} = [x_{ij}]_{m\times n}$, where $x_{i\times j}$ is the value of the j indicator of category i, $i = 1,2$; $j = 1,2,3,\cdots,n$.

Step 2. In order to eliminate the influence of the inverse indicators and magnitude on the evaluation results, the values of the indicators are standardized and normalized to obtain $R = [r_{ij}]_{m\times n}$, $0 \leq r_{i\times j} \leq 1$. The standardization process is as follows.

$$\text{Positive indicators: } r_{ij} = \left[\frac{r_{ij} - \min(r_{1j}, r_{2j}, \cdots, r_{nj})}{\max(r_{1j}, r_{2j}, \cdots, r_{rj}) - \min(r_{1j}, r_{2j}, \cdots, r_{nj})}\right] \times 100 \tag{1}$$

$$\text{Negative indicators: } r_{ij} = \left[\frac{\max(r_{1j}, r_{2j}, \cdots, r_{nj}) - r_{ij}}{\max(r_{1j}, r_{2j}, \cdots, r_{nj}) - \min(r_{1j}, r_{2j}, \cdots, r_{nj})}\right] \times 100 \tag{2}$$

$$\text{Matrix normalization: } r'_{ij} = \frac{r_{ij}}{\sum_{i=1}^{n} r_{ij}}, (i = 1, 2, \cdots, n; j = 1, 2, \cdots, m) \tag{3}$$

Step 3. Calculate the entropy value e_j and utility value d_j for the j indicator. The magnitude of the entropy value e_j is inversely proportional to the utility value and the weight, where $k = (\text{lnm})^{-1} \geq 0$, $d_j = 1 - e_j$.

$$e_j = -k\sum_{i=1}^{m} r'_{ij}\ln r'_{ij} \tag{4}$$

Step 4. The weight coefficients of each indicator, where $\sum_{j=1}^{n} \mathcal{U}_j. = 1$.

$$\mathcal{U}_j = \frac{d_j}{\sum_{1}^{m} d_j} \tag{5}$$

3.3.2. Coefficient of variation method to determine the weight

The coefficient of variation method is an objective weighting method that uses the coefficient of variation and standard deviation of the data to calculate the weight coefficient of each indicator (Yosboonruang *et al.* 2022). The steps for determining the weight of indicators using the coefficient of variation method are as follows:

Step 1. The evaluation indicator raw data matrix $B = [b_{i\times j}]$, where $b_{i\times j}$ is the j indicator value;

Step 2. In order to eliminate the influence of the scale on the evaluation indicators, the degree of variation of each indicator is measured by the coefficient of variation, where D_j is the standard deviation of the j indicator; $\overline{b_j}$ is the mean value of the j term.

$$\sigma_j = \frac{D_j}{\overline{b_j}} \tag{6}$$

Step 3. Index weight.

$$h_j = \frac{\sigma_j}{\sum_{j=1}^{n} \sigma_j} \tag{7}$$

3.3.3. Combination weighting methods to determine weights

In order to make up for the shortcomings of the entropy method for finding weight, the advantages of the coefficient of variation method and the entropy method are combined. Thus, indicator weights are assigned more reasonably, where λ is the equilibrium coefficient and $00 < \boldsymbol{\lambda} < 1$.

$$\mathcal{W}_j = \lambda \mathcal{U}_j + (1 - \lambda) h_j \tag{8}$$

3.4. Integrated development level model

Based on the calculation of weight, the integrated evaluation model was used to evaluate the integrated development level of each subsystem in the ecological–economic–social complex system of the study area. The comprehensive evaluation index of each subsystem was calculated to reflect its integrated inter-system development status (Dai *et al.* 2022), where O_k is the comprehensive evaluation index of k subsystem, $k = 1,2,3$; O_1, O_2, O_3 are the social subsystem, economic subsystem, and ecological subsystem, respectively; $\mathcal{W}_{ij}$ is the entropy weight of the i indicator in the j year.

$$O_k = \sum_{i=1}^{m} y_{ij} \times \mathcal{W}_{ij} \tag{9}$$

3.5. Coupling coordination degree models

In this study, the coupled coordination degree model is employed to assess the sustainable development of the ecological–social–economic complex system within the water source region. This model serves to depict the level of coordination among two or more systems in a manner that closely aligns with real-world scenarios. Its application mitigates the influence of subjective human factors, thereby enhancing the objectivity and validity of the evaluation results across diverse complex situations (Li *et al.* 2022). The coupling degree mainly reflects the strength of interactions and interactions between systems.

