Fuzzy comprehensive evaluation for safety guarantee system of reclaimed water quality

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Abstract

Two-steps fuzzy comprehensive evaluation model was constructed by developing evaluating indicators system on guarding quality safety of reclaimed water and weighting evaluating indicators with analytic hierarchy process (AHP). By employing the fuzzy comprehensive evaluation model to reclaimed water demonstrate base in Liantang of Shenzhen, the following results were acquired: when calculating weights of evaluating indicators, AHP displays these virtues, such as independence of evaluation personnel's diathesis, authority and ability, possessing scientific test methods and having tiny error; further, safety guarantee system is comprehensively appraised with fuzzy comprehensive evaluation model combining qualitative appraisal with quantitative appraisal, so it avoids subjective arbitrariness and is coincident to actual circs.

Keywords: reclaimed water; water quality safety; guarantee system; safety evaluation; analytic hierarchy process; fuzzy comprehensive evaluation

1. Introduction

From the view of human sustainable development, wastewater reclamation and reuse is one of the practicable ways to solve the water crisis in China. As a new water source of city, reclaimed water is gradually coming into people's life\cite{1-2}. Under the influence of traditional view in using water, it is also not possible for people to accept reclaimed water quickly psychologically, therefore, constructing safety guarantee system for the quality of reclaimed water reuse system has great significance for people's health, and for improving the usage rate of renewable water, and for promoting the construction of water-saving cities\cite{3}. Safety guarantee system of reclaimed water quality involves technology, economy, environmental impact,
management and many other factors, in these factors, a considerable amount of them are qualitative factors that are difficult to be quantified, it has become a more tough issue about how to determine safety guarantee system of reclaimed water, whether it is superior or inferior. Based on the above background, the paper put forward using fuzzy comprehensive evaluation method of multi-level, combing quantitative with qualitative, to evaluate the safety guarantee system for reclaimed water comprehensively, and established the guarantee system judgement model based on 2-steps fuzzy comprehensive evaluation. According to the established fuzzy comprehensive evaluation model, comprehensive evaluation of the safety guarantee system was carried out for water quality of the demonstration base, Water Liantang in Shenzhen City. The evaluation results are consistent with the experts audit results, thus verified the accuracy of the established model.

2. Construction of evaluation index system

Safety guarantee of reclaimed water quality relates to various aspects of water security, not only a stable, adequate water supply, robust and reliable water treatment facilities, safe and stable water supply network, but also advanced, reliable and efficient water quality monitoring techniques and systemic, flexible, fast emergency handling mechanism are acquired, which are important factors for ensuring the quality security of renewable water[4]. This shows that, guarantee measures of reclaimed water quality security covered in the four main components: water, waterworks, pipeline network, and the user. Therefore the evaluation index system is constituted by using the influence factors of water quality safety in these links e, as is shown in Table 1.

<table>
<thead>
<tr>
<th>Factor subset</th>
<th>Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>U1</td>
<td>water indicators</td>
</tr>
<tr>
<td></td>
<td>1. water selection and switch</td>
</tr>
<tr>
<td></td>
<td>2. water conservation and management</td>
</tr>
<tr>
<td></td>
<td>3. site selection</td>
</tr>
<tr>
<td>U2</td>
<td>treatment facility indicators</td>
</tr>
<tr>
<td></td>
<td>1. process stability</td>
</tr>
<tr>
<td></td>
<td>2. ancillary facilities normative</td>
</tr>
<tr>
<td>U3</td>
<td>transmission and distribution system indicators</td>
</tr>
<tr>
<td></td>
<td>1. pipeline design and material selection</td>
</tr>
<tr>
<td></td>
<td>2. water quality pipe network guarantee measures</td>
</tr>
<tr>
<td>U4</td>
<td>user indicators</td>
</tr>
<tr>
<td></td>
<td>1. up-to-standard situation of water quality index</td>
</tr>
<tr>
<td></td>
<td>2. the channels of safe use</td>
</tr>
<tr>
<td>U5</td>
<td>management indicators</td>
</tr>
<tr>
<td></td>
<td>1. water quality monitoring and early-warning</td>
</tr>
<tr>
<td></td>
<td>2. unexpected events emergency rescue measures</td>
</tr>
</tbody>
</table>

