Method Article

Method for a new risk assessment of urban water quality: IFN-SPA

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Abstract

Water quality is one of the most essential factors to influence human daily life and environment health. Risk assessment of water quality has critical significance to sustainable development of human society and natural systems. Set pair analysis (SPA) methods are widely used in risk assessment, especially in water resources. The essence of SPA is to classify assessment samples consider the uncertainties exist in risk assessment system based on the viewpoints of unity, difference, and opposition. The existing SPA methods are classified into two types, including (i) original SPA and (ii) comprehensive SPA. Both the original and comprehensive SPA methods have the following limitations: (i) it is need to judge whether the assessment factor belongs to type I or type II; (ii) it is need to judge whether the assessment factor is positive or negative. This method article gives a detailed description of the application of the existing SPA method. The method article is a companion paper with the original article [1].

- Description of SPA methods.
- Application of SAP methods in risk assessment of water quality.
- Calculate the weights of assessment factors.

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Introduction of SPA methods

Original SPA

Suppose that set A and set B are two related sets, in which each set has n factors, e.g. \( A = (a_1, a_2, \ldots, a_n) \), where \( x_i \) is the actual value of assessment factor and \( n \) is the number of assessment factors. Set B is assumed to be the assessment criteria. \( B_k = b_k (k = 1, 2, 3 \cdots K) \), where \( b_k \) is the criterion value of level \( k \) and \( K \) is the classification level of the assessment sample. Set \( B = (b_1, b_2, \ldots, b_n) \). The connection degree between set A and set B can be described as below [2].

\[ \mu_{A \leftrightarrow B} = a + bi + cj \]  

(1)

where \( \mu_{A \leftrightarrow B} \) is the connection degree between set A and set B, \( a = \) identity degree, \( b = \) difference degree, and \( c = \) opposition degree, \( a + b + c = 1 \). The Eq. (1) can be referred to as a three-dimensional connection degree function (\( K = 3 \)). If \( K = 5 \), Eq. (1) can be expressed as

\[ \mu_{A \leftrightarrow B} = a + b_1i_1 + b_2i_2 + b_3i_3 + cj \]  

(2)

where \( a + b_1 + b_2 + b_3 + c = 1 \). \( b_1, b_2, b_3 \) are the difference components, which indicate the different levels of difference degree (such as mild difference, moderate difference, severe difference, etc.).

The original SPA method includes type I and type II. Table 1 lists the assessment criteria for types I and II. The risk level \( K \) is generally defined as three or five (\( K = 3 \) or \( K = 5 \)). Fig. 1 shows the connection degree membership of type I and type II when \( K = 5 \). As shown in Fig. 1, type I uses a single value to express the risk level, whereas type II uses an interval value to express the risk level. For most of the decision makers, it is easier to assess the risk level using an interval value other than a single value. Therefore, type II is commonly used in risk assessment.

The connection degree function of types I and II can be classified into positive factors and negative factors [3].

(1) In type I:

(1) for a positive factor, the connection degree function can be expressed using Eq. (3) [2],

\[ \mu_I = \begin{cases} 
1 + o_{i_1} + o_{i_2} + \cdots + o_{i_{K-2}} + o_j & (x_i \geq p_1) \\
\frac{x_i - p_2}{p_1 - p_2} + \frac{p_1 - x_i}{p_1 - p_3} + o_{i_1} + o_{i_2} + \cdots + o_{i_{K-2}} + o_j & (p_2 \leq x_i < p_1) \\
0 + \frac{x_i - p_3}{p_2 - p_3} + o_{i_1} + \frac{p_2 - x_i}{p_2 - p_3} + o_{i_2} + \cdots + o_{i_{K-2}} + o_j & (p_3 \leq x_i < p_2) \\
\vdots \\
0 + o_{i_1} + o_{i_2} + \cdots + \frac{x_i - p_{K-1}}{p_{K-1} - p_K} + \frac{p_{K-1} - x_i}{p_{K-1} - p_K} + o_{i_{K-2}} + o_j & (p_K \leq x_i < p_{K-1}) \\
0 + o_{i_1} + o_{i_2} + \cdots + o_{i_{K-2}} + 1j & (x_i < p_K) 
\end{cases} \]  

(3)

Table 1

Assessment criteria for the original SPA.

| Type | 1 | 2 | ... | \( K-1 \) | \( K \) |
|------|---|---|-----|---------|------|
| \( p_1 \) | \( p_2 \) | ... | \( p_{K-1} \) | \( p_K \) | \( <p_1 \) | \( p_1-p_2 \) | ... | \( p_{K-2}-p_{K-1} \) | \( >p_{K-1} \) |
Fig. 1. Collection degree membership of the original SPA (K = 5).

(2) for a negative factor, the connection degree function can be expressed using Eq. (4)

\[
\mu_i = \begin{cases} 
1 + 0i_1 + 0i_2 + \cdots + 0i_{K-2} + 0j \\ 
\frac{p_2 - x_i}{p_2 - p_1} + \frac{x_i - p_1}{p_2 - p_1}i_1 + 0i_2 + \cdots + 0i_{K-2} + 0j \\ 
0 + \frac{p_3 - x_i}{p_3 - p_2}i_1 + \frac{x_i - p_2}{p_3 - p_2}i_2 + \cdots + 0i_{K-2} + 0j \\ 
\vdots \\ 
0 + 0i_1 + 0i_2 + \cdots + 0i_{K-2} + j 
\end{cases} 
\quad \text{for } x_i \leq p_1 \\
\frac{p_k - x_i}{p_k - p_{K-1}}i_{K-2} + \frac{x_i - p_{K-1}}{p_k - p_{K-1}}j 
\quad \text{for } p_{K-1} < x_i \leq p_k \\
0 + 0i_1 + 0i_2 + \cdots + 0i_{K-2} + 1j 
\quad \text{for } x_i > p_k 
\]