Step 1. Calculate the coupling degree functions, where C_1, C_2 are the three couples and the degree of coupling between the two, reflecting the degree of coupling development of the system. The value is 0–1, and the larger the value, the more coordinated the development between the systems.

$$C_1 = \left[\frac{O_1 \times O_2 \times O_3}{\left(\frac{O_1 + O_2 + O_3}{3} \right)^3} \right]^{1/3} \tag{10}$$

$$C_2 = \left[\frac{O_1 \times O_2}{\left(\frac{O_1 + O_2}{2} \right)^2} \right]^2 \tag{11}$$

Step 2. The coupling coordination degree function is calculated. Compared with the coupling degree model, the coupling coordination degree can better measure the coordination degree of interactive coupling between systems. It is very necessary to go further to evaluate the coupling coordination degree of the region, where $\boldsymbol{D}$ is the coupling coordination degree; $\boldsymbol{T}$ is the integrated coordination index of the three subsystems; $\boldsymbol{\alpha}$, $\boldsymbol{\beta}$, γ are the coefficients to be determined.

4. RESULTS AND DISCUSSION

In accordance with the index system for assessing the sustainable development capacity of water sources outlined in Part 3, the weights are initially determined using the combination assignment method. Subsequently, the comprehensive development level is computed and applied to assess the coupling coordination degree among the subsystems. The Zhangwei New River Basin encompasses six or five rivers situated on both sides of the Chen Gong Dike, featuring 12 tributaries ranging from 300 to 1,000 km^2. Beyond these major tributaries, there are an additional 53 tributaries with a watershed area of 100–300 km^2 and 114 tributaries with a watershed area of 30–100 km^2. This has essentially formed a network of interconnected dry and branch rivers, facilitating the discharge and transfer of river water throughout the basin. However, recent years have seen a water shortage from the Yellow River, and the rivers within the region primarily rely on rainfall. The water quantity is intricately linked to the climate characteristics of the upstream areas, and the distribution of precipitation in the city is highly uneven. During the rainy season, water levels rise, leading to floods that can escalate into disasters. Conversely, in the dry season, many rivers progressively dry up. The sustainability of water sources has attracted widespread attention from scholars. The data in this paper are from the 2013–2022 Shandong Statistical Yearbook, see S2.

4.1. Calculation of the social-economic-ecological coupling coordination of water sources in Shandong from 2013 to 2022

Step 1. The raw data were standardized using the outlier leveling method, where B8, B16, B17, and B19 are negative indicators. The standard matrix R is as follows.

$$\begin{pmatrix}
1.0000 & 0.3333 & 0.6667 & 0.3333 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.3333 \\
0.0000 & 0.2468 & 0.3203 & 0.3636 & 0.4459 & 0.5498 & 0.7316 & 0.8312 & 0.9264 & 1.0000 \\
1.0000 & 0.9432 & 0.8148 & 0.7111 & 0.6494 & 0.5383 & 0.4519 & 0.2741 & 0.1259 & 0.0000 \\
0.0000 & 0.0340 & 0.4339 & 0.5297 & 0.5520 & 0.5288 & 0.6522 & 0.7976 & 0.9271 & 1.0000 \\
1.0000 & 0.9074 & 0.7855 & 0.6848 & 0.4924 & 0.3223 & 0.1793 & 0.1289 & 0.0987 & 0.0000 \\
0.3149 & 0.1849 & 0.1244 & 0.0892 & 0.0000 & 0.0361 & 0.2170 & 0.4364 & 0.7011 & 1.0000 \\
0.0000 & 0.0952 & 0.2062 & 0.3008 & 0.4289 & 0.5465 & 0.6679 & 0.7907 & 0.9201 & 1.0000 \\
0.0000 & 0.1554 & 0.3097 & 0.4216 & 0.5628 & 0.6492 & 0.8058 & 0.8747 & 0.9493 & 1.0000 \\
1.0000 & 0.8592 & 0.8169 & 0.6901 & 0.5915 & 0.5352 & 0.5211 & 0.3803 & 0.2394 & 0.0000 \\
0.0000 & 0.1278 & 0.2360 & 0.3422 & 0.4475 & 0.5594 & 0.6854 & 0.8105 & 0.9366 & 1.0000 \\
0.0000 & 0.1073 & 0.2213 & 0.3366 & 0.4378 & 0.5367 & 0.6491 & 0.7629 & 0.9056 & 1.0000 \\
0.0000 & 0.1949 & 0.4055 & 0.5939 & 0.6974 & 0.7015 & 0.7917 & 1.0000 & 0.9056 & 1.0000 \\
0.0000 & 0.1193 & 0.2563 & 0.3596 & 0.4949 & 0.5910 & 0.7099 & 0.8142 & 0.9287 & 1.0000 \\
0.0000 & 0.1205 & 0.2458 & 0.3766 & 0.4971 & 0.6232 & 0.7568 & 0.8843 & 1.0000 & 0.9998 \\
0.9552 & 0.7964 & 0.9661 & 1.0000 & 0.8612 & 0.1724 & 0.0000 & 0.1993 & 0.2494 & 0.0793 \\
1.0000 & 0.9448 & 0.9082 & 0.8881 & 0.8470 & 0.7755 & 0.6294 & 0.4310 & 0.1518 & 0.0000 \\
0.4445 & 0.6304 & 0.7107 & 0.8139 & 1.0000 & 0.0191 & 0.0000 & 0.4310 & 0.1518 & 0.0000 \\
1.0000 & 0.8000 & 0.8000 & 0.8000 & 0.6000 & 0.4000 & 0.2000 & 0.2000 & 0.2000 & 0.0000 \\
1.0000 & 0.9512 & 0.8841 & 0.8171 & 0.8171 & 0.3293 & 0.1402 & 0.0915 & 0.0549 & 0.0000 \\
0.7185 & 0.5094 & 0.4906 & 0.0000 & 0.0000 & 0.3557 & 1.0000 & 0.0180 & 0.0196 & 0.5330
\end{pmatrix}$$

