Multi-criteria analysis via the VIKOR method for prioritizing groundwater remediation strategies

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Abstract. The multiple criteria decision making (MCDM) methods VIKOR is applied to the selection of the most desirable remediation for a chlorinated hydrocarbons-contaminated aquifer located in Pudong district of Shanghai. Ranking index based on the particular measure of ‘‘closeness’’ to the ideal solution is introduced. Five influential criteria (i.e. daily total pumping rate, total cost, average remaining contaminant concentration, maximum excess life time cancer risk and remediation period) and 8 alternative remediation strategies were considered. It is found that A2 is the most appropriate remediation strategy among the alternatives.

Introduction

The increasing scarcity and degradation of groundwater resources has been contaminated seriously by organic pollutants since they are toxic and with long cycle, causing considerable remediation cost and time [1, 2]. This is an issue of global concern and is urgently needed to take the innovative remediation technologies. Pump and treat (PAT) have been identified as one of the established techniques to improve the remediation effectiveness of contaminated aquifers. In this system, contaminated groundwater is extracted from the subsurface by pumping, then treated over-ground through remediation technologies and finally injected to confine the pollutant plume and decontaminating groundwater effectively [3, 4].

Multicriteria decision making (MCDM) that contains multiple decision criteria and multiple decision alternatives is able to deal with such discrete decision problems, which is considered as a one of the most prevalent decision method for conflict management aiming to find the most desirable alternative from a set of available alternatives [5]. Based on the particular measure of ‘‘closeness’’ to the ‘‘ideal’’ solution, VIKOR can identify a compromise solution and criteria weights, and select and rank from a set of alternatives in the conflicting criteria among the MCDA methods [6]. In this study, VIKOR method is used for evaluating the performance of alternatives for identifying the most desirable groundwater remediation strategy in China.

Methodology

To summarize the methodology, the steps of the VIKOR approach are given in the following:

Step 1: Identify the alternatives with respect to evaluation criteria. The various alternatives are denoted as A={A_1; A_2, …, A_i, …, A_m}. Letting C={C_1,C_2,…C_j, …, C_n} be a criteria set. f_{ij} is the value of jth criterion function for the alternative A_i.

Step 2: Define weight w = {w_1, w_{t2}, …, w_j, …,w_n} to the corresponding criteria. Based on pairwise comparisons, Analytic Hierarchy Process (AHP) is used to determine the relative importance of selection criteria.

Step 3: Determine the maximum f_j^* and the minimum f_j^- values of all criterion functions.

$$f_j^* = \max_i \left[(f_{ij}) \mid i = 1, 2, ..., \mathrm{m} \right] \tag{1}$$

$$f_j^- = \min_i \left[(f_{ij}) \mid i = 1, 2, ..., \mathrm{m} \right] \quad (2)$$

Step 4: Compute the utility measure S_i and the regret measure R_i.

$$S_i = \sum_{j=1}^{n} w_j (f_j^* - f_{ij}) / (f_j^* - f_j^-) \quad (3)$$

$$R_i = \max_j \left[w_j (f_j^* - f_{ij}) / (f_j^* - f_j^-) \right] \quad (4)$$

Step 5: Compute the restriction index Q_i.

$$Q_i = v(S_i - S^*) / (S^- - S^*) + (1 - v)(R_i - R^*) / (R^- - R^*) \quad (5)$$

$$S^* = \min S_i ; S^- = \max S_i ; R^* = \min R_i ; R^- = \max R_i \quad (6)$$

where v is introduced as the weight of the strategy of the maximum group utility.

Step 6. Rank the alternatives according to the values *S*, *R* and *Q* in decreasing order. The larger the value of *Q* is, the better decision of the alternatives is. The alternative which is ranked the best by the minimum *Q* should be considered as compromise solution (*A'*) if the following two conditions are satisfied: (1) $Q(A'') - Q(A') \geq 1/(m-1)$, *A"* is the alternative with second position in the ranking list; (2) *A'* must also be the best ranked by *S* or/and *R*.

Results

This method is applied to a contaminated aquifer that located in Pudong district of Shanghai to demonstrate the applicability of the approach. The study area is engaged in the production of automobile air conditioning system. During the production of automobile air conditioner, barrels for liquid storage had been placed directly on the asphalt and was not covered, contaminating the surrounding soils and groundwater seriously. Two injection wells and four extraction wells are built in this area. Eight monitoring wells are designed in the system to identify contaminant, concentration.

The alternatives with respect to criteria are evaluated as presented in Tables 1. In this study, eight alternative remediation strategies and five influential criteria is considered. C_1 is the daily total pumping rate of injection/extraction wells in the containment system. C_2 is total cost during the groundwater remediation process. C_3 is the average remaining contaminant concentration at all monitoring wells. C_4 is the maximum excess life time cancer risk which could measure the degree of human health risks. C_5 is the remediation period.

Table 1 Evaluation matrix of each alternative

Action	C_1	C_2	C_3	C_4	C_5
A_1	92.969	65.661	0.838	32.703	5
A_2	97.862	68.533	0.732	27.680	5
A_3	73.397	97.249	0.795	24.845	10
A_4	78.290	102.993	0.634	29.892	10
A_5	58.717	114.479	0.981	24.057	15
A_6	53.824	105.864	1.051	24.128	15
A_7	48.931	125.966	1.445	36.327	20
A_8	44.038	114.479	1.299	25.680	20

Table 2 lists the dimensionless criteria selected for multi-criteria analysis. The five criteria belong to cost criteria (i.e., a smaller value indicates a greater preference), not benefit criteria (i.e., a larger value indicates a greater preference). Table 3 list the maximum f_j^* and the minimum f_j^- values.

