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RESEARCH ARTICLE

VFS-based OFSP model for groundwater pollution study of domestic waste landfill

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Abstract

The groundwater quality is essential for high quality of life and social development. Thus, the importance and necessity of the accurate and rigorous requirements for contaminated groundwater assessment has increasingly attracted engineers' and researchers' attentions. In order to improve the precision and robustness of the groundwater quality evaluation of domestic waste landfills, based on the variable fuzzy set (VFS) pair and the optimized N.L. Nemerow index, we develop an optimized fuzzy set pair (OFSP) model for groundwater quality assessment. Then, we devise the OFSP model by five key elements of optimized synthesis operator “C”, relative difference“u_i'”, connection degree“u_i”, optimized N.L. Nemerow index “P_i,” and pollution load ratio “J_i”, which can achieve the reasonable groundwater quality assessment model, the stable groundwater quality evaluation process, and the convincing evaluation results. Finally, a case study on groundwater quality assessment of various domestic landfills in China is conducted to explore the comprehensive impacts of domestic landfills in different regions and types on groundwater pollution from multiple perspectives, and demonstrate the effectiveness of the proposed OFSP model. The groundwater quality assessment results of various domestic landfills indicate that the pollution level of groundwater under unregulated domestic landfills in eastern and southern China is the worst. Based on the assessment results of groundwater quality, we compare the groundwater quality levels obtained by various mainstream methods. In line with precision (0.985), correlation (0.934), robustness (0.953), and rationality (0.946), our designed OFSP model has the best performance. In addition, according to the indexes of discrimination (0.217) and versatility (0.837), the designed OFSP model also has a good ability. Results of experiments well prove that the proposed OFSP model could play a good performance on groundwater quality evaluation in domestic landfills, compared with other mainstream models.

Keywords Groundwater pollution · Groundwater quality evaluation · OFSP model · Optimized N.L. Nemerow index · Multiple impact factor · Impact law

Introduction

Rapid urbanization has led to the migration of people from villages to cities, which generate thousands of tons of municipal solid waste (MSW) daily. After waste is disposed at landfills, it undergoes a number of physical, chemical, and microbiological changes that lead to the release of a toxic liquid known as leachate. The leachate will continuously migrate through the soil strata, eventually contaminating the groundwater system if no action is taken to prevent this phenomenon (Kanmani and Gandhimathi 2013; Liao et al. 2020). Contamination of groundwater from leachate is a potential environmental problem and needs to be addressed and many studies have been conducted (Locosselli et al. 2019; Molinos-Senante et al. 2015). Physicochemical analysis and indexing method are the most common in assessment the impact of a landfill on groundwater quality.

Physicochemical analysis is commonly used in assessment of the impact of a landfill on groundwater quality (Cumar and Nagaraja 2011; Zaharia and Suteu 2011; Grisey and Aleya 2016; Teta and Hikwa 2017; D Browska et al. 2018).

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Researchers can select specific physicochemical parameters to analyze according to the unique situation of study area, such as heavy metal concentration (Kanmani and Gandhimathi 2013; D Browska et al. 2018), pH (Zaharia and Suteu 2011; Grisey and Aleya 2016; Teta and Hikwa 2017), or chlorides (Cumar and Nagaraja 2011). However, the physicochemical analysis has two disadvantages. Firstly, it cannot analyze multiple inter-relationships among selected physicochemical parameters. Secondly, there is no unified index for selecting physicochemical parameters, which means the method lacks robustness and normalization. In order to explore inter-relationships among all the physicochemical parameters, some researchers conducted statistical analyses based on the physicochemical parameters (Biswas et al. 2010; Nagarajan et al. 2012; Mor et al. 2006; Smahi et al. 2013; Magda et al. 2014; Maitia et al. 2016; Nathan et al. 2018; Jeykumar and Chandran 2018; Cipranic et al. 2019; Aderemi et al. 2011). The main statistical analysis methods contain factor analysis and Person's correlation (Biswas et al. 2010; Maitia et al. 2016), correlation matrix for parameters, principal component analysis (PCA), descriptive statistics analysis and multivariate statistical analyses, etc. (Nagarajan et al. 2012; Mor et al. 2006; Aderemi et al. 2011; Smahi et al. 2013). The statistical analysis can easily explore the relation of different physicochemical parameters, but the lack of robustness and normalization still cannot be solved (Magda et al. 2014; Jeykumar and Chandran 2018; Nathan et al. 2018).

To make the assessment more robust and normal, many researchers used standard indices in assessing pollution impact of a landfill. Environmental indices such as the Water Quality Index (WQI) (Deshmukh and Aher 2016; Reymond et al. 2019), Nemerow index (expressed as “P_i”) (Krčmar et al. 2018; Kapelewska et al. 2019; Tenodi et al. 2020), and Leachate Pollution Index (LPI) (Rana et al. 2018; Han et al. 2016) have been developed to determine the extent of pollution. WQI is one of the simplest and widely used methods which can provide a comprehensive model of the groundwater quality and be used to transform large quantities of water quality data into a single number (Wang et al. 2013). To improve the effectiveness of assessing the negative impact of the pollution emitter on water quality, Nemerow index (P_i) was developed which is a comprehensive parameter based on national and international standards (Kapelewska et al. 2019). Leachate from landfill is one of the main pollutions on groundwater (Chonattu et al. 2016; Tenodi et al. 2020). In an effort to develop a method for comparing the leachate pollution potential of various landfill sites in a given geographical area, LPI was developed to represent the level of leachate contamination potential of a given landfill (Rana et al. 2018). In order to improve accuracy and reliability of assessment, some researchers combined two indices to assess the impact of leachate percolation on the groundwater quality (Singh et al. 2016; Rana et al. 2018; Krčmar et al. 2018; Kapelewska et al. 2019; Tenodi et al. 2020). However, with the improvement of reliability, assessment complex was also raised.

In addition to the WQI, PI, and LPI, many groundwater quality assessment methods can be used in assessment of the impact of a landfill on groundwater quality. EWQI, NSFWQI, VFEM, FSEVFS, ICAUCA, and VFSPA have been widely used in groundwater assessment but less used in assessing the impact of leachate on the groundwater quality (Wu et al. 2020; Ocampoduque et al. 2006; Vasanthavigar et al. 2010; Mohebbi et al. 2013; Hoseinzadeh et al. 2015; Xi Chen and Wang 2019). Besides, few above efforts have been made for optimizing both the double judgment approach and the “P_i” equation of N.L. Nemerow index for improving assessment accuracy. With the improvement of accurate and rigorous requirements for groundwater pollution research, practitioners and researchers have not only paid more attention to the regional and complex characteristics of groundwater in various domestic landfills, but also put more efforts into a great deal of the perspective of study area location, domestic landfill type, and the dimension of groundwater pollution component.

Hence, this study includes two main objectives. The first main goal of this study is to develop a new model of optimized fuzzy set pair (OFSP) according to variable fuzzy set (VFS) pair and optimized N.L. Nemerow index for accurate and rigorous evaluation of groundwater under domestic landfills (Shuang et al. 2016;Wang et al. 2011;Zou et al. 2006), and devise the OFSP model by five key elements of optimized synthesis operator “C,” relative difference“u_i',” connection degree“u_i, ” optimized N.L. Nemerow index “P_i,” and pollution load ratio “J_i”, so as to achieve the reasonable groundwater quality assessment model, the stable groundwater quality evaluation process, and the convincing groundwater quality evaluation results. The second main purpose of this study is to compare the performance of OFSP model with some mainstream models by their assessment results of groundwater quality to various domestic waste landfills in China.

Study area

In this section, we elaborate the natural characteristics of the study area including the local soil conditions, geography, climate, and hydrogeological setting, to obtain more rigorous research results of groundwater quality assessment in domestic waste landfills.

Based on the Report on the National General Survey of Soil Contamination published by the Ministry of L and Resources of the People's Republic of China in 2014, the state of soil environment across the country is not optimistic (National Bulletin on Soil Pollution Status 2014). The country's total soil over-standard rate was 16.1%, of which the proportions of slightly, lightly, moderately, and severely polluted points were 11.2%, 2.3%, 1.5%, and 1.1% respectively. Inorganic pollution is the main type of pollution, followed by organic pollution. The level of inorganic pollutants exceeding standard points accounts for 82.8% of all exceeding standard points, in which eight kinds of inorganic pollutants containing cadmium, mercury, arsenic, copper, lead, chromium, zinc, and nickel exceed the standard rates 7.0%, 1.6%, 2.7%, 2.1%, 1.5%, 1.1%, 0.9%, and 4.8%. In terms of pollution distribution, soil pollution in the South is more serious than that in the North.

China located in the eastern part of Asia and on the west coast of the Pacific Ocean is selected for this study (Jingyun et al. 2018; Chen et al. 2019). The land area is about 9.6 million square kilometers. The terrain characteristic, which is high in the west and low in the east, is descended in three ladders. The geographic location of it is shown in Fig. 1. The mountains, plateaus, and hills account for about 67% of the land area, and basins and plains account for about 33% of the land area (Zheng et al. 2015). Western China has the largest Qinghai-Tibet Plateau in the world, with an average elevation of over 4,000 m. The terrain is high, and the snowy mountain glaciers are large in size, which is called the first ladder of China’s topography. The eastern and northern parts of the Qinghai-Tibet Plateau are the second ladder of China’s topography. It includes areas such as Inner Mongolia, Xinjiang, Loess Plateau, Sichuan Basin, and Yunnan-Guizhou Plateau, with an average elevation of 1000–2000 m. In the region, there are many grasslands, Gobi, deserts, plateaus, and the surface, which are covered with deep loess. Their surface is broken, the vegetation is small, the soil and water loss are serious, the terrain is rugged, and the limestone is widely distributed. The rest of the area is known as the third ladder of China’s topography, which is mostly plains and hills. It ranges from east to the coastline. That terrain has dropped to between 500 and 1000 m. From the north to the south, the northeast plain, the North China Plain, and the middle and lower reaches of the Yangtze River are distributed. The region is rich in soil, and abundant in rain, and the river network is the most important farming area in China. And the hilly areas of the third ladder of China’s topography are generally densely forested and rich in minerals.

The monsoon climate in China is very significant, most of China being affected by the monsoon climate (Fang et al. 2015; Jingyun et al. 2018). And most of the inland areas north of 40° N are temperate continental climate. The precipitation in these areas is sparse, and the annual precipitation is between 300 and 500 mm. The temperature varies greatly between different times of the day as well by year. The northwestern region is a temperate continental climate with cold winters and hot summers with less precipitation. The southwest region belongs to the plateau mountain climate. The average daily temperature is lower than 10 °C, and the hottest temperature is lower than 5 °C, even lower than 0 °C. Different from the year, the temperature varies greatly between different times of the day, but the solar radiation is strong and the sunshine is sufficient. The North China region is a temperate monsoon climate with high temperatures and rains in summer and cold and dry winters. The coldest month average temperature is − 28–0 °C, and the average summer temperature is about 22 °C. Central China has a temperate monsoon climate and a subtropical monsoon climate. The rainfall is concentrated in the summer and there is often heavy snow in the north of the winter. Generally, the climate is mild, the heat is sufficient, the precipitation is concentrated, the spring temperature is changeable, the summer and autumn are dry, the cold period is short, and the heat cycle is long. East China and most of the regions in South China have subtropical monsoon climates, with high temperatures and rains in summer and low temperatures and low rainfall in winter. That is a transition zone between the subtropical zone and the temperate zone. The temperature in summer is quite high and the temperature in winter is quite low. Hainan Island, the southern part of Taiwan Island, the Leizhou Peninsula, and Xishuangbanna belong to the tropical monsoon climate. The average temperature of the coldest month is not lower than 15 °C, and the annual minimum temperature is not less than 5 °C on average, and there is no frost all year round.

China has a vast territory, and the geologic, climate, and hydrogeological setting features of different regions vary greatly (Chen et al. 2019). As a whole, it shows that the southern region has developed water systems and abundant rainfall, while the northern region is cold and dry with less rain. The groundwater quality is closely related to multiple factors such as geography, geomorphology, climate, and hydrology. Therefore, the selection of the sampling area in this study should consider multiple factors including geomorphology, climate, and hydrology to reflect the representativeness and comprehensiveness of the collected samples, and finally ensure the rationality and authority of the research results. The sample collection points (locations) of this study area (Fig. 1) are shown as follows.

As we know, groundwater is widely used in China’s domestic water, agricultural irrigation, and industrial production. It is closely related to people’s life and production. It is also directly related to the high-quality development of the national economy and its positive contribution to world economic security and stability. In recent years, due to problems such as chemical pollution of domestic waste landfill, the quality of groundwater has been seriously affected. Therefore, excavating the impact of domestic waste landfill on groundwater quality and clarifying the relationship between the two are necessary and important for regulating waste sorting and targeted treatment of groundwater. In order to obtain convincing research results, in this study, we randomly collect the various representative domestic landfills of China as groundwater sample collection points (Table 1) to select sample data

Fig. 1 Geographic location of domestic waste landfills

to fully reflect the overall situation of groundwater quality under domestic waste landfills in China. By collecting the groundwater quality samples in monitoring well, dive well, or agricultural irrigation well, etc. from different regions in China, and testing the collected samples with standardized and uniform precision, the sample data that meet the requirements of this study can be obtained.

Materials and methods

Sample collection and preparation

Based on the data collection method and detailed process above, for the selected research areas such as "Asowei$^{\#}$," "Shandong Yidi$^{\#}$, and "Fuxin city landfill," we collect the corresponding measured data of groundwater pollution components under domestic waste landfills (Table 2) such as "MPN," "CFU," and "NH_3–N," respectively (Wu et al. 2020; Xi Chen and Wang 2019; Ocampoduque et al. 2006; Vasanthavigar et al. 2010; Mohebbi et al. 2013; Hoseinzadeh et al. 2015). For example, the measured values of "MPN," "CFU," "NH_3–N," "As," "Hg," "Na," "$CaCO_3$," "COD," "Mn," and "Pb" of Asowei$^{\#}$ are 7.212, 8.339, 10.887, 8.359, 10.126, 12.338, 5.562, 15.347, 9.935, and 14.551, respectively. In the same way, all relevant measured values of groundwater pollution components in the study are present in the table below.

