# Inexact multi-attribute decision analysis of groundwater remediation strategies with inputs of interval data

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**Abstract.** This study introduced an inexact interval-based multi-attribute decision analysis (IMADA) method with AHP for identifying the compromised groundwater remediation strategies in different periods. This IMADA method has the following advantages: (1) provides a systematic and quantitative analysis procedure for comparing potential pumping alternatives under four remediation duration; (2) reflects the priorities of the project based on the points of view of different decision makers; (3) compromises among possibly tangible and intangible attributes according to a final ranking of pumping alternatives. The method is applied to a contaminated aquifer located in southeastern China, where a period of remediation action should be taken. Ten influential attributes were considered and 50 alternative remediation strategies were generated. Results from the case study indicate that action 48 is the optical remediation strategy under 5-year period, action 5 in 10-year, action 33 during 15-year period and action 26 in 20-year.

## 1 Introduction

Due to the rapid development of the city and industrial transformation, the problem of groundwater pollution in industrial sites has become increasingly prominent due to the "running and leaking" caused by the aging of industrial enterprise facilities and the illegal disposal of waste materials [1, 2]. The condition is potential, imperceptible, persistence, toxicity and long-range migration. As one of the most widely physical method, pump and treat (P&T) can remove contaminants directly through flushing and collecting the contaminants from a highly risky zone [3, 4].

Previously, multi-attribute decision analysis (MADA) method has been undertaken for determining the optimal remediation strategies [5, 6]. As a matter fact, identification of a suitable groundwater remediation technology is a complex process and involves many inexactness and/or imprecision, which affect the proposed design significantly [7]. However, the lack of dealing with such inexactness or imprecision may mislead eventual decision-making reliability and even cause the remediation performance to be far from the real one. Thus, the uncertainty regarding whether the groundwater strategy will significantly increase with the uncertain parameters. At present, interval analysis has been demonstrated effective in dealing with inexact information, with its lower- and upper-bounds being known yet the specific distribution functions being unclear. Motivated by this, the present study aims to evaluate the effectiveness of the interval-based multi-attribute decision analysis (IMADA) approach for groundwater remediation.

## 2 Methodology

### 2.1 Interval analysis

A two-dimensional multiphase and multicomponent model were introduced since it provides data support to determination of contaminant concentrations, one of attributes selected by IMADA. The model incorporates a variety of physical, chemical, and biological processes for simulating the fate and transport of contaminants in the groundwater under different remediation alternatives. This model is capable not only of accommodating multiple mobile phases (i.e. water, NAPL and gas), but also of identifying the flow of fluid phases, mass transfer of species between phases, and transport of species in each phase. The basic mass conservation equation for constituents in the subsurface can be written as follows [8, 9]:

$$R_k = \frac{\partial}{\partial t}\left(\phi \tilde{C}_k \rho_k\right) + \dot{\nabla} \cdot \left[\sum_{l=1}^{n_p} \rho_k \left(C_{kl} \dot{u}_l - \phi S_l \dot{D}_{kl} \dot{\nabla} C_{kl}\right)\right] \quad (1)$$

### 2.2 Interval analysis

Interval analysis is also detailed as required by the IMADA procedures. In this analysis, total cost (*TC*) and remaining contaminant concentration (*RCC*) are treated as interval numbers with known upper and lower bounds but unknown distribution information, respectively. Take *TC* as an example:

$$TC_{it} = [TC_{it}^L, TC_{it}^U] = \left\{TC_{it} \mid TC_{it}^L, \le TC_{it} \le TC_{it}^U\right\} \quad (2)$$

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where $TC_{it}$ is the original data for action $A_i$ under the criterion $TC$ during $t$ period; $TC_{it}^L$ and $TC_{it}^U$ are the lower and upper bounds of $TC_{it}$, respectively. When $TC_{it}^L = TC_{it}^U$, $TC_{it}$ becomes a deterministic number. A natural definition of arithmetic for intervals follows from elementary properties of the inequality relation and binary operation. For $TC_{it}$ and $TC_{jt}$, we have:

