

A new method for water quality assessment: by harmony degree equation

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Abstract Water quality assessment is an important basic work in the development, utilization, management, and protection of water resources, and also a prerequisite for water safety. In this paper, the harmony degree equation (HDE) was introduced into the research of water quality assessment, and a new method for water quality assessment was proposed according to the HDE: by harmony degree equation (WQA-HDE). First of all, the calculation steps and ideas of this method were described in detail, and then, this method with some other important methods of water quality assessment (single factor assessment method, mean-type comprehensive index assessment method, and multi-level gray correlation assessment method) were used to assess the water quality of the Shaying River (the largest tributary of the Huaihe in China). For this purpose, 2 years (2013–2014) dataset of nine water quality variables covering seven monitoring sites, and approximately 189 observations were used to compare and analyze the characteristics and advantages of the new method. The results showed that the calculation steps of WQA-

HDE are similar to the comprehensive assessment method, and WQA-HDE is more operational comparing with the results of other water quality assessment methods. In addition, this new method shows good flexibility by setting the judgment criteria value HD_0 of water quality; when $HD_0 = 0.8$, the results are closer to reality, and more realistic and reliable. Particularly, when $HD_0 = 1$, the results of WQA-HDE are consistent with the single factor assessment method, both methods are subject to the most stringent “one vote veto” judgment condition. So, WQA-HDE is a composite method that combines the single factor assessment and comprehensive assessment. This research not only broadens the research field of theoretical method system of harmony theory but also promotes the unity of water quality assessment method and can be used for reference in other comprehensive assessment.

Keywords Harmony degree equation (HDE) · Assessment method · Water quality assessment · The Shaying River

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Introduction

In recent years, global water issues become more and more serious (Isçen et al. 2008). Among them, the issue of water pollution has always been a hot topic discussed by people, and the problem is widespread in all countries, especially in developing countries (Ongley 2001). As the largest and most populous developing country, this kind of phenomenon is particularly serious

in China (Lindberg et al. 2014; Zhou et al. 2014), and it has brought serious impact on people's lives and the development of society and economy. Therefore, it is urgent and meaningful to carry out water quality assessment.

The water quality assessment refers to according to the different purposes and requirements, by selecting the appropriate water quality assessment indexes (the physical, chemical, and biological indexes of water bodies), criteria and methods to assess the status, utilization value, protection, and improvement measures of water quality. With the progress of science and technology, more and more extensive and in-depth researches have been carried out on water quality assessment (Vega et al. 1998; Janssen and Carpenter 1999; Dustin and Miller 2001; Newton et al. 2003; Singh et al. 2004; Hantush 2007; Kannel et al. 2007; Ip et al. 2009; Simões et al. 2008; Ramesh et al. 2010; Yan et al. 2010; Kalin et al. 2010; TzeLing et al. 2011; Shi et al. 2012; Duque et al. 2013; Liu et al. 2013; Li et al. 2014), and in recent years, researchers have made a series of studies on the choice of water assessment methods (Yang et al. 2014), which have achieved fruitful research results. Jha et al. (2015) and Şener et al. (2017) assessed water quality by using methods of water quality indexes (WQI) and GIS, and discussed the effects of each water quality parameter on the WQI values; Mohan and Jairaj (2016) developed a Fuzzy-Entropy (FE) model that evolved to incorporate the imprecision associated with the observed data using fuzzy comprehensive evaluation combined with an objective weight determining approach, and compared the model with the traditional FLS model; Gharibi et al. (2012) developed a novel water quality index based on fuzzy logic, which is a comprehensive artificial intelligence approach to the development of environmental indices for routine assessment of surface water quality; On the basis of the fuzzy binary comparison method (FBCM) and the theory of variable fuzzy sets (VFS), Wang et al. (2014) proposed an integrated variable fuzzy evaluation model (VFEM) and compared the present method with other traditional methods. It can be found that the new methods of water quality assessment are constantly emerging and becoming more and more diversified and complicated. However, no matter which method, it can be divided into two categories according to the number of selected assessment items, the single factor assessment method or the

