Mine Water Environ (2012) 31:192–198
DOI 10.1007/s10230-012-0196-2

TECHNICAL ARTICLE

Choosing an Optimal Groundwater Lowering Technique for Open Pit Mines

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Received: 5 December 2011 / Accepted: 13 June 2012 / Published online: 28 June 2012

Abstract Various dewatering methods are used to lower groundwater at surface mining operations. Determining which method to use involves analyzing factors such as technical applicability, economic efficiency, and environmental protection. It is generally hard to find an alternative that meets all the criteria simultaneously, so a good compromise is preferred. We have developed a new decision support system based on a fuzzy multi-attribute decision-making method. We integrated 12 compendious decision criteria by fuzzy extent analysis to process an extensive inventory of groundwater-lowering techniques. An applied case study, Iran's Sechahoun open pit iron ore mine, was used to demonstrate the model. The model systematically evaluated alternatives; at the Sechahoun mine, an underground gallery (with a score of 33.9 %) was identified as the most appropriate groundwater lowering method.

Keywords Decision support system · Fuzzy extent analysis · Groundwater lowering program · Open pit mining

Introduction

Increased demand, exhaustion of shallow-bedded resources, and development of machinery that enables surface mining to be cost effective at greater depths all help explain why groundwater often causes major problems during mining operations. Dewatering is necessary at many mines that operate below the water table because water flows from the surrounding strata toward the excavation. This groundwater can have a detrimental effect on pit slope stability. Commonly, it diminishes the shear strength of potential failure surfaces due to increased pore pressure or increases the moisture content of materials such as clays, shales, and mudstones, which can cause accelerated weathering and a decrease in shear strength. Less commonly, it can cause local instability at locations where the toe of a slope is undermined, or a block of rock is loosened as a result of erosion of low strength infillings or weathered rock by surface water, or wedges form when groundwater in fissures freeze (Wyllie and Mah 2004). These negative aspects increase the likelihood of slope failures and potentially lead to remedial measures, such as decreasing the slope, to compensate for the reduced overall rock mass strength.

Groundwater can also lead to standing water within the pit. Adverse effects of this include loss of access to all or part of the working mine area; greater use of explosives, increased explosive failures due to wet blast holes, or the need to use special explosives; increased wear to equipment and tyres; inefficient loading and hauling, and; unsafe working conditions (Morton and van Mekerk 1993).

Groundwater will flow into the open excavation until the original groundwater flow regime is re-established (Brassington 2007). Hence, all mines excavated below the water table need some form of groundwater lowering programs (GWLPs). GWLPs at large surface mines accomplish three basic objectives: keeping working conditions dry, stable, and safe; lowering hydrostatic pressure and increasing the effective stress of rock mass to improve slope stability; and ensuring pit floor workability (Kecojevic et al. 2003).

The scale of the GWLP depends on three factors: the hydrogeological characteristics of the rock mass in which the excavation takes place; the depth of the excavation below the water table, and; the strength of the materials

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making up the pit slopes. At some mines excavated below the water table, evaporation of minor groundwater seepage from the pit floor or pit walls in a strong and stable rock mass can take care of all GWLP requirements. At other mines, major pumping operations are necessary, using external wells to control groundwater inflow to the pit and to lower the pore pressure in the rocks making up the pit slopes.

In some instances, a decision to configure the GWLP is based simply on projected savings in operating or equipment maintenance costs. For example, Beale (2009) presented an example of a dewatering program for the Morenci mine Metcalf pit in Arizona (Table 1); only the operational benefits for a given mine design were itemized, and the potential economic benefit of a depressurized, steeper wall was not considered.

A comprehensive decision on which GWLP to use involves investigating a number of alternatives, while giving appropriate attention to government regulations and guidance. The actual decision may be complicated because of a multiplicity of governing criteria, which are usually resolved by simplifications, e.g. eliminating some conflict criteria. We have developed a new decision support system to determine the appropriate drainage system method for a specific site based on a fuzzy multi-attribute decision-making method (fuzzy analytic hierarchy process or fuzzy-AHP). We demonstrate it using actual site data from Iran's Sechahoun iron ore mine.