$$TC_{it}+TC_{jt}=[TC_{it}^L+TC_{jt}^L, TC_{it}^U+TC_{jt}^U] \tag{3}$$

$$TC_{it}+TC_{jt}=[TC_{it}^L-TC_{jt}^U, TC_{it}^U-TC_{jt}^L] \tag{4}$$

$$TC_{it}\times TC_{jt}=[\min\{TC_{it}\times TC_{jt}\}, \max\{TC_{it}\times TC_{jt}\}], TC_{it}^L\le TC_{it}\le TC_{it}^U, TC_{jt}^L\le TC_{jt}\le TC_{jt}^U \tag{5}$$

$$TC_{it}\div TC_{jt}=[\min\{TC_{it}\div TC_{jt}\}, \max\{TC_{it}\div TC_{jt}\}], TC_{it}^L\le TC_{it}\le TC_{it}^U, TC_{jt}^L\le TC_{jt}\le TC_{jt}^U \tag{6}$$

### 2.3 Interval multi-attribute decision analysis

Large spatial variability and uncertainty can be encountered during determination of a groundwater remediation strategy. Previously, interval number has been shown good performance in addressing uncertainties when it is unclear the exact value of a parameter, with its upper and lower bounds being available. Therefore, interval numbers are allowed for by the multi-attribute decision analysis, and an improved tool (i.e., IMADA) is proposed based on traditional MADA methods. The detailed methodologies of IMADA are discussed below:

Step 1: Suppose there are m possible alternatives $A = \{A_{1t}, A_{2t}, \ldots, A_{nt}\}$ and $n$ attribute $C = \{C_{1t}, C_{2t}, \ldots, C_{mt}\}$ during $t$ period, $OD_{ikt}$ is the original data for action $A_i$ under the attribute $C_k$ during $t$ period ($i = 1, 2, \cdots, m$; $k=1, 2, \cdots, n$). The following ten attributes are described in detail:

① *TPV* is total pumping volume for ten wells in each period ($10^6$ $m^3$).

Step 2: Calculate the normalized decision matrix. The pairwise normalized matrix $SD_{ikt}$ is obtained by normalizing the comparison matrix $OD_{ikt}$.

$$SD_{ikt}^L=\frac{\frac{1}{OD_{ikt}^U}}{\sum_{i=1}^{m}\frac{1}{OD_{ikt}^L}} \tag{7}$$

$$SD_{ikt}^U=\frac{\frac{1}{OD_{ikt}^L}}{\sum_{i=1}^{m}\frac{1}{OD_{ikt}^U}} \tag{8}$$

Step 3: Calculate the weight $w= \{w_{1t}, w_{2t}, \ldots, w_{nt}\}$ of the $j$ attribute for the $i$ alternative through analytical hierarchy process (AHP) by using the pairwise comparison matrix basis of judgment formation.

$$w_{kt}\ge 0 \text{ and } \sum_{k=1}^{n} w_{kt}=1, \quad i=1, 2\ldots, n \tag{9}$$

Step 4: Determining the preference index. The preference of alternative $A_{it}$ over alternative $A_{i't}$ for a particular $C_{kt}$ can be determined by means of this preference degree $P(OD_{ikt}, OD_{i'kt})$. *sine* preference function is used to deal with the uncertain situation.

$$P(OD_{ikt}, OD_{i'kt})=\begin{cases}0 & p(SD_{ikt}\le SD_{i'kt})\le 0.5\\ \sin\left[\frac{\pi}{2}\tilde{d}_2(SD_{ikt}, SD_{i'kt})\right] & p(SD_{ikt}\le SD_{i'kt})>0.5\end{cases} \tag{10}$$

$$p(SD_{i'kt}\le SD_{ikt})=\max\left\{1-\max\left\{(SD_{i'kt}^U-SD_{ikt}^L)/\left[(SD_{i'kt}^U-SD_{i'kt}^L)+(SD_{ikt}^U-SD_{ikt}^L)\right],0\right\},0\right\} \tag{11}$$

$$\tilde{d}_2(SD_{ikt}, SD_{i'kt})=\sqrt{\frac{(SD_{ikt}^L-SD_{jkt}^L)^2+(SD_{ikt}^U-SD_{jkt}^U)^2}{2}} \tag{12}$$

If $p(SD_{i'kt}\le SD_{ikt})$ =0, which means the value of $SD_{ikt}$ is less than $SD_{i'kt}$ completely. If $p(SD_{i'kt}\le SD_{ikt})$ =1, which means the value of $SD_{ikt}$ is larger than $SD_{i'kt}$ completely. $\tilde{d}_2(SD_{ikt}, SD_{i'kt})$ is the norm of interval grey numbers between $SD_{ikt}$ and $SD_{i'kt}$.