Based on the single connection degree ($\mu_i$), the comprehensive connection degree ($\mu_{A\leftrightarrow B}$) of all assessment factors can be calibrated using Eq. (5) [2].

\[
\mu_{A\leftrightarrow B} = \sum_{i=1}^{n} w_i \mu_i \\
= \sum_{i=1}^{n} w_i a_i + \sum_{i=1}^{n} w_i b_{i,1}i_1 + \sum_{i=1}^{n} w_i b_{i,2}i_2 + \cdots + \sum_{i=1}^{n} w_i b_{i,2}i_{K-2} + \sum_{i=1}^{n} w_i c_i j 
\]

where $\mu_{A\leftrightarrow B}$ is the comprehensive connection degree between set A (assessment sample) and set B (assessment criterion); $w_i$ is the weight of assessment factor; $\mu_i$ is the single connection degree of factor $i$.

(II) In type II:
(1) for a positive factor, the connection degree function can be expressed using Eq. (6)
\[
\mu_l = \begin{cases} 
1 + 0i_1 + 0i_2 + \cdots + 0i_{k-2} + 0j & (x_l \leq p_1) \\
\frac{p_1 + p_2 - 2x_l}{p_2 - p_1} + \frac{2(x_l - p_1)}{p_2 - p_1}i_1 + 0i_2 + \cdots + 0i_{k-2} + 0j & (p_1 < x_l \leq \frac{p_1 + p_2}{2}) \\
0 + \frac{p_2 + p_3 - 2x_l}{p_3 - p_1}i_1 + \frac{2x_l - p_1 - p_2}{p_3 - p_1}i_2 + \cdots + 0i_{k-2} + 0j & \left( \frac{p_1 + p_2}{2} < x_l \leq \frac{p_2 + p_3}{2} \right) \\
\cdots \\
0 + 0i_1 + \cdots + \frac{2(p_{k-1} - x_l)}{p_{k-1} - p_{k-2}}i_{k-2} + \frac{2x_l - p_{k-2} - p_{k-1}}{p_{k-1} - p_{k-2}}j & \left( \frac{p_{k-2} + p_{k-1}}{2} < x_l \leq p_{k-1} \right) \\
0 + 0i_1 + 0i_2 + \cdots + 0i_{k-2} + 1j & \left( x_l < p_{k-1} \right)
\end{cases}
\] (6)

When \( K = 5 \), the connection degree function can be expressed as below.
\[
\mu_l = \begin{cases} 
1 + 0i_1 + 0i_2 + 0i_3 + 0j & (x_l \leq p_1) \\
\frac{p_1 + p_2 - 2x_l}{p_2 - p_1} + \frac{2(x_l - p_1)}{p_2 - p_1}i_1 + 0i_2 + 0i_3 + 0j & (p_1 < x_l \leq \frac{p_1 + p_2}{2}) \\
0 + \frac{p_2 + p_3 - 2x_l}{p_3 - p_1}i_1 + \frac{2x_l - p_1 - p_2}{p_3 - p_1}i_2 + 0i_3 + 0j & \left( \frac{p_1 + p_2}{2} < x_l \leq \frac{p_2 + p_3}{2} \right) \\
0 + 0i_1 + 2\frac{p_3 - x_l}{p_3 - p_1}i_2 + \frac{2x_l - p_3 - p_4}{p_3 - p_4}i_3 + 0j & \left( \frac{p_2 + p_3}{2} < x_l \leq \frac{p_3 + p_4}{2} \right) \\
0 + 0i_1 + 0i_2 + 2\frac{p_4 - x_l}{p_4 - p_3}i_3 + \frac{2x_l - p_3 - p_4}{p_4 - p_3}j & \left( \frac{p_3 + p_4}{2} < x_l \leq p_4 \right) \\
0 + 0i_1 + 0i_2 + 0i_3 + 1j & \left( x_l > p_4 \right)
\end{cases}
\] (7)

where \( \mu_l \) is the single connection degree of assessment factor \( l \) and \( x_l \) is the actual value of assessment factor \( l \).

(2) for a negative factor, the connection degree function can be expressed using Eq. (8)
\[
\mu_l = \begin{cases} 
1 + 0i_1 + 0i_2 + \cdots + 0i_{k-2} + 0j & (x_l \geq p_1) \\
\frac{2x_l - p_1 - p_2}{p_1 - p_2} + \frac{2(p_1 - x_l)}{p_1 - p_2}i_1 + 0i_2 + \cdots + 0i_{k-2} + 0j & \left( p_1 + p_2 \leq x_l < p_1 \right) \\
0 + \frac{2x_l - p_2 - p_3}{p_1 - p_3}i_1 + \frac{p_1 + p_2 - 2x_l}{p_1 - p_3}i_2 + \cdots + 0i_{k-2} + 0j & \left( \frac{p_2 + p_3}{2} \leq x_l < \frac{p_1 + p_2}{2} \right) \\
\cdots \\
0 + 0i_1 + \cdots + \frac{2(x_l - p_{k-1})}{p_{k-2} - p_{k-1}}i_{k-2} + \frac{p_{k-2} + p_{k-1} - 2x_l}{p_{k-2} - p_{k-1}}j & \left( \frac{p_{k-2} + p_{k-1}}{2} \leq x_l < \frac{p_{k-2} + p_{k-1}}{2} \right) \\
0 + 0i_1 + 0i_2 + \cdots + 0i_{k-2} + 1j & \left( x_l < p_{k-1} \right)
\end{cases}
\] (8)