3. Factor weight decision

The method of analytic hierarchy process(AHP) is used to seek the weights of various factors. The evaluation factor is expressed by $u_i \in U (i = 1, 2, \cdots, m)$, $u_{ij}$ represents the relative importance of $u_i$.
compared to \( u_j(j = 1, 2, \ldots, m) \), the referents value of \( u_j \) is shown in Table 2 [5-6].

Table 2. Table for the relative importance values of various factors.

<table>
<thead>
<tr>
<th>Scale</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>that the element ( u_i ) compared with ( u_j ), have the equal importance</td>
</tr>
<tr>
<td>3</td>
<td>that the element ( u_i ) compared with ( u_j ), ( u_i ) is more important slightly than ( u_j )</td>
</tr>
<tr>
<td>5</td>
<td>that the element ( u_i ) compared with ( u_j ), ( u_i ) is more important obviously than ( u_j )</td>
</tr>
<tr>
<td>7</td>
<td>that the element ( u_i ) compared with ( u_j ), ( u_i ) is more important strongly than ( u_j )</td>
</tr>
<tr>
<td>9</td>
<td>that the element ( u_i ) compared with ( u_j ), ( u_i ) is more important extremely than ( u_j )</td>
</tr>
<tr>
<td>2, 4, 6, 8</td>
<td>2, 4, 6, 8 denote respectively mean-value of adjacent judgment 1-3, 3-5, 5-7, 7-9</td>
</tr>
</tbody>
</table>

According to above significance of symbols to determine the judgement matrix \( P \):

\[
P = \begin{bmatrix}
  u_1 & u_2 & \cdots & u_m \\
  u_{11} & u_{12} & \cdots & u_{1m} \\
  u_{21} & u_{22} & \cdots & u_{2m} \\
  \vdots & \vdots & \ddots & \vdots \\
  u_{m1} & u_{m2} & \cdots & u_{mm}
\end{bmatrix}
\]

With the judgement matrix, the maximum eigenvalue \( \lambda_{max} \) and the corresponding eigenvector \( W \) are obtained. The homogenized obtained eigenvectors represents the importance ranking of evaluation factor, which is the distribution of weights.

To judge whether the allocation of weights is reasonable or not, the consistency check of judgement matrix is needed, using the following formula to test:

\[
CR = CI / RI
\]

where, \( CR \) is random consistency ratio of judgment matrix; \( CI \) is general consistency index of judgement matrix, given by the following formula:

\[
CI = \frac{1}{m-1}(\lambda_{max} - m)
\]

\( RI \) is the average random consistency index of judgment matrix, for 1-9 steps judgment matrix, the \( RI \) values are shown in Table 3.
Table 3. The value of ri.

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>$RI$</td>
<td>0.00</td>
<td>0.00</td>
<td>0.58</td>
<td>0.90</td>
<td>1.12</td>
<td>1.24</td>
<td>1.32</td>
<td>1.41</td>
<td>1.45</td>
</tr>
</tbody>
</table>

When $CR<0.1$, it is considered that the judge matrix has the consistency of satisfaction, which means that the allocation of weights is reasonable; or else, they need to adjust the matrix to get the consistency.

4. The establishment of fuzzy comprehensive evaluation model

4.1. Form evaluation matrix

Evaluation matrix $R$ is the comprehensive survey to the index of safety evaluation of reclaimed water. Matrix $R$ would have $m$ rows and $v$ lines, that’s to say $R=\{r_{ij}\}$, if it has $m$ indicators, $v$ grades. It has to calculate the scores at all levels of evaluation indicators to establish the evaluation matrix. To the quantitative indicators, it has formula to calculate, to the qualitative indicators, actual value judgments are given by the experts.