Step 2. The results of the entropy method calculation are shown in Table 1. Analyzing the table, it is evident that certain items exhibit lower entropy values, indicating a more focused and predictable nature, while others have higher entropy values,

Table 1 | Entropy method calculation results

Item	The information entropy value	Information utility value	Weight
1	0.649	0.351	0.129
2	0.912	0.088	0.033
3	0.903	0.097	0.036
4	0.897	0.103	0.038
5	0.856	0.144	0.053
6	0.802	0.198	0.073
7	0.882	0.118	0.043
8	0.852	0.148	0.055
9	0.924	0.076	0.028
10	0.893	0.107	0.040
11	0.889	0.111	0.041
12	0.921	0.079	0.029
13	0.896	0.104	0.038
14	0.893	0.107	0.039
15	0.851	0.149	0.055
16	0.798	0.202	0.074
17	0.903	0.097	0.036
18	0.9	0.1	0.037
19	0.824	0.176	0.065
20	0.841	0.159	0.059

suggesting a broader range of considerations. The distribution of weights reflects the varying contributions of each item to the overall evaluation, allowing for a nuanced understanding of the factors influencing water source sustainability.

Step 3. The coefficient of variation method was used to determine index weights, as shown in Table 2. Table 2 systematically organizes the calculations derived from the coefficient of variation method, providing a transparent and quantitative basis for the determination of index weights. The resulting weights play a pivotal role in shaping the overall evaluation of the sustainability of the water source under consideration.

Step 4. The combined weights are calculated, and the results are shown in Table 3. This table presents the results of the evaluation of various indicators using three different methods: the entropy value method, the coefficient of variation method, and the combination weighting method. Each row corresponds to a specific indicator, and the columns display the weights assigned to each indicator by the respective evaluation method.

Step 5. The integrated development level of each subsystem in the ecological–economic–social complex system was calculated. The results obtained by Equation (9) are shown in Figure 4.

Step 6. Combined with the actual situation of the study area, considering that the importance of the study area as a water source ecosystem is relatively more important than the economic and social systems, the coefficients are taken as 0.4, 0.3, and 0.3 for the case of equally important economic and social development. economic and social coupling is (0.5, 0.5), and ecological and economic coupling is (0.6, 0.4). In order to clearly delineate the coordinated development status among the subsystems in Shandong water sources, the coupled coordinated development status among the systems was divided into 3 stages and 10 types with reference to relevant studies, as shown in Figure 5.

Step 7. The coupling coordination degree between the three subsystems is calculated according to the coupling coordination degree model, which is shown in S3.

4.2. Analysis of social–economic–ecological system coupling coordination in the study area

Figure 6 illustrates the coupling coordination among the systems within Shandong water sources from 2013 to 2022, portraying the dynamics of the social, economic, and ecological subsystems. Over this period, the interplay between these subsystems

Table 2 | Calculation results of coefficient of variation method

Item	The average	The standard deviation	CV coefficient	The weight
1	157.8	1.033	0.007	0.002
2	54.11	7.498	0.139	0.039
3	5,733.1	137.097	0.024	0.007
4	77,328.3	5,529.968	0.072	0.020
5	4,212.7	362.414	0.086	0.024
6	501.269	22.025	0.044	0.012
7	27,157.447	8,261.443	0.304	0.085
8	24,901.906	2,995.056	0.12	0.034
9	7.6	2.14	0.282	0.079
10	33,022.8	7,562.099	0.229	0.064
11	13,529.7	3,486.114	0.258	0.072
12	4,049.2	775.38	0.191	0.053
13	57,230.8	10,790.324	0.189	0.053
14	22,367.576	5,537.226	0.248	0.069
15	162,343.4	55,452.591	0.342	0.095
16	13,404,226.2	1,014,050.215	0.076	0.021
17	432,335.3	72,698.516	0.168	0.047
18	0.076	0.002	0.022	0.006
19	103	69.125	0.671	0.187
20	144,109.2	16,256.58	0.113	0.031