Development of approach

Variable fuzzy set

To evaluate groundwater quality, the basic operational principles of variable fuzzy set (called VFS), which is a necessary part of optimized fuzzy set pair (OFSP) model, is required in this paper (Wang et al. 2011; Xu et al. 2015; Li et al. 2020). And the unstandardized relative membership variable (u_i') of

Table 1 Background of regulated and unregulated domestic landfills

Serial number	Sampling city	Sampling location	Location situation	Landfill period
1	Beijing	Asowei#, Anding#, Beishenshu, Liulitun, Gaoantun, Jiaojiapo, etc. (1–6)	Monitoring well	33~40
2	Beijing	Chaoyang District#/Daxing District/Fengtai District (7–9)	Monitoring well, dive well	30~36
3	Beijing	A domestic waste landfill# (10)	The fourth porosity dive water	20~27
4	Beijing	A landfill# (11)	Monitoring well	19
5	Shenyang	Heping District: Shandong Yidi#, Huanggu District: Shenyang Medical College#, Shenhe District: Stadium#, Huanggu District Light Industry Machinery Plant#, Shenhe Residential Company#, Garbage Dumping Site#, etc. (12–17)	Well, *h*=12~25 m	37~44
6	Shenyang	Dadong District North: Paoziyan, Yuhong District: Stadium, Dongling District: Wanghua, Tiexi District: Yuhong Examination Site, Dadong District: Battery Plant, etc. (18–22)	Well, *h*=17~26 m	40~65
7	Shenyang	Rubbish storage yard (23)	Monitoring well	34~51
8	Fuxin.liaoning	Fuxin city landfill (24)	Monitoring well	28
9	Liaoning	The harmless treatment domestic garbage landfill in downtown area# (25)	Monitoring well	22
10	Harbin	Chengjiagang garbage dump (26)	Well, *h* = 18~70 m; Manual digging, *h*= 2 m	28
11	Shijiazhuang	Taitou garbage dump(27)	*h*>40 m	27
12	Shijiazhuang	A domestic waste landfill# (28)	Monitoring well and agricultural irrigation well	20
13	Huabei	Non-standard landfill (29)	Well, divewater	31
14	Tangshang. Hebei	A landfill# (30)	Monitoring well/water well/use well/borehole, divewater, *h*=30 m	31
15	Tangshang. Hebei	A domestic waste landfill# (31)	*h* = 14 m	31

"#" represents regulated landfill (garbage dump). Due to space limitations, only parts of the sample collection points are shown

variable fuzzy set, which is not affected by assessment system error, is crucial for assessment of groundwater quality in domestic waste landfills (Chen et al. 2012;Yan et al. 2016). Therefore, a key equation of $u_i^{'}$ of variable fuzzy set is constructed as follows.

The assumption is that the number of both groundwater pollution assessment indexes and assessment levels are "*t*" and "*n*," respectively. Hence, the "$u_i^{'}$ " equation (Eq. 1) and its sub-equations (Eqs. 2 and 3) of VFS for groundwater quality assessment of OFSP are respectively expressed below.

$$u_i^{'} = {}^{1}\Big/_{\left[1+\left({}^{d_{hg}}/_{d_{hb}}\right)^{\alpha}\right]}; \mathrm{i} = \mathrm{h} \tag{1}$$

$$d_{hg} = \left\{\sum_{i=1}^{t}\left[w_i\left(1-\mu_{\underset{A}{\sim}}(u_{ih})\right)\right]^{p}\right\}^{1/p} \tag{2}$$

$$d_{hb} = \sum_{i=1}^{t}\left[\mu_{\underset{A}{\sim}} w_i-(u_{ih})^{p}\right]^{1/p} \tag{3}$$

where "α," "*p*," and "*h*" respectively represent various parameter, and "w_i" represents the corresponding weight of the *i*th evaluation metrics.

In addition, the location map is also crucial for assessment of groundwater quality in domestic waste landfill. It is easy to find that the location map, which is demonstrated in Fig. 2, could intuitively reflect the attraction and exclusion domains of the VFS of groundwater pollution assessment.

Based on the location map, whether the point of "*x*" is to the left or right of "*M*" in the *X* interval, the value of $D_{\underset{A}{\sim}}(u)$ can be obtained by the following equations (Eqs. 4 and 5).

$$D_{\underset{A}{\sim}}(u) = \left(\frac{x-a}{M-a}\right)^{\beta}, x\in[a, M]; D_{\underset{A}{\sim}}(u) = \left(\frac{x-a}{c-a}\right)^{\beta}, x\in[c, a] \tag{4}$$

$$D_{\underset{A}{\sim}}(u) = \left(\frac{x-b}{M-b}\right)^{\beta}, x\in[M, b]; D_{\underset{A}{\sim}}(u) = -\left(\frac{x-b}{d-b}\right)^{\beta}, x\in[b, d] \tag{5}$$

where "β" represents the non-negative parameter.

Set pair analysis

For the aim of the OFSP model is to optimize groundwater assessment, set pair analysis devotes the connection degree matrix of "*Q*" to the calculation of "P_i" of groundwater quality in various domestic waste landfills of China (Chen et al. 2012; Wang et al. 2013). The main steps of employing set pair analysis (SPA) to determine the connection degree matrix of "*Q*" are formed in the following manner.

Table 2 The measured values of groundwater pollution components

Sampling landfill	Sampling city	MPN (mg/L^{-2})	CFU (mg/L^{-3})	NH_3–N (mg/L^{-1})	As (mg/L^{-3})	Hg (mg/L^{-5})	Na (mg/L^{-1})	$CaCO_3$ (mg/L^{-2})	COD	Mn (mg/L^{-2})	Pb (mg/L^{-2})
Asowei$^{\#}$	Beijing	7.212	8.339	10.887	8.359	10.126	12.338	5.562	15.347	9.935	14.551
Daxing District	Beijing	8.357	6.235	11.245	22.562	12.347	11.451	5.469	30.468	13.465	15.420
Heping District: Shandong Yidi$^{\#}$	Shenyang	7.834	5.456	7.893	6.537	8.563	13.773	5.328	16.417	8.922	9.658
Dadong District North: Paoziyan	Shenyang	8.337	7.435	8.743	16.459	8.234	12.457	5.467	26.853	13.112	10.673
Rubbish storage yard	Shenyang	8.468	9.036	7.896	24.565	7.581	12.567	6.531	30.017	13.376	11.302
Fengcun village garbage dump	Zhanjiang. Guangdong	13.276	13.158	13.772	34.258	17.315	11.544	4.012	29.869	14.528	18.774
A domestic waste landfill$^{\#}$	Nanning	14.027	10.579	10.027	13.572	10.427	14.396	4.005	17.676	9.803	12.534

The unit is “mg/L.” The dimension of mg/L^{-2} is “mg/L×10^{-2}”. Due to space limitations, only parts of the measured values of groundwater pollution components are shown

Solution steps of SPA

Step 1: Design a new equation of “$u_{P_n-Q_m}$,” in which the number of logic category is increased to k+2. The structure of the equation is constructed as follows.

$$u_{P_n-Q_m} = \sum_{n=1}^{L} w_n a_n + \sum_{t=1}^{K}\sum_{n=1}^{L} w_n b_{n,t} i_t + \sum_{n=1}^{L} w_n c_n j \qquad (6)$$

where b_t =1, 2, …, k.

Step 2: With the help of a measurement schematic chart (Fig. 3), the result of “u_{ik}” can be computed by the following function equation.

The equation (Eq. 7) of function relationship between the measure metric “a” and the connection are written as follows.

$$u_{ik} = 1-|\cos a_{ik}| = 1-\left|\frac{S_{ik}-x_i}{\sqrt{1+(x_i-S_{ik})^2}}\right| \qquad (7)$$

Note that “k” is the grade; “a_{ik}” is the angle of the metric “i”; “x_i” is actual measured result; “S_{ik}” is one of criterion values.

Step 3: Devise the connection degree matrix of “Q” for groundwater quality in various domestic landfills. The connection degree matrix of “Q” is consisted by the connection degrees of “u,” which include the connection degree values of p grades corresponding to n evaluation indexes of groundwater samples. The corresponding matrix of “Q” (Eq. 8) is displayed below.

Fig. 2 Location map

$$Q = [u_{ik}]_{n\times p} = \begin{bmatrix} u_{11} & u_{12} & \dots & u_{1p} \\ u_{21} & u_{21} & \dots & u_{2p} \\ \dots & \dots & \dots & \dots \\ u_{n1} & u_{n2} & \dots & u_{np} \end{bmatrix} \qquad (8)$$

Optimized assignment of weights

Game theory, which is one of the measure to optimizing the weight assignment, has been adopted to determine “w” of each metric to acquire the equilibrium weight in this paper (Amiri et al. 2014). Thus, the game theory is used to compute the weights assignment of various metrics by optimized assignment of weights (OAW).

For the purpose of objective assessment to groundwater quality of domestic waste landfills, OAW dedicates the optimized assignment method, which can reasonably assign weight to each assessment index, to OFSP. According to the calculation of OAW, the corresponding equilibrium weights of various evaluation metrics can be obtained. The core algorithm of OAW to calculate weights are constructed (Algorithm 1) as follows.

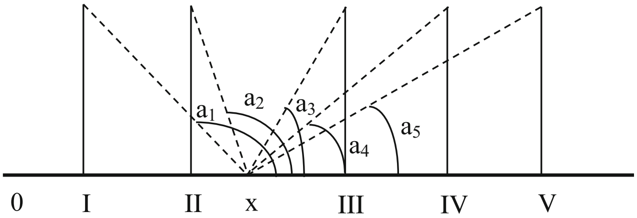


Fig. 3 The measurement schematic chart

Algorithm 1 OAW for equilibrium weight

Step 1: Compute the metrics weights of w^1using the following equation of entropy model.

$$w^1 = \frac{1-f_k}{\sum_{k=1}^{m}(1-f_k)} \tag{9}$$

Step 2: Calculate the metrics weights of w^2 by the equation (10) of AHP model.

$$w^2 = \sum_{i=1}^{m} w_i w_{ij} \tag{10}$$

Step 3: Regulate the results of *"w^1"* and *"w^2"*obtained by Step 1and Step 2, individually.

$$\mathrm{w}_1 = \{\mathrm{w}_{11}, \mathrm{w}_{12}, \dots, \mathrm{w}_{1m}\};\ \mathrm{w}_2=\{\mathrm{w}_{21},\ \mathrm{w}_{22}, \dots, \mathrm{w}_{2m}\}$$

Then, the metrics weight form of w could be achieved by randomly linear combination of some weight vectors from "m" groups (Formula 11).

$$\mathrm{w} = \sum_{i=1}^{m} \alpha_i w_i^T \quad ; \quad \alpha_i > 0 \tag{11}$$

where "α_i" is the corresponding coefficient, and "m" is the groups of methods of determine indicator weight.

Step 4: Optimize the i linear combination coefficients "α_i" to minimize the deviation between "w_i" and each various basic weight "w_j" through formula (12). The corresponding formula of that is presented as follows.

$$\min \left\| \sum_{i=1}^{m} \alpha_i {w_i}^T - {w_j}^T \right\|_2 \quad ; \ j = 1,2, \dots, m. \tag{12}$$

Step 5: Based on the differential properties of correlation matrix (Formula 13), we get the optimal conditions for solving the first derivative. Then, we use the following formula to compute the results of "$\alpha_1, \alpha_2, \dots, \alpha_m$".

$$\begin{bmatrix} w_1 {w_1}^T & w_1 {w_2}^T & \cdots & w_1 {w_m}^T \\ w_2 {w_1}^T & w_2 {w_2}^T & \cdots & w_2 {w_m}^T \\ \cdots & \cdots & \cdots & \cdots \\ w_m {w_1}^T & w_m {w_2}^T & \cdots & w_m {w_m}^T \end{bmatrix} \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \cdots \\ \alpha_m \end{bmatrix} = \begin{bmatrix} w_1 {w_1}^T \\ w_2 {w_2}^T \\ \cdots \\ w_m {w_m}^T \end{bmatrix} \tag{13}$$

Step 6: Normalize the coefficients of α_i, and then substitute them into the above formula (11) to obtain the optimal equilibrium weight of w.

Note that, w^1represents the objective weight of the evaluation index; w^2represents the subjective weight; and "w" represents equilibrium weight.

Optimized N.L. Nemerow index

In the following, this study designs an optimized N.L. Nemerow index to form the mathematics equation of “$P_i=\sqrt{a\left(\overline{P}^2_{\max 1}+\overline{P}^2_{\max 2}+\overline{P}^2_{\max 3}+\overline{P}^2_{\max 4}+\overline{P}^2\right)}$”, so as to make OFSP more balanced and robust for asseement of contaminated groundwater quality (Yan et al. 2014; Xu et al. 2015; Nambiar et al. 2020).

Groundwater pollution study of regulated and unregulated domestic waste landfills is closely related to the drinking water safety of groundwater. Therefore, the evaluation of groundwater quality of domestic waste landfill is very important, and performance metrics requirements such as accuracy and stability of the evaluation are very high. This study considers the diversity of groundwater pollution components under domestic waste landfill, and their different levels of pollution and efficiency for groundwater, so, it is necessary to create a novel groundwater quality assessment method to reflect the actual effect of various chemical elements on groundwater pollution. For example, the pollution components including “Hg,” “As,” and “Pb,” which have a great impact on water quality, are not reasonable to use only their weights to indicate the pollution effect.