When \( K = 5 \), the connection degree function can be expressed as below.
\[
\mu_l = \begin{cases} 
1 + 0i_1 + 0i_2 + 0i_3 + 0j & (x_l \geq p_1) \\
\frac{2x_l - p_1 - p_2}{p_1 - p_2} + \frac{2(p_1 - x_l)}{p_1 - p_2}i_1 + 0i_2 + 0i_3 + 0j & \left( p_1 + p_2 \leq x_l < p_1 \right) \\
0 + \frac{2x_l - p_2 - p_3}{p_1 - p_3}i_1 + \frac{p_1 + p_2 - 2x_l}{p_1 - p_3}i_2 + 0i_3 + 0j & \left( \frac{p_2 + p_3}{2} \leq x_l < \frac{p_1 + p_2}{2} \right) \\
0 + 0i_1 + 2\frac{p_3 - x_l}{p_3 - p_1}i_2 + \frac{p_2 + p_3 - 2x_l}{p_2 - p_3}i_3 + 0j & \left( \frac{p_3 + p_4}{2} \leq x_l < \frac{p_2 + p_3}{2} \right) \\
0 + 0i_1 + 0i_2 + 2\frac{x_l - p_4}{p_3 - p_4}i_3 + \frac{p_3 + p_4 - 2x_l}{p_3 - p_4}j & \left( p_4 \leq x_l < \frac{p_3 + p_4}{2} \right) \\
0 + 0i_1 + 0i_2 + 0i_3 + 1j & \left( x_l < p_4 \right)
\end{cases}
\] (9)
where $\mu_l$ is the single connection degree of assessment factor $l$, $x_i$ is the actual value of assessment factor $l$. For a five levels risk assessment system ($K = 5$), the connection degrees with the coefficients of $a$, $b_1$, $b_2$, $b_3$ and $c$ can be calibrated using Eq. (7) or Eq. (9).

**Comprehensive SPA**

Eq. (10) shows the connection degree function of a comprehensive SPA [4].

$$
\mu_{pjk} = \begin{cases} 
1 - 2 \left( \frac{x_{pjk} - P_{j,k-1}}{P_{j,k-1} - P_{j,k-2}} \right) & (x_{pjk} \in k - 1) \\
1 & (x_{pjk} \in k) \\
1 - 2 \left( \frac{x_{pjk} - P_{j,k}}{P_{j,k+1} - P_{j,k}} \right) & (x_{pjk} \in k + 1)
\end{cases}
$$

(10)

If the assessment factor is positive and $K = 5$, the connection degree function of $\mu_{pjk}$ can be expressed by using Eqs. (11)–(15).

$$
\mu_{j1} = \begin{cases} 
1, & (x_j \leq p_{j1}) \\
1 - 2 \cdot (x_j - p_{j1})/(p_{j2} - p_{j1}), & (p_{j1} < x_j \leq p_{j2}) \\
-1, & (x_j > p_{j2})
\end{cases}
$$

(11)

$$
\mu_{j2} = \begin{cases} 
1 - 2 \cdot (x_j - p_{j1})/(p_{j2} - p_{j1}), & (x_j \leq p_{j1}) \\
1, & (p_{j1} < x_j \leq p_{j2}) \\
1 - 2 \cdot (x_j - p_{j2})/(p_{j3} - p_{j2}), & (p_{j2} < x_j \leq p_{j3}) \\
-1, & (x_j > p_{j3})
\end{cases}
$$

(12)

$$
\mu_{j3} = \begin{cases} 
-1, & (x_j \leq p_{j2}) \\
1 - 2 \cdot (x_j - p_{j1})/(p_{j2} - p_{j1}), & (p_{j1} < x_j \leq p_{j2}) \\
1, & (p_{j2} < x_j \leq p_{j3}) \\
1 - 2 \cdot (x_j - p_{j3})/(p_{j4} - p_{j3}), & (p_{j3} < x_j \leq p_{j4}) \\
-1, & (x_j > p_{j4})
\end{cases}
$$

(13)

$$
\mu_{j4} = \begin{cases} 
-1, & (x_j \leq p_{j3}) \\
1 - 2 \cdot (x_j - p_{j1})/(p_{j3} - p_{j2}), & (p_{j2} < x_j \leq p_{j3}) \\
1, & (p_{j3} < x_j \leq p_{j4}) \\
1 - 2 \cdot (x_j - p_{j4})/(p_{j5} - p_{j4}), & (p_{j4} < x_j \leq p_{j5}) \\
-1, & (x_j > p_{j5})
\end{cases}
$$

(14)

$$
\mu_{j5} = \begin{cases} 
-1, & (x_j \leq p_{j3}) \\
1 - 2 \cdot (x_j - p_{j1})/(p_{j4} - p_{j3}), & (p_{j3} < x_j \leq p_{j4}) \\
1, & (p_{j4} < x_j \leq p_{j5})
\end{cases}
$$

(15)

where $\mu_{j1}$, $\mu_{j2}$, $\mu_{j3}$, $\mu_{j4}$ and $\mu_{j5}$ are the connection degree with corresponding to risk level ($K = 1$, $K = 2$, $K = 3$, $K = 4$ and $K = 5$); $p_{j1}$, $p_{j2}$, $p_{j3}$, $p_{j4}$ and $p_{j5}$ are the bounds of the criteria from level 1 to 5. If the assessment factor is positive and $K = 5$, the connection degree function of $\mu_{pjk}$ can be expressed using Eqs. (16)–(20).

