Multi-attribute decision making approach for green efficiency of water utilization in Taiyuan

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Abstract. The problem of water shortage and pollution exists in Taiyuan. Under the advocacy of the concept of green development, it is necessary to carry out the research on the green efficiency of water utilization (WUGE) from the three-dimensional perspective of “economy environment society”. In this study, the evaluation index system of WUGE was optimized, which consist of 17 attributes. Interval analytic hierarchy process is used to determine the weight of attributes, and multi-attribute decision making approach is used to evaluate the WUGE from 2009 to 2018. The evaluation results show that the comprehensive evaluation value of WUGE in 2018 is the highest.

1. Introduction
In 2018, the total amount of water resources in Taiyuan is 615.39 million m³ [1], which is only 0.02% of the total amount of water resources. The water resource of the whole city is 139.2 m³ per capita, which is far lower than the extreme water shortage limit of 500 m³ per capita. It is one of the cities with serious water shortage. The discharge of industrial wastewater in Taiyuan is 37.39 million tons, and the reuse rate is not high, which leads to the imbalance of water supply and demand. Therefore, in order to realize the sustainable development of water resources, improving the efficiency of water resources utilization is an important way to deal with the problems of resources and environment [2, 3].

Green development is a mode innovation on the basis of traditional development, which aims to realize the sustainable development of economy, society and environment. Its essence is “people-oriented” social development [4-6]. Therefore, this study will integrate the concept of green development into the water resources efficiency system of Taiyuan, and expand the research perspective from “economy environment” to “economy environment society”. On the basis of summarizing the research on water resources utilization efficiency, this study constructs the evaluation system of WUGE, and uses the multi-attribute decision making method (MADM) to evaluate the WUGE in Taiyuan.

2. Methodology
To summarize the methodology, the steps of the MADM approach are given in the following:

(1) Let $OD = \{ OD_{11}, ..., OD_{1N}, ..., OD_{mn} \}$ be a decision matrix for the multi-attributes preference model, in which $OD_{ij}$ represents the original data under the attribute $j$ in $i$th year $Y_i$. By consulting relevant literature and combining the relationship between the water resources system and other systems, 3 criterion levels, 8 first-level attributes, and 17 second-level attributes are selected to evaluate the green efficiency of Taiyuan’s water resources (Table 1).
Table 1. Attributes for green efficiency of water utilization.

| Criterion layer | First level attributes                  | Second level attributes                                                                 |
|-----------------|----------------------------------------|------------------------------------------------------------------------------------------|
| Economic criterion (EC) | Fixed assets workload                   | Growth rate of fixed assets investment                                                 |
|                  | Economic development                     | GDP per capita                                                                            |
| Sociological criterion (SC) | Industrial water efficiency (IWE)       | Water consumption per RMB 10000 of industrial GDP; Reduction rate of water consumption per unit of industrial added value |
|                  | Domestic water efficiency (DWE)         | Per capita daily domestic water consumption                                             |
|                  | Rural/Urban per capita daily domestic water consumption |
|                  | Agricultural water use efficiency (AWUE) | Irrigation water and grain yield per square meter of farmland; Water consumption per RMB 10000 of agricultural GDP; Average water consumption per mu for farmland irrigation |
| Social development index (SDI) | Natural population growth rate; Proportion of employees in the whole society; Proportion of non-agricultural population; Proportion of science and education expenditure in financial expenditure; Number of college students per 10000 people |
| Environmental criterion (E_C) | Sources of water pollution (SWP)         | Industrial wastewater discharge                                                        |
|                  | Sewage treatment and disposal (STD)     | Centralized treatment rate of sewage treatment plant                                     |

(2) In order to eliminate the influence of different dimensions of each index on the evaluation results, the range transformation idea is used to normalize the original interval number. The attributes divide into beneficial attributes (larger-the-better type) and non-beneficial attributes (small-the-better type).

For beneficial attributes,
\[
NOD_j = \frac{O_{D_j} - \min\{O_{D_j}\}}{\max\{O_{D_j}\} - \min\{O_{D_j}\}} 
\]

For non-beneficial attributes,
\[
NOD_j = \frac{\max\{O_{D_j}\} - O_{D_j}}{\max\{O_{D_j}\} - \min\{O_{D_j}\}} 
\]

(3) The relative importance or weight \(w_j\) for \(j\)th attribute is defined by interval-AHP (Analytic Hierarchy Process) method. \(w_j = [\underline{w_j}, \overline{w_j}]\) is defined as an interval with lower bound (\(\underline{w_j}\)) and upper bound (\(\overline{w_j}\)).