Based on the N.L. Nemerow index idea (Eq. 14) and the equilibrium idea of synthetic operator (Eq. 16), this study develops the method of N.L. Nemerow index (Xu et al. 2015; Wu et al. 2018).

$$p=\sqrt{\left(P^2_{\max}+\overline{P}^2\right)/2} \tag{14}$$

$$P_i=\frac{c_i}{s_{ij}};i=1,2,\ldots,n;j=1,2,\ldots,m \tag{15}$$

$$b_j=\bigvee_{i=1}^{m}\left(a_i\cdot r_{ij}\right)=\max_{1\le i\le m}\left\{a_i\cdot r_{ij}\right\},i=1,2\ldots n \tag{16}$$

where Eq. 16 uses the method of basic real multiplication.

By analyzing the principle of the above formula for groundwater assessment, it can be seen that Formula 14 over-emphasizes the impact of the maximum pollution factor on water pollution, and does not highlight the pollution effects of other heavily polluted chemical elements. Therefore, in order to balance the actual effect of each chemical element and approximate the real pollution effect, this study devises OFSP for assessment of contaminated groundwater quality. The innovatives and improvements of the OFSP are carried out below: (1) Add 3 variable parameters, such as $\overline{P}^2_{\max 2}$, $\overline{P}^2_{\max 3}$ *and* $\overline{P}^2_{\max 4}$, so as to highlight the large actual pollution effect of the heavily polluted elements while taking into account the comprehensive calculation of multiple variable indicators; (2) employ $\overline{P}^2_{\max}$ instead of $P^2_{\max}$ to restore and highlight the actual pollution effect of the heavy pollution elements as much as possible; (3) compute the arithmetic mean of P_i with $P_{\max 1}$, $P_{\max 2}$, $P_{\max 3}$, and $P_{\max 4}$, respectively, so that the conversion values of $\overline{P}^2_{\max 1}$, $\overline{P}^2_{\max 2}$, $\overline{P}^2_{\max 3}$, and $\overline{P}^2_{\max 4}$ are achieved.

Based on the above ideas and method improvements, the mathematics equation (Eq. 17) of OFSP is obtained as follows.

$$p=\sqrt{a\left(\overline{P}^2_{\max 1}+\overline{P}^2_{\max 2}+\overline{P}^2_{\max 3}+\overline{P}^2_{\max 4}+\overline{P}^2\right)}$$
$$;P_i=\frac{c_i}{s_{ij}}\ ;\mathrm{i}=1,2,\ldots,\mathrm{n};\mathrm{j}=1,2,\ldots,\mathrm{m};a=\frac{1}{k+1} \tag{17}$$

where “C,” “S,” and “$\overline{\mathrm{P}}$ ” represent measured element concentration, criterion element concentration, and mean, respectively. $\overline{\mathrm{P}}$max1 is the mean of P_i and $P_{\max 1}$; “k” is the number of values of the maximum first k-bit weighting factors.

It is not difficult to find that our designed OFSP compensates for the disadvantages such as the invalidation of the weight of contaminated pollution components and the distortion of the information of contaminated pollution components in the groundwater assessment. The weight of each pollution factor in water quality evaluation was further weighed, and the effect of the largest amount of pollution factors on groundwater quality was diluted. It shows the significant advantages of balance and robustness.

OFSP model

In this section, based on the theory of variable fuzzy set pair and optimized N.L. Nemerow index (Wu et al. 2018; Su et al. 2009), we develop an optimized fuzzy set pair (OFSP) model for groundwater quality assessment of domestic waste landfill. The OFSP consists of seven specific operation steps, the advantages and reasons for improvement of each operation link, which are explained in Algorithm 2.

In order to achieve the reasonable assessment model, the stable experimental process, and the convincing experiment results, we devise the OFSP model by five key elements of optimized synthesis operator “C,” relative difference“u_i',” connection degree “u_i, ” optimized N.L. Nemerow index “P_i,” and pollution load ratio “J_i” (Dadzie 2020; Yan et al. 2014; Su et al. 2009). The core algorithm of optimized fuzzy set pair model is compiled below.

Algorithm 2 OFSP core algorithm

Step 1: Based on the mode of optimized synthesis operator, the equation of "C" can be written as:

$$C = W \otimes Q$$

$$= \begin{bmatrix} w_1, & w_2, & ..., & w_m \end{bmatrix} \otimes \begin{bmatrix} u'_{11} & u'_{12} & \dots & u'_{1p} \\ u'_{21} & u'_{21} & \dots & u'_{2p} \\ \dots & \dots & \dots & \dots \\ u'_{n1} & u'_{n2} & \dots & u'_{np} \end{bmatrix} \qquad (18)$$

This study proposes the equation of "C" in the OFSP algorithm. The devised "C" breaks through the limitations of traditional synthesis algorithms, which improves the pertinence and accuracy of groundwater quality assessmentin domestic waste landfill.

Step 2: According to the relative difference"u_i'", the connection degree"u_i"are obtained using the following equation.

$$\mathrm{u}_i = \alpha_i u_i' = \alpha_i \, {}^{1}\Big/_{[1 + ({}^{d_{ig}}/_{d_{ib}})^{\alpha}]} \qquad (19)$$

where "α_i" represent various parameters of assessment levels.

To further improve the accuracy of the groundwater pollution assessment of the domestic waste landfill, this study replaces the corresponding level of "u_i'" with "u_i" to devise an optimized variable fuzzy set.

Step 3: The formula (20) is achieved by replacing the relative difference"u_i'"with the connection degree"u_i"and substituting it into formula (18). The corresponding formula can be constructed as follows.

$$C = \begin{bmatrix} w_1, & w_2, & ..., & w_m \end{bmatrix} \otimes \begin{bmatrix} u_{11} & u_{12} & \dots & u_{1p} \\ u_{21} & u_{21} & \dots & u_{2p} \\ \dots & \dots & \dots & \dots \\ u_{n1} & u_{n2} & \dots & u_{np} \end{bmatrix}$$

$$= \begin{bmatrix} w_1 u_{11} & w_1 u_{12} & \dots & w_1 u_{1p} \\ w_2 u_{21} & w_2 u_{21} & \dots & w_2 u_{2p} \\ \dots & \dots & \dots & \dots \\ w_n u_{n1} & w_n u_{n2} & \dots & w_n u_{np} \end{bmatrix}$$

$$= \begin{bmatrix} P_{11} & P_{12} & \dots & P_{1p} \\ P_{21} & P_{21} & \dots & P_{2p} \\ \dots & \dots & \dots & \dots \\ P_{n1} & P_{n2} & \dots & P_{np} \end{bmatrix} \qquad (20)$$

Step 4: In light with the optimized N.L. Nemerow idea, let:

$$C = (p_1, p_2, ..., p_p) \; = \; (\sqrt{a\left(\bar{P}^2_{1max1} + \bar{P}^2_{1max2} + \bar{P}^2_{1max3} + \bar{P}^2_{1max4} + \bar{P}_1{}^2\right)}, \qquad (21)$$

$$\sqrt{a\left(\bar{P}_{2max1}^2+\bar{P}_{2max2}^2+\bar{P}_{2max3}^2+\bar{P}_{2max4}^2+\bar{P}_2{}^2\right)},\ldots,$$

$$\sqrt{a\left(\bar{P}_{pmax1}^2+\bar{P}_{pmax2}^2+\bar{P}_{pmax3}^2+\bar{P}_{pmax4}^2+\bar{P}_p^2\right)}\ \ );$$

Where, i = 1, 2, …, p. The variable of P_{imax1}, P_{imax2}, P_{imax3} and P_{imax4} respectively denote four P_i values of the highest weight contaminants in P_{1i}, P_{2i}, …, P_{ni}.

Then, the all optimized N.L. Nemerow indexes (P_i) are computed according to the above formula. In the following, based on maximum connection principle, it can be obtained that p_j= max (p_1, p_2, …, p_p). Then, the remaining operation model of groundwater quality level assessment method is expressed as follows (Step 5-6).

Step 5: M_j can be determined by the calculation result of M_{ik}. By establishing the relationship between "u_{ik}" and "a" in the figure.2, the equation of M_{ik} can be achieved as follows.

$$M_{ik}=\begin{cases}u_{ik};\ a\geq 90°\\-u_{ik};\ a<90°\end{cases}\qquad(22)$$

where "a" is the angle produced by the corresponding value of "u_{ik}"in the figure.

Step 6: Calculated by equation (23), the value of "M_j" is obtained below:

$$M_j=\sum_{i=1}^{n}w_iM_{ij},\qquad(23)$$

Then, according to the result of "M_j", the pollution level "j" (or "j+1") is judged. The judgment method of pollution class, which is called "the double judgment, is established as follows.

$$\text{Class}=\begin{cases}j;\ \ \text{Mj}<0\\ \text{j}+1;\ \text{Mj}>0\end{cases}\qquad(24)$$

Step 7: In accordance with the calculation result of "P_i" and according to formula (25), the pollution load ratio "J_i" of various types of contaminants can be obtained. If J_i>70%, it is usually called the main contaminant.

$$J_i={}^{Pi}\!/_{\sum_{i=1}^{n}Pi}\qquad(25)$$

Note that, according to the needs of different perspectives analysis in this study, the "P_i" value in step 7 can be replaced by different variables such as the pollution detection value or the number of pollution levels.

It is noted that compared with the single judgment principle of "p_j," the proposed algorithm adds a sub-algorithm of the double judgment to evaluate the groundwater quality, so as not to reduce the accuracy of the assessment level.

The research proposes a novel OFSP groundwater assessment model by improving some basic theories such as variable fuzzy sets model, set pair analysis theory, entropy method, Nemerow index method, and cumulative pollution load

Table 3 Assessment metrics and level criteria of groundwater

Serial number	Metrics/Contamination	"I"	"II"	"III"	"IV"	"V"
1	MPN	≤30	≤30	≤30	≤1000	>1000
2	CFU	≤1000	≤1000	≤1000	≤10000	>10000
3	TP	≤0.02	≤0.1	≤0.2	≤0.3	≤0.4
4	NH_3-N	≤0.15	≤0.5	≤1	≤1.5	≤2
5	Pb	≤0.01	≤0.05	≤0.20	≤0.50	≤0.50
6	As	≤0.001	≤0.001	≤0.01	≤0.05	≤0.05
7	$CaCO_3$	≤150	≤300	≤450	≤650	>650
8	Hg	≤0.0001	≤0.0001	≤0.0001	≤0.0002	>0.0002
9	TDS	≤300	≤600	≤1000	≤1500	>1500
10	C_7H_8	≤0.5	≤140	≤700	≤1400	>1400

The unit of "1-17" is "mg/L." The unit of "18-21" is μg/L. Only parts of assessment metrics of groundwater pollution components are shown

ratio method (Wang et al. 2011; Li 2020; Chen et al. 2012; Wang et al. 2013; Amiri et al. 2014; Yan et al. 2014; Xu et al. 2015; Nambiar et al. 2020; Wu et al. 2018). Firstly, based on the characteristics and assessment requirements of groundwater pollution in the north and south of China, we improve the calculation method of the variable fuzzy set. Secondly, using the refined evaluation index and evaluation grade in the improved variable fuzzy set module to calculate the raw data, we get the result of the comprehensive relative membership degree ($u_i^{'}$) of IVFS. Thirdly, integrating the sub-modules of optimized set pair analysis model, we calculate the connection degree matrix $\underline{Q}$ with the optimized set pair analysis module. Fourthly, based on the game theory, we create an optimized weight assignment method, which determine balance weight "*w*" corresponding the value of each measurement parameter. Fifth, we propose the optimized Nemerow index method, and develop an improved algorithm and its function corresponding to the optimized Nemerow index method, which is as follows: $P_i = \sqrt{a\left(\overline{P}^2_{\max1}+\overline{P}^2_{\max2}+\overline{P}^2_{\max3}+\overline{P}^2_{\max4}+\overline{P}^2\right)}$. Finally, based on the ideas of traditional cumulative pollution load index, we propose an improved cumulative pollution load ratio method module. By logically fusing the above theoretical methods and their corresponding sub-modules, combined with the comprehensive fuzzy operator "C," relative difference degree "$u_i^{'}$," relative connection degree "u_i," Nemerow index value "P_i," and cumulative pollution load ratio "J_i" and other core elements, we achieve accurate assessment and classification analysis on regional groundwater pollution status, significantly improving the accuracy of pollution evaluation and other multiple performance. In addition, using randomly collected groundwater quality data in China, we compare our method with some state-of-art groundwater pollution assessment models such as IVFSPA, PCA, and ICAUCA to test the assessment performance of OFSP. Based on the numerical results of performance indicators from the perspectives of accuracy, relevance, stability, and rationality, it can fully prove that the proposed OFSP evaluation model performs the best. At the same time, based on the numerical results of performance indicators such as difference and universality, it can also prove that the OFSP model has multiple performance advantages for groundwater pollution evaluation.

Assessment metrics and level criteria

According to the characteristics of groundwater pollution under domestic landfills in southern and northern China, this study specifically selects "MPN," "CFU," and "Hg," etc. (Table 3) as the key metrics (Wu et al. 2020; Ocampoduque et al. 2006; Vasanthavigar et al. 2010; Mohebbi et al. 2013; Hoseinzadeh et al. 2015; Xi Chen and Wang 2019) of groundwater quality assessment to evaluate corresponding groundwater, and to objectively reflect the overall situation of groundwater quality in domestic waste landfills (Verma 2020; Osborne and Kovacic 2010; Beck et al. 1988).

The various criteria values of "I," "II," "III," "IV," and "V" of the assessment metrics are displayed in the following table.