Step 5: The marginal preference index $\pi(A_{ikt}, A_{i'kt})$ is calculated by considering the attribute weights $w_{kt}$:

$$\pi(A_{it}, A_{i't})=\sum_{k=1}^{n} w_{kt}P(OD_{ikt}, OD_{i'kt}) \tag{13}$$

Step 6: Compute the outranking flows for alternative $A_{it}$.

$$\phi^+(A_{it})=\sum_{i=1}^{m}\pi(A_{it}, A_{i't})=\sum_{i=1}^{m}\sum_{k=1}^{n} w_{kt}P(OD_{ikt}, OD_{i'kt}) \tag{14}$$

$$\phi^-(A_{it})=\sum_{i=1}^{m}\pi(A_{i't}, A_{it})=\sum_{i=1}^{m}\sum_{k=1}^{n} w_{kt}P(OD_{ikt}, OD_{i'kt}) \tag{15}$$

Step 7: Obtain the net outranking flow $\phi(A_{it})$ for each alternative. The higher, the more key the monitoring point is the best groundwater remediation alternative.

$$\phi(A_{it})=\phi^+(A_{it})-\phi^-(A_{it}) \tag{16}$$

## 3 Results

A real-world contaminated aquifer in coal-fired power plant located in Anhui located in southeastern China was selected as a case study, where a most-desirable remediation strategy was required to be determined. A total of 2 injection, 4 extraction, and 8 monitoring wells were installed in or around the plume. To identify the most desirable groundwater remediation strategies under various remediation periods, ten influential attributes at each monitoring well, i.e. total pumping volume (*TPV*), total cost (*TC*) and remaining contaminant concentration (*RCC*) at each monitoring well, were considered and 50 alternative remediation strategies were generated for four remediation periods (i.e. 5, 10, 15 and 20 years).

The detailed evaluation of ten attributes and their corresponding weights (Table 1) for different remediation duration are determined. The pair-wise comparison matrix of weights and the preference function for remediation duration were determined according to questionnaire survey from related experts and stakeholders. Compared with that of 5-year period, the weight of cost would increase from 0.191 to 0.275 and the weight of *RCC*5 would be adjusted from 0.372 to 0.253 when the remediation time is 10 years. Because remediation of a large aquifer with serious concentration distribution is a time-consuming and costly process, the weights of pumping rate and cost during 20-year periods are increased as 0.157 and 0.385, respectively.

**Table 1.** Attribute weights for four remediation durations

| Years | *TPV* | *TC* | *RC C* 1 | *RC C* 2 | *RC C* 3 | *RC C* 4 | *RC C* 5 | *RC C* 6 | *RC C* 7 | *RC C* 8 |
|---|---|---|---|---|---|---|---|---|---|---|
| 5 | 0.03 | 0.191 | 0.034 | 0.105 | 0.046 | 0.094 | 0.372 | 0.046 | 0.033 | 0.051 |
| 10 | 0.041 | 0.275 | 0.041 | 0.097 | 0.041 | 0.145 | 0.253 | 0.044 | 0.2 | 0.043 |
| 15 | 0.109 | 0.318 | 0.043 | 0.073 | 0.041 | 0.176 | 0.149 | 0.043 | 0.023 | 0.025 |
| 20 | 0.157 | 0.385 | 0.048 | 0.062 | 0.036 | 0.1 | 0.105 | 0.044 | 0.031 | 0.023 |

Ten evaluation attributes for fifty alternatives can be ranked according to the IMADA procedure, and the results is listed in Table 2. According to the results, it can be obtained that the rank orders of fifty alternatives in different remediation periods are completely different. The one with the maximum net outranking flow value would be the most preferable groundwater remediation strategy, i.e A48 for 5-year, A5 for 10-year, A33 for 15-year, A26 for 20-year.

