The identification research of emergency treatment technology for sudden heavy metal pollution accidents in drainage basin based on D-S evidence theory

Yulan Luo, Ying Liu, Qianying Du, Qingsong Chen and Zhihui Cheng

ABSTRACT

As a sudden heavy metal pollution accident occurs in a drainage basin, decision makers need to quickly select the optimal emergency treatment technology and formulate emergency schemes according to the actual accident characteristics. Therefore, a two-step identification method of emergency treatment technology for sudden heavy metal pollution accidents based on Dempster-Shafer (D-S) evidence theory is proposed, in order to screen the optimal emergency treatment technology effectively and solve the conflict among fusion data in the process of index quantification. Firstly, the available technologies were screened preliminarily by the primary identification indexes (technical characteristic indexes). Secondly, the weight synthesis method based on the D-S evidence theory and attribute assignment was utilized to score the secondary identification indexes (technical evaluation indexes) of each available technology comprehensively. Finally, the optimal emergency treatment technology for this sudden pollution accident was obtained. Taking the sudden arsenic pollution accident of the Picang flood diversion channel in Linyi, Shandong Province as an example, the activated alumina adsorption dam technology was extracted successfully, which is in accordance with the actual treatment situation. The result shows that the method has strong feasibility and practicability, which can provide strong decision support for dealing with sudden pollution accidents in drainage basins efficiently.

Key words | D-S evidence theory, emergency treatment, sudden heavy metal pollution, technology identification

INTRODUCTION

Accidents of heavy metal pollution have occurred frequently in drainage basins in China. Heavy metals or their compounds entered a water body through human production activities, enterprise sewage discharge and other ways, which caused grave water pollution problems. In addition, it can enter the human body through biological enrichment and is a serious threat to human health (Cheng & Li 2017; Zhang et al. 2018). Therefore, it is particularly important to establish a comprehensive identification method for sudden heavy metal pollution accidents in the drainage basin and quickly obtain the optimal emergency treatment technology.

At present, research on sudden pollution accidents in drainage basins is mostly focused on monitoring work, the emergency response mechanism and risk assessment (Protano et al. 2014; Sun et al. 2016; Zhang et al. 2017; Abd el-Azim et al. 2018; Zhao et al. 2018), while the identification of emergency treatment technology in pollution accidents is rarely reported. Haider et al. (2015) designed a method of fuzzy multi-criteria analysis to screen the water quality emergency management scheme of the Ravi River in Pakistan. Karimi et al. (2011) utilized fuzzy analytic hierarchy process to evaluate and screen the treatment technology for a water pollution accident in an industrial zone of Iran, and used sensitivity analysis to verify the feasibility of the method. Qu et al. (2015) used analytic hierarchy process to construct the index system of technology assessment based on judgment of the degree of threat. Yu (2013) constructed a comprehensive evaluation method based on the weight assignment method of permutation centroid and linear weighted average, and analyzed the water bloom accident of Xinlicheng Reservoir in Changchun. Shi et al. (2014) established an analytic hierarchy process based on group
decision-making to analyze the emergency treatment technology for the sudden aniline pollution accident in the Zhuozhang River Basin of Handan. The above researches have been based on an expert scoring process, ranking the importance of indexes through the knowledge and experience of individual field experts, then the weight of the indexes were obtained by different mathematical methods. But the fuzzy multi-criteria analysis, fuzzy analytic hierarchy process and other methods used in the above researches have more qualitative components and less quantitative data in the decision-making process, and cannot avoid the problem of large deviation in judging the relative importance of indexes by diverse experts.

The data of each index are incomplete in the identification process for emergency treatment technology, so only expert knowledge and experience can be used in the process of determining the indexes’ weight. However, due to the influence of many factors such as diverse expert experience and knowledge, judgment level and personal preference, as well as the fuzziness and uncertainty of the multi-attribute decision-making problem itself, the weighting results are greatly affected by subjectivity. Then how to effectively gather expert viewpoints and overcome conflicts has attracted the attention of scholars in various fields. Some scholars have proposed the Delphi method (Liu et al. 2011; Zangenehmadar & Moselhi 2016; Benson et al. 2020), the three-point estimation method (Sun & Yang 2009), the order weighted averaging (OWA) operator (Wang & Xu 2008; Wu et al. 2012; Amin & Siddiq 2019), and so on. The process of the Delphi method is that experts intuitively judge the weight of each index without mutual interference, and then the organizer collates the data and feeds back the results to experts, and re-weights the indexes with large deviation, until a consistent conclusion is obtained. Finally, the arithmetic means of index weights are used as the weight coefficients. This method can integrate the viewpoints of various experts and avoid the influence of authority on the viewpoints of other experts. However, it will consume a lot of valuable emergency response time in the process of repeated data revision, and the organizers have a greater impact on the results of the weight. The three-point estimation method approximates the expert's weighting result as normal distribution, and utilizes the normal distribution characteristics of the data to determine the weight of the indexes. This method can optimize the final weight of indexes from a statistical point of view, but it needs a large number of data as support, and its preponderance can only be reflected when the amount of data is abundant. OWA operator is a frequently employed decision-making approach in weight determination, which aggregates expert viewpoints with position-weighted vector. However, only the information on the data ranking position is considered, the relations among the whole data groups given by experts are not explored, and the consistency judgments among the expert viewpoints are not analyzed in depth.

