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A multi-criteria evaluation of water management for sustainable development in mining

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Abstract: Mining is a water intensive activity. Mining companies are expected to bear responsibility for their impacts on water resources. Mine water management is a significant issue for sustainable development to maximise shareholder's value, secure production, and minimize environmental impacts. The identification of sustainable mining water management practices is technically challenging because of the lack of scientific tools available to evaluate optimal decisions.

The paper proposes a multi-criteria evaluation method that aims at selecting reasonable water management practices for sustainable development in mining. The method is based on the analytic hierarchy process (AHP) together with a technique for order preference by similarity to ideal solution (TOPSIS). Water must be managed at all stages of the life cycle of mining operations. However, the focus in this paper is the evaluation of mine water management practices at the mine operating stage. A decision hierarchy and a criterion set for assessing sustainability of mine water management were proposed, and used to evaluate management practices in six coal mines in the Bowen Basin. The AHP method was used to determine the weights of evaluative criteria. The ranking of the mine water management practices was calculated with the fuzzy TOPSIS method. The evaluation results illustrate the usefulness of the proposed method in identifying leading mine water management practices. Finally, some management implications were derived from the work to improve water management towards a more sustainable mining industry.

Keywords: *Mine water management, Multi-criteria evaluation method, Sustainable development, Analytic hierarchy process, Fuzzy TOPSIS*

1. INTRODUCTION

In recent years there has been a renewed debate about sustainable mining, due to strong public sentiment on environmental and social issues surrounding mining (Rolfe et al, 2007). Mining is a water intensive activity (Lambooy, 2011). Risks and opportunities must be managed at both corporate and site level to ensure that shareholder’s value is maximised, production is secure and community and environmental values associated with water are maintained or enhanced (DRET, 2008). The target of moving towards a more sustainable industry has been imposing new requirements on mine water management. Security of water supply can reduce the risks associated with reduction in revenue from loss of production, and the risks of purchasing water at a high price in drought period. Excessive water needs to be well managed, either to be compliantly discharged into receiving water bodies, or to be stored for future use in dry years. Therefore, responsible water management is a key ingredient in ensuring that its contribution to sustainable development is positive over the long term. Optimal selection of mine water management practices requires one comprehensively evaluate management options against a number of requirements, thus becomes a problem in multiple criteria decision-making (MCDM) (Chen and Paydar, 2012; Chen et al, 2013; Gao and Hailu, 2013b; Ho et al, 2010).

This paper presents a case study of the evaluation of sustainable water management practices in six mines located in the Bowen Basin. Currently major mining activities in the basin are coal mining and coal seam methane gas production. There are plans to significantly increase production through current mine expansions and by developing new mines. Therefore, it is significant to evaluate how sustainable current water management is in the mines in this area. Water is required to be managed at all stages of the life cycle of mining operations (DRET, 2008). The focus is the evaluation of mine water management practices at the mine operating stage in this work. The other stages, such as final closure and decommissioning, are not considered here.

An evaluation method is proposed with an AHP plus a technique for order performance by similarity to ideal solution (AHP-TOPSIS) (Da˘gdeviren et al, 2009; Gao and Hailu, 2012). The decision problem hierarchy is developed. Three criteria are included in the hierarchy. Each criterion has several indicators. The AHP method is used to determine the weight for evaluation criteria. The rankings of these mine water management practices is calculated with fuzzy TOPSIS method, which is expressed in linguistic values parameterized with triangular fuzzy numbers (Zadeh, 1975). The paper is organised as follows. In the next section, we propose a decision hierarchy and the AHP-fuzzy TOPSIS method for the mine water management. Section 3 presents the application of the decision hierarchy and the evaluation method into six mines in the Bowen Basin. Section 4 presents the conclusions of this paper.

2. METHODS

This section first proposes a decision hierarchy for evaluating sustainable mine water management. The preference weights of decision indicators are derived using the AHP method. The ranking process can be done using the fuzzy TOPSIS-based method.