$$
\mu_{j1} = \begin{cases} 
1, & (x_j \geq p_{j1}) \\
1 - 2 \cdot (x_j - p_{j1})/(p_{j2} - p_{j1}), & (p_{j1} < x_j \geq p_{j2}) \\
-1, & (x_j < p_{j2})
\end{cases}
$$

(16)
\[
\mu_{j2} = \begin{cases} 
1 - 2 \cdot (p_{j1} - x_j)/(p_{j1} - p_{j2}), & (x_j \geq p_{j1}) \\
1 - 2 \cdot (x_j - p_{j2})/(p_{j3} - p_{j2}), & (x_j \geq p_{j3}) \\
1 - 2 \cdot (x_j - p_{j2})/(p_{j1} - p_{j2}), & (x_j \geq p_{j1}) \\
-1, & (x_j < p_{j3}) \\
-1, & (x_j < p_{j1}) \\
1 - 2 \cdot (p_{j3} - x_j)/(p_{j3} - p_{j2}), & (p_{j1} > x_j \geq p_{j2}) \\
1, & (p_{j2} > x_j \geq p_{j3}) \\
-1, & (x_j < p_{j4}) \\
-1, & (x_j \geq p_{j2}) \\
1 - 2 \cdot (p_{j3} - x_j)/(p_{j3} - p_{j2}), & (p_{j1} > x_j \geq p_{j3}) \\
1, & (p_{j3} > x_j \geq p_{j4}) \\
1 - 2 \cdot (x_j - p_{j3})/(p_{j3} - p_{j4}), & (p_{j1} > x_j \geq p_{j3}) \\
-1, & (x_j \geq p_{j3}) \\
1 - 2 \cdot (x_j - p_{j3})/(p_{j4} - p_{j3}), & (p_{j3} > x_j \geq p_{j4}) \\
1, & (p_{j4} > x_j \geq p_{j5}) \\
\end{cases}
\]

where \( \mu_{pj} \) is the single connection degree of factor \( p \) to level \( k \) (\( -1 \leq \mu_{pj} \leq 1 \)); \( \mu_{pk} \) is the comprehensive connection degree of factor \( p \) to level \( k \). When the value of \( \mu_{pk} \) is closer to 1, the factor \( p_i \) has more possibility to belong the level \( k \), while when the value of \( \mu_{pk} \) is closer to \(-1 \), the factor \( p_i \) has more impossibility to belong the level \( k \).

**Proposed IFN-SPA**

Both the original and comprehensive SPA methods have the following limitations: (i) it is need to judge whether the assessment factor belongs to type I or type II; (ii) it is need to judge whether the assessment factor is positive or negative. This method article gives a detailed description of the application of the existing SPA method. Based on the review of the existing SPA methods, the IFN-SPA is proposed to modify the existing SPA methods by using the interval-based fuzzy numbers, in which an axis with interval criteria was adopted to express the connection degree of the assessment samples. The proposed IFN-SPA overcomes the limitations of the existing SPA methods. Fig. 2 draws the concept of the IFN-SPA. The detailed information of the proposed IFN-SPA method is presented in the companioned research article [1].

**Application of the method**

The SPA method is combined with analytical hierarchy process (AHP) and others to assess risk [5-9]. The AHP is used to calibrate the weights of assessment factors. The AHP method uses pairwise comparison to establish the judgment matrix. Each element in the judgment matrix reflects the relative importance of assessment factors. The relative importance is quantified using number from
1 to 9 or their reciprocals [10]. Eq. (22) lists the judgment matrix \( \mathbf{A} \) of the risk assessment of water quality in Shanghai. The detailed information of the assessment factors was presented in the original article [1].

\[
\mathbf{A} = (a_{ij})_{n \times n} = \begin{pmatrix}
R_1 & R_2 & R_3 & R_4 & R_5 & R_6 & R_7 & R_8 \\
R_1 & 1 & 1 & 1 & 1 & 2 & 1.5 & 2 & 3 \\
R_2 & 1 & 1 & 1 & 1 & 1 & 2 & 2 & 3 \\
R_3 & 1 & 1 & 1 & 1.5 & 1 & 1.5 & 3 & 2 \\
R_4 & 1 & 1 & 0.667 & 1 & 2 & 2 & 1 & 3 \\
R_5 & 0.5 & 1 & 1 & 0.5 & 1 & 3 & 2 & 3 \\
R_6 & 0.667 & 0.5 & 0.667 & 0.5 & 0.333 & 1 & 5 & 6 \\
R_7 & 0.5 & 0.5 & 0.333 & 1 & 0.5 & 0.2 & 1 & 5 \\
R_8 & 0.333 & 0.333 & 0.5 & 0.333 & 0.333 & 0.167 & 1 & 1
\end{pmatrix} \tag{22}
\]

Based on the establishment of the judgment matrix \( \mathbf{A} \), the weights \( \mathbf{w}_i \) of the factors can be calculated from Eq. (23):

\[
\mathbf{w}_i = \frac{M_i}{\sum_{i=1}^{n} M_i} \tag{23}
\]

where \( M_i = \sum_{j=1}^{n} a_{ij} \).

