Construction of evaluation index system of reclaimed water development and utilization potential based on AHP

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Abstract. The shortage of water resources has severely restricted the rapid development of modern cities in China, and the recycling of reclaimed water is one of the important methods to effectively solve the bottleneck problem of urban water shortages. Based on the Analytic Hierarchy Process (AHP), this study determines the evaluation indexes and their weights from social and technical levels respectively and constructs an evaluation index system of reclaimed water development and utilization potential, which contains 3 levels, 5 criteria and 19 alternatives, focusing on the production, utilization and benefit of reclaimed water and other characteristic indexes. From the weighting results of the index system, among the main influencing factors of reclaimed water development and utilization, the water quantity factor has the greatest influence, the influence of water usage and water quality assurance ranks second, and the economic factor has the least influence. This evaluation system provides a useful reference for the reasonable development and utilization of regional reclaimed water in the future.

1. Introduction

As a second source of water resources development and utilization, reclaimed water can alleviate the problem of water shortage to a considerable extent [1, 2]. After proper treatment of urban sewage, pollutants are effectively removed, and water quality is stable. Reclaimed water has been widely used in industry, agriculture, municipal miscellaneous use, landscape environment, groundwater supply and other fields, effectively reducing the demand for fresh water [3–5]. Wastewater recycling is a key measure to alleviate urban water stress, improve urban water environment and protect urban water ecology [6, 7].

In the past 10 years, the use of reclaimed water in China has shown a rapid growth trend, from 2.15 billion m³ in 2009 to 8.55 billion m³ in 2018, an increase of nearly four times, but its proportion in the total national water supply is still less than 1.5%, and there is a large gap with the world's advanced level [8]. Therefore, it is necessary to establish an index system for evaluating the potential level of reclaimed water development and utilization to improve the scale and efficiency of reclaimed water utilization and break the bottleneck that restricts reclaimed water development. Based on the Analytic Hierarchy Process, this study determines the evaluation indexes and their weights from social and technical levels respectively and constructs an evaluation index system of reclaimed water development and utilization potential, to provide reference for the rational development and utilization of reclaimed water.
2. Materials and methods

AHP is a multi-objective and multi-criteria decision-making technology proposed by Satty, which is characterized by flexibility, simplicity, and systematism. As a typical method of comprehensive integration from qualitative analysis to quantitative analysis, AHP has been widely used in the evaluation of sustainable water resources utilization [9–11].

(1) Establishment of hierarchical structure model

Regarding a complex multi-objective decision-making problem as a system, the goal is decomposed into multiple goals or criteria, and then decomposed into multiple levels (hierarchical structure) of multiple alternatives, as shown in Figure 1.

![Figure 1. Figure with short caption (caption centred).](image)

(2) Construction of judgment matrix

The judgment matrix is used to express the relative influence between the elements of this level that belong to the adjacent upper-level dimension. If the element $A$ in the upper layer (layer $A$) is determined by the elements $B_1$, $B_2$, ..., $B_n$ in the next layer (layer $B$), $U_{ij}$ is used to represent the relative influence of $S_i$ and $S_j$ for factor $A$. The values of $U_{ij}$ using the representation are shown in Table 1.

| Scaling | Meaning                        |
|---------|--------------------------------|
| 9       | Extremely preferred            |
| 8       | Very strongly to extremely preferred |
| 7       | Very strongly preferred        |
| 6       | Strongly to very strongly preferred |
| 5       | Strongly preferred             |
| 4       | Moderately to strongly preferred |
| 3       | Moderately preferred           |
| 2       | Equally to moderately preferred |
| 1       | Equally preferred              |

Reciprocal: $U_{ij}=1/U_{ji}$, $U_{ii}=1$

(3) Calculate the weight

According to the judgment matrix, find the eigenvector corresponding to the largest eigen root (weight, ranking of influence of each evaluation index). The eigenvector $W$ corresponding to the largest eigenvalue in the judgment matrix:

$$W = (W_1 \ W_2 \ ... \ W_n)^T$$

$$Wi = \frac{1}{\sqrt[n]{\prod_{j=1}^{n} U_{ij}}}$$

$$Wi = \frac{1}{\sum_{i=1}^{n} \sqrt[n]{\prod_{j=1}^{n} U_{ij}}}$$

(4) Consistency inspection
Calculate the maximum eigenvalue $\lambda_{\text{max}}$ of the judgment matrix:

$$\lambda_{\text{max}} = \frac{1}{n} \sum_{i=1}^{n} \frac{(UW)_i}{W_i}$$  \hspace{1cm} (3)

$(UW)_i$ is the $i$-th element of the vector $UW$.

The calculation method of the consistency test index of the judgment matrix:

$$C.R. = \frac{C.I.}{R.I.}$$  \hspace{1cm} (4)

$$C.I. = \frac{1}{n-1} (\lambda_{\text{max}} - n)$$  \hspace{1cm} (5)

$R.I.$ refers to the random consistency index of the judgment matrix, and the specific values are shown in Table 2.