comprehensive assessment method. The former is to assess the water quality category of each assessment factor by comparing the assessment factors and assessment criteria, and using the worst category as the final result of water quality assessment. The idea of this method was derived from the approach of functional accessibility in America, and it can be used to determine the main pollution factors in water bodies. The latter is developed on the basis of the former method, it can be processed by different mathematical calculations to get a comprehensive assessment value of water quality, and the application is also very extensive. Both categories of methods have their own advantages and disadvantages, the single factor assessment method has the advantages of simpleness and easy promotion; therefore, this method is widely used, but its water quality assessment results are often too "pessimistic," because the situation of "One vote and veto" often appeared. On the contrary, the comprehensive assessment method can better reflect the comprehensive situation of water quality. Many of the new proposed methods also belong to the comprehensive assessment method, but the calculation process of the comprehensive evaluation method was often complicated and inconvenient in practical application. In addition, in the actual water quality assessment work, the use of single factor assessment method or comprehensive assessment method is still not unified, how to combine the single factor assessment method and the comprehensive assessment method into one method is not available in the existing methods.

Given the above considerations, the purpose of this study is to explore a new method for water quality assessment, which is easy to calculate and master, and can also carry out single factor assessment and comprehensive assessment. To this end, the three time points in 2 years (2013.7, 2013.12, 2014.12) of the water quality monitoring data were obtained from seven water quality monitoring sites of the Shaying River in China, and used for the proposed method WQA-HDE to assess the water quality of the Shaying River. In addition, in order to reflect the advantages of this method, the results of WQA-HDE were analyzed and compared with several major water quality assessment methods (single factor assessment method, mean-type comprehensive index assessment method and multi-level gray correlation assessment method). It is hoped that this study can provide a new method and research approach for water quality assessment and other related research fields.

Assessment method (WQA-HDE)

Method description

HDE

In the real life, the harmonious problems can be seen everywhere, such as harmonious society, harmonious family, and harmonious life; it is obvious that there is also a harmonious relationship between human and water. In the context of the global water problem increasingly serious, the harmony between human and water is also getting more and more attention, but how to use the quantitative method to study the harmony issues is still hard work. In order to solve this problem, the author Zuo in 2009 innovatively proposed HDE, and used to quantify the harmony degree. Then, the HDE was systematically discussed in the book of “Harmony Theory: theory, method and application,” and a harmonious theory method system was constructed with the characteristic of quantitative research. Subsequently, the harmony theory quantitative research method and the HDE were published by the foreign periodicals for the first time in 2013 (Zuo et al. 2013); and it is called “Zuo-harmony degree equation” by the editor of the journal “The Scientific World Journal” in 2015 (Zuo et al. 2015a). In 2016, the HDE has been modified and improved in the new edition of the book “Harmony Theory: theory, method and application (Second Edition),” and the construction of HDE is given as follows:

$$HD = ai - bj \tag{1}$$

where HD is the harmony degree and the variable a is the unity degree, and it refers to the proportion of harmonious participants in accordance with the rules of harmony has the same goal; the variable b is the difference degree, and it refers to the proportion of harmonious participants with different harmony rules and objectives. Note that $a \in [0, 1]$, $b \in [0, 1]$, and $a + b \leq 1$. The variable i , which is the harmony coefficient, reflects the satisfaction degree of the harmony goals; the variable j , which is the disharmony coefficient that reflects the divergent harmony participants, i and $j \in [0, 1]$. $HD \in [-1, 1]$, a higher value of HD (closer to 1) indicates a higher harmony degree and vice versa. If $HD \in [-1, 0]$, it shows the state of opposition; if $HD \in [0, 1]$, it shows the state of harmony.

Until now, the HDE has been applied and verified in some research work, such as analyzing the harmonious way of human-water relationship and the development and utilization strategy of water resources based on the HDE (Zuo and Zhang 2008; Zuo et al. 2014b, 2015a, b); assessing the harmony degree of human-water relationship in the basin or region (Zuo et al. 2008, 2014a; Zuo and Mao 2012); constructing an optimal allocation model of water resources based on HDE to solve the problem of water resource allocation and scheduling (Liang and Zuo 2013); constructing a water pollutant emission distribution model based on a harmonious target, which is used to formulate a pollutant emission distribution plan into rivers (Zuo and Pang 2011); applying water quantity allocation in trans-boundary river (Zuo et al. 2011); and so on. Of course, due to the HDE that was proposed for a short time, it is only a preliminary application. According to the author Zuo (2016), HDE can be more widely used, in which he proposed the assessment method based on HDE can be applied to comprehensive assessment, but the specific application and calculation process has not been further studied, so this is the research motivation of this article.