Table 3 | Calculation results of combined weights

Indicators	Entropy value method	Coefficient of variation method	Combination weighting method
Number of cultural centers	0.129	0.002	0.066
Number of beds (10,000)	0.033	0.039	0.036
Employed persons (10,000)	0.036	0.007	0.022
Number of health institutions (10,000)	0.038	0.020	0.029
Non-agricultural households (10,000)	0.053	0.024	0.039
Number of students in general secondary schools (10,000)	0.073	0.012	0.043
Tertiary industry (billion)	0.043	0.085	0.064
Secondary industry (billion)	0.055	0.034	0.045
Economic growth rate (%)	0.028	0.079	0.054
Urban per capita annual disposable income (yuan)	0.040	0.064	0.052
Rural per capita annual disposable income (yuan)	0.041	0.072	0.057
Fiscal revenue (billion)	0.029	0.053	0.041
GDP per capita (yuan)	0.038	0.053	0.046
Retail sales of social consumer goods (billion)	0.039	0.069	0.054
Current year afforestation area (hm^2)	0.055	0.095	0.075
Fertilizer application amount (t)	0.074	0.021	0.048
Wastewater emissions (million tons)	0.036	0.047	0.042
Arable land per capita (hm^2)	0.037	0.006	0.022
Industrial sulfur dioxide emissions (t)	0.065	0.187	0.126
Unit crop yield (kg/hm^2)	0.059	0.031	0.045

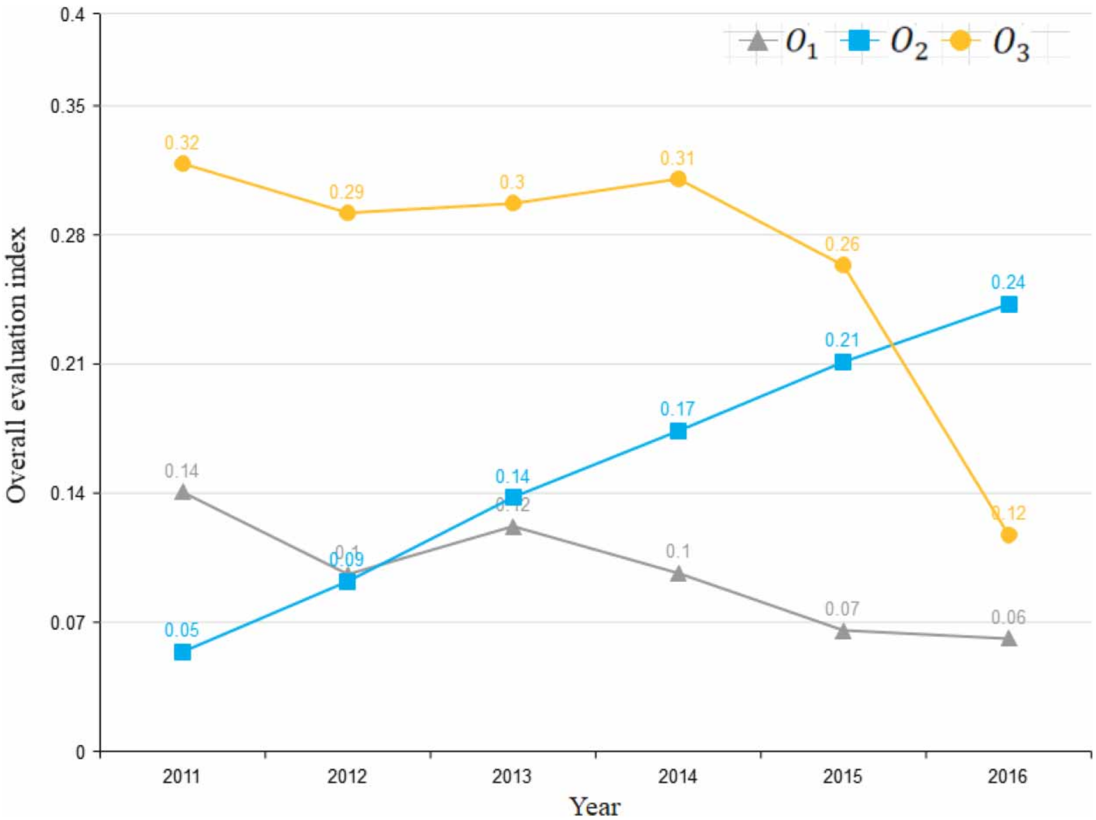

Figure 4 | Levels of economic development of the eco-economic-social subsystems.

experienced both serious and moderate dissonance. Notably, from 2013 to 2016, there was a discernible reduction in the absolute deviation of the evaluation index, coinciding with an upward trend in the coupling coordination degree across the three subsystems.

However, a pivotal shift occurred in 2018 when the coupling coordination degree reached its lowest point. In response, local governance initiatives sought to address this challenge by expediting the transformation and upgrading of the service industry. This strategic move resulted in a significant shift in the industrial structure from the previous 'two, three, one' configuration to a more balanced 'three, two, one' paradigm (Qiu *et al.* 2017). This restructuring aimed to alleviate the dissonance and enhance coordination among the social, economic, and ecological dimensions.