The judgment matrix \( \mathbf{A} \) is reasonable, if the consistency ratio (CR) is less than 0.1. If the CR is greater than 0.1, then the judgment matrix is unreasonable and must be re-determined [11]. The value of CR can be calculated using Eq. (24).

\[
CR = \frac{CI}{RI} \tag{24}
\]

where \( CI = (\lambda_{\text{max}} - n) / (n - 1) \) and \( \lambda_{\text{max}} \) is the largest eigenvalue of the judgment matrix; which can be calculated from Eq. (25). \( RI \) is the average random consistency index.

\[
\lambda_{\text{max}} = \frac{1}{n} \sum_{i=1}^{n} \sum_{j=1}^{n} a_{ij} w_i \tag{25}
\]

When \( n = 8 \), the \( RI = 1.41 \) [11], thus the value of \( CR = 0.0923 < 0.1 \). Therefore, the judgment matrix \( \mathbf{A} \) is reasonable. Then the weights of assessment factor can be calibrated as \( \mathbf{w}_i = (0.1632, 0.1551, 0.1574, 0.1474, 0.1372, 0.1152, 0.0764, 0.0481) \).

**Computational tool**

The study used Excel sheets to calculate the evaluation of Shanghai water quality case for further illustration. The Excel include 10 sheets: IFN-SPA, AHP, R1 to R8 sheets, respectively. R1 to R8 sheets...
Table 2
Connection degree calibrated from original SPA.

| District | Pudong | Huangpu | Xuhui |
|----------|--------|---------|-------|
| $\mu_i$  | $\mu_{PP}$ | $\mu_{CDDP}$ | $\mu_{OLUX}$ | $\mu_{BAR}$ | $\mu_{CAG}$ | $\mu_{WUR}$ | $\mu_{WRUR}$ | $\mu_{STA}$ | $\mu$ | $\mu_{PP}$ | $\mu_{CDDP}$ | $\mu_{OLUX}$ | $\mu_{BAR}$ | $\mu_{CAG}$ | $\mu_{WUR}$ | $\mu_{WRUR}$ | $\mu_{STA}$ | $\mu$ |
| $a$ (I)  | 0  | 0.9162 | 0.0838 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1.0782 | 2.0782 | 0 |
| $b_1$ (II) | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 1  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 1  | 0  | 0  | 1.0782 | 2.0782 | 0 |
| $b_2$ (III) | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 1  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 1  | 0  | 0  | 1.0782 | 2.0782 | 0 |
| $b_2$ (IV) | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 1  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 1  | 0  | 0  | 1.0782 | 2.0782 | 0 |
| $c$ (V)  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 1  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 1  | 0  | 0  | 1.0782 | 2.0782 | 0 |

(continued on next page)
| District | Baoshan | Jiading | Jinshan |
|----------|---------|---------|---------|
|          | $\mu_i$ | $b_1$ (I) | $b_2$ (II) | $b_3$ (III) | $b_4$ (IV) | $c$ (V) | $\mu_i$ | $b_1$ (I) | $b_2$ (II) | $b_3$ (III) | $b_4$ (IV) | $c$ (V) | $\mu_i$ | $b_1$ (I) | $b_2$ (II) | $b_3$ (III) | $b_4$ (IV) | $c$ (V) |
| $\mu_{FP}$ | 0.4626 | 0.5374 | 0 | 0 | 0.2985 | 0.7015 | 0 | 0 | 1 | 0 | 0 | 0 | 0.6623 | 0.3377 | 0 | 0 |
| $\mu_{CDPP}$ | 0 | 0 | $-0.5463$ | $1.5463$ | 0 | 0 | 0.1629 | 0.8371 | 0 | 0 | 0 | 0.326 | 0.674 | 0 | 0 |
| $\mu_{GDP}$ | 0 | 0 | $-0.608$ | $1.608$ | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0.326 | 0.674 | 0 | 0 |
| $\mu_{BAR}$ | 0 | 0.3538 | 0.6462 | 0 | 0 | 0.8576 | 0.1424 | 0 | 0 | 0 | 0.9665 | 0.0335 | 0 | 0 |
| $\mu_{CAR}$ | 0 | 0 | 0 | 0 | 0 | 0.1728 | 0.8272 | 0 | 0 | 0 | 0.4627 | 0.5373 | 0 | 0 |
| $\mu_{WRUR}$ | 0 | 0 | $-0.9613$ | $1.9613$ | 0 | 0 | 0 | $-0.1093$ | 1.1093 | 0 | 0 | 0 | 0 | $-0.9692$ | 1.9692 | 0 |
| $\mu_{STA}$ | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.7 | 0.3 | 0 | 0 |
| $\mu$ | 0.0724 | 0.1778 | $-0.1029$ | $0.7161$ | 0.1366 | 0.0964 | 0.3605 | $0.2591$ | 0.1273 | 0.1567 | 0.4741 | $0.3373$ | $-0.0373$ | 0.2259 | 0 |