WQA-HDE

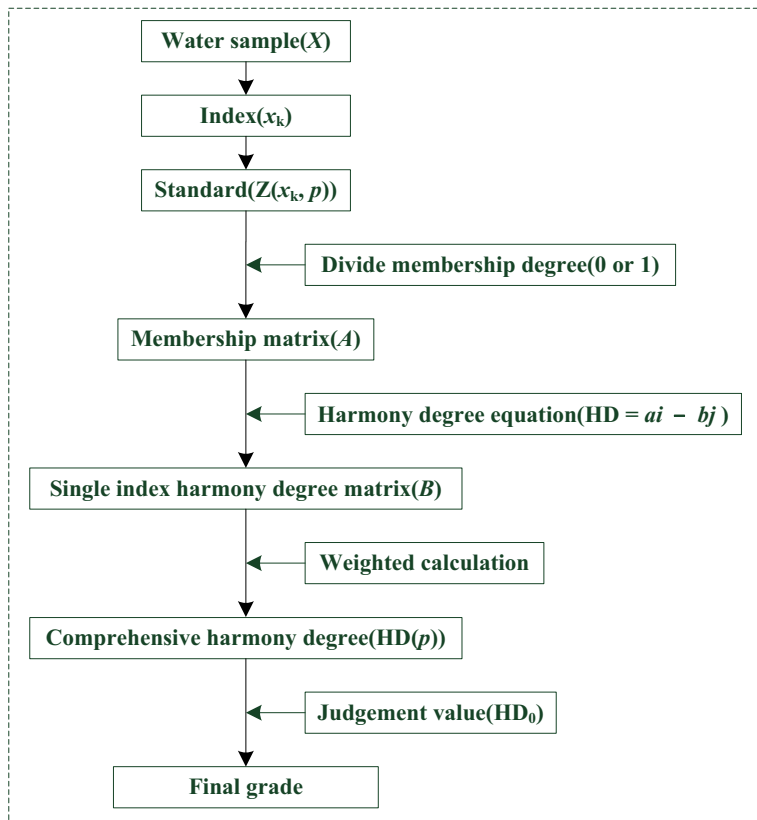
Based on the existing research results of the HDE, this paper aims to further explore the application field and scope of the HDE, in combination with the relevant contents of water quality assessment, a new water quality assessment method based on HDE (WQA-HDE) was proposed, and the application process of the WQA-HDE was given in Fig. 1. It should be noted that this method is not only applicable to water quality assessment in areas with water quality standards but also can apply the ideas and processes of this method to other assessment studies with similar types. In this paper, the water quality assessment of the Shaying River in China will be used as an example to discuss the processes and advantages of the method in detail.

The procedures of WQA-HDE are described as follows:

- 1) Determination of the water quality assessment indexes and standards

According to the systematic, scientific, comparability, measurable, and independent principles of index selection, some water quality indexes were selected and used for assessment. At present, the

Fig. 1 The process of WQA-HDE



relevant researches of water quality assessment index are more extensive and mature, and there are many existing water quality assessment indexes and standards that can be used to choose, such as the indexes and standards used in this paper to assess the water quality of the Shaying River in China that were detailed and clear introduced in the “surface water environmental quality standard” (GB3838-2002). Here, we set X as the water quality assessment index, and n represents the number of indexes, so the water quality assessment index set can be expressed as $x_1, x_2, x_3, \dots, x_n$.

The standard in the “surface water environmental quality standard” (GB3838-2002) has specific provisions, it is divided into five grades, and arranged according to the order from good to poor, they are I, II, III, IV, and V. The value range of the p -th assessment standard corresponding to the k -th index is represented by the variable $Z(x_k, p)$, and the specific forms of classification are shown in Table 1.

