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Multi-criteria decision-making model for wastewater reuse application: a case study from Iran

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ABSTRACT

Wastewater reuse is considered as a solution to better management of the water resources that presents a viable method to solve water shortage problems, especially in regions where available water resources are limited. Selection of wastewater reuse application for different uses is a multidimensional process which involves multiple criteria and multiple stakeholders. Multi-Criteria Decision-making (MCDM) approach is often used to solve various decision-making problems. The analytical hierarchy process (AHP) method has been widely used to solve MCDM problems. In this study, a MCDM model based on AHP has been implemented in order to find the best alternative for using wastewater in Iran as a case study. For this purpose, a hierarchy structure with different levels (four criteria, sixteen sub-criteria, and five alternatives) is applied, and after performing the model and sensitivity analysis, the results are presented. Results show that groundwater recharge is the best alternative for wastewater reuse, followed by environmental use. The applied method is an effective approach and could help decision-makers through giving solutions to manage water resources.

Keywords: Wastewater reuse; AHP; Multi-criteria decision-making; Water resource management; Iran

1. Introduction

Water shortage is currently one of the global problems that seriously effect on the lives of high numbers of the world population [1]. The decreasing natural water resources, increasing water demand triggered by population growth and urbanization, deteriorated water quality, and highly changing climate have grown the environmental problems. So, it is very important to find all other possible water resources before using-up limited surface water and groundwater supplies [2]. In the context of a more sustainable water management, water reclamation and reuse appears to be an alternative dependable water resource [3]. The recovery of treated wastewater for different uses is an interesting practice that can contribute to a better management of water resources all over the world. This fact is especially important in arid and semi-arid zones where water resources are becoming both quantitatively and qualitatively scarce [4,5].

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Central regions of Iran are suffering from serious water shortage crises due to some problems such as prolonged drought, low rainfall, limited water resources, and population growth. This finally results in decrease in the surface water quantity and groundwater levels in most parts of these areas as well as the quality of these resources. Therefore, it is necessary to use all of the conventional and non-conventional water resources.

The environmental and social impacts derived from treated wastewater reuse are an intrinsically complex multidimensional process which involves multiple criteria and multiple stakeholders [6]. The multi-criteria decision-making (MCDM) methods deal with the process of making decisions in the presence of multiple criteria [7].

In the literature, various studies regarding wastewater reuse management were reported in some countries which are described below:

L. Petta et al. in 2007 in the Efficient Management (EM) water project tried to promote efficient wastewater management and reuse in Mediterranean countries through creation of public awareness and implementation of innovative and suitable solutions in wastewater treatment and reuse. The main target countries of project were Jordan, Lebanon, Palestine, and Turkey [1]. In a research which was done by Almasri and McNeil in 2009, optimal planning of wastewater reuse was evaluated using the suitability approach and based on a conceptual framework for the West Bank, Palestine. The outcomes showed that the development of the map required a multidisciplinary expertise as well as necessity of the collaboration among experts from different fields [8]. In order to create a strategic decision-making system (DMS) incorporating multiple criteria, available alternatives, and environmental externalities, Sa-nguanduan and Nititvattananon in 2011 adopted a system development for urban water resource application based on a case of Pattaya City, Thailand. They concluded that this DMS is proven to be a straightforward method for giving not only an appropriate application but also the strengths and weaknesses of the alternatives. In addition, applying this DMS could contribute to proper strategies for water resource management and could be considered as an accessible tool for communicating with stakeholders [9]. Kalavrouziotis et al. in 2011 applied a multi-criteria decision analysis (MCDA) to find an optimum solution for the treated wastewater and sludge reuse which were used in agriculture and land development in Greek as a case study. Three scenarios were formulated based on spatial, technological, environmental, social, and economic criteria, and finally, the best scenario was selected [10]. In 2012, Chen et al. investigated a method to put forward several alternatives management regarding the application of recycled water for household laundry in Sydney, Australia. Based on different recycled water treatment techniques, five alternatives were proposed. Accordingly, a comprehensive quantitative assessment on the trade-off was performed among variety of criteria. This was achieved by a computer-based MCDA using the rank order weight generation together with preference ranking organization method for enrichment evaluation (PROMETHEE) outranking techniques. They concluded that the washing machine usage is the best alternative for treated recycled water [11]. The potentials for the development of three recycled water including livestock feeding and servicing, household laundry, and swimming pool were assessed by Chen et al. in 2014. To validate the strengths of these new applications, a conceptual decision analytic framework was proposed by them. Their results showed that the proposed approach could adapt to particular circumstances of each case under study [2]. The effect of wastewater evapotranspiration on citrus cultivation was determined by Skarlatos et al. in 2014. They established a Mamdani fuzzy logic model that used the most influential variables of soil and leaves samples. The model applied to a citrus orchard and that suggested the optimal wastewater irrigation rate at 125% of crop evapotranspiration [12]. Kalavrouziotis et al. in 2004 described the formulation and analysis of dynamics models growth for irrigation of trees with wastewater in Greek. The dynamics models growth were designed on the basis of the Group Method of Data Handling (GMDH). They found that qualitative features of the models may be assessed and compiled with general linear models for different treatment cases [13]. Although there are some references about the application of MCDM in wastewater management none of them have utilized the analytical hierarchy process (AHP) method in their studies. The AHP is widely used for tackling MCDM problems in real situations [14].