Despite these efforts, the coupling coordination degree witnessed a continuous decline after 2019, accompanied by an increase in the absolute deviation of the evaluation index. This trend highlights the intricate relationship between the three subsystems, where inhibiting factors within one subsystem impact the others. The data underscore a crucial insight – the absolute value of the deviation in the comprehensive evaluation index is inversely proportional to the coupling coordination degree. This implies that true harmony can only be achieved through mutual promotion and collective improvement.

The findings reveal that the ecological environment construction and socio-economic development in the Shandong water source area did not achieve synchronized progress. Instead, there is evidence of a reciprocal inhibition and influence between socio-economic development and ecological environment development. This suggests that the rapid socio-economic advancements in the region are intricately linked to the state of the ecological environment, emphasizing the need for a holistic approach to achieve sustainable and coordinated development.

4.3. Suggestions on sustainable development of the Liwu River water source

For the sustainable and healthy development of the water source area of six or five rivers, the following aspects should be emphasized when carrying out ecological construction of the water source area: as the origin of six or five rivers in Xiajin

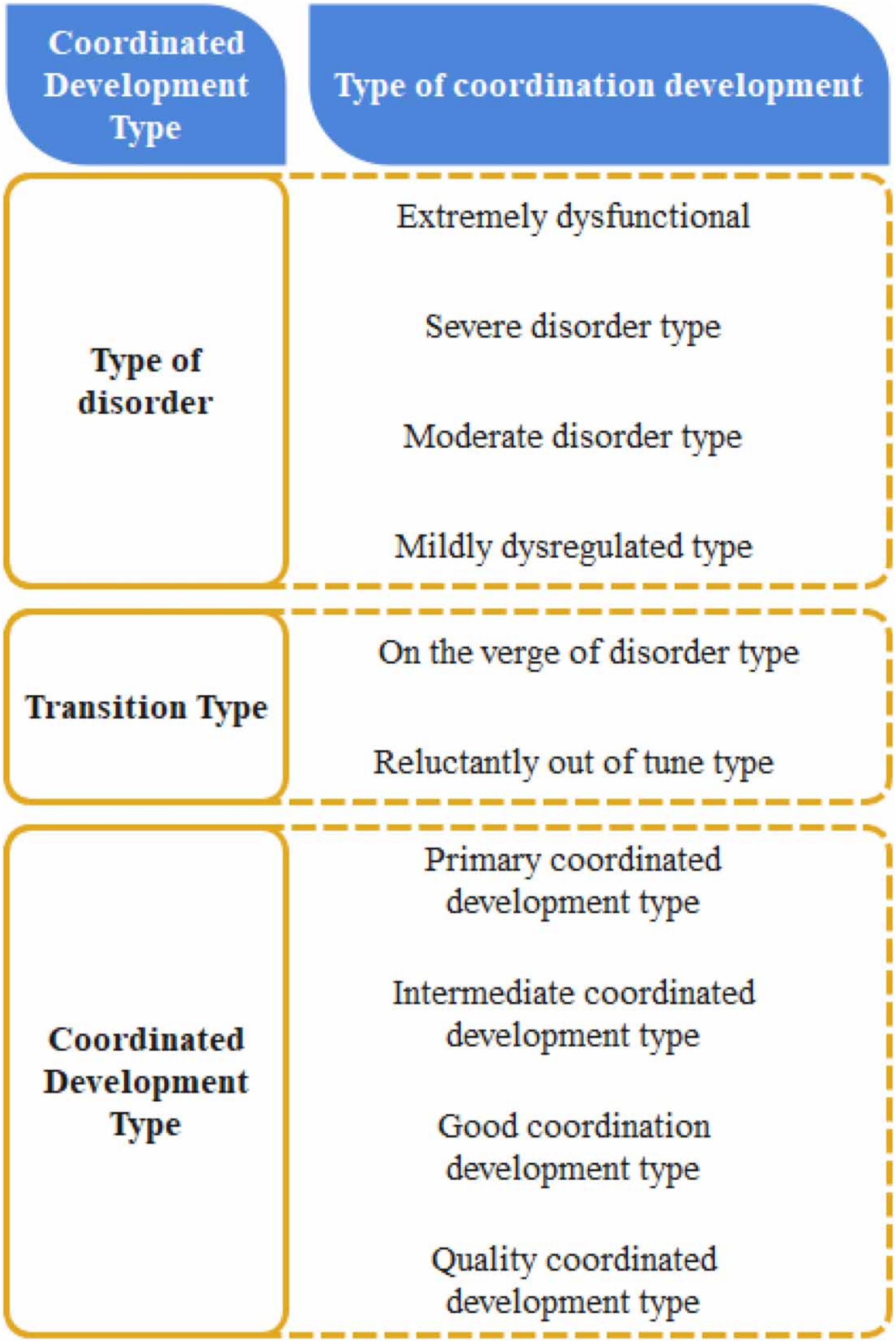

Figure 5 | Criteria for discriminating the type of coordinated development.