2) Weight calculation of water quality index

The index weight reflects the importance of each water quality assessment index within the index set,

in order to be more consistent with the corresponding usage mode. However, the weights of different water quality assessment indexes cannot be directly determined because of the different dimensions. At present, the common methods used to determine the weight are equal weight method, AHP method, Delphi method, variation coefficient method, and so on. Set the weight vector that has been determined as $W = (w_1, w_2, w_3, \dots, w_n)$, and the variable n represents the number of assessment indexes, $w_k \in [0, 1], \sum_{k=0}^n w_k = 1$.

Table 1 The grade standard division of the indexes

Index	Rank				
	I	II	III	IV	V
x_1	$Z(x_1, I)$	$Z(x_1, II)$	$Z(x_1, III)$	$Z(x_1, IV)$	$Z(x_1, V)$
x_2	$Z(x_2, I)$	$Z(x_2, II)$	$Z(x_2, III)$	$Z(x_2, IV)$	$Z(x_2, V)$
x_3	$Z(x_3, I)$	$Z(x_3, II)$	$Z(x_3, III)$	$Z(x_3, IV)$	$Z(x_3, V)$
\vdots	\vdots	\vdots	\vdots	\vdots	\vdots
x_n	$Z(x_n, I)$	$Z(x_n, II)$	$Z(x_n, III)$	$Z(x_n, IV)$	$Z(x_n, V)$

3) Judge the grade of single index or the membership degree

If one water sample index set is assumed, $X = (x_1, x_2, x_3, \dots, x_n)$, the variable n as the number of indexes, then select each water quality index of X one by one, and the classification membership degree of these indexes is divided according to Table 1. If the value of the water quality index x_k is in one of the corresponding water quality assessment grade standard p , then labeled as 1 in this position, which proved that x_k is completely subordinate to the grade of p . At the same time, all grades that are worse than p for x_k are also labeled as 1 (that is, the value of x_k is also satisfied with the low grade of water quality), otherwise labeled as 0, and then replaced with another index, until all classification membership degrees of the water quality indexes are completely divided. Thereby, we will get a membership matrix with n rows and five columns, which consist of 0 and 1, it can be called as matrix A , as shown below:

$$A = \begin{pmatrix} A_{11} & A_{12} & A_{13} & A_{14} & A_{15} \\ A_{21} & A_{22} & A_{23} & A_{24} & A_{25} \\ \dots & \dots & \dots & \dots & \dots \\ A_{n1} & A_{n2} & A_{n3} & A_{n4} & A_{n5} \end{pmatrix} \quad (2)$$

4) Calculate the harmony degree of different water quality grades

According to the definition of Eq. (1), we can know that the membership degrees in the matrix A are equivalent to the unity degrees which are affiliated to different water quality grades, and it also refers to the proportion of indexes in accordance with the standards of grade with the same goal. At this point, we can choose values of the variable i and j according to the specific circumstances, and then bring them into Eq. (1) to calculate the harmony degree $HD(x_k, p)$. So, we will get another matrix that is composed of $HD(x_k, p)$, which can be called the single index harmony degree matrix, referred to as B matrix. Of course, in order to simplify the calculation, we can set $i = 1$ and $j = 0$, so its unity degrees will equal to $HD(x_k, p)$, in other words, $A = B$.

And then, the $HD(x_k, p)$ of the water quality assessment object X that belongs to

the grade p are weighted by the multi-index harmony degree calculation method, the calculation formula is as follows:

$$HD(p) = \sum_{k=1}^n \omega_k \times HD(x_k, p) \quad (3)$$

where $HD(p)$ is the comprehensive harmony degree of water quality assessment object X that belongs to the water quality grade p , and $HD(p) \in [0, 1]$; $HD(x_k, p)$ is a single index harmony degree of the index x_k corresponding to the water quality grade p , $HD(x_k, p) \in [0, 1]$; other parameters are as mentioned above.

According to the above steps, we can get an HD vector of the water quality assessment object X : $(HD(I), HD(II), HD(III), HD(IV), \text{ and } HD(V))$.