4.2. Single-factor evaluation

From the judgement of factors, we can find influencing factor $u_i$'s membership $r_{ij}$, to which the evaluations of the $v$ grades belong, and then we can establish the single-factor evaluation set:

$$R_{im} = (r_{im1}, \ldots, r_{imj}, \ldots, r_{imp})$$

$r_{imj}$ is the membership of $im$ belonged to grade $j$. It denotes the reasonable degree of $vj$ hierarchy when judged by the factor $u_{im}$. All the single-factor evaluation sets compose the single-factor evaluation matrix, which expresses the fuzzy relationship between factor and judge. The relationship also means a reasonable relationship between influencing factors and the evaluation object[7-8].

All factors are divided into the number of $M$ factor subset. The single-factor evaluation matrix of each subset will be showed in the formula (3).

$$R_i = \begin{bmatrix}
R_{i1} \\
\vdots \\
R_{ik_i}
\end{bmatrix} = \begin{bmatrix}
\begin{array}{cccc}
r_{i11} & \ldots & r_{i1j} & \ldots & r_{i1p} \\
& \ddots & \vdots & \ddots & \vdots \\
& & r_{ik_i1} & \ldots & r_{ik_ij} & \ldots & r_{ik_ip}
\end{array}
\end{bmatrix}$$

$$i = 1, \ldots, M$$

$$\sum_{i=1}^{M} k_i = n$$

4.3. The first level comprehensive evaluation

According to the first level fuzzy comprehensive evaluation model, we evaluate the number of $k_i$ factors in the subset of the factors $U_i$. 

The second level comprehensive evaluation

The results of the first level comprehensive evaluation compose the evaluation matrix of the subset in the second level comprehensive evaluation.

\[ B_i = A_i \circ R_i = (a_{i1}, a_{i2}, ..., a_{ik}) \circ \begin{bmatrix} r_{i11} & ... & r_{i1j} & ... & r_{i1p} \\ ... & ... & ... & ... & ... \\ r_{ik1} & ... & r_{ikj} & ... & r_{ikp} \end{bmatrix} \]

\[ = (b_{i1}, ..., b_{ij}, ..., b_{ip}) \]

\[ i = 1, ..., M \]  \hspace{1cm} (4)

4.4. The second level comprehensive evaluation

The results of the first level comprehensive evaluation compose the evaluation matrix of the subset in the second level comprehensive evaluation.

\[ \bar{R} = \begin{bmatrix} B_1 \\ ... \\ B_M \end{bmatrix} = \begin{bmatrix} b_{11} & ... & b_{ij} & ... & b_{1p} \\ ... & ... & ... & ... & ... \\ b_{M1} & ... & b_{Mj} & ... & b_{Mp} \end{bmatrix} \]

The total membership \( b_{ij} \), between the influencing factors in the safety guarantee system of water quality and the level of evaluation, is the index of fuzzy comprehensive evaluation.

\[ \bar{z} = A \circ \bar{R} = (a_1, a_2, ..., a_M) \circ \begin{bmatrix} B_1 \\ ... \\ B_M \end{bmatrix} = (b_{1}, ..., b_{j}, ..., b_{p}) \]  \hspace{1cm} (5)

If has more level, it can be divided into three or more advanced model. Now, we use two-level model of water quality and safety security system for comprehensive evaluation.

5. Application of evaluation model

5.1. Evaluation object

Huajing Road flood drainage canal in Luohu Region of Shenzhen located in the eastern Liantang, which originated from the foothills of the north side of the Wutong Mountain, southward flows to Liantang River is one of the main floodway channels. As a result of the inflow of domestic sewage along the river, especially for the non-rainy days, the water quality of drainage canal is worse, which can increase the total amount of pollutants in Liantang River. There is large greening area and high greening rate in Liantang area, so the daily greening water is about 300 tons, the water derived from the municipal water supply, the price is high, the amount is large. To save the city "clean water" resources, and to a certain extent, reduce the emission of pollutants to Liantang River, the Water Supplies Department of Luohu Region decides to build a demonstration project of reclaimed water treatment and reuse, and studies out the treatment scale is 200 tons/day. Here take demonstration project of reclaimed water treatment and reuse of Liantang for evaluation object, which located in Luohu region, Shenzhen, and make an evaluation to its water Safety Guarantee System.

