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Dynamic evaluation of water source safety based on fuzzy extension model

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Abstract. The information matter-element system was built to assess safety of water source. Based on the thought of multi-index fusion, fuzzy matter-element model evaluating water source behavior was constructed by matter-element transform. This model can process comprehensively hydrogeological data, ecological environment, water pollution, surface disturbance, and so on. Water source safety behavior can be described by the qualitative and quantitative manners. According to the development trend of quantitative results, water source safety behavior can be expressed dynamically. As an example, the proposed method was used to assess safety status of 7 water sources in the region. The numerical example shows that the proposed method is feasible and effective, and the evaluation results are reasonable.

Keywords: water source; extension theory; fuzzy matter-element model; dynamic evaluation

1. Introduction

Water source is a basic livelihood guarantee for its security has been highly valued by all sectors of society. Water source is a multivariate and complex system composed of reservoir and surrounding environment. Its safety state is affected by the combination of primary factors and humanistic factors, which determines that the indicators affecting the safety state of water source have the characteristics of diversity, complexity, correlation and uncertainty, which are shown in the following aspects: (1) the relationship between individual indexes is independent ostensibly, but in fact they have a certain relationship with each other. (2) some indexes that affect the safety of water sources cannot be quantitatively expressed. (3) the position and function of each index in the safety evaluation of water source are not equal, and there is a possibility of conversion between the main and secondary factors. If these changes are not taken into consideration, the wrong conclusions will be drawn.

The safety evaluation is a complex contradiction problem due to the complex system characteristics of the drinking water source. It not only needs to give the qualitative description of each index, but also quantitatively depicts the impact of each index on the safety of the water source, and finally gives the results of the comprehensive evaluation of the safety of the drinking water source. Based on the analysis of the factors affecting the safety of water sources, the existing research methods (Zhang *et al.* 2005, Zhong *et al.* 2004, Zhu *et al.* 2010a, Zhu *et al.* 2010b, Ma *et al.* 2018, Zeng *et al.* 2014, Shi *et al.* 2013) are built on 3 levels of water source safety evaluation index system including multiple indexes. The index weight is determined by analytic hierarchy process (AHP), and then the evaluation results are obtained by using set pair analysis and fuzzy comprehensive evaluation. There are two main problems in the research methods mentioned above. First, it is difficult to include both the index importance information and the transition characteristics of the primary and secondary indexes when the index weight is drawn up. Secondly, it only reflects the safety characteristics at a given time and lacks the dynamic determination of the safety state of the drinking water source. In this paper, some theories, methods and ideas of extension theory are used to combine the water source (thing), evaluation index (the characteristics of things) and the running situation (corresponding value) into a whole with the concept of safety evaluation of water source matter-element. Quantitative description of the impact degree can be used to evaluate the safety performance of water sources from the angle of qualitative to quantitative integration.

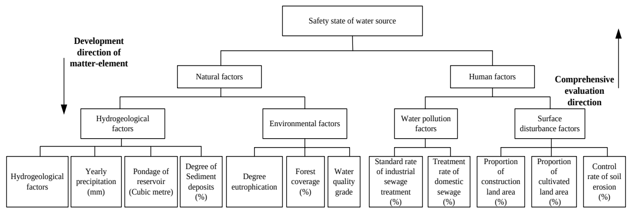

Fig. 1 System of information matter element on safety assessment for water source

2. Information matter-element system for safety evaluation of water source

The safety state of water source can be described from several indexes and links. According to the concept of system engineering and matter-element extension, based on

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two aspects of natural factors and humanistic factors, 12 indexes to describe the safety state of water source land are constructed, as shown in Fig. 1.