5) Results judgment and rationality analysis

From the previous set conditions and calculation processes, we can be certain that the comprehensive harmony degree in HD vector must meet the following relationship:

$$0 \leq HD(I) \leq HD(II) \leq HD(III) \leq HD(IV) \leq HD(V) \leq 1$$

Setting HD_0 as the judgment criteria value of the water quality assessment, this value can be obtained by the relevant regulations or artificial, $HD_0 \in [0, 1]$. Then, in accordance with the order from good to poor, that is p changes from I to V, and compare HD_0 with $HD(p)$, when it first showed up $HD(p) \geq HD_0$, then the grade p will be the final water quality grade of water sample X . It should be noted that the greater the HD_0 value, the more stringent the determination criteria. When $HD_0 = 1$, it indicates that the grade of the worst index in the assessment object X is the final grade of the water quality, that is equivalent to the single factor assessment; when $HD_0 = 0.9$, it indicates that it allows 10% of the indexes to be inferior to the p grade; when $HD_0 = 0.8$, it indicates that it allows 20% of the indexes to be inferior to the p grade. Therefore, the value of HD_0 is very flexible, combining with the purpose of assessment and the actual situation of the assessment object, it can be reasonably assigned, so that the assessment results obtained will be more truly satisfactory.

Application of the WQA-HDE

Index acquisition and representation of water quality assessment

In order to verify the utility of the proposed method WQA-HDE, the method is applied to assess the water quality of the Shaying River in China. The Shaying River is the largest tributary of the Huaihe River in China; it spans the middle of Henan province and the northwest of Anhui Province, a total length of 624 km, the basin area of 39,075.30 km², among them, the territory of Henan province basin area of 34,467.00 km², accounting for 88.21% of the total area of the basin, the territory of Anhui Province basin area of 4608.30 km², accounting for 11.79%. The Shaying River has significant characteristics of serious pollution, bigger watershed population density, highly degree industrialization, and multi-sluiques (Zuo and Li 2013).

The data used in this paper is the monitoring data that comes from seven monitoring sites of the Shaying River in China, from upstream to downstream, and the seven monitoring sites are located at Zhaopingtai, Baiguishan, Luohe, Zhoukou, Huaidianzha, Fuyang, and Yingshang. Figure 2 is a simplified map of the Shaying

River Basin, which mainly shows the monitoring sites of surface water quality. The top-right corner shows the Chinese Mainland on a smaller scale. One red flag on the map represents the geographical location of a monitoring site.

According to the actual situation of the water quality indexes, the assessment and analysis model is established based on nine quantitative parameters (DO, pH, TDS, NH₃-N, BOD₅, COD_{Mn}, COD_{Cr}, TP, and TN), which are the most important and basic indexes in surface water quality monitoring and inspecting. The water quality assessment standard reference to “surface water environment quality standard” (GB 3838-2002), and different water quality grade standards of each index are listed in Table 2.

Determination of weight

The method of determining weight is introduced at the WQA-HDE section in this paper, and taking into account the need to compare and analyze four methods of water quality assessment, in order to simplify the calculation and facilitate comparison, an equal weighted method is adopted.



Fig. 2 The Shaying River Basin map with monitoring sites

Table 2 Surface water environment quality standard (GB3838-2002)

Index	Rank				
	I	II	III	IV	V
DO(mg/L)≥	7.5	6	5	3	2
pH	6.5~8.5	6.5~8.5	6.5~8.5	>9 or ≤6	≥9 or ≤5
TDS(us/cm)≤	400	1000	1500	2000	2900
NH ₃ -N(mg/L)≤	0.15	0.5	1	1.5	2
BOD ₅ (mg/L)≤	3	3	4	6	10
COD _{Mn} (mg/L)≤	2	4	6	10	15
COD _{Cr} (mg/L)≤	15	15	20	30	40
TP(mg/L)≤	0.01	0.025	0.05	0.1	0.2
TN(mg/L)≤	0.2	0.5	1	1.5	2

Result and discussion

Process of WQA-HDE

According to the calculation procedures of WQA-HDE that are introduced in the WQA-HDE section, this new method is applied to comprehensively assess and visually monitor water quality of the Shaying River in China. We calculated the water quality of all the seven monitoring sites in the Shaying River, and the results are shown in Table 6. In order to make the application of the method more clear, and to reduce the length of the article, two monitoring sites located in the upper reaches of Shaying River were taken as examples (any sites is ok) to elaborate the practical application process and effect of the method. The detailed calculating steps of these two monitoring sites (Zhaopingtai and Baiguishan (2013.12.7)) are given as follows. The measured values of water quality indexes in two monitoring sites are shown in Table 3.