2.1. The decision problem hierarchy

Water input, water output, and operational activities (such as tasks, stores, and treatment plants) often reside within different departments. Water accounting is a reporting mechanism that quantifies the mine’s water supply, consumption and discharge (Cote et al, 2010; Kemp, 2010). We have developed a decision hierarchy and the goal of the hierarchy is to evaluate sustainable mine water management. The intermediate level includes three criteria (i.e. input, operational activity, and output). Some relative and important factors for each criterion are in the lowest level. Firstly, as to input, security of supply can mitigate the risks associated with reduction in revenue from loss of production. Secondly, as to operational activities, water reuse efficiency should be improved to reduce the need for water extraction on mines, particularly water-deficient mines. Finally, as to output, water excess should be well managed to discharge when excess water is captured from heavy rainfall events or keep an appropriate amount of water to maintain the viability of the operation in dry periods. Consequently sound water management is fundamental for all mining operations.

2.2. AHP

AHP is a qualitative-quantitative analysis with the multi-objective decision making and comprehensive evaluation method. This method can help decision makers determine the quantitative experience in order to achieve optimal decisions (Saaty, 1980). The basic steps involved in this method are as follows.

1. Structuring a decision problem and selection of criteria.

This step decomposes a decision problem into its constituent parts. In its simplest form, this structure comprises a goal or focus at the topmost level, criteria (and sub-criteria) at the intermediate levels, while the lowest level contains the options. Arranging all the components in a hierarchy provides an overall view of the complex relationships.

2. Establishing a pair-wise comparison decision matrix.

This involves describing preferences over outcomes in the form of relative weights on a pair-wise comparison basis. The weight specification is simplified by using a pair-wise comparison decision matrix. The relative importance of two factors is rated using a scale with the values 1, 3, 5, 7, and 9, where 1 refers to 'equally important', 3 denotes 'more important', 5 equals 'obviously more important', 7 represents 'strongly more important' and 9 denotes 'extremely more important'. Also, 2, 4, 6, and 8 are used for compromise between the above values. The reciprocal denotes inverse comparison (Saaty, 1980).

3. Normalizing the decision matrix and calculate the priorities of this matrix.

Construct an n-criteria evaluation matrix A in which every element $\alpha_{ij}(i, j = 1,2, \ldots, n)$ is the quotient/ratio of preference values attached to the criteria. Transform the pair-wise preferences summarized in the evaluation matrix A into a vector of weights that could be attached to the multiple outcomes.

4. Checking consistency.

The maximum eigenvalue λ_{max} and a corresponding eigenvector w for the matrix A are calculated. The maximum eigenvalue is used to develop a consistency measure, using a procedure that accounts for the effects of the size of the criteria set n as shown below. A consistency index (CI) in terms of Eq. (1)

$$CI = \frac{\lambda_{max-n}}{n-1} \tag{1}$$

where n is the number of pair-wise comparison.

A consistency ratio *CR* is calculated as the ratio of the CI and the random index (*RI*) as indicated,

$$CR = CI/RI \tag{2}$$

Compare the CR to the accepted upper limit value of 0.1. If the CR exceeds this value, A will be modified and the evaluation procedure has to be repeated to improve consistency (Saaty, 1980).

2.3. Fuzzy TOPSIS-based comprehensive evaluation

The TOPSIS method is based on the idea that the best alternative should have the shortest distance from the positive ideal solution and farthest distance from the negative ideal solution. In the classical TOPSIS method, the weights of criteria and the ratings of alternatives are known precisely and crisp values are used in the evaluation process. However, under many conditions data are inadequate to model real-life decision problems. Therefore, the fuzzy TOPSIS method is proposed where the weights of criteria and ratings of alternatives are evaluated by linguistic variables represented by fuzzy numbers to deal with the deficiency in the traditional TOPSIS. In this paper, the extension of TOPSIS method is considered which was proposed by Da˘gdeviren et al. The method can be described as follows (Da˘gdeviren, 2009).

Step 1. Choosing the linguistic ratings $r_{ij} = (r_{ij1}, r_{ij2}, r_{ij3})$, where r_{ij1} , r_{ij2}, r_{ij3} are three elements of this triangular fuzzy number, i represents the index of a management alternative, $i = 1,2, \ldots m$ and j denotes the index of an attribute or criterion $j = 1,2, \ldots, n$ for alternatives with respect to criteria. The fuzzy linguistic rating r_{ij} preserves the property that the ranges of normalized triangular fuzzy numbers belong to [0, 1]; thus, there is no need for normalization.