Inventory of GWLP Techniques

The techniques available for control of groundwater in mines fall into two principal groups: migration or exclusion of water from around the pit (*ex-pit* dewatering), and drainage and pumping the groundwater from inside the pit (*in-pit* dewatering). It is important to note that these two approaches are generally complementary rather than competitive (Younger 2007). The aim of groundwater control by ex-pit dewatering is to prevent groundwater from entering the working area. The exclusion technique

Table 1 Example of operating cost savings due to dewatering (after Beale 2009, with permission)

Cost element	Benefit ($/year)
Savings in blasting costs	389,000
Reduced slope maintenance	960,000
Reduced operation of in-pit sumps	164,000
Savings in haulage costs	709,000
Savings in maintenance costs	800,000
Savings in power	53,000
Total cost benefit	2,969,000

allows work to proceed below groundwater levels with minimal effects on groundwater levels outside the site (Cashman and Preene 2001), which avoids the potential side effects of dewatering. In-pit dewatering methods control groundwater by collecting the water in sumps and then pumping, affecting a local lowering of groundwater levels. The aim of this approach is to lower groundwater levels to a short distance (say 0.5 m) below the deepest excavation formation level (Brassington 2007; Woodward 2005). Inventory of conventional techniques and typical usage conditions are summarized in Table 2 (Cashman and Preene 2001; Younger et al. 2002).

The decision on which dewatering measure to use often leads to using combined methods, e.g. impermeable cut-off walls and wells, wells and underground galleries, or wells with horizontal drains (Libicki 1985). There are clearly instances where this is necessary, such as when an excavation will penetrate a succession of widely varying lithology (Cashman and Preene 2001), so the configured GWLP must allow this option.

Governing Features of the Optimal GWLP

Based on the results of a field investigation and a literature review (Libicki 1985; Morton and van Mekerk 1993; Younger et al. 2002), 12 compendious features were found to incorporate all of the major technical, economical, safety, and environmental factors (Fig. 1).

Successful linking between mining operations, hydrological conditions, and dewatering is also critical in achieving GWLP goals. For example, an open pit operated in loose, water-saturated formations will have many not-very-high benches; a quick face advance can be difficult due to the need to reproduce sheared wells on each bench, together with their electrical supply and water removal installations. Technical factors (*T*) such as these are summarized below:

- *Response time (T_1):* required time and duration for the local water table to be lowered.
- *Hydrological condition compatibility (T_2):* appropriateness of a dewatering system based on hydrologic factors, such as permeability (K) and coefficient of volume compressibility (C_v).
- *Experiences with the system (T_3):* unexpected discordance may lead to poor efficiency or even system failure; relevant experience with similar situations could eliminate such uncertainties.
- *Flexibility (T_4):* adaptability of the dewatering system to possible variation in design assumptions.
- *(T_5) Interfere with mining operations:* the GWLP should adversely affect mining operations as little as

Table 2 Inventory of techniques in GWLP and their typical usage condition

Approach	Condition of use
Ex-pit techniques	
Drainage pipes or ditches (e.g. French drains)	Upstream; favorable topography; using tunnels where topography is unfavorable
Sump pumping	Clean coarse soils
Drying of the near springs or lakes	Available destination storage
Deep wells with electric submersible pumps	Sandy gravels to fine sands and water-bearing fissured rocks
Deep wells with electric submersible pumps and vacuum	Silty fine sands, where drainage from the soil into the well may be slow
Steel sheet-piling (displacement barrier)	Most soils, but obstructions such as boulders or timber baulks may impede installation
Vibrated beam wall (displacement barrier)	Silts and sands; will not support the soil
Slurry trench cut-off wall using bentonite or native clay (excavated barrier)	Silts, sands, and gravels with hydraulic conductivity coefficient, K, less than 5×10^{-3} m^3/s
Jet grouting (injection barrier)	Soils and weak rocks
Mix-in-place columns (injection barrier)	Soils and very weak rocks
In-pit techniques	
Unloading	Where coefficient of volume compressibility, C_v, is less than 10^{-4} m^2/s
Drainage wells	Where C_v is greater than 10^{-2} m^2/s
Underground galleries[a]	Where C_v is greater than 10^{-4} m^2/s
Horizontal drain holes	Where C_v is greater than 10^{-4} m^2/s; attainable length is less than 150 m
Needle filters	Attainable length is less than 10 m
Ditches	Single side pit in mountain area; 1–2 deg. dip in benches with approximately impermeable face
Pumping stations	Where C_v greater than 10^{-2} m^2/s; capacity for rain of 10 % probability