3. Fuzzy matter-element model for safety assessment of water source

3.1 Fuzzy matter-element basic unit

Ordered triples (things, characteristics, quantities) are used as the basic unit to describe the safety of water sources, which is called the matter-element of the safety of water sources (Tang *et al.* 2006, Ince *et al.* 2018, Tang *et al.* 2012). Among them, the object of study is things, the evaluation index is characteristic, the *n*ormalized value of the index is characteristic value, and the fuzzy matter-element of water source safety state evaluation can be described as follows (Su *et al.* 2006a, Lee *et al.* 2017, Su *et al.* 2006b, Zhang *et al.* 2017)

$$R=(N,C,V)=\begin{bmatrix} \text{Object} & \text{Characteristic } c_1 & \text{Characteristic value } \mu_{I_1} \\ & \text{Characteristic } c_2 & \text{Characteristic value } \mu_{I_2} \\ & \cdots & \cdots \\ & \text{Characteristic } c_n & \text{Characteristic value } \mu_{I_n} \end{bmatrix} \tag{1}$$

3.2 Point assessment model

A research object is evaluated according to the evaluation index corresponding to the lower level, called point evaluation. It is the basis for the overall safety assessment of water source.

3.2.1 Classical field matter-element

According to the standard of water source safety level, the classical matter-element of object in matter-element system can be obtained

$$R_j=\begin{bmatrix} N_j, & c_1, & \mu_{j1} \\ & c_2, & \mu_{j2} \\ & \ldots, & \ldots \\ & c_n, & \mu_{jn} \end{bmatrix}=\begin{bmatrix} N_j, & c_1, & \langle a_{j1},b_{j2}\rangle \\ & c_2, & \langle a_{j2},b_{j2}\rangle \\ & \ldots, & \ldots \\ & c_n, & \langle a_{jn},b_{jn}\rangle \end{bmatrix} \tag{2}$$

Where R_j is the j level of the safety of water source(j=1,2,…,m), m is the number of classes divided, c_j is the j feature of the research object(j=1,2,…,n), n is the characteristic number of a certain research object, $\mu_{ij}=\langle a_{ij},b_{ij}\rangle$ represents the level i, the j characteristic c_j value range, that is, the classical field of each grade about the object evaluation index.

3.2.2 Segment field matter-element

The segment field matter-element is

$$R_p=\begin{bmatrix} N_p, & c_1, & \mu_{p1} \\ & c_2, & \mu_{p2} \\ & \ldots, & \ldots \\ & c_n, & \mu_{pn} \end{bmatrix}=\begin{bmatrix} N_j, & c_1, & \langle a_{p1},b_{p1}\rangle \\ & c_2, & \langle a_{p2},b_{p2}\rangle \\ & \ldots, & \ldots \\ & c_n, & \langle a_{pn},b_{pn}\rangle \end{bmatrix} \tag{3}$$

Where P is the whole of the evaluation indexes, $\langle a_{pi},b_{pi}\rangle$ is the range of c_i.

3.2.3 Current matter-element

The data of evaluation indexes at a certain time t is represented by the matter-element matrix shown in Eq. (4). $R_t(N(t), C,\mu(t))$ called the current matter-element of research object N.

$$R_t\left(N(t),C,\mu(t)\right)=\begin{bmatrix} N(t) & c_1, & \mu_1(t) \\ & c_2, & \mu_2(t) \\ & \ldots, & \ldots \\ & c_n & \mu_n(t) \end{bmatrix} \tag{4}$$

Where $N(t)$ is the object to be evaluated in the matter-element system, $\mu_i(t)$ is the normalized value of the evaluation index c_i at a certain time t.