In view of the above problems, this study utilized the D-S evidence theory based on the similarity coefficient among evidences to determine the index weight. Dempster-Shafer (D-S) evidence theory was proposed by Dempster (Dempster 1967, 1968), and perfected by Shafer (Shafer 1976). It established a one-to-one correspondence between propositions and sets. The uncertainties of propositions were transformed into the uncertainties of sets, and then developed into a mathematical theory to deal with uncertainties (Jiang & Deng 2018). At present, the D-S evidence theory has been widely used in many fields such as risk assessment, fault diagnosis and target recognition (Fan et al. 2014; Rassafi et al. 2018; Li et al. 2019). It is utilized to fuse and redistribute the weight assignments of different experts, which can better quantify the qualitative evaluation. Moreover, the similarity coefficient among evidences can reflect the consistency of the diverse expert viewpoints, and solve the conflict based on the overall similarity and support degree among data groups. In addition, it can reduce the subjective influence of experts’ knowledge and experience, and makes the result of weight allocation more reasonable and effective. Therefore, a two-step identification method of emergency treatment technology for sudden heavy metal pollution accidents in drainage basins is established in this paper, which combined the identification index system and D-S evidence theory.

**METHODS**

**Establishment of the identification index system of emergency treatment technology**

The emergency treatment process for sudden pollution accidents in drainage basins is different from the conventional industrial wastewater treatment process, which is characterized by greater uncertainty, scale and long-term impact (Zhang et al. 2010). Based on a large number of technology investigations and literature collections, it was found that the feasibility and applicability of emergency treatment technologies mainly related to water environment characteristics, technical performance, economic cost and social environmental impact. Therefore, considering the above
Factors, four criteria and 20 indexes were selected to realize the evaluation and optimization of emergency treatment technology. And then the identification index system of emergency treatment technology was constructed, as shown in Figure 1.

As can be seen from Figure 1, the basic applicable conditions of emergency technology are: water discharge, pH range, temperature, range of treatable concentrations and reliance on engineering (which refers to whether there are water conservancy facilities such as bridges, gate dams or ditches in the polluted area of the drainage basin) can be objectively measured and quantified by monitoring and investigating the accident scene. Therefore, they were regarded as the primary identification indexes, and the available technologies were preliminarily screened out from the emergency treatment technology library for sudden heavy metal pollution accidents in drainage basins.

After preliminary identification of emergency treatment technology, it needs further optimization. It can be seen that the remaining indexes of technical performance, economic cost, and social environmental impact are related to each other to a certain extent, such as infiltration, interference and so on. The implementation of emergency technology will bring indispensable economic consumption and social environmental impact, the amount of economic consumption and the degree of social environmental impact varies with technology. Therefore, in order to avoid the redundancy of indexes caused by the potential interaction among them, and improve the objectivity and accuracy of technology evaluation, in this paper, the secondary identification indexes were chosen by establishing the interaction relationship among the remaining indexes, which were used to evaluate the available technologies, and then the optimal emergency treatment technology can be selected.
Identification indexes screening and weight determination model based on D-S evidence theory

Synthesis of the relations among identification indexes

Definition 1: Supposing a frame of discernment is defined by $\Pi$, which is a finite nonempty set of the relations between two identification indexes. The subset is represented by $A_j$ ($j = 1, 2, 3, ..., N$), which is a relation between two identification indexes. The basic probability assignment (BPA) of $A_j$ is $m(A_j)$, which is expert belief measure in $A_j$, where $m(A)$ satisfies Equation (1):

$$m(\emptyset) = 0, \quad \sum_{j=1}^{N} m(A_j) = 1 \quad (1)$$

where $m(\emptyset) = 0$ represents the empty set, and should assign zero; $\sum_{j=1}^{N} m(A_j) = 1$ indicates the sum of all BPAs for each subset given by an expert, and is equal to one.