$C.R. \leq 0.1$ indicates that the judgment matrix is consistent and proves that the weight setting is reasonable; if not, the judgment matrix needs to be reset until the consistency condition is met.

### Table 2. The value of the random consistency index of the judgment matrix.

| n  | 1 or 2 | 3  | 4  | 5  | 6  | 7  | 8  | 9  |
|----|--------|----|----|----|----|----|----|----|
| R.I. | 0.00 | 0.58 | 0.89 | 1.12 | 1.24 | 1.32 | 1.41 | 1.45 |

3. Results

3.1 Establishment of hierarchical structure model

The development and utilization of reclaimed water is an issue related to economy, society, environment, and technology. It is necessary to construct an index system from these four aspects. The economic aspect is represented by the economic benefits of reclaimed water development and utilization, the social aspect is reflected by the efficiency of reclaimed water utilization and the objects of reclaimed water supply, the environmental aspect is reflected by the environmental benefits of reclaimed water development and utilization, and the technical level is characterized by the production of reclaimed water. Based on the concept of sustainable development and circular economy, an evaluation index system for the development and utilization potential of reclaimed water was constructed from the perspectives of technical level of reclaimed water treatment, reclaimed water supply and demand, social and economic characteristics, environmental characteristics, and water management policies, as shown in Figure 2, which including three levels of mutual influence, namely the target level, the criterion level, and the index level.

(1) Goal level: the potential for the development and utilization of reclaimed water.

(2) Criteria level: It is divided into 5 criteria for reclaimed water production, reclaimed water utilization efficiency, reclaimed water supply objects, environmental benefits of reclaimed water development and utilization, and economic benefits of reclaimed water development and utilization.

(3) Alternatives level: 19 evaluation alternatives including the number of patents granted in the water treatment industry, sewage collection rate, sewage treatment rate, and sewage treatment capacity.

3.2 Constructing the judgment matrix

Based on the data collected by the questionnaire, the respondents' consensus on these five criteria is: 1) The production of reclaimed water is the basis of the development and utilization of reclaimed water, and only after the production of reclaimed water can it be used for subsequent use; 2) The utilization efficiency of reclaimed water reflects the utilization of reclaimed water, and only high efficiency can sustainably develop and utilize reclaimed water; 3) The supply object of reclaimed water is the supply situation of reclaimed water, and the development and utilization of reclaimed water is meaningful only when there is a supply demand; 4) The environmental benefits of the development and utilization of reclaimed water are one of the meanings of the development and utilization of reclaimed water, and alleviate a series of ecological and environmental problems caused by over-exploitation and utilization.
of water resources; 5) The economic benefits of reclaimed water development and utilization reflect the economic advantages of reclaimed water development and utilization. The importance of the 5 dimensions relative to the other dimensions is shown in Table 4.

Table 3. Evaluation index system of reclaimed water development and utilization potential.

| Goal | Criteria | Alternatives |
|------|----------|--------------|
|      | A1 - Reclaimed water production | A11 - The number of patents granted in the water treatment industry |
|      |      | A12 - Sewage collection rate |
|      |      | A13 - Sewage treatment rate |
|      |      | A14 - Sewage treatment capacity |
|      |      | A15 - Reclaimed water production rate |
|      | A2 - Reclaimed water utilization efficiency | A21 - Density of reclaimed water supply pipe network |
|      |      | A22 - Reclaimed water utilization rate |
|      | A3 - Reclaimed water supply objects | A23 - Wastewater recycling |
|      |      | A31 - Supply ratio of reclaimed water in industrial water |
|      |      | A32 - Proportion of reclaimed water supply in agricultural water |
|      |      | A33 - Proportion of reclaimed water supply in municipal water |
|      |      | A34 - Proportion of reclaimed water supply in landscape recreational water |
|      |      | A35 - Proportion of reclaimed water supply in supplementary water source |
|      | A4 - Environmental benefits of reclaimed water development and utilization | A41 - Groundwater recharge volume of reclaimed water |
|      |      | A42 - Groundwater supply ratio |
|      |      | A43 - Water resources development and utilization rate |
|      | A5 - Economic benefits of reclaimed water development and utilization | A51 - Reclaimed water price |
|      |      | A52 - Sewage treatment unit price |
|      |      | A53 - Sewage treatment facility cost |

Table 4. The importance of each dimension at the criterion level.

| Criteria | A1 | A2 | A3 | A4 | A5 |
|----------|----|----|----|----|----|
| A1       | 1.00 | 2.00 | 2.00 | 3.00 | 4.00 |
| A2       | 0.50 | 1.00 | 2.00 | 3.00 | 4.00 |
| A3       | 0.50 | 0.50 | 1.00 | 2.00 | 3.00 |
| A4       | 0.33 | 0.33 | 0.50 | 1.00 | 2.00 |
| A5       | 0.25 | 0.25 | 0.33 | 0.50 | 1.00 |