There are four calculation steps:

Step one: according to the water quality index values that are measured in the two monitoring sites (Zhaopingtai and Baiguishan), the classification

membership degree is divided in Table 2, and the membership degree matrixes will be obtained, as shown in Table 4.

Step two: using Eq. (1) to calculate the HD (x_k, p) of each indexes, here, we make the $i = 1, j = 0$ in Eq. (1), so the single index harmony degree matrix which composed of HD (x_k, p) is equal to the membership degree matrix.

Step three: using Eq. (3) and according to the equal weighted method, the comprehensive harmony degree HD(p) of each water sample that belongs to the water quality grade p will be obtained; it is also called HD vector, as shown in Table 5.

Step four: based on the calculation results of Table 5, the HD₀ value is set to determine the final water quality assessment results. From Table 5, we can see that the values of comprehensive harmony degree HD (p) in Zhaopingtai and Baiguishan increase gradually according to the water quality grade from good to poor; this is in full compliance with the relationship mentioned above. If set HD₀ = 1, then the water quality assessment results obtained by WQA-HDE method are that the water quality of Zhaopingtai is in grade III and

Table 3 Measured values of water quality indexes in Zhaopingtai and Baiguishan monitoring sites (2013.12.7) (mg/L)

Site	Time	DO	pH	TDS	NH ₃ -N	BOD ₅	COD _{Mn}	COD _{Cr}	TP	TN
Zhaopingtai	2013.12.7	10.88	8.45	317	0.2	2	0.97	10	0.016	0.93
Baiguishan	2013.12.7	11.65	8.37	815	0.48	2	1.97	10	0.024	1.56

Table 4 The membership degree matrixes of single index for water samples in Zhaopingtai and Baiguishan (2013.12.7)

Index	Zhaopingtai					Baiguishan				
	I	II	III	IV	V	I	II	III	IV	V
DO	1	1	1	1	1	1	1	1	1	1
pH	1	1	1	1	1	1	1	1	1	1
TDS	1	1	1	1	1	0	1	1	1	1
NH ₃ -N	0	1	1	1	1	0	1	1	1	1
BOD ₅	1	1	1	1	1	1	1	1	1	1
COD _{Mn}	1	1	1	1	1	1	1	1	1	1
COD _{Cr}	1	1	1	1	1	1	1	1	1	1
TP	0	1	1	1	1	0	1	1	1	1
TN	0	0	1	1	1	0	0	0	0	1

Baiguishan is in grade V; if set $HD_0 = 0.8$, the final results are Zhaopingtai is in grade II and Baiguishan is in grade II.

Result comparison analysis between several assessment methods

In order to compare the differences between the four methods, and reflect the advantages of the WQA-HDE method that are proposed in this paper, the water quality data of July 2013, December 2013, and July 2014 are employed to test the different methods (WQA-HDE, single factor assessment method, mean-type comprehensive index assessment method, and multi-level gray correlation assessment method) on the water quality assessment of seven monitoring sites in the Shaying River. The final results of each method are shown in Table 6, and it is important to note that the WQA-HDE method is just given the results when $HD_0 = 1$ and $HD_0 = 0.8$.