[a] Also available as an ex-pit application , known as adit dewatering

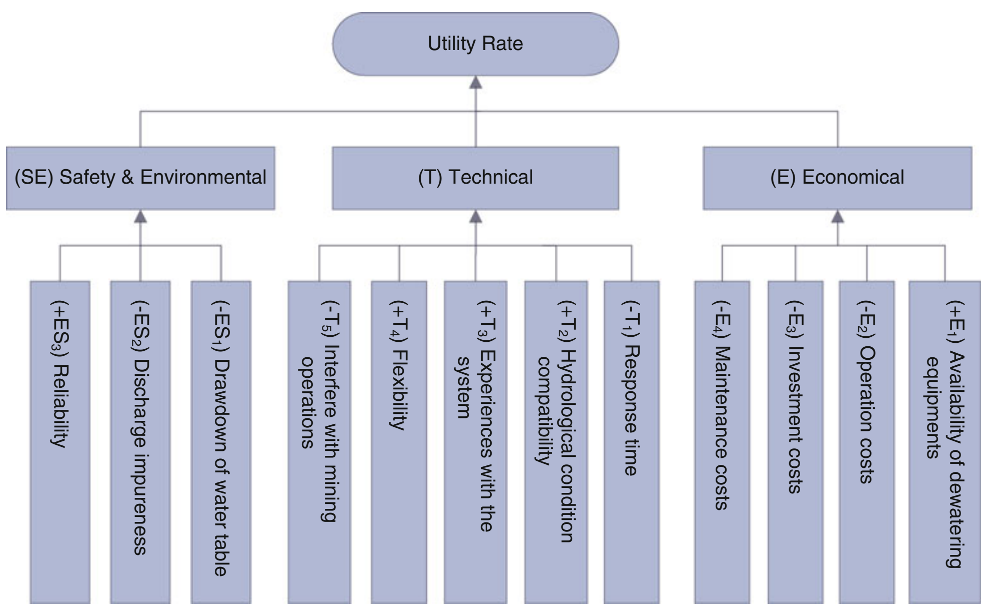

Fig. 1 Interactions of leading factors in detection of optimum dewatering system

possible. Generally, ex-pit techniques are less inconvenient to mining than in-pit ones.

- Financial aspects are another integral part of the decision. In this paper, they are materialized by economic factors, *E*, which have the following sub-attributes:
- Availability *of dewatering equipment (E_1):* accessibility and delivery time relevant to its need with respect to

infrastructure. Although availability of dewatering equipment is not an apparent financial attribute, it could affect the closing price. Hence, it affects the economics.

- *Operation costs (E_2):* energy consumption, labor costs, and so forth;
- *Investment costs (E_3):* equipment, construction materials, installation, and other expenditures.
- *Maintenance costs (E_4):* replacement or repair of equipments and structures, monitoring, etc.

Finally, safety and environmental factors (SE) are considered. These include:

- *Drawdown of water table (SE_1):* adverse influence of the mine on streams, water intakes, and soils in the vicinity.
- *Discharge quality (SE_2):* environmental protection requirements are critical, and if disregarded, will prevent mine closure due to unallowable environmental disturbances. GWLPs definitely affect discharge quality. For instance, the water that comes from dewatering wells with submersible pumps is relatively clean, while water that flows over rocks in the open-pit or in underground galleries is polluted, and has to be purified before it can be discharged.
- *Reliability (SE_3):* probability that the system will work successfully.