Results and discussion

Evaluation results of OFSP model

In this section, this study takes random sample data collected from every landfill in Table 1 as sample to compute the P_i values and groundwater quality assessment level by the model of OFSP, and to analyze groundwater pollution characteristics in regulated and unregulated domestic waste landfills (Shuang et al. 2016; Chen et al. 2012; Yan et al. 2016; Amiri et al. 2014; Yan et al. 2014; Su et al. 2009; Zhang et al. 2011; Su et al. 2010). The brief simulation calculations of the key parts

Table 4 The evaluation results of OFSP

Sampling landfill	Sampling city	I	II	III	IV	V	Assessment level
Asowei#	Beijing	0.0616	0.0632	0.0522	0.0418	0.0337	II
Daxing District	Beijing	0.0437	0.0546	0.0747	0.0537	0.0318	III
Heping District: Shandong Yidi#	Shenyang	0.0563	0.0663	0.0608	0.0405	0.0339	III
Dadong District North: Paoziyan	Shenyang	0.0378	0.0614	0.0689	0.0573	0.0326	III
Rubbish storage yard	Shenyang	0.0435	0.0547	0.0556	0.0505	0.0348	III
Fuxin city landfill	Fuxin. Liaoning	0.0437	0.0624	0.0675	0.0603	0.0443	III
Chengjiagang garbage dump	Harbin	0.0382	0.0586	0.0643	0.0582	0.0419	III
Taitou garbage dump	Shijiazhuang	0.0458	0.0604	0.0668	0.0563	0.0434	III
A domestic waste landfill#	Shijiazhuang	0.0669	0.0784	0.0651	0.0420	0.0307	II
Non-standard landfill	Huabei	0.0407	0.0603	0.0693	0.0547	0.0521	III
Baiyangdian zhongcun non-standard Landfill	Baoding. Hebei	0.0453	0.0682	0.0724	0.0543	0.0457	III
Maiji District: laogougou landfill#	Tianshui. Gansu	0.0712	0.0783	0.0607	0.0556	0.0439	II
Jiangcungou village landfill	Xi' An	0.0548	0.0579	0.0605	0.0578	0.0403	III
Jinan landfill	Jinan	0.0533	0.0774	0.0804	0.0627	0.0408	III
Laizhou municipal solid waste landfill#	Laizhou. Shandong	0.0637	0.0738	0.0614	0.0455	0.0433	II
A domestic waste landfill#	Shanghai	0.0530	0.0639	0.0527	0.0403	0.0401	II
Laogang landfill	Shanghai	0.0474	0.0573	0.0701	0.0783	0.0684	IV
Yanqun lomestic waste sanitary landfill#	Xuzhou. Jiangsu	0.0697	0.0779	0.0678	0.0542	0.0349	II
Suining municipal solid waste sanitary landfill# (karst area)	Xuzhou. Jiangsu	0.0733	0.0753	0.0704	0.0568	0.0347	II
Cuipingshan domestic solid waste landfill#	Xuzhou. Jiangsu	0.0624	0.0687	0.0577	0.0427	0.0337	II
Ruian Dongshan garbage dump	Wenzhou. Zhejiang	0.0437	0.0537	0.0711	0.0765	0.0694	IV
A county domestic waste landfill#	An' hui	0.0717	0.0793	0.0704	0.0573	0.0446	II
A domestic waste landfill	Luoyang. Henan	0.0336	0.0518	0.0783	0.0707	0.0492	IV
A domestic waste landfill#	Zhoukou. Henan	0.0356	0.0627	0.0667	0.0563	0.0253	III
Jinkou village landfill	Wuhan	0.0382	0.0441	0.0633	0.0753	0.0465	IV
Chenjiachong landfill#	Wuhan	0.0666	0.0702	0.0533	0.0431	0.0402	II
A domestic waste landfill	Wuhan	0.0487	0.0535	0.0704	0.0728	0.0687	IV
An unregulated domestic waste landfill#	Chengdu	0.0623	0.0873	0.0481	0.0335	0.0310	II
A domestic waste sanitary landfill	Chengdu	0.0321	0.0368	0.0456	0.0764	0.0411	IV
A domestic waste landfill#	Kunming	0.0676	0.0768	0.0663	0.0459	0.0477	II
Xingfeng domestic waste landfill#	Guangzhou	0.0545	0.0805	0.0863	0.0787	0.0552	III
Fengcun village garbage dump	Zhanjiang. Guangdong	0.0231	0.0346	0.0604	0.0535	0.0329	IV
A domestic waste landfill#	Nanning	0.0671	0.0675	0.0663	0.0547	0.0455	II

Only parts of representative results are shown in Table 4

From Table 4, the groundwater pollution levels of various domestic waste landfills and their corresponding P_i, namely the values of "I," "II," "III," "IV," and "V," can be easily found. Then, the results of groundwater quality assessment level and P_i values are used to analyze groundwater pollution in regulated and unregulated domestic waste landfills in different regions.

of the OFSP model and their corresponding results are explained below.

As stated, based on the groundwater sample data of Asowei# in Beijing, we employ Eqs. 7 and 8 to compute the parametric values of u_{11}. Then the evaluation result of class "I" of the parameters (u_{11}) are acquired. Similarly, we get the other four evaluation results of class "II", "III", "IV," and "V" of the corresponding parameters. Then, all evaluation results of groundwater pollutants can be regulated to the matrix form of Q. According to the variable values of w^1 and w^2, which were respectively computed by Eqs. 9 and 10, we obtain the "w" value of various groundwater pollutants using Eqs. 11 to 13. In the following, the results of "C" and their "P" matrix are acquired by using the corresponding equations in Algorithm 2. At last, we obtain the P_i values (0.0616, 0.0632, 0.0522, 0.0418, and 0.0337) and groundwater quality assessment level ("II") of Asowei# in Beijing.

In the same way, based on the same groundwater pollutant data of the rest sampling landfills of different regions such as "Daxing District" in Beijing, "Heping District: Shandong

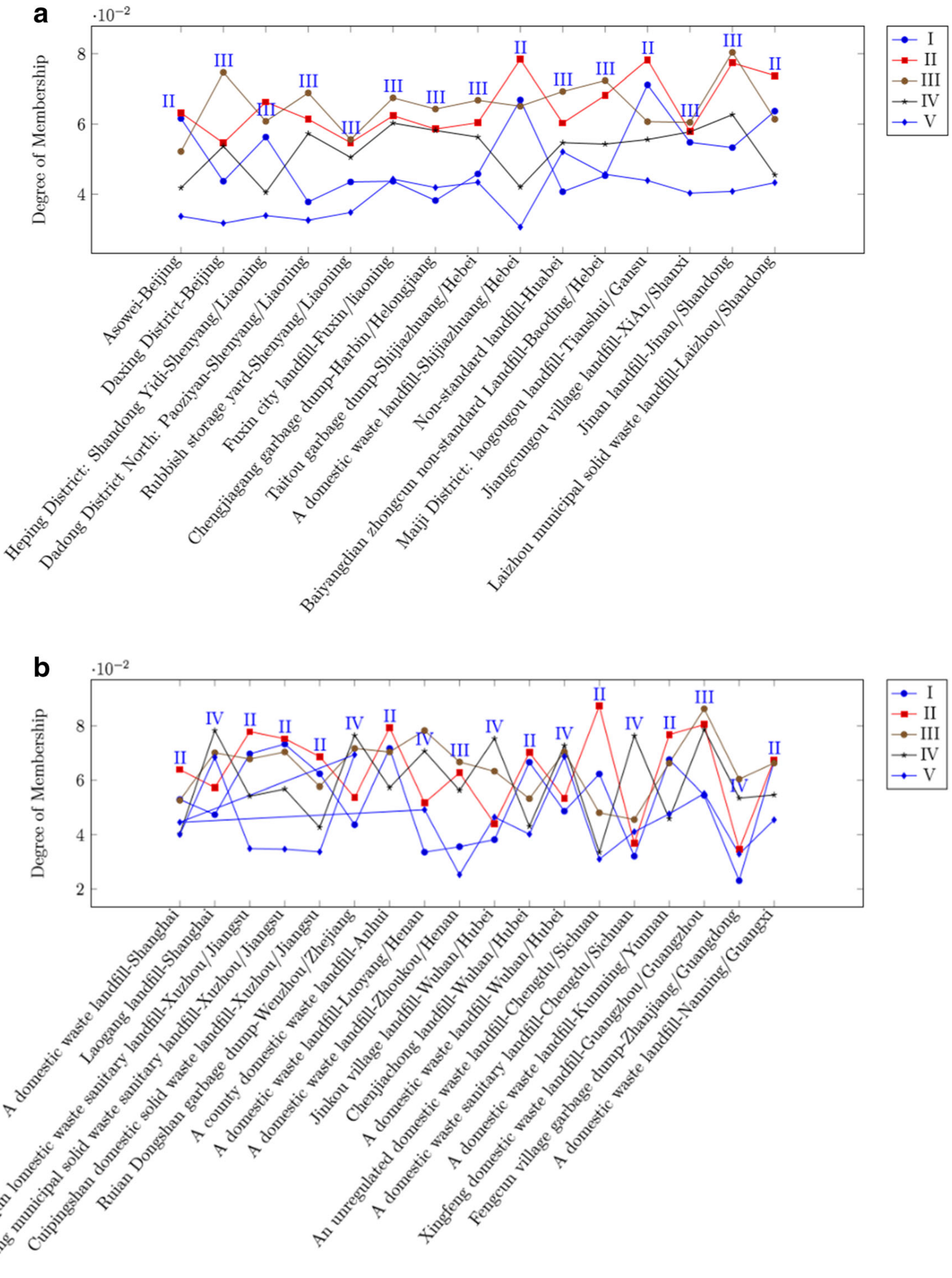


Fig. 4 **a** Pollution degree of study area (Northern China). **b** Pollution degree of study area (Southern China)

Yidi#" and "Dadong District North: Paoziyan" in Shenyang, Liaoning Province, etc., we calculate their groundwater evaluation level and P_i values through the OFSP model. By categorization, the P_i values and groundwater quality assessment levels (Table 4) of all sampling landfills in China could be presented as follows.

It is not difficult to find that there are 7 domestic waste landfills with the highest level (IV) of groundwater pollution in this study, which are "Laogang landfill" in Shanghai; "Ruian Dongshan garbage dump" in Wenzhou, Zhejiang Province; and "A domestic waste landfill" in Luoyang, Henan Province, etc. And there are 13 domestic waste

Table 5 The evaluation results of various models

Sampling landfill	Sampling city	OFSP	VFSPA	VFEM	LPI	FSEV FS	NSFWQI	EWQI	PCA	ICAUCA
Asowei$^{\#}$, Anding$^{\#}$, Beishenshu, Liulitun, Gaoantun, Jiaojiapo, etc.	Beijing	II, II, III, IV, IV, III	II, II, III, IV, III, III	II, III, III, IV, IV, III	II, II, IV, IV, IV, III	II, III, III, IV, IV, III	II, II, IV, IV, IV, III	II, II, III, IV, III, III	II, III, III, IV, IV, III	II, II, III, IV, IV, IV
Chaoyang District$^{\#}$/Daxing District/Fengtai District	Beijing	II, III, IV	II, III, III	II, II, IV	II, III, III	II, IV, IV	II, III, III	II, IV, IV	II, III, IV	II, IV, IV
A domestic waste landfill$^{\#}$	Beijing	II	II	II	II	III	II	II	III	II
A landfill$^{\#}$	Beijing	II	II	III	II	II	II	II	II	II
Heping District: Shandong Yidi$^{\#}$, Huanggu District: Shenyang Medical College$^{\#}$, Shenhe District: Stadium$^{\#}$, Huanggu District: Light Industry Machinery Plant$^{\#}$, Shenhe Residential Company$^{\#}$, Garbage Dumping Site$^{\#}$,	Shenyang	III, II, II, III, II, II	III, III, II, III, II, II	III, II, II, III, II, III	III, II, II, III, II, III	III, III, III, III, II, II	III, II, III, III, II, II	III, II, II, III, II, III	III, II, II, III, II, III	III, II, III, III, II, II
Dadong District North: Paoziyan, Yuhong District: Stadium, Dongling District: Wanghua, Tiexi District: Yuhong Examination Site, Dadong District: Battery Plant, etc.	Shenyang	III, III, IV, III, III	III, IV, IV, III, III	III, IV, IV, III, III	III, III, III, III, III	III, III, IV, III, IV	III, III, IV, III, IV	III, IV, IV, III, III	III, III, III, III, III	III, IV, IV, III, III
Rubbish storage yard	Shenyang	III	IV	III	III	III	IV	III	III	III
Fuxin city landfill	Fuxin/liaoning	III	III	IV	III	IV	III	III	III	IV
The harmless treatment domestic garbage landfill in downtown area$^{\#}$	liaoning	II	II	II	II	II	II	II	II	II
Chengjiagang garbage dump	Harbin	III	III	III	IV	III	III	III	III	III
Taitou garbage dump	Shijiazhuang	III	III	III	III	III	III	IV	IV	III
A domestic waste landfill$^{\#}$	Shijiazhuang	II	II	II	II	III	II	II	II	II
Non-standard landfill	Huabei	III	III	III	III	III	III	IV	III	III
A landfill$^{\#}$	Tangshang. Hebei	II	II	III	II	II	II	II	II	II
A domestic waste landfill$^{\#}$	Tangshang. Hebei	II	II	II	II	II	II	II	III	II
Baiyangdian zhongcun non-standard Landfill	Baoding. Hebei	III	IV	III	III	III	IV	III	III	IV
Maiji District: laogougou landfill$^{\#}$	Tianshui. Gansu	II	II	II	II	II	III	III	II	II
Jiangcungou village landfill	Xi' An	III	III	III	IV	III	III	III	III	III
A domestic waste landfill$^{\#}$	Lanzhou	II	II	II	II	II	II	II	II	II
A domestic waste landfill$^{\#}$	Xining	II	II	III	II	II	III	II	II	II
Jinan landfill	Jinan	III	III	III	III	III	III	III	III	III
Guolou village simple landfill$^{\#}$	Jining. Shandong	II	II	II	II	III	II	II	II	II
Laizhou municipal solid waste landfill$^{\#}$	Laizhou. Shandong	II	II	II	II	II	II	II	II	II
A domestic waste landfill$^{\#}$	Shanghai	II	II	II	III	II	II	II	III	II
Laogang landfill	Shanghai	IV	IV	IV	IV	IV	IV	IV	IV	IV
Yanqun lomestic waste sanitary landfill$^{\#}$	Xuzhou. Jiangsu	II	II	III	II	II	II	II	II	II
Suining domestic waste sanitary landfill	Xuzhou. Jiangsu	IV	IV	IV	IV	III	IV	III	IV	IV