County, Shandong Province, the implementation of the water transfer project has undoubtedly intensified the burden of ecological protection for the people of the water source area. For Xiajin County, which provides high-value ecosystem services and is poor and backward, ecological compensation can be provided by the ecological beneficiary area as a way to improve the sustainable development of people in the water source area.

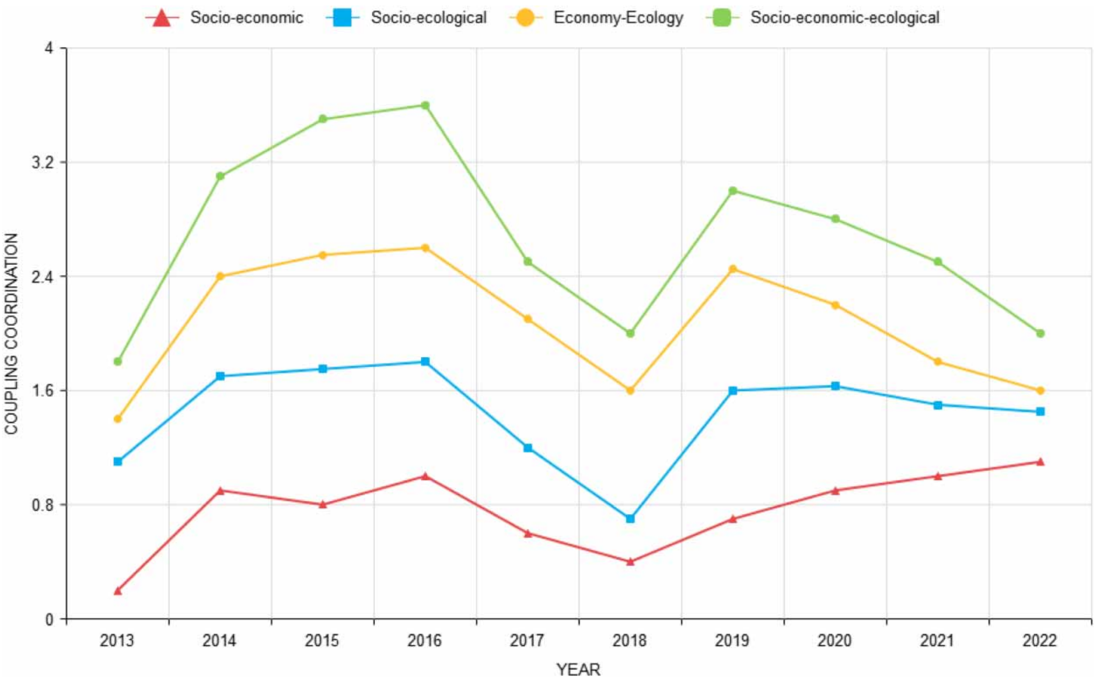

Figure 6 | 2013–2022 couplings and coordination among water source systems in Shandong.

In the social development factor, the urbanization level of the water source area should be improved. Increase the proportion of non-agricultural population in the total population and improve the living conditions of residents in the water source area. In terms of economic development factors, efforts should be made to increase farmers' income and local financial income; in terms of ecological environment factors, environmental pollution control needs to be further strengthened. Reduce the amounts of pesticides and chemical fertilizers used in agriculture and strictly control industrial waste gas and wastewater emissions.

5. CONCLUSION

Water source is an important ecological barrier of a region, and it is necessary to provide a scientific method for the evaluation of the sustainability of a water source. It has been proved that the method can effectively solve this problem. It also provides a reference for the sustainability evaluation of other water sources. Second, in view of the shortage of current methods, this paper proposes a method for combining the entropy value method and variation coefficient method, which lay a solid foundation for the determination of weight. Next, to address the shortcomings of the current method, this paper proposes a method that combines the entropy value method and the coefficient of variation method. A solid foundation is laid for the determination of weight. Finally, a study is conducted on the example of the South-North Water Transfer of Six or Five Rivers in Shandong, China, and the coupled coordination degree model is applied to the evaluation of the sustainable development capacity of water sources. The rationality and validity of the evaluation model in the evaluation of the sustainable development capacity of water sources were verified. It provides a new research idea for the evaluation of water sources. The issue of water source development has always been a focus of attention, but there is little literature on the study from the perspective of coupled social–ecological–economic coordination, and this paper attempts to contribute to this part. Despite the valuable insights gained in this study, certain limitations and gaps exist in our evaluation of water source sustainability. The current evaluation index system is hindered by a lack of hands-on experience in water source engineering projects. Additionally, limitations stemming from the researcher's experience and knowledge background are acknowledged.