Definition 2: If $n$ is the number of experts involved in reasoning, $n$ sets of independent evidences given by $n$ experts under the frame of discernment are represented by $\{E_1, E_2, ..., E_n\}$, which are $n$ sets of BPAs given by $n$ experts for the relations between two indexes according to their knowledge and experience. The BPA function is represented by $m_i$ ($i = 1, 2, 3, ..., n$), and $m_i(A_j)$ is the BPA of the $i$th expert to subset $A_j$ (Yang & Wang 2010). The BPA function $m(A)$ based on Dempster-Shafer’s rule of evidence aggregation is given by Equation (2):

$$m(A) = \begin{cases} 
\prod_{i=1}^{n} m_i(A_j) & \text{if } \bigcap_{j \in A \neq \emptyset} = \emptyset, A = \emptyset \\
1 - K & A = \emptyset, K = \sum_{i=1}^{n} \prod_{j \in A \neq \emptyset} m_i(A_j) \end{cases} \quad (2)$$

where $\prod_{i=1}^{n} m_i(A_j)$ represents the product of the BPAs that are simultaneously assigned to a relation between two indexes by $n$ experts; and $K = \sum_{i=1}^{n} \prod_{j \in A \neq \emptyset} m_i(A_j)$, which is the conflict coefficient that reflects the extent of the conflict among evidences. The larger the $K$ is, the greater the conflict coefficient among pieces of evidence. Conversely, the smaller the $K$ is, the higher the consistency.

Determination of weight coefficient

Definition 3: Supposing a frame of discernment is defined by $\Pi$, which is a finite nonempty set of the $V$ indexes. The subset is represented by $A_j$ ($j = 1, 2, ..., V$) $E_p, E_q$ ($p, q = 1, 2, ..., v$) are the two sets of independent evidences given by two experts under the frame of discernment $\Pi$, which are the two sets of weights assigned by two experts to all indexes. The BPA functions are represented by $m_p$ and $m_q$. The BPA of the $p$th expert to subset $A_j$ is $m_p(A_j)$, and the BPA of the $q$th expert to subset $A_j$ is $m_q(A_j)$. Then the similarity coefficient $S_{pq}$ between evidence $E_p$ and evidence $E_q$ can be expressed as the following equation (Wang 2007):

$$S_{pq} = \frac{\sum_{r=1}^{V} m_p(A_r) m_q(A_r)}{\sqrt{\left(\sum_{r=1}^{V} m_p^2(A_r)\right) \left(\sum_{r=1}^{V} m_q^2(A_r)\right)}} \quad (3)$$

In the frame of discernment $\Pi$, the similarity degree among the evidences given by diverse experts are different. A greater similarity coefficient indicates that other evidences further support the evidence. In addition, the similarity degree among multiple sets of evidences can be expressed by the similarity coefficient matrix $S$ as follows:

$$S = \begin{bmatrix}
1 & s_{12} & s_{13} & \cdots & s_{1q} & \cdots & s_{1v} \\
s_{21} & 1 & s_{23} & \cdots & s_{2q} & \cdots & s_{2v} \\
s_{31} & s_{32} & 1 & \cdots & s_{3q} & \cdots & s_{3v} \\
\vdots & \vdots & \vdots & \ddots & \vdots & \cdots & \vdots \\
s_{p1} & s_{p2} & s_{p3} & \cdots & s_{pq} & \cdots & s_{pv} \\
\vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\
s_{v1} & s_{v2} & s_{v3} & \cdots & s_{vq} & \cdots & 1
\end{bmatrix} \quad (4)$$

On the basis of the similarity coefficient matrix, adding each row of similarity coefficient matrix $S$, we can get the total support degree of evidence $E_p$, which is expressed as follows:

$$\mu(E_p) = \sum_{q=1}^{v} S_{pq} \quad (5)$$

The reliability of evidence $E_p$ is obtained by normalizing the total support degree of evidence, which is expressed as $\lambda(E_p)$:

$$\lambda(E_p) = \frac{\mu(E_p)}{\sum_{p=1}^{v} \mu(E_p)} \quad (6)$$

If there is a big conflict coefficient between a set of evidence and other evidences, it indicates it is less supported
by the other evidences. It brings low reliability, and less impact on the final weight synthesis results. The synthesized weight of index \(A_r\) is determined based on the similarity coefficient using the following equation:

\[
\omega(A_r) = \sum_{p=1}^{v} m_p(A_r) \cdot \lambda(E_p)
\]  

(7)