Table 5 (continued)

Sampling landfill	Sampling city	OFSP	VFSPA	VFEM	LPI	FSEVFS	NSFWQI	EWQI	PCA	ICAUCA
Suining municipal solid waste sanitary landfill[#] (karst area)	Xuzhou. Jiangsu	II	III	II	II	II	II	II	II	II
Cuipingshan domestic solid waste landfill[#]	Xuzhou. Jiangsu	II	II	II	III	II	III	II	II	III
Pizhou domestic waste landfill	Xuzhou. Jiangsu	III	IV	III	III	IV	III	III	III	IV
Ruian Dongshan garbage dump	Wenzhou. Zhejiang	IV	IV	IV	IV	IV	IV	IV	IV	IV
A county domestic waste landfill[#]	An' hui	II	II	II	III	III	III	II	II	II
A domestic waste landfill[#]	An' hui	III	II	III	III	II	III	III	II	III
Datong landfill	Huainan. An' hui	IV	IV	III	IV	IV	IV	IV	III	IV
Luhuagang village landfill	Kaifeng. Henan	IV	IV	IV	IV	IV	IV	IV	IV	IV
A domestic waste landfill	Luoyang. Henan	IV	III	III	III	III	III	III	III	III
A domestic waste landfill[#]	Zhoukou. Henan	III	III	III	III	III	III	III	III	III
A domestic waste landfill	Zhoukou. Henan	IV	IV	IV	IV	IV	IV	IV	IV	IV
Jinkou village landfill	Wuhan	IV	IV	IV	IV	IV	IV	IV	IV	IV
Chenjiachong landfill[#]	Wuhan	II	III	III	III	III	II	II	III	III
A domestic waste landfill	Wuhan	IV	IV	IV	IV	IV	IV	IV	IV	IV
A domestic waste landfill[#]	Changsha	II	II	II	II	III	III	III	II	II
A domestic waste sanitary landfill	Chengdu	IV	IV	III	IV	IV	IV	IV	IV	IV
An unregulated domestic waste landfill[#]	Chengdu	II	II	II	III	II	II	II	III	II
A domestic waste sanitary landfill	Chengdu	IV	IV	IV	IV	IV	IV	IV	IV	IV
A domestic waste landfill	Nanchong. Sichuan	III	III	III	III	III	III	III	III	III
A domestic waste sanitary landfill[#]	Guizhou	II	II	III	II	II	II	III	II	II
A domestic waste landfill[#]	Kunming	II	III	II	II	III	II	II	II	II
A domestic waste landfill	Lhasa. Tibet	III	III	IV	IV	IV	III	III	III	IV
Xingfeng domestic waste landfill[#]	Guangzhou	III	IV	III	III	III	IV	IV	IV	III
A domestic waste landfill	Guangzhou	IV	IV	III	III	III	IV	IV	IV	IV
Fengcun village garbage dump	Zhanjiang. Guangdong	IV	III	III	III	III	III	III	III	III
A domestic waste landfill[#]	Nanning	II	II	III	III	II	III	III	III	II

landfills with the lowest level (II) of groundwater pollution, which are "Asowei$^{\#}$" in Beijing; "A domestic waste landfill$^{\#}$" in Shijiazhuang, Hebei Province; and "Maiji District: laogougou landfill$^{\#}$," in Tianshui, Gansu Province etc. Where in southern China, the P_i values of "I," "II," "III," "IV," and "V" of "Laogang landfill" in Shanghai (class "IV") are 0.0474, 0.0573, 0.0701, 0.0783, and 0.0684, respectively. The P_i values of "I," "II," "III," "IV," and "V" of "A domestic waste landfill$^{\#}$" in Shanghai (class "II") are 0.0530, 0.0639, 0.0527, 0.0403, and 0.0401, respectively. In northern China, the P_i values of "I," "II," "III," "IV," and "V" of "Daxing District" in Beijing (class "III") are 0.0437, 0.0546, 0.0747, 0.0537, and 0.0318, respectively. The P_i values of "I," "II," "III," "IV," and "V" of "Laizhou municipal solid waste landfill$^{\#}$" in Laizhou, Shandong Province (class "II"), are 0.0637, 0.0738, 0.0614, 0.0455, and 0.0433 respectively. Obviously, the groundwater pollution levels of domestic waste landfills in China range from "II" to "IV" (Fig. 4), which is a relatively serious pollution situation.

Analysis of various evaluation results

In this section, in order to get more persuasive analysis conclusions of the various evaluation results, we randomly select the same sample values as a method of the proposed OFSP model, and employ eight various assessment models, such as the models of VFSPA, VFEM, LPI, FSEVFS, NSFWQI, EWQI, PCA, and ICAUCA, to achieve the assessment computation separately (Singh et al. 2016;Rana et al. 2018;Manimekalai 2012;Bahroz 2015;Chonattu et al. 2016;Mishra et al. 2016;Ocampoduque et al. 2006;Vasanthavigar et al. 2010;Mohebbi et al. 2013;Hoseinzadeh et al. 2015;Xi Chen and Wang 2019). In the following, according to the above computations of various models, the corresponding assessment results (Table 5) of groundwater under the domestic waste landfills are acquired.

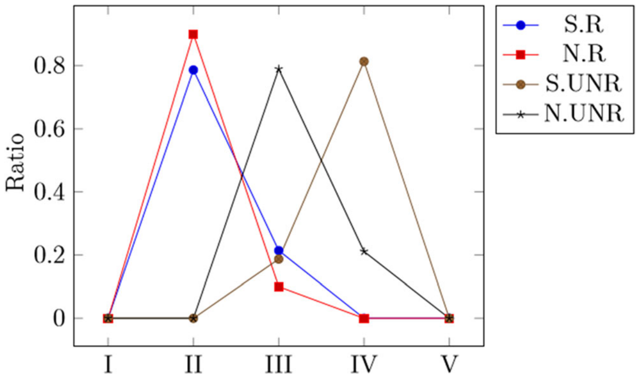


Fig. 5 Ratio results of area location and landfill type. Note that "S.R" ("N.R") means regulated domestic landfills in southern (northern) China; "S.UNR" ("N.UNR") means unregulated domestic landfills in southern (northern) China

The groundwater quality assessment results of domestic waste landfills in different regions by various assessment methods in Table 5 show that, based on OFSP, the groundwater pollution level of "Beishenshu, Liulitun" in Beijing is grade "IV." The groundwater pollution level of "Heping District: Shandong Yidi$^{\#}$" in Shenyang, Liaoning Province, is grade "III." And the groundwater pollution level of "A domestic waste landfill$^{\#}$" in Shanghai is grade "II," etc. Where, in all regulated domestic landfills, there are 0 landfills with the groundwater pollution level of IV. The number of landfills of groundwater pollution level "III" is 5, which include the landfills of "Heping District: Shandong Yidi$^{\#}$," "Shenhe District: Stadium$^{\#}$," and "Huanggu District: Light Industry Machinery Plant$^{\#}$." And the landfills such as "Asowei$^{\#}$," "Anding$^{\#}$," and "Chaoyang District$^{\#}$," which are the groundwater pollution level "II," have 29. Meanwhile, in all unregulated domestic landfills, the number of landfills of groundwater pollution level "IV" is 17, which include the landfills of "Liulitun," "Gaoantun," and "Fengtai District." The number of groundwater pollution level "III" is 18, including "Beishenshu," "Jiaojiapo," and "Daxing District" etc. And there are 0 landfills with the groundwater pollution level of II.

Dual perspective of area location and landfill type

Analyzing from the dual perspective of regional orientation and landfill type, we find that although the percentage of regulated domestic landfills in the southern region is higher than that in the northern region, the pollution degree of their groundwater is on the whole higher than that in the northern region (Xin et al. 2017; Shao et al. 2018). Then, in terms of the dimension of regulated domestic landfill, the level of groundwater pollution in the southern region is roughly the same as that in the northern region of China, while on the basis of the dimension of unregulated domestic landfill, the level of groundwater pollution in the southern region is also higher than that in the northern region of China.

Furthermore, based on the corresponding data in the above Table 5, the results of their "J_i" values can be respectively calculated by Eq. 25. For example, the "J_i" values of regulated domestic landfills in southern China are $J_{\mathrm{I}}=0$, $J_{\mathrm{II}}=0.786$, $J_{\mathrm{III}}=0.214$, $J_{\mathrm{IV}}=0$, and $J_{\mathrm{V}}=0$. Then, according to the analysis of the above calculation results of J_i, the same quantitative conclusions can be obtained as follows.

That is, the overall pollution level of the regulated domestic landfills in southern China is at class "II" ($J_{\mathrm{II}}=0.786$), which belongs to the "II" major pollution area; and the overall pollution level of the regulated domestic landfills in northern China is also at class "II" ($J_{\mathrm{II}}=0.900$), which belongs to the "II" major pollution area. And the overall pollution levels of the unregulated domestic landfills in southern and northern China are class "IV" ($J_{\mathrm{IV}}=0.813$) and class "III" ($J_{\mathrm{III}}=0.789$), respectively. The corresponding numerical results figure produced by the OFSP model is intuitively shown in Fig. 5.

Perspective of domestic landfill type

Based on the analysis of perspective of domestic landfill type, the pollution degree of regulated domestic waste landfills, which has 29 "II" landfills, 5 "III" landfills, and 0 "IV" landfill, etc., is significantly lower than the unregulated domestic waste landfills, which has 0 "II" landfill, 18 "III" landfills, and 17 "IV" landfills, etc. Taking the landfills in East China as an example, according to the corresponding results in Table 5, the pollution level of regulated domestic waste landfills in this area is much lower than that of unregulated landfills. In addition, in line with the data in Table 5, the "J_i" values of corresponding regulated (or unregulated) domestic landfills such as J_{II}, J_{III}, and J_{IV} can be respectively computed by Eq. 25.

In the following, according to the discussion of the above numerical results of J_i, we use the double judgment mode to judge overall pollution level (San et al. 2018). Then, the judgment conclusion can be formed as follows. On the whole, the main pollution level of the unregulated domestic landfills is the class "IV," and on the whole, the main pollution level of the regulated domestic waste landfill is the class "II." The above numerical results figure (Fig. 6) produced by the OFSP model is displayed.

Dimension of groundwater pollution component

Based on the level of pollution component categories, we analyze the distribution of all chemical elements (such as "MPN," "CFU," and "NH_3–N", etc.) in groundwater, and their distribution characteristics in the groundwater of various types of domestic waste landfills (Wu et al. 2020; Hoseinzadeh et al. 2015; Yan et al. 2019). From the perspective of indiscriminate chemical contamination, "CFU," "MPN," and "$CaCO_3$" are the chemical elements with the largest proportion of polluting components in the groundwater of domestic waste landfills. Then, from the perspective of heavy pollutant, the proportions of "As," "Mn," and "COD" in the groundwater of the unregulated domestic landfills are higher, and their proportions in the groundwater of the regulated domestic landfills are lower. The proportions of pollution components such as "Na," "NH_3–N," and "Pb" in the groundwater of both the regulated domestic landfills and the unregulated domestic landfills are similar, which are at ordinary levels. And the proportions of "MPN," "CFU," "$CaCO_3$," "Hg," and "$KMnO_4$" in the groundwater of both the regulated and unregulated domestic waste landfills are relatively high.

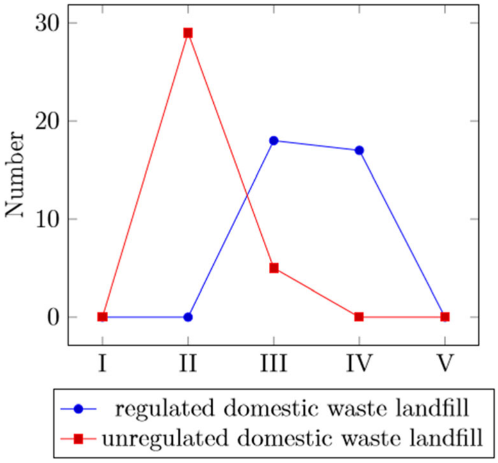


Fig. 6 Number results of domestic landfill type

It is worth noting that although the percentage of regulated domestic waste landfills in southern China is higher than that in northern China, the proportion of groundwater pollution components such as "Hg" and "Pb" in groundwater in that area is much higher than that in northern China. Similarly, the proportions of contaminations of "MPN" and "CFU" in the groundwater of domestic landfills in the southern region are generally higher than those in the northern region.

Here, in light of the data in Table 2, the results of J_i of various contaminations can be operated using Eq. 25. For example, $J_{\mathrm{NH3-N}}$ =0.975, J_{TDS} =0.563, and J_{Mo} =0.074. Then, based on the numerical results of "J_i" values, the universal pollution indexes of groundwater (J_i >60%), which include the chemical elements of "NH_3–N," "$KMnO_4$," and "Hg," are determined. The pollution indicators of "Mn," "TDS," and "Pb," etc. ($60\% \geq J_i > 10\%$) are local pollution components in groundwater. And the remaining pollution metrics, such as "Mo," "Cu," and "Cd" ($J_i \leq 10\%$), belong to the point source pollution component in groundwater under domestic waste landfills. The percentage histogram (Fig. 7) corresponding to the analysis results is shown.