To address these shortcomings, future research endeavors can focus on innovating the identification method for water source evaluation indexes. This innovation can contribute to a more comprehensive and robust evaluation framework. Furthermore, staying attuned to emerging evaluation methods is crucial, and conducting a comparative study of these methods can enhance the sophistication of our assessments. Improvements in data selection are essential for enhancing the representativeness of our findings. Future studies should aim for more diverse and scientifically rigorous data sources to ensure the accuracy of the evaluation model. As the field evolves, researchers should strive to refine the evaluation process, incorporating new methodologies and ensuring a more holistic understanding of water source sustainability.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Cao, X. H., Lu, Y. L., Wang, C. C., Zhang, M., Yuan, J. J., Zhang, A. Q., Song, S., Baninla, Y., Khan, K. & Wang, Y. C. 2019 Hydrogeochemistry and quality of surface water and groundwater in the drinking water source area of an urbanizing region. *Ecotoxicology and Environmental Safety* **186**, 109628. doi:10.1016/j.ecoenv.2019.109628.

Dai, C., Tang, J., Li, Z. Y., Duan, Y. C., Qu, Y. K., Yang, Y., Lyu, H., Zhang, D. & Wang, Y. T. 2022 Index system of water resources Development and utilization level based on water-saving society. *Water* **14** (5), 802. doi:10.3390/w14050802.

Ding, X. W., Zhu, Q., Zhai, A. F. & Liu, L. 2019 Water quality safety prediction model for drinking water source areas in Three Gorges Reservoir and its application. *Ecological Indicators* **101**, 734–741. doi:10.1016/j.ecolind.2019.01.068.

Dosu, B., Asibey, M. O. & Abubakari, M. 2023 Cultural meanings of water to source water protection in rural Ghana. *Sustainable Water Resources Management* **9**. doi:10.1007/s40899-023-00864-9.

Hou, L., Zhou, Z. Y., Wang, R. Y., Li, J. X., Dong, F. & Liu, J. Q. 2022 Research on the non-point source pollution characteristics of important drinking water sources. *Water* **14** (9), 92. doi:10.3390/w14020211.

Jin, H. J., Zhang, C. Y. & Chai, X. S. 2022 Determination of methanol partition coefficient in octanol/water system by a three-phase ratio variation headspace gas chromatographic method. *Journal of Chromatography A* **1665**, 462825. doi:10.1016/j.chroma.2022.462825.

Lee, J. & Lee, K. 2022 A method for neutralizing entropy measurement-based ransomware detection technologies using encoding algorithms. *Entropy* **24** (2), 239. doi:10.3390/e24020239.

Leya, R. S., Bala, S. K., Newton, I. H., Chowdhury, M. A. & Haque, S. M. 2022 Water security assessment of a peri-urban area: A study in Singair Upazila of Manikganj district of Bangladesh. *Environment Development and Sustainability* **24**, 14106–14129. doi:10.1007/s10668-021-02023-6.

Li, Y. H. & Hu, Z. Q. 2022 A review of multi-attributes decision-making models for offshore oil and gas facilities decommissioning. *Journal of Ocean Engineering and Science* **7**, 58–74. doi:10.1016/j.joes.2021.05.002.

Li, R. R., Ding, Z. Y. & An, Y. 2022 Examination and forecast of relationship among tourism, environment, and economy: A case study in Shandong Province, China. *International Journal of Environmental Research and Public Health* **19** (5), 2581. doi:10.3390/ijerph19052581.

Liu, Z. Z., Zhu, H. H., Cui, X. W., Wang, W., Luan, X. Y., Chen, L., Cui, Z. J. & Zhang, L. 2021 Groundwater quality evaluation of the Dawu water source area based on water quality index (WQI): Comparison between Delphi method and multivariate statistical analysis method. *Water* **13** (8), 1127. doi:10.3390/w13081127.

Liu, B., Tan, W. B., Zhang, X., Peng, Z. Q. & Cao, J. 2022 Recognition study of denatured biological tissues based on multi-scale rescaled range permutation entropy. *Mathematical Biosciences and Engineering* **19**, 102–114. doi:10.3934/mbe.2022005.

Loges, K. & Tiberius, V. 2022 Implementation challenges of 3D printing in prosthodontics: A ranking-type Delphi. *Materials* **15** (2), 431. doi:10.3390/ma15020431.

Mosquera-Romero, S., Ntagia, E., Rousseau, D. P. L., Esteve-Nunez, A. & Prevoteau, A. 2023 Water treatment and reclamation by implementing electrochemical systems with constructed wetlands. *Environmental Science and Ecotechnology* **16**, 100265. doi:10.1016/j.ese.2023.100265.

Qin, G. S., Liu, J. W., Xu, S. G. & Sun, Y. 2021 Pollution source apportionment and water quality risk evaluation of a drinking water reservoir during flood seasons. *International Journal of Environmental Research and Public Health* **18** (4), 1873. doi:10.3390/ijerph18041873.