**Constructing the identification method of emergency treatment technology**

The identification and screening process for emergency treatment technology is the linchpin to the reduction of heavy metal pollutants in the whole emergency treatment process. Only the accurate screening of appropriate emergency technologies can rapidly reduce the harm from pollutants to the water environment and surrounding sensitive areas, on the basis of sufficient data collection, establishment of a heavy metal pollution emergency treatment technology library and an emergency treatment technology identification index system. The primary identification indexes were determined by analyzing the technology characteristic, and the secondary identification indexes were determined by adopting expert knowledge. For the first step, after a sudden water pollution accident, the primary identification indexes were adopted to preliminarily select the available technologies based on the emergency treatment technology library. For the second step, the secondary identification indexes were utilized to comprehensively evaluate and rank the available technologies, and the technology with the highest score was selected as the optimal emergency treatment technology for the pollution accident. Finally, a practical accident was utilized to analyze the feasibility of the proposed method. So, the procedure of the emergency treatment technology identification system for sudden heavy metal pollution accidents in drainage basins was designed and completed. The construction framework of the two-step identification method based on D-S evidence theory developed is presented in Figure 2.

**Determination of identification indexes**

(1) Determination of the primary identification indexes

Based on the foregoing analysis, water discharge, pH range, temperature, range of treatable concentrations and reliance on engineering were regarded as the primary identification indexes. After the accident, the pollutant name was selected in the identification system, and then the accident scene data corresponding to the primary identification indexes was input to screen out the available technologies.

(2) Determination of the secondary identification indexes

The residual indexes in the indexes layer were analyzed, and the interaction relations among the remaining indexes were established based on expert knowledge. Firstly, the relations between two indexes were determined; \(A_s \rightarrow A_b\) indicates that the index \(A_s\) directly affects the \(A_b\); \(A_s \leftarrow A_b\) indicates that the index \(A_x\) directly affects the \(A_s\); \(A_s \leftrightarrow A_b\) indicates that the index \(A_s\) and \(A_b\) have no direct influence relations; \(A_s \rightarrow A_b\) indicates that the influence relations between the indexes \(A_s\) and \(A_b\) cannot be determined. Then, the experts gave the basic probability assignment (BPA) of the above four relations in the range of \([0, 1]\) based on their knowledge and experience. The closer the BPA is to 1, the higher the reliability of the existing relation. Finally, Equation (2) was utilized to synthesize the BPAs of the above four relations given by diverse experts, and the maximum composite value was taken as the relations among the indexes, the synthesis results are shown in Table 1; the relations diagram of the indexes was obtained, as shown in Figure 3.

According to Figure 3, the principle of selecting the secondary identification indexes is that: Firstly, the independence of the indexes is ensured; that is, the selected secondary identification indexes have no direct influence relations. Secondly, considering the comprehensiveness of the indexes, which include the technical performance, economic costs and social environmental impact at the same time. And then quantitative indexes take precedence over qualitative indexes. Taking \(A_{22} \rightarrow A_{44}\) as an example, the impact to social economic activities mainly considers the economic impact of emergency treatment technology on local enterprises, agriculture, fisheries, tourism and other aspects. In the process of implementing emergency treatment technology, the higher the removal rate, the less time-consuming the treatment process, and the less the impact to social economic activities. Therefore, considering independence and quantifiability, the removal rate \(A_{22}\) was selected from the indexes pair \(A_{22} \rightarrow A_{44}\). Similarly, nine secondary identification indexes were selected as follows: application \((A_{21})\), removal rate \((A_{22})\), removal efficiency \((A_{23})\), manpower cost \((A_{31})\), material cost \((A_{32})\), transportation cost \((A_{33})\), waste disposal cost \((A_{34})\), environmental impact of waste \((A_{42})\), environmental impact of residues \((A_{43})\).

**Establishment of the index weights sets by individual experts**

In the process of comprehensive evaluation, the weight is utilized to express the importance of the index in the indexes system through quantitative forms. Therefore, determining
the more realistic index weight is the crux to improve the accuracy of the method. Experts, who were selected from academia, government and industry, were invited to determine the weights of each secondary identification index within the scope of [0, 1] according to the accident scene. The larger the score, the greater the importance of the index. Then, the D-S evidence theory based on the similarity coefficient among evidences is utilized to synthesize the index weights from individual experts, which solved the conflict of weights assigned and reduced the subjective influence caused by the difference in expert experience.

