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A hybrid fuzzy multi-criteria decision making approach for desalination process selection

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HIGHLIGHTS

► A hybrid model was developed based on the fuzzy-AHP and TOPSIS methods.
► Fuzzy-AHP was used to determine the weights of the criteria and sub-criteria.
► TOPSIS method was used to calculate the final ranking of the desalination technologies.
► A real world application of the model demonstrated its feasibility and reliability.

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ABSTRACT

In this paper an integrated two-step model was developed based on the fuzzy-AHP and TOPSIS methods. The performance and reliability of the model were then evaluated in a real world case study concerning the selection of the most suitable desalination technology for the treatment of brackish groundwater typical of an area located in north-east of Iran. The desalination technologies included in this study were reverse osmosis, electrodialysis, ion exchange, multistage flash distillation, multi-effect distillation, and vapor compression. The comparison of the technologies was based on various environmental, technical and economical criteria and sub-criteria. The fuzzy-AHP was used to analyze the structure of the selection process and to determine the weights of the criteria and sub-criteria, and the TOPSIS method was used to calculate the final ranking of the technologies. The outcome results of the two-step model revealed that electrodialysis, with a closeness coefficient value of 0.7547, was the most applicable desalination technology for the study area. Moreover, sensitivity analysis demonstrated that any variation in the criteria weights does not affect the outcome of the model.

1. Introduction

In recent years, the scarcity of fresh water resources in countries located in the arid and semi arid regions of the world has become more critical due to resource limitations, global warming and the increase in water consumption. As such, the use of brackish groundwater and the application of different technologies to improve their quality for various consumptions have gained special attention in water resource management programs.

At the present, there are many different types of desalination technologies available in the market, each with its own technical specifications and applicability. These technologies can be categorized in three general groups of distillation, membrane-based and ion exchange. In distillation processes, water is transformed into vapor and then is condensed into a liquid state. Commercially available technologies of this type include multistage flash distillation (MSF), multi-effect distillation (MED), and vapor compression (VC) [1]. In contrast, membrane-based desalination techniques use different types of membrane to separate dissolved solids from water. The most popular membrane-based desalination technologies are reverse osmosis (RO) and electrodialysis (ED). In ion exchange process (IE) the ions in the solution are exchanged by the ions of a resin [2].

Because of the advantages and disadvantages associated with each desalination technology, the selection of the optimum technique for any specific area is a complicated task due to the diversity of objectives and constraints that should be considered and satisfied simultaneously. With these types of problems, decision makers cannot go through the standard single criteria mathematical programming techniques to find the best option. Moreover, like most other real-life problems, there always exists a lack of sufficient data which will add an extra dimension of complexity. In such situations where the decision maker confronts many criteria and constraints, multi criteria decision making (MCDM) methods can offer a proper solution, as they provide techniques for comparing and ranking many criteria and choices. Another major advantage of most MCDM techniques is their ability to analyze both quantitative and qualitative criteria together. Many techniques and methodologies are reported in the literature for MCDM [3]. Among most popular ones

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are the analytic hierarchy process (AHP) [4], the technique for order preference by similarity to an ideal solution (TOPSIS) [5], elimination and choice corresponding to reality (ELECTRE) [6], preference ranking organization method for enrichment of evaluations (PROMETHEE) [7], decision-making trial and evaluation laboratory (DEMATEL) [8], analytic network process (ANP) [9], and Vlsekriterijumska Optimizacija I Kompromisno Resenje (VIKOR) [10].

In regard to desalination technologies, Hajeeh and Al-Othman [11] used a two-stage AHP process to select the most appropriate alternative. Seven criteria were selected and used in order to identify the most suitable desalination technology from four desalination plants. Mohsen and Al-Jayyousi [12] also applied a five-step AHP model to evaluate various desalination technologies. The criteria adopted for evaluation were based on technical, economic, and environmental aspects. Hajeeh [13] presented a hierarchy model based on the fuzzy set theory to deal with the desalination technology selection problem. The linguistic values were used to assess the ratings and weights for the technology evaluating factors. The selection process was limited to six factors and three commercially available desalination technologies including MSF, MED, and RO. Bick and Oron [14] developed an AHP-based decision making approach to select the best post-treatment technology for a specific seawater reverse osmosis plant. Post-treatment systems were evaluated based on seven criteria. A sensitivity analysis was performed to examine the response of alternatives when the relative importance rating of each criterion was changed.

In this study, an integrated model consisting of fuzzy-AHP and TOPSIS was established to provide a stepwise methodology for the selection of the optimum desalination technology among different available technologies. The model was then applied in a case study to demonstrate its applicability in a real world pilot study and prove its reliability.

The fuzzy-AHP has a strong ability to handle the uncertainty and ambiguity present in deciding the priorities of different alternatives in an MCDM situation. Moreover, it allows for approximate values and inferences as well as incomplete or ambiguous data (fuzzy data) as opposed to only relying on crisp data (binary yes/no choices) [15]. TOPSIS is an efficient model in handling the sensible attributes and there is no limit in terms of number of criteria, sub-criteria or alternatives. As a result, the integration of AHP-fuzzy and TOPSIS can provide a strong base for the analysis of complex decision problems [16–20]. Furthermore, the AHP-fuzzy and TOPSIS methods can be easily programmed by using a spreadsheet to automate the decision making process.