5.2. Determination of the index weight

The evaluation index weights are obtained by Analytic Hierarchy Process as shown in Table 4.
Table 4. Evaluation index weight form.

<table>
<thead>
<tr>
<th>First grade indexes</th>
<th>Second grade indexes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>Code</td>
</tr>
<tr>
<td>Water index</td>
<td>$U_1$</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Treatment facility index</td>
<td>$U_2$</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Transmission and distribution system index</td>
<td>$U_3$</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>User index</td>
<td>$U_4$</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5.3. Establishment of judgment set

Making a comprehensive assessment by using five-level division method, that is excellent, good, medium and poor, the worst in five grades. Based on the evaluation criteria and select five experts to evaluate the water safety precautions of reclaimed water, Statistical evaluation results as shown in Table 5.

Table 5. Index evaluation form.

<table>
<thead>
<tr>
<th>Number</th>
<th>Index</th>
<th>Excellent</th>
<th>Good</th>
<th>Medium</th>
<th>Poor</th>
<th>Worst</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Choice and switch of water</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>Conservation and management of water</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>site selection</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>process stability</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>auxiliary facilities normative</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>Pipeline design and selection</td>
<td>2</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>measures to guarantee the water of pipe network</td>
<td>0</td>
<td>2</td>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>standard reaching of water quality index</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>ways for safe use</td>
<td>4</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>monitoring and early warning of water</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>11</td>
<td>emergency rescue measures of sudden event</td>
<td>0</td>
<td>1</td>
<td>4</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
First order evaluation matrix availed from Table 5 is as follow:

\[
R_{\text{water source}} = \begin{pmatrix}
0.2 & 0.6 & 0.2 & 0 & 0 \\
0.4 & 0.2 & 0.4 & 0 & 0 \\
\end{pmatrix}
\]

\[
R_{\text{treatment equipment}} = \begin{pmatrix}
0.6 & 0.2 & 0.2 & 0 & 0 \\
0.2 & 0.6 & 0.2 & 0 & 0 \\
0.4 & 0.2 & 0.4 & 0 & 0 \\
\end{pmatrix}
\]

\[
R_{\text{transmission and distribution system}} = \begin{pmatrix}
0.4 & 0.6 & 0 & 0 & 0 \\
0 & 0.4 & 0.6 & 0 & 0 \\
\end{pmatrix}
\]

\[
R_{\text{user}} = \begin{pmatrix}
0.2 & 0.4 & 0.4 & 0 & 0 \\
0.8 & 0.2 & 0 & 0 & 0 \\
\end{pmatrix}
\]

5.4. Fuzzy comprehensive evaluation

1) First order fuzzy comprehensive evaluation

Set first order fuzzy comprehensive evaluation on factors of water as follow:

\[
B_i = A_i \circ R_i = (w_1, w_2, \ldots, w_j) \circ \begin{pmatrix}
r_{i11} & r_{i12} & r_{i13} & r_{i14} & r_{i15} \\
r_{i21} & r_{i22} & r_{i23} & r_{i24} & r_{i25} \\
\end{pmatrix} = (b_{i1}, b_{i2}, b_{i3}, b_{i4}, b_{i5})
\]

In which \( A_i \) is weight of factors in water source subset, \( R_i \) is first order evaluation matrix of water source subset. Similarly, first fuzzy comprehensive evaluation of other factor subsets \( B_2 \), \( B_3 \), \( B_4 \), \( B_5 \) are obtained.