Step 2. Considering the weighted decision matrix $V = [v_{ij}]_{m\times n}$. The weighted value v_{ij} is calculated as

$$v_{ij} = (w_j)(r_{ij}) \ \ , = 1,2, \ldots m \ , j = 1,2, \ldots, n \tag{3}$$

where w_j is the weight of the jth attribute and $\sum_{j=1}^{n} w_j = 1$.

Step 3. Determining the fuzzy positive ideal solution (FPIS) A^+ and fuzzy negative ideal solution (FNIS) A^-. The FPIS and FNIS of the alternatives are computed as follows:

$$A^+ = \{(max_i v_{ij} | j \in J), (min_i v_{ij} | j \in J'), i = 1,2, \ldots, m\} = \{v_1^+, v_2^+, \ldots, v_n^+\} \tag{4}$$

$$A^- = \{(min_i v_{ij} | j \in J), (max_i v_{ij} | j \in J'), i = 1,2, \ldots, m\} = \{v_1^-, v_2^-, \ldots, v_n^-\} \tag{5}$$

where J is a set of benefit attributes and J' is a set of cost attributes.

Step 4. Calculating the distances of each alternative from FPIS and FNIS as follows:

$$S_i^+ = \sum_{j=1}^{n} d\left(v_{ij}, v_j^+\right), i = 1,2, \dots m \tag{6}$$

$$S_i^- = \sum_{j=1}^{n} d\left(v_{ij}, v_j^-\right), i = 1,2, \dots m \tag{7}$$

where $d(a, b)$ is the Euclidean distance measurement between two fuzzy numbers a and b.

Step 5. Computing the closeness coefficient (CC_i) of each alternative. The closeness coefficient CC_i represents the distances to the FPIS A^+ and FPIS A^- simultaneously. The closeness coefficient of each alternative is calculated as:

$$CC_i = \frac{S_i^-}{S_i^+ + S_i^-} \quad i = 1,2, \dots m \tag{8}$$

where $0 \leq CC_i \leq 1$.

Step 6. Ranking the alternatives. The different alternatives are ranked according to the closeness coefficient CC_i in decreasing order. The best alternative is closest to the FPIS and farthest from the FNIS.

3. CASE STUDY

Identifying preferred management practices involves the following four basic steps: (1) determining a set of decision criteria and structuring a decision hierarchy over these criteria; (2) calculating a consistent set of preference weights for outcomes in the criteria set using the AHP; (3) evaluating alternative management options using the fuzzy TOPSIS approach; and (4) identifying preferred management practices from those under consideration.

3.1. Decision hierarchy and data sources

From the functional elements, we select required indicators whose descriptions are shown in Table 1. The objective is evaluating sustainable mine water management and there are three criteria: input, operational activity, and output. For input criterion, water supply resources and quality and potential water demands are considered. As to operational activity, water efficiency and worked water are important. The discharge risk and water loss are vital for output criterion. These indicators could vary depending on the preferences of mine water managers. A decision hierarchy structured with criteria and alternative management options is shown in Figure 1. We apply the proposed method to identity the sustainable mine water management practices. To maintain confidentiality of individual site-level data, the location and name of the region is not disclosed. This does not affect the illustration of the method. In the evaluation, six open-cut mines (i.e. Mine 2, 4, 7, 8, 9, and 10) are selected and the original data is reported by Cote et al. (2008).

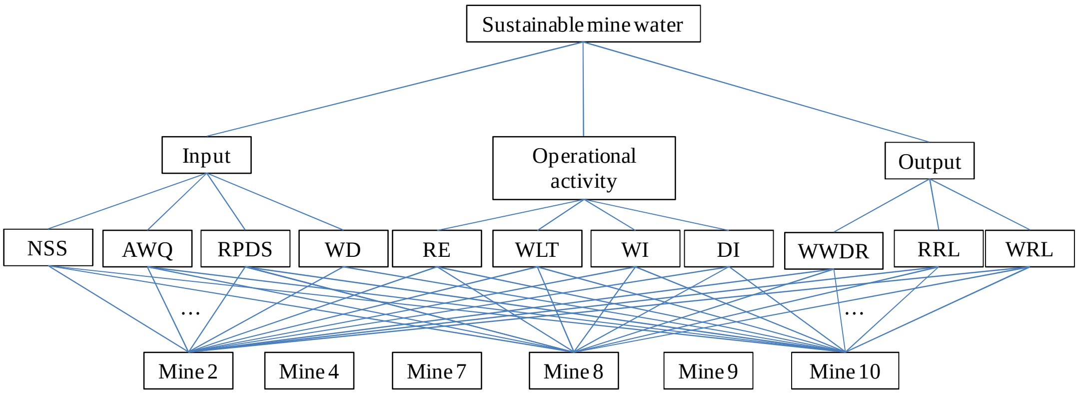

Figure 1. The decision hierarchy of strategy identification.