(4) Since preference function is considered to be used to provide the preference strength of action \(A_i\) over \(A_j\) with respect to each criterion. \(P(O_{D_j}, O_{D_i})\) is a positive non-decreasing preference function.
\[
P(O_{D_j}, O_{D_i}) = \begin{cases} 
0 & \text{if } NOD_j \leq NOD_i \\
\sin \left[ \frac{\pi}{2} \times \text{abs}(NOD_j - NOD_i) \right] & \text{if } NOD_j > NOD_i 
\end{cases} 
\]

(5) Compute the preference degree which is primarily based on pair-wise comparisons between two arbitrary alternatives. The global preference degree of \(Y_i\) over \(Y_j\) which varies between 0 and 1 is computed as follows:
\[
\pi(Y_i, Y_j) = \sum_{j=1}^{n} P(O_{D_j}, O_{D_i}) \cdot w_j = P(O_{D_1}, O_{D_i}) \cdot w_1 + \ldots + P(O_{D_n}, O_{D_i}) \cdot w_n + \ldots \\
= P(O_{D_1}, O_{D_i}) \cdot [\underline{w_j}, \overline{w_j}] + \ldots + P(O_{D_n}, O_{D_i}) \cdot [\underline{w_j}, \overline{w_j}] + \ldots 
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= P(O_{D_1}, O_{D_i}) \cdot [\underline{w_j}, \overline{w_j}] + \ldots + P(O_{D_n}, O_{D_i}) \cdot [\underline{w_j}, \overline{w_j}] + \ldots 
\]
The positive and negative outranking flow scores are defined as follows:

\[
\phi'(Y_i) = \frac{1}{n-1} \sum_{j=1}^{n-1} P(OD_{i,j}, OD_{i,n}) \cdot [w_i, w_j] + \ldots + P(OD_{i,j}, OD_{j,n}) \cdot [w_i, w_j] + \ldots
\]

\[
\phi(Y_i) = \frac{1}{n-1} \sum_{j=1}^{n-1} P(OD_{i,j}, OD_{i,n}) \cdot [w_i, w_j] + \ldots + P(OD_{i,j}, OD_{j,n}) \cdot [w_i, w_j] + \ldots
\]

The positive outranking flow expresses how the WUGE in the \(i\)th year outranks all other years. The higher the value of \(\phi'(Y_i)\), the better in this year. The negative outranking flow expresses how the WUGE in the \(i\)th year is being outranked by the others. Lower value of \(\phi'(Y_i)\) signifies better WUGE.

(7) Calculate the net flow \(\phi(Y_i)\) which can provide a complete rank preorder of the WUGE in different years. The net outranking flow in each year can be obtained using the following equation:

\[
\phi(Y_i) = \phi'(Y_i) - \phi(Y_i) = [\phi'(Y_i), \phi'(Y_i)] - [\phi(Y_i), \phi(Y_i)]
\]

(8) Define the possibility degree \(pd(\phi(Y_i) > \phi(Y_j))\) and corresponding ranking values \(Rank(Y_i)\). The higher the value of \(Rank(Y_i)\), the better the WUGE is in this year.

\[
Rank(Y_i) = \frac{1}{n(n-1)} \left( \sum_{j=1}^{n} pd(\phi(Y_i) > \phi(Y_j)) + \frac{n}{2} - 1 \right)
\]

3. Results

By calculating the pairwise comparison matrices based on interval-AHP method, the weights expressed as interval values are determined. In criterion levels, the weight of economic criterion is between 0.494 and 0.579, which occupies more than half of the whole weights, which means that this criterion has greater influence than others. In first-level indicators, the weight of economic development (i.e., [0.263, 0.365]) greatly affect the resulting orders of result. In second-level attributes, the weight of GDP per capita is estimated to be within an interval of [0.263, 0.365] and higher than other evaluation attributes, which is determined as the most important attributes for the WUGE in Taiyuan.

![Figure 1. Performance of green efficiency of water utilization under different years.](image-url)
The decision matrix is introduced into the multi-attribute evaluation model of green efficiency of water utilization in Taiyuan and the rankings in different years are obtained. By comparing the comprehensive priority in different years, it can be concluded that there are spatial differences in the green utilization efficiency of water resources. The preference performances with respect to different attributes are quite different in each year. The years with the highest value $\phi(Y)$ or $\text{Rank}(Y)$ are considered the most efficient in water utilization. Generally, the green efficiency of water utilization shows a trend of "increase-decrease-increase" as shown in Figure 1. The values $\phi(Y)$ for all years range from -2.484 to 3.130 (Table 2). The year (i.e., 2018) with the maximum (i.e., 0.143) is deemed the highest in the green efficiency, followed by 2013 and 2012.