From the comparison results in Table 6, we can get the following conclusions:

- 1) When $HD_0 = 1$, the assessment results of WQA-HDE method are consistent with single factor

assessment method, and all follow the most severe “one vote and veto” judgment condition, which leads to the fact that the water quality of majority monitoring sites in the three groups of experiments are grade V, and the upstream is better than the downstream. So in this case, the WQA-HDE method is single factor assessment method. The single factor assessment method is often too “pessimistic,” and its result is the worst of all water quality assessment methods, because as long as one of the indexes is seriously polluted, regardless of the degree of pollution of other indexes, the result of water quality assessment will become very poor, and is greater deviation with actual water quality (Yang et al. 2015). In fact, the single factor assessment method only considered the impact of the most polluting assessment index on the result, the index which most seriously exceeded the standard played a decisive role in the whole assessment result, while the other indexes were weakened (Zeng et al. 2007). However, this method also has significant advantages, it is simple and clear, although the overall condition of water quality cannot be fully reflected, but the assessment results can directly reflect the exceeding

Table 5 Calculation results of vector value of comprehensive harmony degree $HD(p)$

Site	Time	Rank				
		I	II	III	IV	V
Zhaopingtai	2013.12.7	0.667	0.889	1.000	1.000	1.000
Baiguishan	2013.12.7	0.556	0.889	0.889	0.889	1.000

Table 6 Comparison of water quality assessment results between WQA-HDE method and other common methods

Site	Time	WQA-HDE		Single factor assessment	Mean-type comprehensive index assessment	Multi-level gray correlation assessment
		HD ₀ = 1	HD ₀ = 0.8			
Zhaopingtai	2013.7.12	III	II	III	II	II
Baiguishan	2013.7.12	V	III	V	II	II
Luohe	2013.7.12	V	IV	V	III	III
Zhoukou	2013.7.13	V	V	V	IV	III
Huaidian	2013.7.13	V	IV	V	IV	III
Fuyang	2013.7.13	V	V	V	IV	III
Yingshang	2013.7.13	V	IV	V	IV	III
Zhaopingtai	2013.12.7	III	II	III	II	II
Baiguishan	2013.12.7	V	II	V	II	II
Luohe	2013.12.7	V	III	V	III	II
Zhoukou	2013.12.8	V	V	V	V	III
Huaidian	2013.12.8	V	V	V	IV	III
Fuyang	2013.12.9	V	IV	V	III	III
Yingshang	2013.12.9	V	V	V	III	III
Zhaopingtai	2014.7.11	V	V	V	III	III
Baiguishan	2014.7.11	IV	III	IV	II	II
Luohe	2014.7.11	V	V	V	IV	III
Zhoukou	2014.7.12	V	V	V	III	III
Huaidian	2014.7.12	V	V	V	IV	III
Fuyang	2014.7.12	V	IV	V	III	III
Yingshang	2014.7.12	V	V	V	III	III

of the single indexes and clearly identify the major pollution indexes and their distribution areas (Zhang et al. 2011; Li et al. 2008). Therefore, the single factor assessment method is often used in general environmental assessment, especially in water quality assessment (Li et al. 2014), so this is also one of the significant advantages we have of the WQA-HDE method.

- 2) The results of the multi-level gray correlation method in the three groups of experiments are all in grade II or III. We all know that due to the uncertainty of the water quality classification boundaries, it is very difficult for the general method to consider the situation near the classification threshold. Small changes in the measured concentration values may lead to changes in the assessment results (Pius et al. 2012; Zhang and Si 2017). However, using the gray correlation method can solve this problem well, because it regards the status of water quality as a gray variable and the water quality grade as a gray

category, which makes the assessment result better than that of the traditional fuzzy assessment method which directly uses the maximum degree of subordination as the assessment result, and the result is continuous, so it can reflect the system status more accurately, especially suitable for the situation where the system status changes insignificantly (Ip et al. 2009; Liu et al. 2014). But this situation also leads to a disadvantage of this method; it has low identification for higher pollution water bodies (such as IV or V). The reason for this phenomenon is due to the fact that the multi-level gray correlation method has a defect of the potential to lose useful information, if there are most indexes in the assessment index system does not exceed the standard, but a small number of indexes exceeded larger, it will result in distortion, and the results of assessment tend to be homogenized (Liu et al. 1999). However, because of the significant difference in the water quality between the upstream and the

downstream of the Shaying River, so this method is obviously not suitable for water quality assessment of the Shaying River. But more satisfactorily, our proposed method WQA-HDE can solve this problem effectively by changing the value of HD_0 to adjust the degree of attention to the main influencing factors, so as to obtain a more satisfactory result. For example, if we set $HD_0 = 1$, it shows that the main influencing factor is very much concerned, even if only one index exceeds the standard, the overall water quality will be considered as poor; if we set $HD_0 = 0.8$, it shows that even if quarter of the indexes do not meet the standards, the water quality assessment results are also acceptable.