**Determination of scoring criteria**

In the identification and decision-making of emergency treatment technology for sudden pollution in a drainage basin, the data of each index of the technical scheme is not complete in most cases, which makes it relatively difficult to determine the attribute value of the index objectively. Therefore, by consulting the literature and analyzing the technical characteristics of each emergency treatment, three criteria (I, II, III) were selected to evaluate indexes, and the corresponding scores were represented by intervals, as shown in Table 2. On the basis of the detailed investigation of the actual pollution situation, the experts combined the characteristics of pollutants, local social economic and environmental conditions, and scored the available technologies according to the scoring criteria. The attribute values of the secondary identification indexes of each available technology take the average of all experts' scores. Then, the formula (8) was utilized to make a linear weighted comprehensive score for each available technology, and the

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**Figure 2** | The construction framework of the identification method for emergency treatment technology.
### Table 1 | Synthesis results of the relations among indexes

| Index     | $A_{21}$ | $A_{22}$ | $A_{23}$ | $A_{24}$ | $A_{25}$ | $A_{26}$ | $A_{27}$ | $A_{28}$ | $A_{29}$ | $A_{30}$ | $A_{31}$ | $A_{32}$ | $A_{33}$ | $A_{34}$ | $A_{35}$ | $A_{36}$ | $A_{37}$ | $A_{38}$ | $A_{39}$ | $A_{40}$ | $A_{41}$ | $A_{42}$ | $A_{43}$ | $A_{44}$ | $A_{45}$ |
|-----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| $A_{21}$  | /        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        |
| $A_{22}$  | ↑        | /        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        |
| $A_{23}$  | ↑        | ↑        | /        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        |
| $A_{26}$  | ↑        | ↑        | ↑        | /        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        |
| $A_{27}$  | ↑        | ↑        | ↑        | /        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        |
| $A_{28}$  | ↑        | ↑        | ↑        | ↑        | /        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        |
| $A_{31}$  | ↑        | ↑        | ↑        | ↑        | ↑        | /        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        |
| $A_{32}$  | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | /        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        |
| $A_{33}$  | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | /        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        |
| $A_{34}$  | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | /        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        |
| $A_{35}$  | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | /        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        |
| $A_{41}$  | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | /        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        |
| $A_{42}$  | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | /        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        |
| $A_{43}$  | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | /        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        |
| $A_{44}$  | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | /        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        |
| $A_{45}$  | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | /        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        | ↑        |

**Figure 3 | The relations among indexes.**
Finally, the optimal emergency treatment technology was selected by ranking the $Q$ values.

$$Q = \sum_{r=1}^{V} C_r o(A_r)$$  \hspace{1cm} (8)

where $Q$ is the linear weighting value of an available technology; $C_r$ is the attribute value of the index $r$ of an available technology; $o(A_r)$ is the weight of the index $r$ of an available technology.

### CASE STUDY

A sudden arsenic pollution accident in the Picang flood diversion channel in Linyi, Shandong, was selected as a case study to illustrate the application of the two-step identification method established.

**Arsenic pollution accidents in Picang flood diversion channel**

This accident occurred on January 7, 2009; a large amount of tail gas circulating washing water from the phosphoric acid production line leaked into the Picang flood diversion channel from the Shandong Hongri Akon chemical co., Ltd. The maximum concentration of the arsenic ion in the eastern deviation region of the Picang flood diversion channel was 1.978 mg/L, which is 39.56 times higher than the standard value. It severely threatened the safety of water for more than 500,000 people and the safety of drinking water sources in the downstream Beijing-Hangzhou Grand