Table 2. The lower and upper bounds of the performance (i.e., $\phi(Y)$, $\phi^-(Y)$ and $\phi^+(Y)$).

| Year | $\phi(Y)$ | $\phi^+(Y)$ | $\phi^-(Y)$ | $\phi^-(Y)$ | $\phi^+(Y)$ | $\phi^+(Y)$ |
|------|-----------|-------------|-------------|-------------|-------------|-------------|
| 2009 | -0.566    | 1.680       | 2.083       | 2.650       | 3.650       |
| 2010 | 0.515     | 1.939       | 2.475       | 1.960       | 2.686       |
| 2011 | 0.122     | 1.687       | 2.138       | 2.016       | 2.770       |
| 2012 | 2.163     | 2.618       | 3.463       | 1.299       | 1.756       |
| 2013 | 2.483     | 2.610       | 3.504       | 1.021       | 1.327       |
| 2014 | -0.592    | 1.281       | 1.673       | 2.265       | 3.044       |
| 2015 | -0.501    | 1.444       | 1.979       | 2.480       | 3.193       |
| 2016 | -1.118    | 1.272       | 1.729       | 2.847       | 3.756       |
| 2017 | 0.970     | 2.155       | 2.934       | 1.964       | 2.557       |
| 2018 | 3.130     | 3.422       | 4.734       | 1.604       | 1.972       |

For economic attributes (EA), the $\text{Rank}(Y)$ in 2018 has the highest value (i.e., 0.150) and is the most relevant attributes; on the contrary, the $\text{Rank}(Y)$ in 2009 has less importance than other attributes in the evaluation. Therefore, if only economic indicators are considered, the priority capacity of 2018 is extremely significant compared with other years. The contribution rate of weighted priority value of this attribute is higher than others.

For sociological attributes (SA), the value in 2018 is at a medium level. If only social indicators are considered, years 2012, 2011, and 2013 are top three in the outranking. For 2018, although the priority value is low in terms of social attributes, the comprehensive ranking is the first. Therefore, the evaluation results of green utilization efficiency of water resources depend on the interaction of the overall attributes, not just individual or partial attributes. For industrial water efficiency (IWE), domestic water efficiency (DWE), agricultural water use efficiency (AWUE), social development index (SDI), year in 2011, 2010, 2018, 2018 have the highest value, respectively (Table 3).

Table 3. Performance under different sociological attributes under in different years.

| Year | IWE  | DWE  | AWUE | SDI  | Year | IWE  | DWE  | AWUE | SDI  |
|------|------|------|------|------|------|------|------|------|------|
| 2009 | 0.093| 0.142| 0.05 | 0.05 | 2014 | 0.113| 0.111| 0.133| 0.086|
| 2010 | 0.085| 0.147| 0.061| 0.066| 2015 | 0.05 | 0.083| 0.13  | 0.127 |
| 2011 | 0.146| 0.114| 0.083| 0.071| 2016 | 0.064| 0.065| 0.105 | 0.114 |
| 2012 | 0.142| 0.117| 0.073| 0.109| 2017 | 0.109| 0.069| 0.116 | 0.135 |
| 2013 | 0.128| 0.103| 0.099| 0.092| 2018 | 0.069| 0.05 | 0.15  | 0.149 |

For environmental attributes (E_A), the overall level was tend to downward and the data in 2018 is the lowest. Due to the limitation of data, only important sources of water pollution and sewage treatment and disposal are considered. Results from the case study indicated that these aspects (i.e., the standards of industrial wastewater treatment, urban domestic sewage collection and treatment, river sewage outlet treatment and so on) still need to be improved.
4. Summary
This paper presented the MADM method to determine the priority ranking of green efficiency of water utilization in Taiyuan in different years. Three criterion levels, including 8 first-level attributes, and 17 second-level attributes, were considered. The attribute weights are calculated by interval-AHP method. The analytical results show that (1) the green efficiency of water utilization showed obvious temporal differences in the study area during the 10 years; (2) the green efficiency of water utilization in 2018 is the highest among the set of years. In future study, many other uncertain parameters related to qualitative attributes could be involved in the analysis.

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