The interactions of leading factors are organized *hierarchically* in Fig. 1. It should be note that each factor is either a cost attribute (e.g. smaller is better) or a benefit attributes (e.g. larger is better), which is indicated in Fig. 1 by minus and plus, respectively.

Fuzzy MADM

Determining the best GWLP system involves multiple decision criteria, several alternatives, unknown mathematical relationships between them, uncertainties, and linguistic variables. These reasons led us to use multiple attributes decision-making (MADM), which identifies optimal compromise solutions from all feasible alternatives, based on both quantitative and qualitative attributes (Erol and Ferrell 2003). In other worlds, the aim of MADM is to select the alternative that has the highest degree of satisfaction for all of the relevant attributes (Yang and Hung 2007). Several application of MADM methods have been reported in the field of water management (e.g. Chung et al. 2011; Hernandez and Uddameri 2010; Hyde et al. 2004; Karnib 2004). Hajkowicz and Collins (2007), who provided a comprehensive review on the application of multiple criteria analysis in water management, identified Saaty's AHP as one of the most practiced well-known MADM methods. It can cope with the uncertainties and inexact definitions of linguistic variables (discussed below) and inadequately crisp data to model real-life problems. Hence, we used a fuzzy AHP method to rank alternatives options.

Linguistic Variables

The concept of linguistic variables is very useful in dealing with situations that are too complex or ill-defined to be reasonably described in conventional quantitative expressions (Li and Yang 2004). For example, the ratings of alternatives on the qualitative attribute *reliability* could be expressed using linguistic variables such as "low", or "very high". Such linguistic values can also be represented using positive triangular fuzzy numbers (TFNs). For example, "very low", "low", "medium", "high" and "very high" can be represented by TFNs (1, 1, 2), (2, 3, 4), (4, 5, 6), (6, 7, 8), and (8, 9, 9), respectively. In a similar vein, TFNs (1, 1, 1), (1/2, 1, 3/2), (1, 3/2, 2), and (3/2, 2, 5/2) are used to present an expert's verbal judgments as "just equal", "slightly important", "very important", and "much more important", respectively.

Fuzzy Extent Analysis Method

Many fuzzy-AHP methods exist (e.g. Buckley 1985; Chang 1996; Mikhailov 2004; Van Laarhoven and Pedrycz 1983). These methods are systematic approaches to the alternative selection and justification problem that use the concepts of fuzzy set theory and hierarchical structure analysis. The current study applies the extent analysis approach of fuzzy-AHP developed by Chang (1996), which is one of the most important methods that integrates triangular fuzzy numbers in fuzzy-AHP.

Let $X = \{x_1, x_2, \ldots, x_n\}$ be an object set, and $U = \{u_1, u_2, \ldots, u_m\}$ be a goal set. According to the method, each object is taken and extent analysis for each goal, g_i, is performed, respectively. Therefore, m extent analysis values for each object can be obtained, with the following signs (Dagdeviren et al. 2008; Gumus 2009):

$$M_{gi}^1, M_{gi}^2, \cdots, M_{gi}^m \quad i = 1, 2, \cdots n \tag{1}$$

Steps of the extent analysis consist of:

Let $A = [\tilde{a}_{ij}]_{n \times n}$ be a preference matrix where $\tilde{a}_{ij} = (a_{ij}^a, a_{ij}^b, a_{ij}^c)$ is a TFN.