3.3 Correlation function

3.3.1 Single index correlation degree

The correlation function of the j level in the i feature of the water source safety assessment object N is recorded as $K_j(\mu_i(t))$, j=1,2,…,m, i=1,2,…,n, and its calculation process is as follows:

(1) When $\mu_i(t)\notin\langle a_{ij},b_{ij}\rangle$, the correlation function is

$$K_j(\mu_i(t))=\frac{\rho\left(\mu_i(t),\langle a_{ij},b_{ij}\rangle\right)}{\rho\left(\mu_i(t),\langle a_{pj},b_{pj}\rangle\right)-\rho\left(\mu_i(t),\langle a_{ij},b_{ij}\rangle\right)} \tag{5}$$

With

$$\rho\left(\mu_i(t),\langle a_{ij},b_{ij}\rangle\right)=\left|\mu_i(t)-\frac{a_{ij}+b_{ij}}{2}\right|-\frac{b_{ij}-a_{ij}}{2} \tag{6}$$

$$\rho\left(\mu_i(t),\langle a_{pj},b_{pj}\rangle\right)=\left|\mu_i(t)-\frac{a_{pj}+b_{pj}}{2}\right|-\frac{b_{pj}-a_{pj}}{2} \tag{7}$$

(2) When $\mu(t)\in\langle a_{ij},b_{ij}\rangle$, the correlation function is

$$K_j(\mu_i(t))=\frac{2\rho\left(\mu_i(t),\langle a_{ij},b_{ij}\rangle\right)}{b_{ij}-a_{ij}} \tag{8}$$

(3) When $\mu(t)\in\langle a_{ij},b_{ij}\rangle$ and, $\mu_i(t)>(a_{ij}+b_{ij})/2$, the correlation function is

$$K_j(\mu_i(t))=1 \tag{9}$$

3.3.2 Multi index comprehensive correlation degree

The correlation degree of object N with grade j is

$$K_{jt}=\sum_{i=1}^{n}\alpha_i K_j(\mu_i(t)) \tag{10}$$

Where α_i is the weight distribution coefficient of the i-th evaluation index, which is satisfied

$$\sum_{i}^{n}\alpha_i=1 \tag{11}$$

If the following equation exists

$$K_{jt} = \max\left\{K_{jt}\right\}(j = 1, 2, ..5) \tag{12}$$

The final category of the object element to be evaluated can be determined, that is, the level corresponding to the maximum correlation degree.

3.3.3 Comprehensive evaluation

Since $K_{jt}\in<-1,1>$, $d_{jt}\in<1-K_{jt}>/2$ and $d_{jt}\in<0,1>$, d_{jt} is regarded as a generalized distance of spatial point columns composed of each characteristic quantity of the object to be evaluated and the spatial points of each characteristic quantity of j level. $d_{jt}=0$ indicates that the degree of correlation between the target and the j level is the largest and the distance is 0, $d_{jt}=1$ indicates that the degree of association is the smallest and the distance is 1. W_{jt} is the weight of the object to be evaluated relative to the degree of j level, so the optimal value of W_{jt} should satisfy the generalized distance squared and minimum between the object to be evaluated and the safety level. Even if $\sum_{j=1}^{m}(W_{jt}d_{jt})^2$ is the minimum value, the optimal solution of W_{jt} meeting the normalization condition ($\sum_{j=1}^{m}W_{jt} = 1$) can be obtained by constructing Lagrange function.

$$W_{jt}^{*} = 1/\sum_{k}^{m}(d_{jt}/d_{kt})^{2} \tag{13}$$

The comprehensive evaluation index is obtained from the above formula.

$$J^{*}(t) = \sum_{j=1}^{m} jW_{jt} \tag{14}$$

When $J^*(t)$ value is an integer, its value is the level $J(t)$ of the object to be evaluated, when the value of $J^*(t)$ is non-integer, the integer with the minimum difference from the value of $J(t)$ is the evaluation level.

3.3.4 Dynamic evaluation model

According to the above assessment steps, the safety condition of water source in T different periods (or times) was analyzed, and the safety grade and comprehensive evaluation indexes of T different periods (or times) were obtained, which were respectively denoted as $J(t)$, $J^*(t)$ (t=1,2,…,T), then the changes of $J(t)\sim t$ and $J^*(t)\sim t$ could be analyzed. When $J(t)$ grade is higher, and $J^*(t)$ increases gradually with the passage of time, it indicates that the safety of this water source is getting worse. Therefore, supervision should be strengthened to avoid further deterioration. If $J^*(t)$ is basically flat or gradually decreasing over time, it indicates that the water source is basically safe or developing to the good. When grade $J(t)$ is low, $J^*(t)$does not gradually increase with time, indicating that the water source is in good safety condition.