### Table 2: Scoring criteria of the indexes

<table>
<thead>
<tr>
<th>Index</th>
<th>Grade</th>
<th>Scoring criteria</th>
<th>Score interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Application ($A_{21}$)</td>
<td>I</td>
<td>The technology is in the maturity stage and has been applied widely</td>
<td>(6,10]</td>
</tr>
<tr>
<td></td>
<td>II</td>
<td>The technology is in the maturity stage and has been applied less</td>
<td>(3,6)</td>
</tr>
<tr>
<td></td>
<td>III</td>
<td>The technology is in the research stage and has no practical application</td>
<td>[0,3]</td>
</tr>
<tr>
<td>Removal rate ($A_{22}$)</td>
<td>I</td>
<td>$\leq 12$ h</td>
<td>(6,10]</td>
</tr>
<tr>
<td></td>
<td>II</td>
<td>12–24 h</td>
<td>(3,6)</td>
</tr>
<tr>
<td></td>
<td>III</td>
<td>$\geq 24$ h</td>
<td>[0,3]</td>
</tr>
<tr>
<td>Removal efficiency ($A_{23}$)</td>
<td>I</td>
<td>$\geq 80%$</td>
<td>(6,10]</td>
</tr>
<tr>
<td></td>
<td>II</td>
<td>50%–80%</td>
<td>(3,6)</td>
</tr>
<tr>
<td></td>
<td>III</td>
<td>$\leq 50%$</td>
<td>[0,3]</td>
</tr>
<tr>
<td>Manpower cost ($A_{31}$)</td>
<td>I</td>
<td>$\leq 30,000$ (yuan)</td>
<td>(6,10]</td>
</tr>
<tr>
<td></td>
<td>II</td>
<td>30,000–75,000 (yuan)</td>
<td>(3,6)</td>
</tr>
<tr>
<td></td>
<td>III</td>
<td>$\geq 75,000$ (yuan)</td>
<td>[0,3]</td>
</tr>
<tr>
<td>Material cost ($A_{32}$)</td>
<td>I</td>
<td>$\leq 5,000$ (yuan/t)</td>
<td>(6,10]</td>
</tr>
<tr>
<td></td>
<td>II</td>
<td>5,000–10,000 (yuan/t)</td>
<td>(3,6)</td>
</tr>
<tr>
<td></td>
<td>III</td>
<td>$\geq 10,000$ (yuan/t)</td>
<td>[0,3]</td>
</tr>
<tr>
<td>Transportation cost ($A_{33}$)</td>
<td>I</td>
<td>Time required for transportation: $\leq 5$ h</td>
<td>(6,10]</td>
</tr>
<tr>
<td></td>
<td>II</td>
<td>5–10 h</td>
<td>(3,6)</td>
</tr>
<tr>
<td></td>
<td>III</td>
<td>$\geq 10$ h</td>
<td>[0,3]</td>
</tr>
<tr>
<td>Waste disposal cost ($A_{34}$)</td>
<td>I</td>
<td>$\leq 5,000$ (yuan/t)</td>
<td>(6,10]</td>
</tr>
<tr>
<td></td>
<td>II</td>
<td>5,000–10,000 (yuan/t)</td>
<td>(3,6)</td>
</tr>
<tr>
<td></td>
<td>III</td>
<td>$\geq 10,000$ (yuan/t)</td>
<td>[0,3]</td>
</tr>
<tr>
<td>Environmental impact of waste ($A_{42}$)</td>
<td>I</td>
<td>Less waste generated and has no harm</td>
<td>(6,10]</td>
</tr>
<tr>
<td></td>
<td>II</td>
<td>Moderate waste generated and is easy to handle</td>
<td>(3,6)</td>
</tr>
<tr>
<td></td>
<td>III</td>
<td>Large waste generated and is hard to handle</td>
<td>[0,3]</td>
</tr>
<tr>
<td>Environmental impact of residues ($A_{43}$)</td>
<td>I</td>
<td>The residual substances are less impact on the environment and do not need to be cleaned</td>
<td>(6,10]</td>
</tr>
<tr>
<td></td>
<td>II</td>
<td>The residual substances are moderate impact on the environment and do not need to be cleaned for the time being</td>
<td>(3,6)</td>
</tr>
<tr>
<td></td>
<td>III</td>
<td>The residual substances have greater impact on the environment and need to be cleaned immediately</td>
<td>[0,3]</td>
</tr>
</tbody>
</table>
Canal and Luoma Lake. On January 13, Linyi Municipal Government launched a timely emergency response plan. Then, the environmental monitoring station and water conservancy department calculated the water quality and quantity of exceedance of standard water. Finally, activated alumina adsorption technology was adopted on February 19, through several meetings and demonstrations by well-known experts in China (Liu et al., 2011; Zhang et al., 2012; Lv et al., 2015). In this paper, a two-step identification method of emergency treatment technology for sudden heavy metal pollution accidents based on D-S evidence theory was utilized to analyze the accident.

**Establishment of identification method**

(1) Selection of the available technologies according to the primary identification indexes

The arsenic pollution accident happened in winter; the water temperature was 3–5 °C, the pH range was 7.2–7.8, the water discharge was about 180 m³/s, the arsenic ion concentration range was 0.512–1.978 mg/L, and there were bridges and dams in the polluted area. According to the above information, the following available technologies were selected in the identification system for emergency treatment technology: activated alumina adsorption dam technology, iron sulfide mineral adsorption dam technology, ferric chloride coagulation sedimentation technology, and lime sedimentation technology.