| District | Qingpu | Fengxian |
|----------|---------|---------|
| $\mu_i$ | $\mu_{FP}$ | $\mu_{CDPP}$ | $\mu_{GDP}$ | $\mu_{BAR}$ | $\mu_{CAR}$ | $\mu_{WRUR}$ | $\mu_{STA}$ | $\mu$ |
|          | 0.543 | 0.457 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| $\mu_{FP}$ | 0 | 0.3022 | 0.6978 | 0 | 0 | 0 | 0.2039 | 0.7961 | 0 | 0 | 0.3219 | 0.6781 | 0 | 0 |
| $\mu_{CDPP}$ | 0 | 0 | 0.482 | 0.518 | 0 | 0.695 | 0.305 | 0 | 0 | 0 | 0 | 0.918 | 0.082 | 0 | 0 |
| $\mu_{GDP}$ | 0 | 0 | 0.9244 | 0.0756 | 0 | 0 | 0.7487 | 0.2513 | 0 | 0 | 0 | 0 | 0.8508 | 0.1492 | 0 | 0 |
| $\mu_{BAR}$ | 0 | 0 | 0 | 0 | 0 | 0.548 | 0.452 | 0 | $-0.638$ | 1.638 | 0 | 0 | 0.3387 | 0.6613 | 0 | 0 |
| $\mu_{CAR}$ | 0 | 0 | 0 | 0 | 1 | 0 | 0 | $-0.7197$ | 1.7197 | 0 | 0 | 0 | 0.9 | 0.1 | 0 | 0 |
| $\mu_{WRUR}$ | 0 | 1 | 0 | 0 | 0 | 0.6 | 0.4 | 0 | 0 | 0 | 0 | 0 | 0.9 | 0.1 | 0 | 0 |
| $\mu_{STA}$ | 1 | 0 | 0 | 0 | 0 | 0.6 | 0.4 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| $\mu$ | 0.1362 | 0.3262 | $0.292$ | $0.1431$ | 0.0725 | 0.3722 | 0.3586 | $-0.0511$ | 0.3203 | 0 | 0 | $0.5321$ | 0.2411 | 0.0003 | 0.2265 | 0 |

| District | Chongming |
|----------|---------|
| $\mu_i$ | $\mu_{FP}$ | $\mu_{CDPP}$ | $\mu_{GDP}$ |
|          | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| $\mu_{FP}$ | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| $\mu_{CDPP}$ | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| $\mu_{GDP}$ | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| District | Pudong | Huangpu | Xuhui |
|----------|--------|---------|-------|
| \( \mu_{PP} \) | -0.2725 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 |
| \( \mu_{GDPP} \) | -1 | -1 | -1 | -1 | 1 | -1 | -1 | -0.4783 | 1 | 0.4783 | -1 | -1 | -1 | -0.911 | 1 | 0.911 |
| \( \mu_{OOUA} \) | -1 | -1 | -1 | -1 | 0.163 | -1 | 0.831 | 1 | -0.831 | -1 | -1 | -1 | -0.467 | 1 | -0.0467 |
| \( \mu_{CAR} \) | -1 | -1 | -0.4635 | 1 | 0.4635 | 1 | 0.7873 | -1 | -1 | -1 | -1 | 0.0893 | 1 | 0.0893 | -1 | -1 |
| \( \mu_{WRIR} \) | -1 | -1 | 0.2 | 1 | 0.2 | 1 | 0.1805 | 1 | -0.1805 | -1 | -1 | -1 | 0.0893 | 1 | -1 |
| \( \mu_{STA} \) | -1 | -1 | -0.1 | 1 | 0.8 | -1 | -1 | -1 | -0.8 | 1 | 0.8 | -1 | -1 | -1 | 1 | 1 |
| \( \mu \) | -0.8813 | -0.3991 | -0.3628 | -0.2377 | \textbf{0.0610} | -0.5896 | -0.1553 | -0.2710 | -0.6479 | \textbf{-0.1394} | -0.8951 | -0.7696 | -0.2977 | \textbf{0.4952} | 0.1928 |
| District | Changning | Jingan | Putuo |
| \( \mu_{PP} \) | -1 | -1 | 0.6024 | 1 | -0.6024 | -1 | -1 | -0.8604 | 1 | 0.8604 | -1 | -1 | -1 | -1 | -1 | -0.1183 | 1 | 0.1183 |
| \( \mu_{GDPP} \) | -1 | -1 | 0.0166 | 1 | -0.0166 | -1 | -1 | -0.5843 | 1 | 0.5843 | -1 | -1 | -1 | 0.2046 | 1 | -0.2046 |
| \( \mu_{OOUA} \) | 0.078 | 1 | -0.078 | -1 | -1 | -0.632 | 1 | 0.632 | -1 | -1 | -1 | 0.148 | 1 | -0.148 | -1 | -1 |
| \( \mu_{CAR} \) | -1 | -1 | 0.1913 | 0.1 | -0.1913 | -1 | -1 | -1 | -1 | -1 | -1 | 0.148 | 1 | -0.148 | -1 | -1 |
| \( \mu_{WRIR} \) | -0.359 | 1 | 0.359 | -1 | -1 | 0.958 | 1 | -0.598 | -1 | -1 | -1 | 0.148 | 1 | -0.148 | -1 | -1 |
| \( \mu_{STA} \) | -1 | -1 | -0.6 | 1 | 0.6 | -1 | -1 | -1 | -0.8 | 1 | 0.8 | -1 | -1 | -1 | 0.953 | 1 | 0.953 |
| \( \mu \) | -0.7565 | -0.4548 | -0.0843 | \textbf{0.0276} | \textbf{-0.1592} | -0.7117 | -0.6852 | -0.4270 | 0.0071 | \textbf{0.1387} | -0.7831 | -0.4548 | -0.1352 | \textbf{0.4548} | 0.0817 |
| District | Hongkou | Yangpu | Minhang |
| \( \mu_{PP} \) | -1 | -1 | -1 | -1 | -1 | -1 | -1 | 0.1252 | 1 | -0.1252 | -1 | -1 | -1 | 0.8111 | 1 | -0.8111 | -1 |
| \( \mu_{GDPP} \) | -1 | -1 | -0.8653 | 1 | 0.8653 | -1 | -1 | -0.5466 | 1 | -0.5466 | -1 | -1 | -1 | 0.0381 | 1 | -0.0381 | -1 |
| \( \mu_{OOUA} \) | 0.64 | 1 | -0.64 | -1 | -1 | -1 | -1 | -0.488 | 1 | -0.488 | -1 | -1 | -1 | -0.252 | 1 | -0.252 | -1 |
| \( \mu_{CAR} \) | -0.7033 | 1 | 0.7033 | -1 | -1 | -1 | -1 | -0.4765 | 1 | -0.4765 | -1 | -1 | -1 | 0.3814 | 1 | 0.3814 | -1 |
| \( \mu_{WRIR} \) | -0.9087 | 1 | 0.9087 | -1 | -1 | -1 | -1 | -0.6405 | 1 | -0.6405 | -1 | -1 | -1 | -0.235 | 1 | -0.235 | -1 |
| \( \mu_{STA} \) | -1 | -1 | 0 | 1 | 0 | -1 | -0.6 | 1 | 0.6 | -1 | 0.2 | 1 | -0.2 | 1 | -0.2 | -1 |
| \( \mu \) | -0.6906 | -0.1804 | -0.4208 | -0.5936 | \textbf{0.1114} | -1.0000 | -0.9808 | 0.1917 | \textbf{0.6660} | -0.1917 | -0.9423 | -0.4046 | \textbf{0.4427} | 0.4046 | -0.5004 | (continued on next page)
### Table 3 (continued)