The following sections cover respectively: a brief description of fuzzy-AHP and TOPSIS, the proposed integrated methodology, the application of the model in a real world situation concerned with the selection of the optimal desalination technology, and the conclusions.

2. Fuzzy-AHP method

AHP is an MCDM technique developed by Saaty [4] for evaluating different alternatives against a set of selected criteria in order to determine the best alternative. AHP assumes that criteria can be expressed in a hierarchical structure. In this model, the criteria are compared pairwise and the final decision is made based on the results of these comparisons [21]. In conventional AHP for pairwise comparisons of the criteria an arbitrary value (acquired by mainly decision makers) is allocated to each criterion. Therefore, due to the high degree of uncertainty involved in the allocated values, the results cannot be completely reliable [22]. To reduce the degree of uncertainty and vagueness associated with the conventional AHP, different versions of the fuzzy-AHP methods were developed [23]. In general, in the fuzzy-AHP models a linguistic approach is applied, in which the optimism/pessimism conceptual rating attitude of decision-makers is taken into account. Because of the linguistic approach, triangular fuzzy numbers (TFNs) are used to quantify conceptual preferring ratings of criteria [24]. The linguistic scale of TFNs can be chosen according to the extent of uncertainty and ambiguity present in the decision making problem. In a literature a range of linguistic scales including 5-point, 6-point and 7-point has been reported [25]. In this research, a 6-point triangular fuzzy scale of preferences was used (Table 1). This scale was proposed by Kahraman et al. [26] and used for solving fuzzy decision making problems [27–29].

Table 1
Triangular fuzzy scale of preferences [26].

Linguistic terms	Triangular fuzzy scale	Triangular fuzzy reciprocal scale
Just equal	(1, 1, 1)	(1, 1, 1)
Equally important	(1/2, 1, 3/2)	(2/3, 1, 2)
Weakly important	(1, 3/2, 2)	(1/2, 2/3, 1)
Strongly more important	(3/2, 2, 5/2)	(2/5, 1/2, 2/3)
Very strong more important	(2, 5/2, 3)	(1/3, 2/5, 1/2)
Absolutely more important	(5/2, 3, 7/2)	(2/7, 1/3, 2/5)

There are many alternatives as solution methods to perform on the fuzzy-AHP based structured model on MCDM problems [23,30–34]. Among the most reliable and simple ones is the Chang [30] extent analysis method which is used in this study. The method is used to determine the extent of an object to be satisfied for the goal. The Chang's [30] method includes several steps which are summarized as follows [21,26].

Assume $X = \{x_1, x_2, \ldots, x_n\}$ be an object set, and $G = \{g_1, g_2, \ldots, g_m\}$ be a goal set. According to the method of extent analysis, each object is taken and extent analysis is performed for each goal, g_i respectively. Therefore, the m extent analysis values for each object can be obtained, with the following signs:

$$\tilde{M}_{gi}^{1}, \tilde{M}_{gi}^{2}, \ldots, \tilde{M}_{gi}^{m}, i = 1, 2, \ldots, n$$

where all the $\tilde{M}_{gi}^{j}, j = 1, 2, \ldots, m$ are TFNs. A TFN is represented by three parameters: the least possible value, the most possible value, and the highest possible value, here are represented by l, m and u respectively.

Step 1 The value of the fuzzy synthetic extent with respect to the ith object is defined as follows:

$$\tilde{S}_i = \sum_{j=1}^{m} \tilde{M}_{gi}^{j} \otimes \left[\sum_{i=1}^{n} \sum_{j=1}^{m} \tilde{M}_{gi}^{j} \right]^{-1}. \quad (1)$$

To obtain $\sum_{j=1}^{m} \tilde{M}_{gi}^{j}$, the fuzzy addition operation of the m extent analysis values for a particular matrix is performed as shown in Eq. (2):

$$\sum_{j=1}^{m} \tilde{M}_{gi}^{j} = \left[\sum_{j=1}^{m} l_j, \sum_{j=1}^{m} m_j, \sum_{j=1}^{m} u_j \right]^{-1}. \quad (2)$$

And to obtain $\sum_{i=1}^{n} \sum_{j=1}^{m} \tilde{M}_{gi}^{j}$ the fuzzy addition operation $\tilde{M}_{gi}^{j}$ ($j = 1, 2, \ldots, m$) values are performed as in Eq. (3):

$$\sum_{i=1}^{n} \sum_{j=1}^{m} \tilde{M}_{gi}^{j} = \left(\sum_{i=1}^{n} l_i, \sum_{i=1}^{n} m_i, \sum_{i=1}^{n} u_i \right). \quad (3)$$

The inverse of the vector above is then computed as presented in Eq. (4):

$$\left[\sum_{i=1}^{n} \sum_{j=1}^{m} \tilde{M}_{gi}^{j} \right]^{-1} = \left(\frac{1}{\sum_{i=1}^{n} u_i}, \frac{1}{\sum_{i=1}^{n} m_i}, \frac{1}{\sum_{i=1}^{n} l_i} \right). \quad (4)$$