4. Construction of index comprehensive weight based on game theory

4.1 Normalization processing

Before calculating the index weight, the original data of each index should be normalized. The normalized formula of attribute value is as follows (Tyc *et al.* 2016, Silva *et al.* 2015).

$$\text{Income-type index:}\quad \xi_{ij} = \frac{u_{ij} - \min u_{ij}}{\max u_{ij} - \min u_{ij}} \tag{15}$$

$$\text{Cost-type index:}\quad \xi_{ij} = \frac{\max u_{ij} - u_{ij}}{\max u_{ij} - \min u_{ij}} \tag{16}$$

Where ξ_{ij} is the standardized index, $\max u_{ij}$ and $\min u_{ij}$ are the maximum and minimum values corresponding to the *j-th* index in each evaluation index sample.

4.2 Index weight vector and possible index weight set

In the comprehensive evaluation of water source safety, the determination of index weight is very important. In order to obtain more scientific and comprehensive evaluation results, N different methods can be used to assign weights to each index.

And then N index weight vectors can be obtained

$$w_i = (w_{i1}, w_{i2}, ..., w_{im}), i = 1, 2, 3, ..., N \tag{17}$$

In this way, an index weight set $\{w_1, w_2,…,w_m\}$ is constructed. Two concepts are introduced, namely, the basic index weight and the possible index weight set. The basic index weight is the independent index weight vector w_i based on N methods alone, while the possible index weight set is the set formed by any linear combination of the weights of the N basic indexes.

Any linear combination of the weight vector w_i of N basic indicators is

$$w = \sum_{i=1}^{N}\alpha_i w_i \tag{18}$$

Where $\alpha_i>0$, and $\sum_{i=1}^{N}\alpha_i = 1$, its entire $\left\{w \middle| w = \sum_{i=1}^{N}\alpha_i w_i\right\}$ is expressed as a set of possible index weights. There is a most satisfactory linear combination of the N basic weight vectors w_i, that is, the most satisfactory weight vector w^*. It can scientifically and comprehensively reflect the importance of each index in water source safety evaluation.

4.3 Index weight optimization model based on game theory

Game theory centralized model is to find equilibrium or compromise between the weights of indicators obtained by different weighting methods, so as to minimize the deviation between the possible weights of indexes and the weights of basic indexes. Therefore, the game theory can be used to optimize the N linear combination coefficients α_i in

Table 1 Indexes safety correlation degree of water source I

Correlation degree	N_1	N_2	N_3	N_4	N_5	Safety level
$K_j(c_1)$	-0.085	+0.085	-0.281	-0.485	-0.673	Slight insafety
$K_j(c_2)$	-0.170	+0.034	-0.034	-0.231	-0.433	Slight insafety
$K_j(c_3)$	-0.664	-0.487	-0.314	-0.112	-0.013	Serious insafety
$K_j(c_4)$	-0.083	+0.083	-0.267	-0.467	-0.667	Basic safety
$K_j(c_5)$	-0.593	-0.171	+0.171	-0.231	-0.642	Slight insafety
$K_j(c_6)$	-0.201	-0.043	+0.026	-0.161	-0.362	Slight insafety
$K_j(c_7)$	-0.130	-0.051	+0.051	-0.174	-0.374	Slight insafety
$K_j(c_8)$	-0.151	+0.062	-0.062	-0.262	-0.463	Basic safety
$K_j(c_9)$	-0.029	+0.029	-0.187	-0.384	-0.581	Basic safety
$K_j(c_{10})$	0	-0.121	-0.242	-0.363	-0.484	Safety
$K_j(c_{11})$	0	-0.185	-0.370	-0.555	-0.740	Safety
$K_j(c_{12})$	0	-0.190	-0.380	-0.570	-0.760	Safety