\[
B_1=(0.267, 0.467, 0.267, 0, 0)
\]

\[
B_2=(0.360, 0.360, 0.280, 0, 0)
\]

\[
B_3=(0.133, 0.467, 0.400, 0, 0)
\]

\[
B_4=(0.400, 0.333, 0.267, 0, 0)
\]

\[
B_5=(0.300, 0.350, 0.350, 0, 0)
\]

2) Second order fuzzy comprehensive evaluation

\[
B = A \circ R = (w_1, w_2, \ldots, w_j) \circ \begin{pmatrix}
B_1 \\
B_2 \\
\vdots \\
B_5 \\
\end{pmatrix} = (w_1, w_2, \ldots, w_j) \circ \begin{pmatrix}
b_{11} & b_{12} & b_{13} & b_{14} \\
b_{21} & b_{22} & b_{23} & b_{24} \\
\vdots & \vdots & \vdots & \vdots \\
b_{51} & b_{52} & b_{53} & b_{54} \\
\end{pmatrix} = (b_1, b_2, b_3, b_4, b_5)
\]

In which \( b_i = \sum_{j=1}^{5} (w_j b_{ij}) = w_1 b_{i1} + w_2 b_{i2} + \cdots + w_5 b_{i5} \)

Similarly, \( b_2 \), \( b_3 \), \( b_4 \), \( b_5 \) can be obtained.

Then, \( B = A \circ R = (0.271, 0.405, 0.324, 0, 0) \)

Through the above calculation, the evaluation grade of evaluation object is determined on maximum membership degree principle. As \( \text{MAX}(B) = 0.405 \), the final result is that the security assurance system of Liantang reclaimed water demonstration base of Shenzhen City is good.

5.5. Verification of the evaluation result

Since the establishment of the reclaimed water demonstration base in December 2005, the disqualification and pollution of water have not occurred. 16 Water quality indexes which is sampled and tested by Environmental Protection and Detection Station of Shenzhen City are better then National standards (\textit{Miscellaneous Domestic Water Quality Standard} CJ/T48-1999), the main water quality
indicators is shown in Table 6.

Table 6. Actual water quality indicators of effluent water.

<table>
<thead>
<tr>
<th>Water Quality Indicator</th>
<th>Water Quality Indicator</th>
<th>The actual effluent water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Colority (degree)</td>
<td>&lt; 30</td>
<td>4</td>
</tr>
<tr>
<td>Suspended solids (mg/L)</td>
<td>&lt; 10</td>
<td>2.5</td>
</tr>
<tr>
<td>Chemical Oxygen Demand (mg/L)</td>
<td>&lt; 50</td>
<td>14.4</td>
</tr>
<tr>
<td>Biochemical Oxygen Demand (mg/L)</td>
<td>&lt; 10</td>
<td>4.68</td>
</tr>
<tr>
<td>Ammonia (mg/L)</td>
<td>&lt; 20</td>
<td>&lt; 0.02</td>
</tr>
<tr>
<td>Detergent (mg/L)</td>
<td>&lt; 1.0</td>
<td>0.037</td>
</tr>
</tbody>
</table>

In addition, the result of evaluation of security assurance system of Liantang reclaimed water demonstration base of Shenzhen City, which is organized by Environmental Protection Station of Shenzhen City, is good. The consistency of the evaluation result and fuzzy comprehensive evaluation result validate the accuracy of the model had been built.

6. Conclusions

When calculating weights of evaluating indicators, AHP displays those virtues, such as independence in evaluation personnel’s diathesis, authority and ability, and possessing scientific test methods and tiny error; it begins with preferably low-level and compares significances on the same level forward high-level, and enhancing comparability. Avoiding discord from comparability each other, it also tests coherence by the greatest eigenvalue.

Safety guarantee system is comprehensively appraised by fuzzy comprehensive evaluation model with qualitative appraisal and quantitative appraisal, so it avoids subjective arbitrariness and is coincident to actual circs. By developing multi-grade fuzzy comprehensive evaluation model, it is strongly instructive to evaluation of safety guarantee system of reclaimed water quality and is in favor of safely producing and healthily using of reclaimed water.

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References