| District | Baoshan | Jiading | Jinshan |
|----------|---------|---------|---------|
| $\mu_i$ | I II III IV V | I II III IV V | I II III IV V |
| $\mu_{FPH}$ | –1 0.6682 1 –0.6682 –1 | 0.2985 1 –0.2985 –1 –1 | –1 –1 –1 –1 –1 |
| $\mu_{GDPH}$ | –1 –1 0.4537 1 –0.4537 | –1 0.3257 1 –0.3257 –1 | –1 0.6754 1 0.6754 –1 –1 |
| $\mu_{IOU}$ | –1 –1 0.696 1 –0.696 | –1 –1 –1 –1 1 | 0.35 –1 –0.353 1 –1 |
| $\mu_{BAR}$ | 0.4246 1 –0.4246 –1 –I1 | –0.8547 1 0.8547 –1 –1 | 0.9665 1 –0.9665 –1 –1 |
| $\mu_{WBR}$ | –1 –1 –1 –1 1 | –1 0.432 1 –0.432 –1 | 0.4627 1 –0.4627 –1 –1 |
| $\mu_{SR}$ | 1 –0.0388 1 –0.0388 | –1 1 0.8908 1 –0.8908 | –1 –1 0.0308 1 –0.0308 |
| $\mu_{STA}$ | 0 1 0 0 –1 | 0 0 0 0 –1 | 0 0 0 0 –1 |
| $\mu$ | 0.543 I II III IV V | 0.543 I II III IV V | 0.543 I II III IV V |
| $\mu_{FPH}$ | 0.543 0.6431 1 –0.6431 –1 | 1 –1 –1 –1 –1 | 1 –1 1 –1 –1 |
| $\mu_{GDPH}$ | –1 0.6431 0.6431 –1 –1 | 0.695 1 –0.695 –1 –1 | 0.918 1 –0.918 –1 –1 |
| $\mu_{IOU}$ | –1 –0.518 0.518 –1 –1 | 0.7487 1 –0.7487 –1 –1 | 0.8508 1 –0.8508 –1 –1 |
| $\mu_{BAR}$ | –0.4535 1 0.4535 –1 –1 | –0.638 1 0.638 –1 –1 | 0.3387 1 –0.3387 –1 –1 |
| $\mu_{WBR}$ | –1 –0.452 0.452 –1 –1 | –1 0.2803 1 –0.2803 –1 | –1 –1 0.026 1 –0.026 |
| $\mu_{SR}$ | –0.3333 1 0.3333 –1 –1 | –1 1 1 1 –1 | –1 0 1 0 –1 |
| $\mu_{STA}$ | 1 –1 –1 –1 1 | 0.6 1 0.6 –1 1 | 1 1 1 1 –1 |
| $\mu$ | 0.5205 0.1739 0.2901 –0.5005 –0.7696 | –0.0224 0.3122 0.0224 –0.6385 –1.0000 | 0.0847 0.2154 –0.2932 –0.6380 –0.7916 |
| $\mu_{FPH}$ | 1 –1 –1 –1 | 0.4952 –0.8472 –1.0000 –1.0000 –0.4952 | 0 0 0 0 –1 |
| $\mu_{GDPH}$ | 1 –1 –1 –1 | 0.4952 –0.8472 –1.0000 –1.0000 –0.4952 | 0 0 0 0 –1 |
| $\mu_{IOU}$ | 1 –1 –1 –1 | 0.4952 –0.8472 –1.0000 –1.0000 –0.4952 | 0 0 0 0 –1 |
| $\mu_{BAR}$ | 1 –1 –1 –1 | 0.4952 –0.8472 –1.0000 –1.0000 –0.4952 | 0 0 0 0 –1 |
| $\mu_{WBR}$ | 1 –1 –1 –1 | 0.4952 –0.8472 –1.0000 –1.0000 –0.4952 | 0 0 0 0 –1 |
| $\mu_{SR}$ | 1 –1 –1 –1 | 0.4952 –0.8472 –1.0000 –1.0000 –0.4952 | 0 0 0 0 –1 |
| $\mu_{STA}$ | 1 –1 –1 –1 | 0.4952 –0.8472 –1.0000 –1.0000 –0.4952 | 0 0 0 0 –1 |
| District       | Pudong | Huangpu | Xuhui |
|---------------|--------|---------|-------|
| μi            |        |         |       |
| μ_{PP}        | 0.2725 | 0.8619  | 0.3567|
| μ_{CDPP}      | 0.1635 | 0.4155  | 0.4783|
| μ_{IOUA}      | 0.8626 | 0.0392  | 0.4671|
| μ_{BAR}       | 0.631  | 0.1783  | 0.4555|
| μ_{WRP}       | 0.2065 | 0.8619  | 0.844 |
| μ_{STA}       | 0.2726 | 0.4255  | 0.6327|