Eq. (18). The objective of optimization is to minimize the deviation between w and each w_i, so as to obtain the most satisfactory index weight vector. In this way, the following decision models can be derived

$$\min\left\|\sum_{j=1}^{N}\alpha_j w_j^T - w_i^T\right\|_2, i=1,2,...,N \tag{19}$$

According to the differential property of matrix, the optimal first derivative condition of the above decision model is

$$\sum_{j=1}^{N}\alpha_j \bullet w_i \bullet w_j^T = w_i \bullet w_i^T, i=1,2,...,N \tag{20}$$

It corresponds to the following system of linear equations

$$\begin{bmatrix} w_1 \bullet w_1^T & w_1 \bullet w_2^T & \dots & w_1 \bullet w_N^T \\ w_2 \bullet w_2^T & w_2 \bullet w_2^T & \dots & w_2 \bullet w_N^T \\ \vdots & \vdots & & \vdots \\ w_N \bullet w_1^T & w_N \bullet w_2^T & \dots & w_N \bullet w_N^T \end{bmatrix}\begin{bmatrix}\alpha_1 \\ \alpha_2 \\ \vdots \\ \alpha_N\end{bmatrix} = \begin{bmatrix} w_1 \bullet w_1^T \\ w_2 \bullet w_2^T \\ \vdots \\ w_N \bullet w_1^T \end{bmatrix} \tag{21}$$

The α_i in the formula (20) is the most satisfactory coefficient of weight vector w^*.

The most satisfactory weight is

$$w^* = \sum_{i=1}^{N}\alpha_i w_i \tag{22}$$

5. Case analysis

The matter-element method and extension theory were used to construct the matter-element extension model for the safety of urban water sources, and the safety of 7 urban water sources in the region is evaluated. The numerical values of evaluation indexes in this paper are obtained directly or indirectly through statistical yearbook, hydrological and meteorological observation data, remote sensing interpretation, field investigation, sampling analysis, etc., and the time span is from 2008 to 2016. The information matter-element system of water source safety assessment is established as shown in Fig. 1.

5.1 Establish classical field, segment field and current matter-element

The evaluation N_p set is divided into 5 grades, that is N_P={N_1(Safety), N_2 (Basic safety), N_3 (Slight insafety), N_4 (Insafety), N_5 (Serious insafety)} relevant data of 2008 are applied to explain the safety assessment process of water source I. Classical field R_j, segment field R_p and current matterelement R_t can be obtained from Eqs. (2), (3) and (4).

$$R_j = \begin{bmatrix} & N_1 & N_2 & N_3 & N_4 & N_5 \\ c_1, & \langle 10,28\rangle & \langle 28,46\rangle & \langle 46,64\rangle & \langle 64,82\rangle & \langle 82,100\rangle \\ c_2, & \langle 900,1200\rangle & \langle 800,900\rangle & \langle 700,800\rangle & \langle 630,700\rangle & \langle 550,630\rangle \\ c_3, & \langle 3000,4000\rangle & \langle 2000,3000\rangle & \langle 1000,2000\rangle & \langle 800,1000\rangle & \langle 450,800\rangle \\ c_4, & \langle 1,3\rangle & \langle 3,5.5\rangle & \langle 5.5,8\rangle & \langle 8,12\rangle & \langle 12,15\rangle \\ c_5, & \langle 40,46\rangle & \langle 46,52\rangle & \langle 52,58\rangle & \langle 58,64\rangle & \langle 64,70\rangle \\ c_6, & \langle 68,80\rangle & \langle 55,68\rangle & \langle 45,55\rangle & \langle 32,45\rangle & \langle 20,32\rangle \\ c_7, & \langle 0,20\rangle & \langle 20,40\rangle & \langle 40,60\rangle & \langle 60,80\rangle & \langle 80,100\rangle \\ c_8, & \langle 90,100\rangle & \langle 85,90\rangle & \langle 75,85\rangle & \langle 70,75\rangle & \langle 60,70\rangle \\ c_9, & \langle 90,80\rangle & \langle 70,80\rangle & \langle 65,70\rangle & \langle 66,65\rangle & \langle 50,60\rangle \\ c_{10}, & \langle 0.03,0.08\rangle & \langle 0.08,0.13\rangle & \langle 0.13,0.18\rangle & \langle 0.18,0.25\rangle & \langle 0.25,0.30\rangle \\ c_{11}, & \langle 0.65,1.85\rangle & \langle 1.85,3.14\rangle & \langle 3.14,4.32\rangle & \langle 4.32,5.53\rangle & \langle 5.53,6.74\rangle \\ c_{12}, & \langle 98,90\rangle & \langle 90,80\rangle & \langle 80,70\rangle & \langle 65,70\rangle & \langle 60,65\rangle \end{bmatrix}$$