(2) Calculation of synthesis weights of the secondary identification indexes

According to the specific information for the accident scene, the experts who are involved in the emergency work assign the weight of each index, and some of the data are shown in Table 3. Equations (3)–(7) were utilized to fuse the weights assigned by experts to each index. The calculation process is as follows. Firstly, the similarity coefficients among the evidences assigned by experts were calculated using Equation (3), such as: $S_{12} = 0.9495$, $S_{13} = 0.8385$, $S_{14} = 0.8673$, $S_{15} = 0.8245$, ..., $S_{1v} = 0.7749$; so the similarity coefficient matrix $S$ is as follows:

$$
S = \begin{bmatrix}
1 & 0.9495 & 0.8385 & 0.8673 & \cdots & 0.7749 \\
0.9495 & 1 & 0.8318 & 0.7829 & \cdots & 0.8584 \\
0.8385 & 0.8318 & 1 & 0.7372 & \cdots & 0.8834 \\
0.8673 & 0.7829 & 0.7372 & 1 & \cdots & 0.6300 \\
\vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\
0.7749 & 0.8584 & 0.8834 & 0.6300 & \cdots & 1
\end{bmatrix}
$$

Equation (5) shows the total degree of support of each group of evidence respectively: $\mu(E_1) = 5.2545$, $\mu(E_2) = 5.1388$, $\mu(E_3) = 5.1313$, $\mu(E_4) = 4.9608$, ..., $\mu(E_v) = 4.7851$. The reliability of each group of evidence was calculated using Equation (6): $\lambda(E_1) = 0.1738$, $\lambda(E_2) = 0.1700$, $\lambda(E_3) = 0.1697$, $\lambda(E_4) = 0.1641$, ..., $\lambda(E_v) = 0.1583$. Then, the synthesized weights were calculated using Equation (7):

$$
\omega(A_{21}) = 0.2328, \omega(A_{22}) = 0.1933, \omega(A_{23}) = 0.1522, \omega(A_{31}) = 0.0493, \omega(A_{32}) = 0.0696, \omega(A_{33}) = 0.0563, \omega(A_{34}) = 0.0648, \omega(A_{42}) = 0.0974, \omega(A_{43}) = 0.1043.
$$

At the same time, this paper used the three-point estimation method in Sun & Yang (2009), the OWA operator based on Olympic-average in Wu et al. (2012), and the OWA operator based on the combination number in Wang & Xu (2008) to synthesize the weights of indexes assigned by experts. The results are shown in Table 4.

The calculation process and result analysis for the above methods shows that: The D-S evidence theory based on the similarity coefficient among evidences solves the conflicts...
Table 4 | The synthesis weights by different methods

<table>
<thead>
<tr>
<th>Index layer</th>
<th>The D-S evidence theory based on similarity coefficient</th>
<th>The three-point estimation method</th>
<th>The OWA operator based on Olympic-average</th>
<th>The OWA operator based on combination number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Application (A21)</td>
<td>0.2328</td>
<td>0.2402</td>
<td>0.1771</td>
<td>0.1896</td>
</tr>
<tr>
<td>Removal rate (A22)</td>
<td>0.1933</td>
<td>0.1965</td>
<td>0.1594</td>
<td>0.1737</td>
</tr>
<tr>
<td>Removal efficiency (A33)</td>
<td>0.1322</td>
<td>0.1349</td>
<td>0.1594</td>
<td>0.1590</td>
</tr>
<tr>
<td>Manpower cost (A31)</td>
<td>0.0493</td>
<td>0.0460</td>
<td>0.0478</td>
<td>0.0434</td>
</tr>
<tr>
<td>Material cost (A32)</td>
<td>0.0696</td>
<td>0.0672</td>
<td>0.0673</td>
<td>0.0667</td>
</tr>
<tr>
<td>Transportation cost (A33)</td>
<td>0.0563</td>
<td>0.0574</td>
<td>0.0571</td>
<td>0.0538</td>
</tr>
<tr>
<td>Waste disposal cost (A34)</td>
<td>0.0648</td>
<td>0.0656</td>
<td>0.0664</td>
<td>0.0716</td>
</tr>
<tr>
<td>Environmental impact of waste (A42)</td>
<td>0.0974</td>
<td>0.0901</td>
<td>0.1169</td>
<td>0.1089</td>
</tr>
<tr>
<td>Environmental impact of residues (A43)</td>
<td>0.1043</td>
<td>0.1020</td>
<td>0.1487</td>
<td>0.1333</td>
</tr>
</tbody>
</table>

Based on the overall similarity and degree of support among data groups in the process of calculation, which can better integrate the viewpoints of various experts and reflect the consistency. For the three-point estimation method, the calculation results are similar to the D-S evidence theory generally, because the data given in this paper is approximately normal distribution, although the amount of data is not abundant enough. When the amount of data is small and has non-normal distribution, it will reflect the limitations and lower universal applicability of the method. And after careful analysis, it was found that the influence of extreme value on the three-point estimation method was greater than the D-S evidence theory in the calculation process, and the relationship among the entire set of data given by experts was not considered. The OWA operator based on Olympic-average and the OWA operator based on combination number are only from the point of view of the data sorting position, without considering the overall relevance among data groups. In addition, for the indexes A21 and A22, the OWA operator excessively weakens the influence of extreme value, which conceals the particularity of decision data. For the indexes A42 and A43, the two sets of weights assigned by experts are quite close on the whole, but the result calculated by the OWA operator is that \( \omega(A_{42}) \) is significantly larger than \( \omega(A_{43}) \). Based on the above analysis, the computation result of D-S evidence theory based on similarity coefficient is more reasonable than the other three data synthesis methods in this paper.