3.3 Calculate the weight

Calculate the weight result of the alternatives layer relative to the criteria layer, and the weight result of the criteria layer relative to the goal layer (Table 5), and then obtain the weight result of the alternatives layer relative to the goal layer (Table 6).
Table 5. Weight results of adjacent levels (Criterion-Goal, Alternatives-Criterion).

| Criteria | Weight result of criterion layer relative to goal layer | Alternatives | Weight result of alternatives layer relative to criteria layer |
|----------|--------------------------------------------------------|--------------|---------------------------------------------------------------|
| A1       | 0.36                                                    | A1           | 0.07                                                          |
|          |                                                        | A2           | 0.12                                                          |
|          |                                                        | A3           | 0.22                                                          |
|          |                                                        | A4           | 0.22                                                          |
|          |                                                        | A5           | 0.37                                                          |
|          |                                                        | B1           | 0.2                                                           |
| A2       | 0.28                                                    | B2           | 0.4                                                           |
|          |                                                        | B3           | 0.4                                                           |
|          |                                                        | C1           | 0.26                                                          |
|          |                                                        | C2           | 0.42                                                          |
| A3       | 0.18                                                    | C3           | 0.16                                                          |
|          |                                                        | C4           | 0.1                                                           |
|          |                                                        | C5           | 0.06                                                          |
|          |                                                        | D1           | 0.5                                                           |
| A4       | 0.11                                                    | D2           | 0.25                                                          |
|          |                                                        | D3           | 0.25                                                          |
|          |                                                        | E1           | 0.49                                                          |
| A5       | 0.07                                                    | E2           | 0.31                                                          |
|          |                                                        | E3           | 0.2                                                           |

Table 6. Weight result of alternatives layer relative to goal layer (Alternatives-Goal).

| Goal | Criterion | Alternatives | Weight result of alternatives layer relative to goal layer |
|------|-----------|--------------|------------------------------------------------------------|
| A1   | A3        | 0.03         |                                                            |
|      | A4        | 0.08         |                                                            |
|      | A5        | 0.14         |                                                            |
|      | B1        | 0.06         |                                                            |
| A2   | B2        | 0.11         |                                                            |
|      | B3        | 0.11         |                                                            |
|      | C1        | 0.05         |                                                            |
| A    | C2        | 0.08         |                                                            |
| A3   | C3        | 0.03         |                                                            |
|      | C4        | 0.02         |                                                            |
|      | C5        | 0.01         |                                                            |
|      | D1        | 0.05         |                                                            |
| A4   | D2        | 0.03         |                                                            |
|      | D3        | 0.03         |                                                            |
|      | E1        | 0.03         |                                                            |
| A5   | E2        | 0.02         |                                                            |
|      | E3        | 0.01         |                                                            |

3.4 Consistency inspection

According to the AHP method, the consistency test of the weighted results is carried out. The consistency test results of the criterion layer to the goal layer are shown in Table 7. According to the
calculation results, the consistency test is passed. Therefore, it is believed that the previous setting of the relative importance of the five dimensions in the criterion layer is reasonable, and the weight result is also reasonable.

Table 7. Consistency test on target weights at all dimensions.

| Criterion | \((UW)_i\) | \((UW)_i\) | \(W_i\) |
|-----------|------------|------------|---------|
| A1        | 1.89       | 5.25       |         |
| A2        | 1.43       | 5.11       |         |
| A3        | 0.93       | 5.17       |         |
| A4        | 0.55       |            | 5.11    |
| A5        | 0.35       |            | 5.17    |
| \(\lambda_{max}\) | \(\frac{5.25 + 5.11 + 5.17 + 5 + 5}{5.106} = 5.106\) |             |         |
| \(C.I.\) | \(\frac{5.106 - 5}{5 - 1} = 0.0265\) |             |         |
| \(C.R.\) | \(\frac{0.0265}{1.12} = 0.024 < 0.1\) |             |         |

4. Conclusions
The development and utilization of reclaimed water is a set of systems engineering, which is affected by many factors. Based on the Analytic Hierarchy Process, this study determines the evaluation indexes and their weights from social and technical levels respectively and constructs an evaluation index system of reclaimed water development and utilization potential, which contains 3 levels, 5 guidelines and 19 evaluation indexes, focusing on the production, utilization and benefit of reclaimed water and other characteristic indexes. From the weighting results of the index system, among the main influencing factors of reclaimed water development and utilization, the water quantity factor has the greatest influence, the influence of water usage and water quality assurance ranks second, and the economic factor has the least influence. This evaluation system provides a useful reference for the reasonable development and utilization of regional reclaimed water in the future.

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