$$R_p = \begin{bmatrix} & c_1 & c_2 & c_3 & c_4 & c_5 & c_6 \\ N_p, & \langle 10,100\rangle & \langle 550,1200\rangle & \langle 450,4000\rangle & \langle 1,15\rangle & \langle 40,70\rangle & \langle 20,80\rangle \\ & c_7 & c_8 & c_9 & c_{10} & c_{11} & c_{12} \\ N_p, & \langle 0,100\rangle & \langle 60,100\rangle & \langle 50,90\rangle & \langle 0.03,0.30\rangle & \langle 0.65,6.74\rangle & \langle 60,98\rangle \end{bmatrix}$$

The current matterelement of the safety assessment for the water source I in 2008 is as follows.

$$R_t = \begin{bmatrix} & c_1 & c_2 & c_3 & c_4 & c_5 & c_6 \\ N(t), & 50 & 730 & 585 & 3.6 & 56.3 & 51 \\ & c_7 & c_8 & c_9 & c_{10} & c_{11} & c_{12} \\ N(t), & 55 & 86 & 75 & 0.07 & 1.45 & 91 \end{bmatrix}$$

5.2 Weight determination

The weights of the evaluation indexes of water source I were calculated by the analytic hierarchy process (AHP) and the entropy weight method respectively (Gong *et al.* 2009, Ren *et al.* 2013), and the most satisfactory weight of each evaluation index was obtained based on the game theory is

$$R_{w^*} = \begin{bmatrix} & c_1 & c_2 & c_3 & c_4 & c_5 & c_6 \\ w^*, & 0.029 & 0.125 & 0.095 & 0.093 & 0.127 & 0.095 \\ & c_7 & c_8 & c_9 & c_{10} & c_{11} & c_{12} \\ w^*, & 0.147 & 0.078 & 0.079 & 0.048 & 0.041 & 0.043 \end{bmatrix}$$

5.3 calculate correlation degree and comprehensive correlation degree

The correlation degree of each indexes corresponding to each level is calculated from Eqs. (5) to (9), and the corresponding safety level of each indexes can be

Table 2 Comprehensive safety correlation degree of water source I

Index	N_1	N_2	N_3	N_4	N_5	Safety level
Hydrogeological factors	-0.240	-0.086	-0.011	-0.145	-0.371	Slight insafety
Environmental factors	-0.456	-0.0153	+0.018	-0.154	-0.463	Slight insafety
Water pollution factors	-0.164	+0.497	-0.084	-0.312	-0.573	Basic safety
Surface disturbance	0	-0.081	-0.247	-0.487	-0.767	Safety
Comprehensive status	-0.116	+0.050	-0.089	-0.281	-0.442	Basic safety