Table 1. The Evaluation indicators and their descriptions

Criteria	Indicator	Explanations
Input	Number of supply sources (NSS)	Surface water, underground water and third-party water which is delivered through a supply scheme operated by a third-party, e.g. dams and rivers.
	Average water quality over sources (AWQ)	Water quality, e.g. high or low quality
	Ratio of potential demand to supply (RPDS)	The proportion of the demand water to the supply water
	Water demand (WD)	The water demand for CHPP (coal handling and preparation plant), dust, and underground per million ton product.
Operational activity	Reuse efficiency (RE)	The proportion of the worked water to the total water
	Water loss in tasks (WLT)	Including CHPP loss, dust, and underground loss per million ton product
	Wet indicator (WI)	The percentage of time above 90% full time for stored water
	Dry indicator (DI)	The percentage of time below 20% full time for stored water
Output	Worked water discharge risk (WWDR)	The discharge risk of affecting the environments, e.g. high, Low, Very Low
	Raw reservoir total loss (RRL)	The proportion of the loss of raw water reservoir to the total input to store
	Worked reservoir total loss(WRL)	The proportion of the loss of worked water to the total worked water store

3.2. Determining the weights of criteria using the AHP method

Using the decision hierarchy shown in Fig. 1, the criteria weights for strategy identification can be calculated using the AHP method. We constructed pair-wise comparison matrices as an example of the preference weights that might be elicited from experts and managers, and then set the criteria by pair-wise comparison. A fundamental scale of values, similar to those shown in Table 1, can be used to simplify the representation of the intensities of preferences. Next, we construct an n-criteria evaluation matrix A in which every element $\alpha_{ij}(i, j = 1,2, \dots, n)$ is the quotient/ratio of preference values attached to the criteria, shown in Table 2 (a-d). Finally, the local weights of all criteria and indicators are derived and listed in Table 3. Besides, the synthesis result for each indicator is shown in Table 3.

Table 2. The constructed pair-wise comparison matrices for evaluated criteria

(a) The pair-wise comparison matrix for macrolayer criteria

	Input	Operational activity	Output	Weight
Input	1	1/2	1/2	0.200
Operational activity	2	1	1	0.400
Output	2	1	1	0.400

$\lambda_{\max} = 3$, CR=0<0.1

(b) The pair-wise comparison matrix for input indicators

	NSS	AWQ	RPDS	WD	Weight
NSS	1	1/2	1/3	1/5	0.0899
AWQ	2	1	1/2	1/2	0.1803
RPDS	3	2	1	1/2	0.2811
WD	5	2	2	1	0.4486

$\lambda_{\max} = 4.041$, CR=0.015<0.1

(c) The pair-wise comparison matrix for operational activity indicators

	RE	WLT	WI	DI	Weight
RE	1	5	3	2	0.5317
WLT	1/5	1	1/2	1/2	0.0972
WI	1/3	2	1	1	0.1856
DI	1/2	2	1	1	0.1856

$\lambda_{\max} = 4.004$, CR=0.001<0.1

(d) The pair-wise comparison matrix for output indicators

	WWD	RRL	WRL	Weight
WWD	1	3	3	0.6000
RRL	1/3	1	1	0.2000
WRL	1/3	1	1	0.2000

$\lambda_{\max} = 3$, CR=0<0.1

3.3. Evaluating water management in six coal mine sites

In this research, fuzzy TOPSIS is used to evaluate the sustainable mine water management systems with respect to criteria presented in Table 3. Linguistic values have been used for evaluation of alternatives and weights of criteria. The linguistic variable VL (Very Low), L (Low), M(Medium), H(High),VH(Very High),and B(Best) corresponds to (0,0,0.2), (0,0.2,0.4), (0.2,0.4,0.6) , (0.4,0.6,0.8), (0.6,0.8,1), and (0.8,1,1), respectively.