(3) Taking the results of D-S evidence theory based on the similarity coefficient as the synthesis weights of indexes, the available technologies were scored and the Q values were calculated. Based on the analysis of emergency technology and investigation of the actual pollution situation, the expert group scored each available technology according to the scoring criteria of the secondary identification indexes. The eventual attribute value was the average value of all experts’ scores. Then, the Q value of each available technology was calculated using Equation (8). Taking the activated alumina adsorption dam technology as an example: 

\[
Q_1 = \frac{0.2328 \times 8.4 + 0.1933 \times 8.6 + 0.1322 \times 8.2 + 0.0493 \times 6.4 + 0.0696 \times 7.0 + 0.0563 \times 8.4 + 0.0648 \times 6.0 + 0.0974 \times 9.2 + 0.1043 \times 9.0}{8.4 + 8.6 + 8.2 + 6.4 + 7.0 + 8.4 + 6.0 + 9.2 + 9.0} = 8.2012.
\]

Similarly: 

\[
Q_2 = 6.9762, Q_3 = 7.7515, Q_4 = 7.3517.
\]

That is: 

\[
Q(Q_1, Q_2, Q_3, Q_4) = (8.2012, 6.9762, 7.7515, 7.3517).
\]

Finally, the optimal treatment technology was obtained by ranking them. The attribute values and the comprehensive score of each available technology are shown in Table 5.

It can be seen from the Table 5 that the optimal treatment technology is the activated alumina adsorption dam technology, which is consistent with the actual pollutant elimination technology scheme adopted in this case. The available technologies are analyzed. The first scheme uses activated alumina adsorption dam technology, which has a better adsorption effect on arsenic ions in water and relatively less secondary pollution to the water environment. However, the treatment process is time-consuming, the adsorbent waste after emergency treatment is difficult to recover, and the waste treatment cost is high. In the second scheme, iron sulfide mineral adsorption dam technology is adopted, which has faster treatment speed and higher removal efficiency. But it can easily lead to the increase of sulfur and iron ion concentration in water, which has a greater impact on water pH. The third scheme adopts ferric chloride coagulation sedimentation.
technology, which has lower treatment costs and better removal efficiency. However, ferric chloride solution is corrosive to some extent, and it is easy to produce a large number of arsenic-containing flocs, so further treatment of the sediment is needed. As for the lime sedimentation technology, although it can reduce the concentration of arsenic ions in water, it is difficult to reach the standard. So it is often used as an auxiliary technology for interception near pollution sources and local treatment.

The water discharge in the pollution area of this accident is large. In order to avoid serious impact of pollutants on the downstream drinking water sources, the activated alumina was encapsulated in woven bags, and the existing bridges in the polluted area used to build interception dams, which greatly saved emergency response time. Moreover, the removal efficiency of activated alumina is better, and the secondary pollution to the water environment is relatively small. In addition, the difficulty of treating bagged adsorbent waste is less than that of sediment dredging and is harmless in the drainage basin. Therefore, the activated alumina adsorption dam technology screened by the two-step identification method proposed in this work is reasonable.

**CONCLUSION**

The two-step identification method of emergency treatment technology for sudden heavy metal pollution based on D-S evidence theory in this work provides an effective approach for selecting the optimal technology. The available technologies were screened out by the primary identification indexes based on the heavy metal pollution emergency treatment technology identification system. Then the secondary identification indexes were determined by analyzing the relations among indexes, which fully considered the redundancy of the indexes to ensure the objectivity and accuracy of the comprehensive evaluation of the emergency technology. The D-S evidence theory was used to synthesize index weights given by individual experts, which solved the conflict of assigned weights among the diverse expert viewpoints. Finally, the optimal treatment technology was selected by ranking the comprehensive score of the available technologies. The feasibility of this two-step identification method was verified using an actual sudden arsenic pollution accident that occurred in Picang flood diversion channel. It indicated that the identification method for emergency treatment technology proposed in this work is consummated, which can provide scientific reference for similar sudden pollution accidents in drainage basins.

**ACKNOWLEDGEMENTS**

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