Table 2 Dimensionless criteria for multi-criteria analysis

Action	C_1	C_2	C_3	C_4	C_5
A_1	0.474	1.000	0.757	0.736	1.000
A_2	0.450	0.958	0.866	0.869	1.000
A_3	0.600	0.675	0.797	0.968	0.500
A_4	0.562	0.638	1.000	0.805	0.500
A_5	0.750	0.574	0.646	1.000	0.333
A_6	0.818	0.620	0.603	0.997	0.333
A_7	0.900	0.521	0.439	0.662	0.250
A_8	1.000	0.574	0.488	0.937	0.250

Table 3 Maximum f_j^* and the minimum f_j^-

	C_1	C_2	C_3	C_4	C_5
f_j^*	1.000	1.000	1.000	1.000	1.000
f_j^-	0.450	0.521	0.439	0.662	0.250

In the next step, the pairwise comparisons of the evaluation criteria and the criteria weights are obtained as in Table 4. It should be noted that the consistency ratio for the evaluation matrix should be checked less than 0.10. Therefore, the comparison results can be considered consistent. We could gather that the weight of C_4 is higher than other, followed by C_5, C_2, C_3, C_1, indicating that the degree of importance for C_4 is higher for decision makers.

Table 4 Evaluation matrix for the weights

	C_1	C_2	C_3	C_4	C_5	Weight
C_1	1.000	0.500	0.500	0.500	0.500	0.109
C_2	2.000	1.000	1.000	0.500	1.000	0.189
C_3	2.000	1.000	1.000	0.500	0.500	0.165
C_4	2.000	2.000	2.000	1.000	1.000	0.287
C_5	2.000	1.000	2.000	1.000	1.000	0.250

Then, S_i, R_i and Q_i values are computed, as shown in Table 5. In the calculations, v is assumed to be 0.5. Finally, the ranked results is listed according the S_i, R_i and Q_i index values in Table 5. As we can see, A_2 that has the highest Q index value can be seemed as the most desirable alternative obtained from the proposed method, thus this strategies should be implemented in priority. Simultaneously, A_7 is identified as the worst remediation design approach.

Table 5 Values and ranking orders of S, R and Q

Action	Value_*S*	Value_*R*	Value_*Q*	Rank_*S*	Rank_*R*	Rank_*Q*
A_1	0.400	0.224	0.420	2	6	4
A_2	0.276	0.111	0.000	1	1	1
A_3	0.461	0.167	0.304	3	2	2
A_4	0.562	0.167	0.383	6	3	3
A_5	0.544	0.222	0.527	5	4	6
A_6	0.527	0.222	0.514	4	5	5
A_7	0.911	0.287	0.999	8	8	8
A_8	0.622	0.250	0.668	7	7	7

Fig. 1 presents the optimal extracting and pumping rates for the most desirable groundwater remediation design approach A_2. As shown, the pumping rate for extracting and injecting wells is different. Well I1 takes most of the injecting rate in the injecting section. Extracting rates at four extraction wells shows no remarkable change. Wells E2 and E4 play the same role in extracting rates. Wells E1 account for a small fraction compared with other extraction wells.

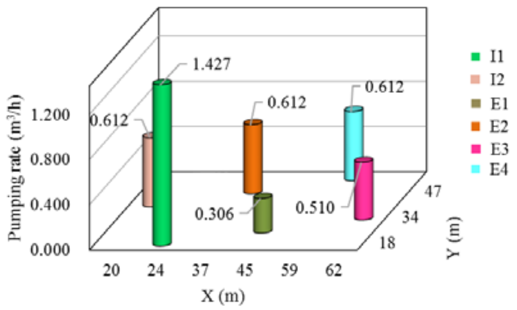

Fig. 1 Optimal pumping rates at each wells for the most desirable remediation approach

Fig. 2 shows the excess life time cancer risk levels for the entire contaminated area. For fig. 2, the peak concentration of contamination migrates southeast, consistent with the flow direction of groundwater. For 5-year remediation period, the pollutant concentration at the entire contaminated site is decreased. The area around well M5 has the highest carcinogenic risk and the southern site has relatively lower carcinogenic risk. Thus, the appropriate adjustments should be strengthened according to the environmental standards and excess life time cancer risk levels after 5 years of remediation.

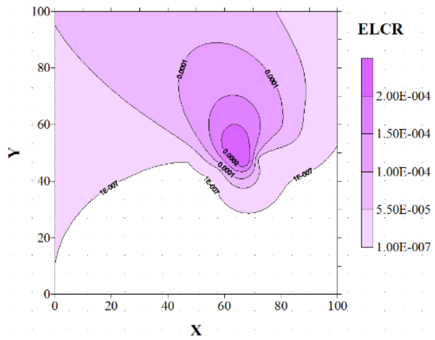

Fig. 2 Excess life time cancer risk levels for the entire contaminated area

Summary

This study applied the VIKOR method to determine the priority ranking of groundwater remediation strategies for a chlorinated hydrocarbons-contaminated aquifer. Five criteria, including daily total pumping rate, total cost, average remaining contaminant concentration, maximum excess life time cancer risk and remediation period, were considered. The criteria weights are determined by AHP method. The compromise solution is determined by S_i, R_i and Q_i. The analytical results show that A_2 is the most potential alternatives among the set of candidates. In the future research, more studies can be conducted based on different multi-criteria decision-making techniques.

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