(continued on next page)
Table 4 (continued)

| μ | 0.1007 | 0.4098 | 0.2012 | 0.3982 | 0.5212 | 0.0000 | 0.0000 | 0.2992 | 0.8234 | 0.2381 | 0.0096 | 0.2367 | 0.5244 | 0.6413 | 0.0559 |
|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| District | Baoshan | Jiading | Jinshan |
| μ₁ | I | II | III | IV | V | I | II | III | IV | V | I | II | III | IV | V |
| μ₁₀₀ | 0 | 0.6682 | 1 | 0 | 0 | 0.2985 | 1 | 0 | 0 | 0 | 0.353 | 1 | 0 | 0 | 0 |
| μ₁₀₁ | 0 | 0 | 0.696 | 1 | 0 | 0 | 0 | 0 | 0 | 0.8645 | 0 | 0 | 0 | 0 | 0 |
| μ₁₀₂ | 0 | 0.4246 | 1 | 0 | 0 | 0 | 0 | 0.432 | 1 | 0 | 0.374 | 1 | 0 | 0 | 0 |
| μ₁₀₃ | 0 | 0 | 0 | 0.4355 | 1 | 0 | 0 | 0 | 0 | 0 | 0.698 | 1 | 0 | 0 | 0 |
| μ₁₀₄ | 0 | 0.6923 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 |
| μ₁₀₅ | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0.4 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
| μ | 0.0764 | 0.2726 | 0.4950 | 0.4874 | 0.1372 | 0.0968 | 0.4396 | 0.5988 | 0.1512 | 0.1574 | 0.4728 | 0.6581 | 0.1847 | 0.1534 | 0.0000 |
| District | Songjiang | Qingpu | Fengxian |
| μ₀₀ | I | II | III | IV | V | I | II | III | IV | V | I | II | III | IV | V |
| μ₀₁ | 0.543 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| μ₀₂ | 0 | 0.6043 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| μ₀₃ | 0 | 0 | 1 | 0.518 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| μ₀₄ | 0 | 1 | 0 | 0.4535 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| μ₀₅ | 0 | 0 | 1 | 0.452 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| μ | 0.1367 | 0.4807 | 0.5420 | 0.2132 | 0.1152 | 0.4118 | 0.6992 | 0.3513 | 0.2387 | 0.0000 | 0.5285 | 0.6750 | 0.2345 | 0.1152 | 0.0000 |
| District | Chongming |
| μ₀₀ | I | II | III | IV | V | I | II | III | IV | V |
| μ₀₁ | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| μ₀₂ | 1 | 0.7625 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| μ₀₃ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| μ₀₄ | 0 | 0 | 0 | 0.0185 | 1 | 0 | 0 | 0 | 0 | 0 |
| μ₀₅ | 0 | 0 | 0 | 0.7823 | 1 | 0 | 0 | 0 | 0 | 0 |
| μ | 0.7476 | 0.1947 | 0.0000 | 0.0927 | 0.2524 | 0.7476 | 0.1947 | 0.0000 | 0.0927 | 0.2524 |
calculate the single connection degree ($\mu_{jk}$) of each safety risk level of water resource (level I to level V) of each district in Shanghai under the same assessment factor. It includes the field measured data ($R_i$) of the water quality assessment factors for each district division, and the grading criteria ($b_0$ to $b_k$) for these assessment indicators. AHP sheet calculates the weight coefficient ($w_i$) of eight assessment factors. It needs to input the comparative score of importance between two adjacent assessment factors. IFN-SPA sheet calculates the comprehensive connection degree under different levels. The calculation parameters of IFN-SPA sheet contain the values of single connection degree ($\mu_{jk}$) and the weight coefficient ($w_i$). Therefore, the specific steps to use the calculation tool are as follows: first, input the measured data ($R_i$) of the corresponding assessment factor into the orange area of sheet R1 to R8 to calculate the single connection ($\mu_{jk}$) and the results are shown in the blue area. Second, it needs input the score of importance into the orange area of AHP sheet to calculate the weights coefficient ($w_i$) of assessment factors in blue area. Finally, it needs input the values of the single connection ($\mu_{jk}$) and the weight coefficient ($w_i$) into the orange area of IFN-SPA sheet to calculate the comprehension connection degree ($\mu$) and the results are shown in the red area of IFN-SPA sheet.

**Method validation**

To verify the advantage of the proposed IFN-SPA method, both the existing SPA methods and the IFN-SPA method were used calibrate the connection degree of the assessment factors to the risk of water quality. Based on the weights of assessment factors calibrated from AHP method, the connection of each assessment samples can be obtained. Table 2 lists the connection degree calibrated from original SPA. Table 3 lists the connection degree calibrated from comprehensive SPA. Table 4 lists the connection degree calibrated from the proposed IFN-SPA. The detailed comparison and analyses of the assessed results can be found in the companioned research article [1].

**Declaration of Competing Interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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**Supplementary materials**

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.mex.2021.101237.

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