Through in-depth analysis of the research results from the abovementioned perspectives, the following comprehensive conclusions and recommendations can be drawn. (1) The measures such as garbage classification and regulatory treatment in domestic landfills are conducive to the improvement of groundwater quality; (2) the current actions of waste sorting and regulatory treatment have effectively curbed heavy pollution components such as "As," "Mn," and "COD." However, these actions are not obvious for the containment of heavy pollution components such as "MPN," "CFU," "$CaCO_3$," "Hg," and "$KMnO_4$," especially the elements of "Hg," "MPN," and "CFU." Hence, the further targeted measures are needed. The reason for this is that although their proportion in groundwater is not large, the intensity of pollution to groundwater is very strong. For non-heavy pollution components, these actions of waste sorting and regulatory treatment are obvious for the containment of "Cu," "Mo," and "Cd," etc., but for the other non-heavy pollution components (e.g., "C_6H_6") in groundwater, the containment is not more

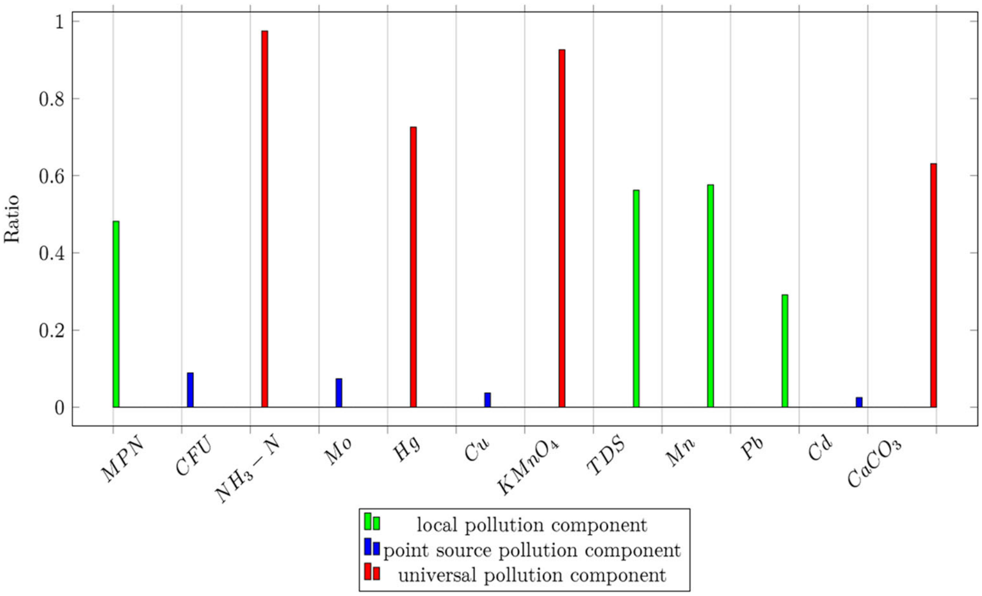


Fig. 7 Analysis results of pollution component dimension. Note that this figure shows the results for only a few representative groundwater pollution components

significant; (3) from the dimension of the results of P_i and assessment level to analyze the distribution characteristics of the regional location of groundwater pollution, it is not difficult to define that the pollution level of groundwater in domestic landfills (especially the unregulated domestic landfills) in the southern region, especially in eastern and southern China, is more serious. Thus, it is necessary to take some targeted and efficient measures for groundwater pollution in domestic landfills, and increase the intensity and pertinence of landfill management.

OFSP model performance

Precision performance analysis

Based on the assessment results of groundwater quality in Table 5 for various domestic waste landfills, we compare the groundwater quality levels obtained by various mainstream methods. The comparison result of assessment levels can well prove the versatility and precision of the proposed OFSP method to groundwater quality evaluation in domestic waste landfills.

In this section, we take the assessment results of both item 30 of "A domestic waste landfill/Luoyang.Henan" and item 40 of "Fengcun village garbage dump/Zhanjiang.Guangdong" in Table 4 as an example to demonstrate the superiority of our proposed OFSP model, and further verify that the OFSP model is more universal and precise for groundwater evaluation (Shuang et al. 2016; Su et al. 2010). From Table 4, we can see that only the assessment results of OFSP are class "IV"; the results of other models are "III." The reason for this is that the "P_1–P_5" values of "A domestic waste landfill/Luoyang.Henan" are 0.0336, 0.0518, 0.0783, 0.0707, and 0.0492, respectively; and the "P_1–P_5" values of "Fengcun village garbage dump/Zhanjiang.Guangdong" are 0.0231, 0.0346, 0.0604, 0.0535, and 0.0329, respectively (Fig. 8). It is clear that the assessment results of both "A domestic waste landfill/Luoyang.Henan" and "Fengcun village garbage dump/Zhanjiang. Guangdong" are initially positioned between class "III" and "IV." Then, through careful analysis, we find that the "P_2" value in the table is significantly lower than "P_4". As such, we adopt the double judgment mode to achieve conclusion that the assessment results of the second judgment to "A domestic waste landfill/ Luoyang.Henan" and "Fengcun village garbage dump/Zhanjiang. Guangdong" are class "IV," which is more precise and universal. The corresponding judgment diagram of numerical result is shown below.

Performance indices validation

To compare the proposed OFSP model with some mainstream models, based on groundwater of domestic waste landfill in

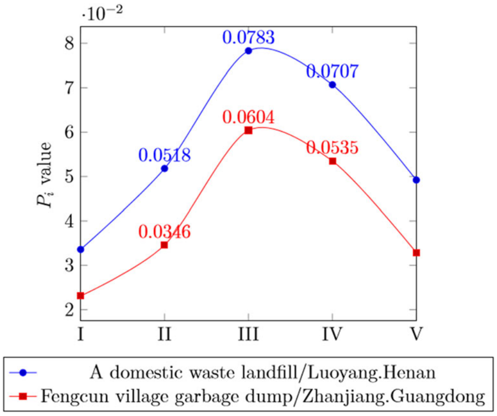


Fig. 8 Judgment diagram of numerical result

various regions of the country, we employ the same way using in the study, and select the random data from 69 sampling wells to run validation experiment about 4000 times, so as to further confirm the superior performance of our OFSP model. The validation results in 6 distinct aspects of performance indices of 9 various models, including of OFSP, VFSPA, VFEM, LPI, FSEVFS, NSFWQI, EWQI, PCA, and ICAUCA, are obtained as follows (Singh et al. 2016; Rana et al. 2018; Manimekalai 2012; Bahroz 2015; Chonattu et al. 2016; Mishra et al. 2016; Ocampoduque et al. 2006; Vasanthavigar et al. 2010; Mohebbi et al. 2013; Hoseinzadeh et al. 2015; Xi Chen et al. 2019).

In Fig. 9, the horizontal axis represents various models, and the vertical axis represents the values of precision. Of all experiments, the proposed OFSP model has the best performance of precision, which obtains the highest precision result (0.985) of all evaluation models in groundwater quality evaluation. Meanwhile, the precision results of ICAUCA, PCA, EWQI, NSFWQI, FSEVFS, LPI, VFEM, and VFSPA are 0.803, 0.873, 0.868, 0.794, 0.756, 0.891, 0.917, and 0.952, respectively. Thus, the mean of precision of all evaluation models is 0.871.

In Fig. 10, the horizon axis represents various methods, and the vertical axis represents the values of robustness. Of all experiments, our OFSP model has a good ability of robustness, which achieves the highest robustness result (0.953) of all evaluation models in groundwater quality evaluation. Meanwhile, we could easily get that the other mainstream models like ICAUCA, PCA, EWQI, NSFWQI, FSEVFS, LPI, VFEM, and VFSPA do not achieve a higher level of robustness compared with the proposed OFSP model. Here, the robustness results of them are 0.778, 0.831, 0.829, 0.882, 0.784, 0.921, 0.927, and 0.936, respectively. Therefore, the mean of robustness of all assessment models is 0.872.

In Fig. 11, the horizon axis represents the various models, and the vertical axis represents the corresponding discrimination results. It is clear that the discrimination results of ICAUCA, PCA, EWQI, NSFWQI, FSEVFS, LPI, VFEM, VFSPA, and OFSP are 0.277, 0.233, 0.284, 0.301, 0.268, 0.211, 0.206, 0.195, and 0.217, respectively. Thus, the mean of discrimination of all assessment models is 0.244. Obviously, in the most experiments, compared with other eight assessment models, we could easily see that the proposed OFSP model achieves the middle level of discrimination for groundwater evaluation. The reason for being inferior to the mainstream models of LPI, VFEM, and VFSPA may be that the proposed OFSP model has a rigorous and comprehensive assessment structure.

In Fig. 12, the horizontal axis represents various models, and the vertical axis represents the values of correlation. Of all experiments, the proposed OFSP model has the best performance of correlation in groundwater evaluation, which obtains the highest correlation result (0.934) of all evaluation models in groundwater quality evaluation. Meanwhile, the correlation results of ICAUCA, PCA, EWQI, NSFWQI, FSEVFS, LPI, VFEM, and VFSPA are 0.773, 0.847, 0.821, 0.759, 0.735, 0.872, 0.908, and 0.926, respectively. Hence, the mean of correlation of all evaluation models is 0.842.

In Fig. 13, the horizon axis represents various methods, and the vertical axis represents the value of rationality. Here, the mean of rationality of all evaluation models is 0.802, and the rationality results of ICAUCA, PCA, EWQI, NSFWQI, FSEVFS, LPI, VFEM, VFSPA, and OFSP are 0.730, 0.805, 0.629, 0.703, 0.702, 0.857, 0.901, 0.943, and 0.946, respectively. Obviously, of all experiments, our designed OFSP model outperforms the other evaluation methods in groundwater quality evaluation.

In Fig. 14, the horizon axis represents the various models, and the vertical axis represents the results of versatility. It is not difficult to find that the results of versatility of ICAUCA, PCA, EWQI, NSFWQI, FSEVFS, LPI, VFEM, VFSPA, and OFSP are 0.812, 0.776, 0.939, 0.927, 0.787, 0.901, 0.913,

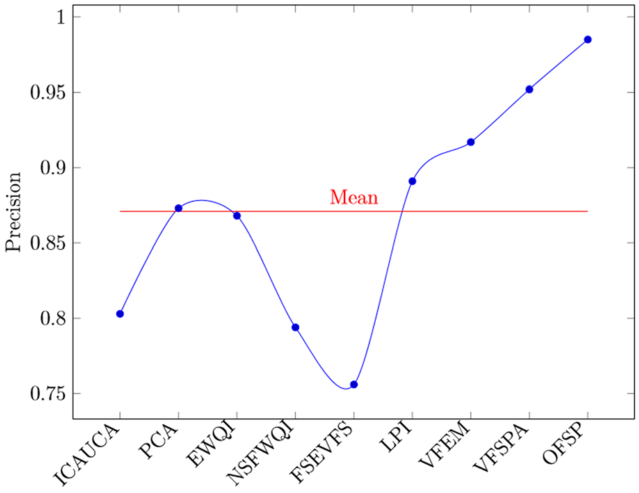


Fig. 9 Precision values

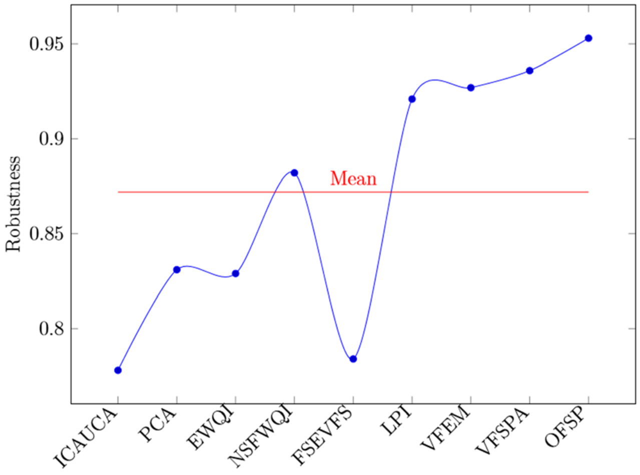


Fig. 10 Robustness values

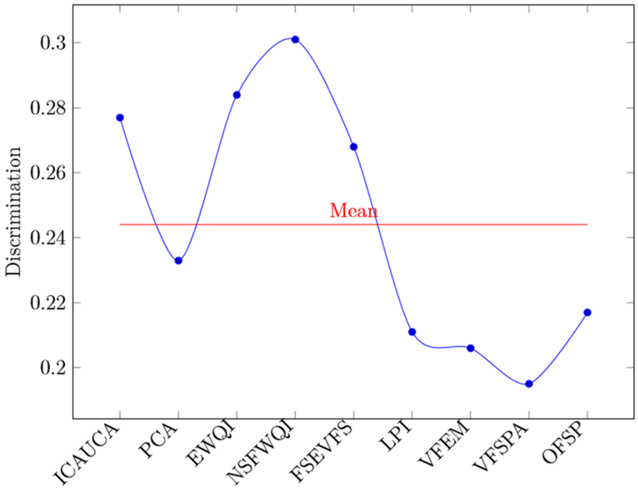


Fig. 11 Discrimination values

0.824, and 0.837, respectively. Hence, the mean of versatility of all assessment models is 0.858. Obviously, in the most experiments, compared with other eight assessment models, we can easily get that the proposed OFSP model achieves the middle rank of versatility. The rigorous and comprehensive evaluation structure is the main reason for being worse than the mainstream models of EWQI, NSFWQI, LPI, and VFEM in performance metric of versatility.

Finally, in order to make comparison of the performance indices of precision, robustness, discrimination, correlation, rationality, and versatility more clearly, we summarize the performance metrics values of precision, robustness, discrimination, etc., into the following table (Table 6) for comparison and analysis. All comparison results of performance indexes are present in Table 6.