Step 1 The value of fuzzy synthetic range with respect to the *i*th object is defined as:

$$S_i = \sum_{j=1}^{m} M_{gi}^{j} \otimes \left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{gi}^{j}\right]^{-1} = \left(\sum_{j=1}^{m} l_j, \sum_{j=1}^{m} m_j, \sum_{j=1}^{m} u_j,\right) \otimes \left(\frac{1}{\sum_{i=1}^{n} u_i}, \frac{1}{\sum_{i=1}^{n} m_i}, \frac{1}{\sum_{i=1}^{n} l_i},\right) \quad (2)$$

Step 2 The degree of possibility of $M_2 \geq M_1$ is defined as:

$$V(M_2 \geq M_1) = \mu_{M_2}(d) = \begin{cases} 1 & \text{if} \quad m_2 \geq m_1 \\ 0 & \text{if} \quad l_2 \geq u_1 \\ \frac{l_1 - u_2}{(m_2 - l_2) - (m_1 - l_1)} & \text{otherwise} \end{cases} \quad (3)$$

where d is the ordinate of the highest intersection point D between μ_{M1} and μ_{M2}. The values of both $V(M_1 \geq M_2)$ and $V(M_2 \geq M_1)$ are needed to compare M_1 and M_2.

Step 3 The degree possibility for a convex TFN to be greater than k convex TFN M_i $(i = 1,2,\ldots,k)$ can be defined by:

$$V(M \geq M_1, M_2, \ldots M_n) = \min V(M \geq M_i), \quad i = 1, 2, \cdots, k. \quad (4)$$

and assume that:

$$d'(\mathrm{A}_i) = \min V(S_i \geq S_k), \; k = 1, 2, \cdots n; \; k \neq i \quad (5)$$

Then, the weight factor is given by:

$$W' = (d'(A_1), d'(A_2), \cdots d'(A_n))^T, \; i = 1, 2, \cdots, n \quad (6)$$

Step 4 The normalized weight vectors via normalization are given by

$$W = (d(A_1), d(A_2), \cdots d(A_n))^T \quad (7)$$

where W is a defuzzified number. According to decreasing order of alternatives by W, the top ranking should be the best GWLP.

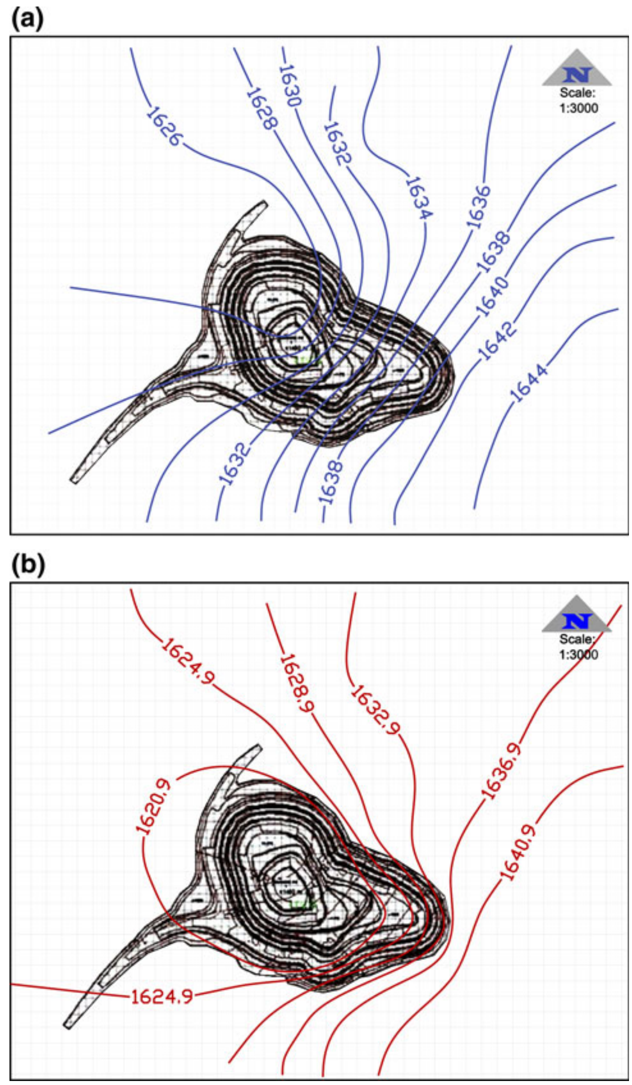

Fig. 2 Groundwater elevations around the Sechahoun mine: **a** natural level, **b** final pit, after 25 years (Katibeh et al. 2010)