Based on Linguistic, alternatives with regards to criteria were assessed and the weighted evaluation for each site is created. Then the fuzzy weighted decision matrix is calculated. This matrix is calculated with Eq. (3). Using Eqs. (4) and (5), the fuzzy positive ideal solution (FPIS, A^+)and fuzzy negative ideal solution (FNIS, A^-) are defined. Then the Euclidean distance of each alternative from A^+ and A^- can be computed by Eqs. (6) and (7). Next, the closeness coefficients are solved by Eq. (8). Finally, the values of each alternative for final ranking have been illustrated in Table 4.

Table 3. The AHP derived criteria weights.

Criteria	Weight of criteria	Indicator	Weights of indicator	Synthesis value
Input	0.2000	NSS	0.0899	0.018
		AWQ	0.1803	0.0361
		RPSD	0.2811	0.0562
		WD	0.4486	0.0897
Operational activity	0.4000	RE	0.5317	0.2127
		WLT	0.0972	0.0389
		WI	0.1856	0.0742
		DI	0.1856	0.0742
Output	0.4000	WWD	0.6000	0.2400
		RRL	0.2000	0.0800
		WRL	0.2000	0.0800

Table 4. The fuzzy TOPSIS results.

Mine	S_i^+	S_i^-	CC_i	Rank
2	0.2863	0.7357	0.7199	2
4	0.3327	0.7008	0.6781	3
7	0.3303	0.6570	0.6655	4
8	0.3758	0.5906	0.6111	6
9	0.2604	0.7126	0.7324	1
10	0.3664	0.6302	0.6324	5

By virtue of the proposed method, the evaluation results of how sustainable the current water management is in each site are obtained. From the results we can see that Mine 9 is the best sustainable one, with a CC value of 0.7324, and Mine 8 is the worst one with a CC value of 0.6111. Reference to the data about Mine 9, there are three water sources, that is, third-party (high quality), surface water (high quality), and ground water (low quality) in the site. The ratio of potential demand to supply is 6.2%, which denotes that the site has plenty of supper water and it needs less water to maintain its coal production. The water reuse efficiency is 93%. The WET indicator is 0 and the DRY indicator is 95%. It denotes that the mine has a risk of using up the water. The worked water discharge risk is ‘Medium’. The site does not need to discharge too much water, but the discharge water may affect the environment. Also its raw and worked reservoir total losses are 42.3% and 45.2%, respectively. The raw reservoir total loss is higher than those of the others while the worked reservoir total loss is not outstanding among these sites.

In terms of Mine 8, there is only one water source, i.e. surface water. The reuse efficiency is 100% and higher than the others’. The ratio of potential demand to supply water is 0 which is lower than others’. The WET indicator value is 0 and the DRY indicator is 86.4%. The worked water discharge is ‘Medium’. The discharge water may affect the environments. But its raw and worked reservoir total losses are 59% and 89.2%, respectively. Both of them are highest value. Analyzing its condition, it is recommended to re-design the drainage area to increase collection of on-site runoff during dry period. The evaporation control measures should be implemented to reduce water loss.

Overall, the worked water storage capacity should be optimized to improve use efficiency, and uncontrolled discharge risk should be avoided to reduce environment contamination. Sufficient water should be available to maintain regular production. Minimising the use of raw water and improving water productivity ratios can increase product benefits and reduce cost savings. Furthermore, the criteria and indicators can be changed according to preferences. The stakeholders or managers can also adjust the weight of each indicator to evaluate the sustainability of mine water management. They can improve their management schemes according to analytic results.

4. CONCLUSIONS

A multi-criteria evaluation method has been provided to aid decision making process for sustainable mine water management practices. The decision hierarchy consists of three criteria: input, operational activity, and output. The AHP method is referenced to derive the weights of the criteria. A fuzzy TOPSIS method is used for assessing strategies based on the original data. With the proposed evaluation method, the water management of six mine sites with eleven indicators are evaluated. The evaluation results illustrate the usefulness of the proposed method in identifying leading mine water management practices. Future work includes integrating the proposed evaluation method with a mine water simulation model (Gao et al. 2013a) for dynamic management strategy evaluation in different climate conditions.

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