It is easy to find that, in line with precision (0.985), correlation (0.934), robustness (0.953), and rationality (0.946), our designed OFSP model has the best performance. In addition, according to the indexes of discrimination (0.217) and versatility (0.837), the designed OFSP model also has a good ability. And the abovementioned sound conclusions can also be confirmed in Fig. 15.

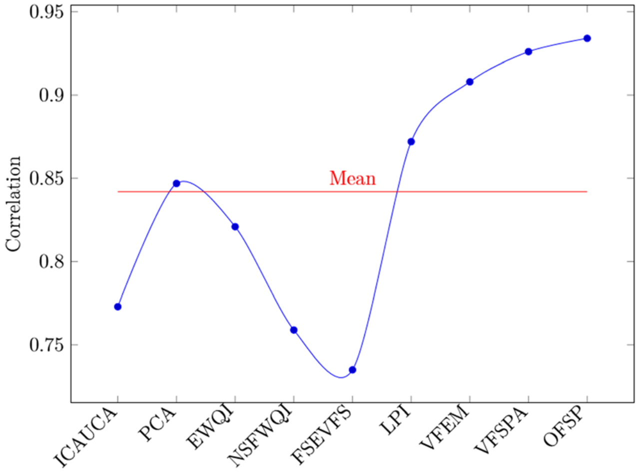


Fig. 12 Correlation values

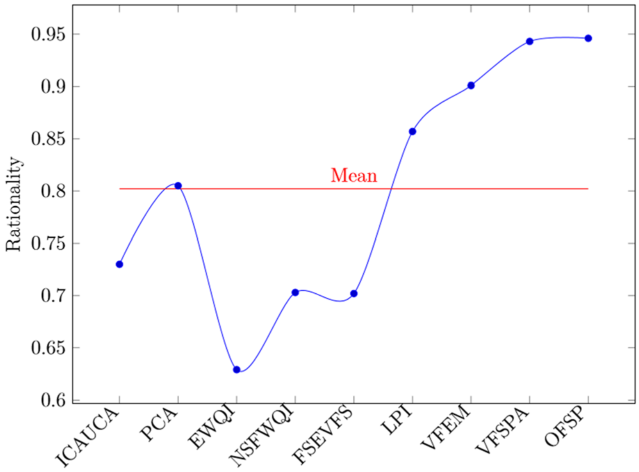


Fig. 13 Rationality values

Discussion

The research randomly collects the values of groundwater pollution index parameter from some representative regions of North and South China and uses the OFSP evaluation model to conduct comprehensive calculations (Yan et al. 2016; Shuang et al. 2016; Amiri et al. 2014; Yan et al. 2014; Chen et al. 2012; Zhang et al. 2011; Su et al. 2010; Su et al. 2009). We obtain the pollution levels "I," "II," "III," "IV," and "V" and the optimized Nemerow index value "P_i" based on the sample evaluation locations corresponding to different locations in the north and south of China. Through the analysis and collection of the groundwater pollution evaluation results, we obtain the overall and local groundwater pollution characteristics in the north and south of China. From the perspective of the whole China, there are 7 domestic waste landfills with the highest level (IV) of groundwater pollution in this study, which are "Laogang landfill" in Shanghai; "Ruian Dongshan

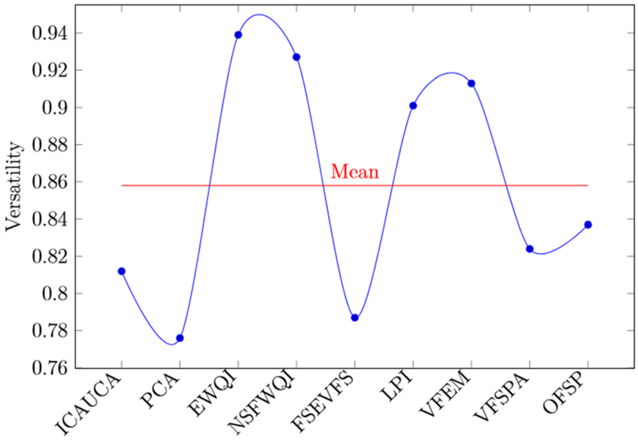


Fig. 14 Versatility values

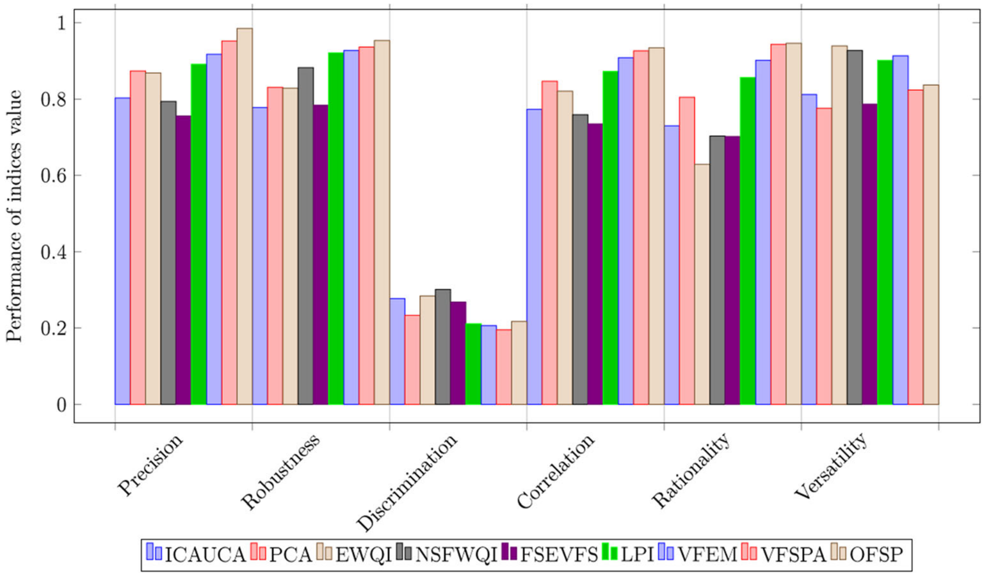
Table 6 The results of performance indices

Method	Precision	Robustness	Discrimination	Correlation	Rationality	Versatility
ICAUCA	0.803	0.778	0.277	0.773	0.730	0.812
PCA	0.873	0.831	0.233	0.847	0.805	0.776
EWQI	0.868	0.829	0.284	0.821	0.629	0.939
NSFWQI	0.794	0.882	0.301	0.759	0.703	0.927
FSEVFS	0.756	0.784	0.268	0.735	0.702	0.787
LPI	0.891	0.921	0.211	0.872	0.857	0.901
VFEM	0.917	0.927	0.206	0.908	0.901	0.913
VFSPA	0.952	0.936	0.195	0.926	0.943	0.824
OFSP	0.985	0.953	0.217	0.934	0.946	0.837

garbage dump" in Wenzhou, Zhejiang Province; and "A domestic waste landfill" in Luoyang, Henan Province, etc. And there are 13 domestic waste landfills with the lowest level (II) of groundwater pollution, which are "Asowei$^{\#}$" in Beijing; "A domestic waste landfill$^{\#}$" in Shijiazhuang, Hebei Province; and "Maiji District: laogougou landfill$^{\#}$," in Tianshui, Gansu Province etc. Therefore, the level of groundwater pollution is serious in the north and south of China. From the perspective of the specific locations of China, in southern China, the P_i values of "I," "II," "III," "IV," and "V" of "Laogang landfill" in Shanghai (class "IV") are 0.0474, 0.0573, 0.0701, 0.0783, and 0.0684, respectively. The P_i values of "I," "II," "III," "IV," and "V" of "A domestic waste landfill$^{\#}$" in Shanghai (class "II") are 0.0530, 0.0639, 0.0527, 0.0403, and 0.0401, respectively. In northern China, the P_i values of "I," "II," "III," "IV," and "V" of "Daxing District" in Beijing (class "III") are 0.0437, 0.0546, 0.0747, 0.0537, and 0.0318, respectively. The P_i values of "I," "II," "III," "IV," and "V" of "Laizhou municipal solid waste landfill$^{\#}$" in Laizhou, Shandong Province (class "II"), are 0.0637, 0.0738, 0.0614, 0.0455, and 0.0433 respectively. Obviously, the groundwater pollution levels of domestic waste landfills in China range from "II" to "IV," which is a relatively serious pollution situation. Therefore, whether it is in southern China or northern China, the level of groundwater pollution is significantly serious.

And then, we apply different groundwater pollution evaluation models such as OFSP, VFSPA, and ICAUCA to calculate and judge the corresponding groundwater pollution levels (Mohebbi et al. 2013; Hoseinzadeh et al. 2015; Xi Chen and Wang 2019; Singh et al. 2016; Rana et al. 2018; Manimekalai 2012; Bahroz 2015; Chonattu et al. 2016; Mishra et al. 2016; Ocampoduque et al. 2006; Vasanthavigar et al. 2010). Based on the groundwater pollution evaluation results calculated by the nine different evaluation models, we conduct a multi-level analysis on groundwater pollution under different landfills in the entire north and south regions. Finally, we get the pollution characteristics and regulations of groundwater pollution in the north and south of China after conducting a multi-level

Fig. 15 Performance of indices values



analysis from dual perspective of area location and landfill type, perspective of domestic landfill type, and dimension of groundwater pollution component. The results are as follows: (1) dual perspective of area location and landfill type—the overall pollution level of the regulated domestic landfills in southern China is at class "II," which belongs to the "II" major pollution area; and the overall pollution level of the regulated domestic landfills in northern China is also at class "II," which belongs to the "II" major pollution area. And the overall pollution levels of the unregulated domestic landfills in southern and northern China are class "IV" and class "III," respectively. (2) Perspective of domestic landfill type: on the whole, the main pollution level of the unregulated domestic landfills is class "IV," and on the whole, the main pollution level of the regulated domestic waste landfill is the class "II." (3) Dimension of groundwater pollution component: from the perspective of indiscriminate chemical contamination, "CFU," "MPN," and "$CaCO_3$" are the chemical elements with the largest proportion of polluting components in the groundwater of domestic waste landfills. Then, from the perspective of heavy pollutant, the proportions of "As," "Mn," and "COD" in the groundwater of the unregulated domestic landfills are higher, and their proportions in the groundwater of the regulated domestic landfills are lower. The proportions of pollution components such as "Na," "NH_3–N," and "Pb" in the groundwater of both the regulated domestic landfills and the unregulated domestic landfills are similar, which are at ordinary levels. And the proportions of "MPN," "CFU," "$CaCO_3$," "Hg," and "$KMnO_4$" in the groundwater of both the regulated and unregulated domestic waste landfills are relatively high.

Due to the significant negative factors such as high pollution, large number of chemical pollution discharge companies, high negative environmental effects on economic aggregation, large discharge of chemical and industrial waste, interaction with some positive factors such as regional groundwater pollutant discharge control, prevention technology, strategy optimization, and financial support, groundwater pollution is generally serious in the north and south of China, especially in the south.

It goes without saying that the key reason for good performance of OFSP model has been its predominant arithmetic module of the optimized N.L. Nemerow index equation and double judgment approach (Shuang et al. 2016; Xu et al. 2015; Wang et al. 2011). The OFSP model balances the actual effect of each chemical element and approximate the real pollution effect through the following methods (Wu et al. 2018; Yan et al. 2014; Aunnop et al. 2019; Tamiris et al. 2019; Beheshti 2019). Firstly, the OFSP model adds three variable parameters, such as $\overline{P}^2_{\max 2}$, $\overline{P}^2_{\max 3}$, and $\overline{P}^2_{\max 4}$, so as to highlight the large actual pollution effect of the heavily polluted elements while taking into account the comprehensive calculation of multiple variable indicators; secondly, it employs $\overline{P}^2_{\max}$ instead of $P^2_{\max}$ to restore and highlight the actual pollution effect of the heavy pollution elements as much as possible; finally, it computes the arithmetic mean of P_i with $P_{\max 1}$, $P_{\max 2}$, $P_{\max 3}$, and $P_{\max 4}$, respectively, so that the conversion values of $\overline{P}^2_{\max 1}$, $\overline{P}^2_{\max 2}$, $\overline{P}^2_{\max 3}$, and $\overline{P}^2_{\max 4}$ are achieved.

However, because the OFSP model incorporates more independent operation modules, its calculation speed is relatively slow, which affects the timeliness of the whole OFSP model for groundwater detection. That is the limitation of this study. Therefore, in further study, we are planning to extend the research from the perspective of timeliness performance. While ensuring the performance of accuracy, we will focus on improving the timeliness performance of the proposed OFSP model.

Conclusion

In this paper, a novel OFSP is presented for accurate and rigorous evaluation of groundwater under domestic landfills. The OFSP model developed in the study in line with VFS and optimized N.L. Nemerow index, which has been equipped with both the optimized double judgment approach and the "P_i" equation of N.L. Nemerow index, can significantly enhance the precision and robustness of the groundwater quality evaluation of domestic waste landfill. Thus, the proposed model can achieve the reasonable groundwater quality assessment model, the stable groundwater quality evaluation process, and the convincing evaluation results. In order to clarify the comprehensive impacts of domestic landfills in different regions and types on groundwater pollution, and demonstrate the effectiveness of OFSP, a case study on groundwater quality assessment of various domestic landfills in China is conducted. The experiment results show that the OFSP model could get a scientific conclusion of comprehensive impacts, and could play a good performance on groundwater quality evaluation in domestic landfills, compared with other mainstream models. As such, the OFSP model proposed in this study would be a reliable tool for environmental managers and engineers to evaluate groundwater in domestic landfills.

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Data availability The data that supports the findings of this study are available within the article (and its supplementary material).

Declarations

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Consent for publication Yes

Conflict of interest The authors declare that they have no conflict of interest.