Case Study of the Sechahoun Open Pit Mine

The Sechahoun iron ore open pit mine, which contains more than 145 Mt of ore, is located east of Yazd, Iran. The natural groundwater level in Sechahoun is 30–40 m below ground level, e.g. ca 1630 m above mean sea level (amsl), as indicated in Fig. 2a (Katibeh et al. 2010). The water inflow to the pit is mainly from a confined aquifer, mostly by horizontal flow in the upper layers and vertical flow at the pit bottom.

The final depth of the Sechahoun pit will be 270 m, e.g. 1,400 m amsl. Katibeh et al. (2010) used a numerical method (MODFLOW software, version PMWIN 5.3), to show that when the pit is excavated under 1600 m amsl, groundwater flow into the pit will be dangerous. Figure 2b shows groundwater elevations after 25 years, based on finite difference modeling.

Figure 2 shows that the hydraulic gradient is highest southeast of the pit. Uncontrolled water behavior may cause additional slope instability, operational difficulties, and adverse environmental impacts. Hence, a GWLP is essential in nearly the entire stages of construction and operation of the pit.

Four GWLPs were considered to address the groundwater problems in the Sechahoun pit:

- Alt. 1: Pumping wells (in-pit)
- Alt. 2: Underground gallery (ex pit)
- Alt. 3: Pumping stations (in-pit)
- Alt. 4: Deep wells with electric submersible pumps (ex pit).

Performance of each alternative with respect to each criterion are shown as an impact matrix in Table 3. The Table's qualitative entries are approximate, based on a conceptual design stage. They could be converted to TFNs for further computational steps.

The pairwise comparisons for the main and sub-attributes mentioned in Fig. 1 were obtained from expert judgments. For instance, Table 4 shows the received judgments about how the main attributes cluster.

The values of fuzzy synthetic extents with respect to the main attributes were calculated as shown below (see Eq. 1):

$$S_T = (2.17, 3, 4.5) \otimes (0.22, 0.33, 0.46) = (0.48, 1, 2.08)$$

$$S_E = (2.5,\ 3.5,\ 4.5) \otimes (0.25,\ 0.37,\ 0.46) \\ = (0.62,\ 1.31,\ 2.08)$$

$$S_{SE} = (2.17,\ 2.67,\ 4) \otimes (0.22,\ 0.29,\ 0.4) \\ = (0.48,\ 1.0.76,\ 1.6)$$

The degrees of possibility were calculated as shown below (see Eq. 3):

$$V(M_T \geq M_E) = 0.823, \\ V(M_T \geq M_{SE}) = 1, \\ V(M_E \geq M_T) = 1, \\ V(M_E \geq M_{SE}) = 1, \\ V(M_{SE} \geq M_T) = 0.825, \\ V(M_{SE} \geq M_E) = 0.639.$$

For each pairwise comparison, the minimum degrees of possibility are found below (see Eq. 5):

Table 4 Expert's pairwise judgments between main attributes

Main criteria	*T*	*E*	*SE*
T	(1, 1, 1)	(2/3, 1, 2)	(1/2, 1, 3/2)
E	(1/2, 1, 3/2)	(1, 1, 1)	(1, 3/2, 2)
SE	(2/3, 1, 2)	(1/2, 2/3, 1)	(1, 1, 1)

$$\min V(M \geq M_T) = 0.823, \\ \min V(M \geq M_E) = 1, \\ \min V(M \geq M_T) = 0.639.$$

The importance weights of the main attributes were calculated via normalization, as follows:

$$W = (d(T), d(E), L, d(SE))^T = (0.334, 0.41, 0.26)^T$$

In a similar way, the importance weights of the all sub-attributes and alternatives were calculated (Table 5). According to the results, *underground gallery*, Alt. 2, with a score of 33.9 %, was identified as the superior GWLP.