**Table 2.** Top 5 groundwater remediation for the for pumping periods

| Rank | 5 years | 10 years | 15 years | 20 years |
|---|---|---|---|---|
| 1 | A48 | A5 | A33 | A26 |
| 2 | A41 | A33 | A50 | A25 |
| 3 | A33 | A24 | A14 | A30 |
| 4 | A39 | A30 | A24 | A37 |
| 5 | A1 | A40 | A36 | A6 |

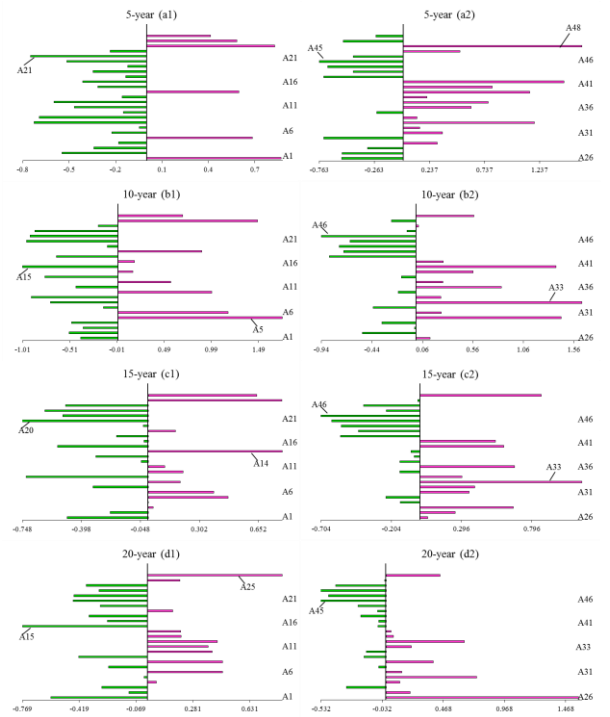


**Fig. 1**. Performance of net outranking flow for each alternative under four remediation scenarios in terms of IMADA

According to Fig. 1a, actions 48 and 45 were determined to be the best (most desirable) and worst (least desirable) alternatives in φ, respectively. On the one hand, action 48 has the highest φ+ value and the smallest φ- value among the alternatives, showing that the degree of action 48 dominating the other alternatives is remarkable. When ten attributes were used, the net flow values of the alternatives were calculated and their rankings were given. According to the IMADA results, it is obvious that action 48 ranks the first according to the value of net flow, indicating that it can be the most desirable remediation strategy for the 5 years of remediation. The application of IMADA to the 10-year remediation scenario produced the following results for φ (Fig. 1b). It can be seen that the entering flows of A24 was less than A5, showing that the outranking of action 24 dominated by all the other alternatives was better than action 5.

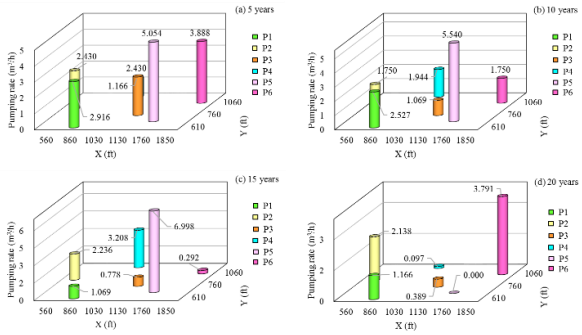


**Fig. 2.** Pumping rate at the injection and extraction wells for the optimal remediation strategies four remediation schemes.

Fig. 2 presents the optimal pumping rates for the most desirable remediation policies according to the four remediation periods. For example, during the 5 years period, the optimal pumping rates of action 48 at wells were 2.916, 2.430, 2.430, 1.166, 5.054 and 3.888 $m^3/h$, respectively. Well-pair P5 and P6 would be the most important contributors. The *TPV* of all the injection/extraction wells ranged from 0.324 to 0.988 × $10^6$ $m^3$. Fig. 1b shows the behaviors of the pumping rate of the injection/extraction wells for the most desirable actions under 10-year period. The minimum and maximum pumping rate of the candidate injection/extraction wells among these actions was limited to 0.097 and 7.193$m^3/h$, respectively. Well P5 would have the most significant remediation contributions to action 5, with its pumping rates being approximately 3 times that at wells P2, P4 and P6. The *TC* of remediation would be increased due to the increasing *TPV* and cleanup time, even though the total pumping rate remains unchanged.