References

Aderemi A, Oriaku AV, Adewumi GA, Otitoloju A (2011) Assessment of groundwater contamination by leach ateneara municipal solid waste landfill. Afr J Environ Sci Technol 5:933–940

Amiri V, Rezaei M, Sohrabi N (2014) Groundwater quality assessment using entropy weighted water quality index (ewqi) in Lenjanat, Iran. Environ Earth Sci 72:3479–3490

Aunnop W, Rakruam P, Siri A, Siyasukh A (2019) Synthesis of porous pig bone char as adsorbent for removal of DBP precursors from surface water. Water Sci Technol J Int Assoc Water Pollut Res 79(5):857–865

Bahroz A (2015) Leachate and ground water assessment at kirkuk sanitary landfill site in Zindana Village, Iraq. Int J Environ Res 9:457–466

Beck AT, Epstein N, Brown G, Steer RA (1988) An inventory for measuring clinical anxiety: Psychometric properties. J Consult Clin Psychol 56:893–897

Beheshti S (2019) Detection of extraneous water ingress into the sewer system using tandem methods - a case study in Trondheim city[J]. Water Sci Technol J Int Assoc Water Pollut Res 79:231–239

Biswas AK, Kumar S, Babu S, Bhattacharyya JK, Chakrabarti T (2010) Studies on environmental quality in and around municipal solid waste dumpsite. Resour Conserv Recycl 55:129–134

Browska DD, Witkowski A, Soltysiak M (2018) Representativeness of the groundwater monitoring results in the context of its methodology: case study of a municipal landfill complex in Poland. Environ Earth Sci 77:266–287

Chen Y, Yeh H, Wei C (2012) Estimation of river pollution index in a tidal stream using kriging analysis. Int J Environ Res Public Health 9:3085–3100

Chen F, Fu B, Xia J, Wu D, Wu S, Zhang Y, Sun H, Liu Y, Fang X, Qin B, Li X, Zhang T, Liu B, Dong Z, Hou S, Tian L, Xu B, Dong G, Zheng J, Yang W, Wang X, Li Z, Wang F, Hu Z, Wang J, Liu J, Chen J, Huang W, Hou J, Cai Q, Long H, Jiang M, Hu Y, Feng X, Mo X, Yang X, Zhang D, Wang X, Yin Y, Liu X (2019) Major advances in studies of the physical geography and living environment of china during the past 70 years and future prospects. Sci China-Earth Sci 62:1665–1701

Chonattu J, Prabhakar K, Pillai HPS (2016) Geospatialandstatistical assessment of groundwater contamination due to landfill leachate—a case study. J Water Resourc Protect 08:121–134

Cipranic I, Markovic R, Đorđievski S, Stevanovic Z, Stevanovic M (2019) The impact of coal ash and slag dump on the quality of surface and groundwaters–acasestudy (note). J Serbian Chem Soc 84:527–530

Cumar SKM, Nagaraja B (2011) Environmental impact of leachate characteristics on water quality. Environ Monit Assess 178:499–505

Dadzie AA, Yuan L, Xing S et al (2020) Survey and assessment of metals distribution in the overlying water of the representative lake and rivers in Zhenjiang, China. SN Applied Sciences 2(4)

Deshmukh K, Aher S (2016) Assessment of the impact of municipal solid waste on groundwater quality near the Sangamner City using GIS approach. Water Resour Manag 30:1–14

Fang X, Su Y, Yin J, Teng JC (2015) Transmission of climate change impacts from temperature change to grain harvests, famines and peasant uprisings in the historical China[J]. Sci China-Earth Sci 58(8):1427–1439

Grisey E, Aleya L (2016) Assessing the impact of leachate plumes on groundwater quality in the Etueffont Landfill (Belfort, France). Environ Earth Sci 75:913–922

Han Z, Ma H, Shi G, He L, Wei L, Shi Q (2016) A review of groundwater contamination near municipal solid waste landfill sites in China. Sci Total Environ 569:1255–1264

Hoseinzadeh E, Khorsandi H, Wei C, Alipour M (2015) Evaluation of Aydughmush river water quality using the national sanitation foundation water quality index (nsfwqi), river pollution index (rpi), and forestry water quality index (fwqi). Desalin Water Treat 54:2994–3002

Jeykumar RKC, Chandran S (2018) Influence of city municipal waste disposal on groundwater quality and assessment of groundwater suitability in agriculture. Global Nest J 20:333–344

Jingyun Z, Xiuqi F, Shaohong WU (2018) Recent progress of climate change research in physical geography studies from China. Prog Geogr 37:16–27

Kanmani S, Gandhimathi R (2013) Assessment of heavy metal contamination in soil due to leachate migration from an open dumping site. Appl Water Sci 3(1):193–205

Kapelewska J, Kotowska U, Karpinska J, Astel A, Zielinski P, Suchta J, Algrzym K (2019) Water pollution indicators and chemometric expertise for the assessment of the impact of municipal solid waste landfills on groundwater located in their area. Chem Eng J 359:790–800

Krčmar D, Tenodi S, Grba N, Kerkez D, Watson M, Rončević S, Dalmacija B (2018) Preremedial assessment of the municipal landfill pollution impact on soil and shallow groundwater in Subotica, Serbia. Sci Total Environ 615:1341–1354

Li J, Shao Y, Qi X (2020) On variable-precision-based rough set approach to incomplete interval-valued fuzzy information systems and its applications[J]. J Intell Fuzzy Syst 1:1–12

Liao R, Jiang J, Li Y et al (2020) Distribution and leaching behavior of organophosphorus and brominated flame retardants in soil in Chengdu[J]. Environ Ence: Processes & Impacts 22:1–19

Locosselli GM, de Camargo EP, TCL M (2019) The role of air pollution and climate on the growth of urban trees. Sci Total Environ 666: 652–661

Magda M, Abd E-S, Gaber I, Abu-Zuid (2014) Impact of landfill leachate on the groundwater quality: a case study in egypt. J Adv Res 6:579–586

Maitia SK, Dea S, Hazrab T, Debsarkarb A, Duttab A (2016) Characterization of leachate and its impact on surface and groundwater quality of a closed dumpsite – a case study at Dhapa, Kolkata, India. Procedia Environ Sci 35:391–399

Manimekalai B (2012) Analysis of leachate contamination potential of a municipal landfill using leachate pollution index. IOSR J Environ Scie Toxicol Food Technol 2:16–39

Mishra H, Rathod M, Karmakar S, Kumar R (2016) A framework for assessment and characterisation of municipal solid waste landfill leachate: an application to the Turbhe Landfill, Navi Mumbai, India. Environ Monit Assess 188:357–369

Mohebbi MR, Saeedi R, Montazeri A, Vaghefi KA, Mohagheghian A (2013) Assessment of water quality in groundwater resources of Iran using a modified drinking water quality index (dwqi). Ecol Indic 30: 28–34

Molinos-Senante M, Maziotis A, Sala-Garrido R (2015) Estimating the cost of improving service quality in water supply: a shadow price approach for England and wales[J]. Sci Total Environ 539:470–477

Mor S, Khaiwal R, Dahiya RP, Chandra A (2006) Leachatecharacterization and assessment of groundwater pollution near municipal solid waste landfill site. Environ Monit Assess 118: 435–456

Nagarajan R, Thirumalaisamy S, Lakshumanan E (2012) Impact of leachate on groundwater pollution due to non-engineered municipal solid waste landfill sites of erode city, Tamilnadu, India. Iran J Environ Health Sci Eng 9:35–55

Nambiar R, Shah C, Kumar J et al (2020) Assessment of contaminants in the northwestern Bay of Bengal. Environ Sci Pollut Res 27(27): 34090–34098

Nathan NS, Saravanane R, Sundararajan T (2018) Statistical evaluation of the effect of secondary municipal wastewater and solid waste leachate on groundwater quality at law Spetinpuducherry, India. Environ Prot Eng 44:101–120

National Bulletin on Soil Pollution Status (2014) Ministry of Environmental Protection. Ministry of Land and Resources, China

Ocampoduque W, Ferrehuguet N, Domingo JL, Schuhmacher M (2006) Assessing water quality in rivers with fuzzy inference systems: a case study. Environ Int 32:733–742

Osborne LL, Kovacic DA (2010) Riparian vegetated buffer strips in water-quality restoration and stream management. Freshw Biol 29(2):243–258

Rana R, Ganguly R, Gupta AK (2018) Indexingmethodforassessment of pollution potential of leachate from non-engineered landfill sites and its effect on ground water quality. Environ Monit Assess 190:46–57

Reymond DJ, Sudarsan JS, Annadurai R, Nithiyanantham S (2019) Groundwater quality around municipal solid waste dump in Tiruchirappalli (South India). Int J Environ Sci Technol 16:7375–7392

San V, Spoann V, Schmidt J (2018) Industrial pollution load assessment in Phnom Penh, Cambodia using an industrial pollution projection system. Sci Total Environ 615:990–999

Shao J, Huang Z, Deng H (2018) Characteristics of nonpoint source pollution load from crop farming in the context of livelihood diversification. J Geogr Sci 28:459–476

Shuang, Z., Zhou, J., Xie, M., Jiang, W., & Ding, X. (2016). A hybrid model integrated variable fuzzy set theory and set pair analysis for water quality assessment in Huai river basin. In 2016 IEEE International Conference on Knowledge Engineering and Applications (ICKEA),1,1-20.

Singh S, Raju NJ, Gossel W, Wycisk P (2016) Assessment of pollution potential of leachate from the municipal solid waste disposal site and its impact on groundwater quality, Varanasi Environs, India. Arab J Geosci 9:131–142

Smahi D, Hammoumi OE, Fekri A (2013) Assessment of the impact of the landfill on groundwater quality: a case study of the Mediouna Site, Casablanca, Morocco. J Water Resourc Protect 5:440–445

Su M, Yang Z, Chen B (2009) Set pair analysis for urban ecosystem health assessment. Commun Nonlinear Sci Numer Simul 14: 1773–1780

Su S, Chen X, Degloria SD, Wu J (2010) Integrative fuzzy set pair model for land ecological security assessment: acase study of Xiao Lang Dire Servoir Region, China. Stoch Env Res Risk A 24:639–647

Tamiris C, de Souza LF, dos Santos Ramos N, da Silva Aparecida B. (2019) Use of chemically activated termite feces a low-cost adsorbent for the adsorption of norfloxacin from aqueous solution. Water Sci Technology: a journal of the International Association on Water Pollution Research

Tenodi S, Krčmar D, Agbaba J, Zrnić K, Radenović M, Ubavin D, Dalmacija B (2020) Assessment of the environmental impact of sanitary and unsanitary parts of a municipal solid waste landfill. J Environ Manag 258:110–119

Teta C, Hikwa T (2017) Heavy metal contamination of ground water from an unlined landfill in Bulawayo, Zimbabwe. J Health Pollut 7:18–27

Vasanthavigar M, Srinivasamoorthy K, Vijayaragavan K, Ganthi RR, Chidambaram S, Anandhan P, Manivannan R, Vasudevan S (2010) Application of water quality index for groundwater quality assessment: Thirumanimuttar sub-basin, Tamilnadu, India. Environ Monit Assess 171:595–609

Verma P, Khosa SK (2020) Theoretical Study of Signature-splitting and Signature-inversion in Doubly-odd Nuclei in A 80 Mass Region. J Phys Conf Ser 1531:012010

Wang X, Zhao R, Hao Y (2011) Flood control operations based on the theory of variable fuzzy sets. Water Resour Manag 25:777–792

Wang X, Zou Z, Zou H (2013) Water quality evaluation of Haihe River with fuzzy similarity measure methods. J Environ Sci (China) 25: 2041–2046

Wu Z, Wang X, Chen Y, Cai Y, Deng J (2018) Assessing river water quality using water quality index in Lake Taihu Basin, China. Sci Total Environ 612:914–922

Wu DL, Zhang M, He LX, Zou HY, Liu YS, Li BB et al (2020) Contamination profile of antibiotic resistance genes in ground water in comparison with surface water. Sci Total Environ 715:136975.1–136975.9

Xi Chen GW, Wang F (2019) Classification of stable isotopes and identification of water replenishment in the Naqu River Basin, Qinghai-Tibet Plateau. Water 1:11–46

Xin X, Yin W, Li K (2017) Estimation of non-point source pollution loads with flux method in Danjiangkou Reservoir Area, China. Water Sci Eng 10:134–142

Xu S, Tianxiang W, Suduan H (2015) Dynamic assessment of water quality based on a variable fuzzy pattern recognition model. Int J Environ Res Public Health 12:2230–2248

Yan A, Zhihong Z, Ranran L (2014) Water quality assessment in the Harbin reach of the Songhuajiang River (China) based on a fuzzy rough set and an attribute recognition theoretical model. Int J Environ Res Public Health 11:3507–3520

Yan F, Liu L, Zhang Y, Chen M, Chen N (2016) The research of dynamic variable fuzzy set assessment model in water quality evaluation. Water Resour Manag 30:63–78

Yan Z, Xu J, Ruan X (2019) An improved source apportionment mixing model combined with a Bayesian approach for nonpoint source pollution load estimation. Hydrol Res 50:849–860

Zaharia C, Suteu D (2011) Analytical control of soil and ground water quality on a northern Romanian solid waste landfill. Environ Eng Manag J 10:1693–1701

Zhang D, Wang G, Zhou H (2011) Assessment on agricultural drought risk based on variable fuzzy sets model. Chin Geogr Sci 21:167–175

Zheng D, Yang QY, Wu SH (2015) General Introduction to physical geography of China (in Chinese), 1st edn. Science Press, Beijing, pp 767–778

Zou Z, Yun Y, Sun J (2006) Entropy method for determination of weight of evaluating indicators in fuzzy synthetic evaluation for water quality assessment. J Environ Sci-China 18:1020–1033