The scores in Table 5 indicates that the underground gallery (column Alt. 2) option would use available equipment (E1), has relatively low operation (E2) and maintenance costs (E5), is compatible with hydrological conditions (T2), is relatively reliable (SE3), and would pose negligible interfere with mining operations (T5). These scores are site-specific and are based on side-by-side comparison of the alternatives and the preferences of the decision makers, based on the decision criteria. They reflect site conditions and the management philosophy at the mine; thus, although this approach should be applicable elsewhere, the conclusions at other sites are likely to be very different.

Table 3 Impact matrix of GWLPs is proposed for Sechahoun open pit mine

Criteria	Sub cr.	Alt. 1	Alt. 2	Alt. 3	Alt. 4
T	T1	M	VH	M	VH
	T2	M	M	M	M
	T3	H	M	VH	M
	T4	H	VL	VH	M
	T5	L	M	VL	M
E	E1	VH	M	VH	M
	E2	M	H	M	VH
	E3	M	H	M	VH
	E4	M	M	L	M
SE	SE1	M	VH	H	H
	SE2	M	H	M	H
	SE3	H	H	H	M

VL very low, *L* low, *M* medium, *H* high, *VH* very high

Table 5 Priority weights driven from the calculations

Main criteria	*W*	Sub-criteria	*W*	Alt. 1	Alt. 2	Alt. 3	Alt. 4
T	0.33	$-T_1$	0.33	0.05	0.00	0.05	0.00
		$+T_2$	0.30	0.00	0.05	0.00	0.05
		$+T_3$	0.26	0.03	0.00	0.06	0.00
		$+T_4$	0.02	0.00	0.00	0.00	0.00
		$-T_5$	0.10	0.00	0.02	0.00	0.02
E	0.41	$+E_1$	0.09	0.00	0.03	0.00	0.00
		$-E_2$	0.41	0.00	0.17	0.00	0.00
		$-E_3$	0.31	0.00	0.00	0.13	0.00
		$-E_4$	0.20	0.00	0.03	0.01	0.03
SE	0.26	$-SE_1$	0.45	0.08	0.00	0.02	0.02
		$-SE_2$	0.11	0.01	0.00	0.01	0.00
		$+SE_3$	0.45	0.04	0.04	0.04	0.00
Final rank				21.6 %	33.9 %	32.7 %	11.8 %

Conclusions

In this age of increasingly competitive markets for mining products, the GWLP selection problem is of enormous interest as a way of decreasing total costs. Successful dewatering requires a thorough understanding of the appropriate techniques. Without this knowledge, any dewatering decision will have a high probability of being sub-optimal, incurring unnecessary costs with a low success rate.

Decision-makers face environments that are more complex today, so decision making often involves uncertainties. Therefore, we designed a multi-criteria decision-making model based on fuzzy set theory (i.e. fuzzy AHP) to select the most acceptable GWLP. For this purpose, the 12 most relevant criteria were integrated to achieve a sustainable decision. Adding decision criteria to an evaluation process can improve accuracy and thereby make a decision support system more robust, but can require additional time and money.

Comparing the four alternatives in this case study led to the *underground gallery* (*Alt. 2*) being the optimal solution, with a normalized score of 33.9 %. One of the advantages of this decision technique is that final rankings are expressed with relative scores, so a user should readily understand the actual difference between alternative preferences and make a realistic decision. For example, although *Alt. 2* had the top ranking, with a score of 33.9 %, *pumping station*, (*Alt. 3*), with a score of 32.7 %, has a very similar score. Therefore, *Alt. 3* could be the superior alternative if the situation was only slightly different or if the decision makers are allowed/encouraged to reexamine their scores. The fuzzy extended analysis eliminated some criteria that were much less relevant by giving them zero weights. Such clustering may help managers make decisions based on the most important criteria, especially in cases where more precise information can be expensive to obtain.

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