Qiu, F. D., Yuan, H., Bai, L. Y. & Li, F. 2017 Spatial-temporal heterogeneity of industrial structure transformation and carbon emission effect in Xuzhou Metropolitan Area. *Chinese Geographical Science* **27**, 904–917. doi:10.1007/s11769-017-0920-8.

Sun, S. Y., Zhang, J. F., Cai, C. J., Cai, Z. Y., Li, X. G. & Wang, R. J. 2020 Coupling of non-point source pollution and soil characteristics covered by *Phyllostachys edulis* stands in hilly water source area. *Journal of Environmental Management* **268**, 110657. doi:10.1016/j.jenvman.2020.110657.

Wan, X., Wang, R. B., Wang, M. Y., Deng, J. R., Zhou, Z. P., Yi, X., Pan, J. N. & Du, Y. F. 2022 Online public opinion mining for large cross-regional projects: Case study of the south-to-north water diversion project in China. *Journal of Management in Engineering* **38** (1). doi:10.1061/(ASCE)ME.1943-5479.0000970.

Wang, L. Z. & Tian, K. 2021 Optimisation of driver's traffic literacy evaluation index from the perspective of information contribution sensitivity. *Journal of Mathematics* **2021**, 9503037. doi:10.1155/2021/9503037.

Wang, S. R., Rao, P. Z., Yang, D. W. & Tang, L. H. 2020 A combination model for quantifying non-point source pollution based on land use type in a typical urbanized area. *Water* **12** (3), 729. doi:10.3390/w12030729.

Wang, R. J., Wang, Q. B., Dong, L. S. & Zhang, J. F. 2021 Cleaner agricultural production in drinking-water source areas for the control of non-point source pollution in China. *Journal of Environmental Management* **285**, 112096. doi:10.1016/j.jenvman.2021.112096.

Wu, D. H., Zhou, Y., Lu, G. H., Hu, K., Yao, J. J., Shen, X. H. & Wei, L. 2019 The occurrence and risks of selected emerging pollutants in drinking water source areas in Henan, China. *International Journal of Environmental Research and Public Health* **16** (21), 4109. doi:10.3390/ijerph16214109.

Xiao, K., Tamborski, J., Wang, X. J., Feng, X. B., Wang, S. C., Wang, Q. Q., Lin, D. B. & Li, H. L. 2022 A coupling methodology of the analytic hierarchy process and entropy weight theory for assessing coastal water quality. *Environmental Science and Pollution Research* **29**, 31217–31234. doi:10.1007/s11356-021-17247-2.

Xu, H. X., Gao, Q. & Yuan, B. 2022 Analysis and identification of pollution sources of comprehensive river water quality: Evidence from two river basins in China. *Ecological Indicators* **135**, 108561. doi:10.1016/j.ecolind.2022.108561.

Yang, X., Zhang, H. Y., Yang, J., Li, H. W. & Zhu, X. B. 2020 Research on ecological compensation of water resources in the Yellow River basin. *Fresenius Environmental Bulletin* **29**, 4426–4429.

Yosboonruang, N., Niwitpong, S. A. & Niwitpong, S. 2022 Bayesian computation for the common coefficient of variation of delta-lognormal distributions with application to common rainfall dispersion in Thailand. *Peerj* **10**, e12858. doi:10.7717/peerj.12858.

Yu, J. H., Lin, H. H., Lo, Y. C., Tseng, K. C. & Hsu, C. H. 2021 Research on sustainable development evaluation of reservoir water source area in Island Area. *Water* **13** (8), 1130. doi:10.3390/w13081130.

Zhang, H. Y., Wang, T. T., Ding, Z. L., Zhang, X. Q. & Han, L. W. 2020 Uncertainty analysis of impact factors of eco-environmental vulnerability based on cloud theory. *Ecological Indicators* **110**, 105864. doi:10.1016/j.ecolind.2019.105864.

Zhang, Q. X., Li, P. Y., Lyu, Q. F., Ren, X. F. & He, S. 2022 Groundwater contamination risk assessment using a modified DRATICL model and pollution loading: A case study in the Guanzhong Basin of China. *Chemosphere* **291**, 132695. doi:10.1016/j.chemosphere.2021.132695.

Zhang, Y., Wang, Y. J., Sun, S. W. & Chen, X. D. 2023 Quantifying interregional flows of ecosystem services to enhance water security in the Yellow River Basin, China. *Journal of Water Resources Planning and Management* **149** (6). doi:10.1061/JWRMD5.WRENG-5891.

Zimmermann, T., Shinde, S., Parthasarathy, D. & Narayanan, N. C. 2023 Linking climate change adaptation and disaster risk reduction: Reconceptualizing flood risk governance in Mumbai. *Journal of Integrative Environmental Sciences* **20**, 1–29. doi:10.1080/1943815X.2023.2169712.

First received 4 September 2023; accepted in revised form 1 March 2024. Available online 15 March 2024