The color turns to darker from the outer region to the center in all scenarios, which means that the contamination becomes more and more serious when moving from the center to the edge (Fig. 3). The peak *RCC* would migrate westward along with the flow direction of the groundwater. After 10 years of remediation, the peak RCC under action 5 would be 2.262 mg/L; though not yet satisfy the environmental requirements, it would have been closer to the environmental standard than that of 5-year period. Along with contamination migration in aquifers followed by groundwater flow, the peak *RCC* for action 33 would be about [0.358, 0.664] mg/L when the pumping duration was 15-year; this was 0.193 to 1.123 times higher than the environmental standard. This shows that 15 years of remediation, would dramatically mitigate the contamination compared to 5 and 10 years. Along with contamination migration in aquifers followed by groundwater flow, the *RCC* of

the area (in a range of 0.238 to 0.442 mg/L) that was located at near well M2 would slightly exceed the environmental standards and that of other contaminated area had satisfied the environmental standards in 20-year remediation duration.

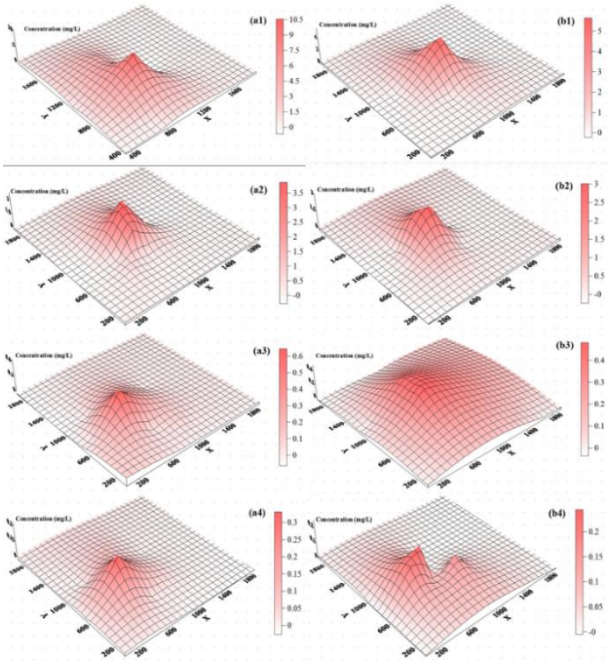


**Fig. 3.** The upper-bound (a1-a4) and lower-bound (b1-b4) of remaining concentrations (mg/L) after the optimal remediation action under four scenarios.

## 4 Discussion and Conclusion

This study introduced an interval multi-attribute decision analysis approach for identifying the compromised groundwater remediation strategies in different periods. To identify the most desired groundwater remediation strategies under various remediation periods, the input required concerns the assessment of ten influential attributes for 50 potential pumping alternatives considered, as well as the weightings needed to reflect their relative importance.

Results from the case study showed that: (1) action 48 is the most desirable remediation strategy under 5-year period and the intensity of contamination in each monitoring well still is considerably higher than the environmental standard; (2) action 5 is recommended as the most desired groundwater remediation strategy in 10-year remediation duration as the weight of M5 decreased; (3) action 33 becomes the most attractive option during 15-year period and the related pollution levels had fallen dramatically; (4) with the maximum weight of cost (i.e. 0.385), action 26 is selected as the best remediation design approach for contaminated groundwater in 20-year remediation process and the concentrations of most contaminated area had been met the environmental standards.

According to the result analysis, it can be obtained that the rank orders of fifty alternatives in different remediation periods are completely different due to the different attributes weights. Compared with that for other alternatives, the value of each evaluation attribute for proposed action is not minimum during each period, which illustrates that the IMADA method is applied to select a best subset of alternatives, not the optimal objective.

## Acknowledgements

This research was supported by the Second Tibetan Plateau Scientific Expedition and Research Program (STEP) (2019QZKK1003), the Key R&D Program of China (Grant No. 2020YFC1807904), National Natural Science Foundation of China (Grant No. 52079088).

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