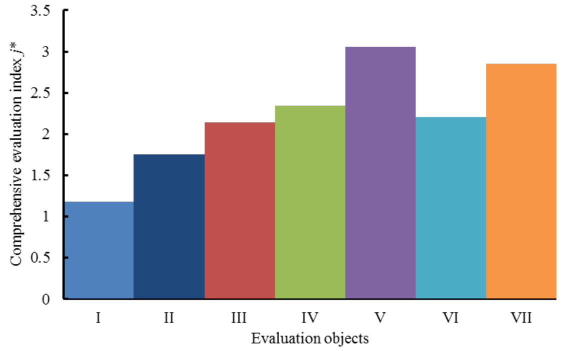

Fig. 2 Results of comprehensive safety assessment of various water sources (2008)

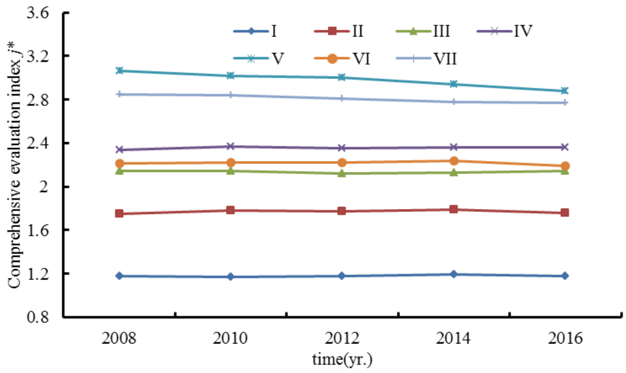

Fig. 3 The dynamic comprehensive evaluation results of the water source safety state from 2008 to 2016

determined by combining Eq. (12), as shown in Table 1.

The correlation degree and weight of each index corresponding to each grade were substituted into Eq. (10), and the comprehensive correlation degree of all indexes corresponding to each evaluation grade was obtained as shown in Table 2.

5.4 Safety state assessment of all water sources

The same calculation process was adopted for the safety assessment of the remaining 6 water sources, and the comprehensive evaluation indexes of the safety state of all water sources in 2008 were obtained by using Eq. (13), as shown in Fig. 2.

It can be seen from Fig. 2 that water source I and II are in the state of basic safety, of which water source I has the highest safety, and water source III, IV, VI and VII are slightly unsafe, of which water source VII is the most unsafe. Water source V is in an unsafe state, which is one of the least safe water sources. In the same security status of the security level of water source different index each are not identical, III and VI mainly ecological environment and water source water pollution problem is bigger, and the water IV and VII are hydrogeological problems more, therefore in the process of water source protection and restoration, the same safe level of water source should also to take corresponding measures according to different index of the security levels, so that a quick and efficient to improve the safety of the water source.

5.5 Dynamic evaluation of the safety state of each water source

According to the above evaluation methods, the comprehensive evaluation values and grades of the safety state of each water source from 2008 to 2016 were calculated respectively, as shown in Fig. 3. From the figure, it can be seen that from 2008 to 2016, the safety state of 7 water sources generally showed a trend of being stable and improving, especially in the unsafe level of water source V, and the comprehensive evaluation index value decreased year by year, changing from unsafe state to slightly unsafe state. The improvement rate of forest coverage rate, industrial sewage and domestic sewage indexes in the safety evaluation indexes of water supply area was obviously improved, which is the main reason for the improvement of the safety level of water supply area.

6. Conclusions

In order to evaluate the safety state of water source, multi-index attributes should be taken into consideration as a whole. In this paper, fuzzy extension theory was applied to 7 water safety state assessment, based on characteristics and eigenvalue combination weighting fuzzy matter-element evaluation model, can be concluded that the safety of each part and the whole water system levels and indexes, and can grasp the dynamic change trend of water safety state, enriched and improved water safety state evaluation method, and the calculation is simple and convenient, consistent results and practical situation of water source, to guide the scientific protection and ecological restoration of water source has important practical significance.

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