- 3) Compared with the WQA-HDE method of $HD_0 = 0.8$, it can be seen that the mean-type comprehensive index method and the WQA-HDE method ($HD_0 = 0.8$) both have higher identification ability for different grades of water quality, and the results are more consistent with the actual situation. In essence, the method of mean-type comprehensive index considers that water quality is affected by various factors, and is the result of interaction among all factors, and the water quality assessment is not affected by the number of indexes in the monitoring area (Lakshmi et al. 2018). However, because of the indexes that are averagely treated by this method, if there is a large difference between the index values of the sample, it is easy to cover up the serious pollutants that exceed the standard, thus weakening the ability to identify the serious pollution, and resulting in the grades of water quality assessment are better than the actual situation in general (Xue et al. 1999). From Table 6, we can see that the assessment results of the mean-type comprehensive index method basically do not have the V grade water quality, especially in the downstream, the water quality assessment results are much better than the actual situation. In addition, compared with traditional water quality assessment, the mean-type comprehensive index method combine multiple environmental parameters, it needs to calculate the exponent value for each index first, and then converts them into a single value reflecting the status of water quality (Debels et al. 2005; Lumb et al. 2011; Mohebbi et al. 2013; Sutadian et al. 2018). Therefore, the assessment process needs to be calculated several times, especially when there are more types of indexes, this method will be very

troublesome. In contrast, the assessment process of WQA-HDE method is very brief and easy to understand by the grass-roots service staffs, because the final assessment result only needs a simple comparison (between indexes and standards) and one time calculation, so WQA-HDE will be a worth promoting method of water quality assessment.

We can see from the actual situation of this case, WQA-HDE method ($HD_0 = 0.8$) overcomes the shortcomings of the above three methods, the assessment results are closer to reality, and more realistic and reliable. As can be seen, compared with the general comprehensive assessment method, WQA-HDE method has the following two significant advantages:

- 1) The WQA-HDE method not only conforms to the train of thought of the general comprehensive assessment method but also covers the single factor assessment method, in other words, the single factor assessment method is just a special case of WQA-HDE method. Therefore, it is clear that the WQA-HDE method is a new method that integrated the single factor assessment method and the comprehensive assessment method;
- 2) This method takes into account the characteristics of the ambiguity of assessment index, the ambiguity of standard, and the difference of weight; in addition, it can choose different judgment criteria (HD_0) to determine the assessment results based on the actual needs, which reflects the flexibility of judging the assessment results and the comprehensiveness of multiple indexes.

Conclusions

In the context of rapid urbanization, the water environment problem has gained more attention, and along with the continuous deepening and developing of the research on assessment methods, the water quality assessment methods are also constantly expanding and growing. Based on the previous research results of harmony theory, in this paper, we developed a new water quality assessment method (WQA-HDE) and applied it to quantitatively assess the grade of surface water quality. The calculation steps and process of this new method are discussed systematically, and the method together with

several major assessment methods are used to the water quality assessment of the Shaying River, which verify the effectiveness and feasibility of the proposed method.

From the perspective of the method itself, the WQA-HDE method has the characteristics of flexibility, and easy to calculate and master. Moreover, it also possesses a unique advantage of integrating the single factor assessment and the comprehensive assessment. From the perspective of the assessment results, the WQA-HDE method avoids the influence of the extreme situation and makes the result more in line with the actual situation by setting different judgment criteria (HD_0), these are the features that other methods do not have.

The WQA-HDE method proposed in this paper has been applied and verified only in water quality assessment, it is a promising monitoring approach for water quality control in the future, and its principle and thought can be used as a reference for other assessment methods, the authors will further study and explore the application of the method in other fields.

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