In this study, a model based on AHP technique is applied for wastewater management in the central areas of Iran with arid climate and then the performance of model is evaluated. The study is organized as follows: First, explanation of the methodology including AHP method, selecting criteria and alternatives, and hierarchy structures is explained in Section 2. Then, in Section 3, the results of the models are presented and discussed. Finally, conclusions are stated in Section 4.

2. Material and methods

2.1. Wastewater reuse in Iran

Iran covers a total area of about 165 million hectares. The climate is very variable due to its geographic location and unique topography. The average annual rainfall is 230 mm, while the rate of evaporation exceeds 2,000 mm annually. Approximately 90 percent of the country is arid or semi-arid and located in the interior and far south which is characterized by long, warm, and dry periods lasting sometimes over seven months [15].

In 2012, the total amount of treated wastewater in Iran was 500 million cubic meters per year that about %57 of that was considered for reusing. The treated wastewater is used for agricultural purpose, irrigation, industrial use, and ground water recharge by usage of 83, 11, 5, and 1%, respectively. There are 136 wastewater treatment plants under operation, and about 76 treatment plants are also under construction with a total capacity of 617 million cubic meters per year (http://isn.moe.gov.ir).

2.2. Analytical hierarchy process (AHP)

MCDM is a procedure that consists in finding the best alternative among a set of feasible alternatives [16]. The AHP method has some advantages. One of the most important advantages of the AHP is based on pairwise comparison. Besides, the AHP calculates the inconsistency index which is the ratio of the decision-makers inconsistency [17].

The AHP method, first proposed by Saaty, is a popular method for solving multi-criteria analysis problems involving qualitative data [18]. Since the presenting of AHP method by Saaty, this method has become one of the most widely used MCDM methods [19]. The AHP is a flexible and yet structured methodology for analyzing and solving complex decision-making problems by structuring them into a simple and comprehensible hierarchical framework [20].

Pairwise comparison is the basic measurement procedure employed in the AHP method. This comparison is used in the decision-making process to form a reciprocal decision matrix, thus transforming qualitative data to crisp ratios and making the process simple and easy to handle [18]. By making pairwise comparisons at each level of the hierarchy, participants can also develop relative weights to differentiate the importance of the criteria [20,21].

Saaty recommended a suitable measurement scale ranging from 1 to 9 for pairwise comparisons in which 1 means no difference in the importance of one criterion in relation to another, and 9 means one criterion is much more important than another (see Table 1). Reciprocals of these numbers are used to express the inverse relationship [22].

An eigenvector method is used to solve the reciprocal matrix to determine the criteria importance and performance of each alternative [22].

In order to measure the degree of inconsistency associated with the pairwise comparison matrix, the consistency index (CI) is calculated as follows:

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

where $\lambda_{\max}$ is the biggest eigenvalue that can be obtained once its associated eigenvector is known and n is the number of columns of matrix A. Further, the consistency ratio (CR), which is defined as follows, can be calculated as follows:

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \tag{2}$$

where RI is the random index, i.e. the CI of a randomly generated pairwise comparison matrix. RI depends on the number of elements being compared [22].

Saaty suggests that if the CR value is smaller than 0.10, it indicates a reasonable level of consistency in the pairwise comparison; and if it is larger than 0.10, there are inconsistencies and the AHP method may not yield meaningful results.

The procedures of the AHP involve six essential steps [19] namely:

(1) Define the unstructured problem and state clearly the objectives and outcomes.
(2) Decompose the complex problem into a hierarchical structure with decision elements (criteria, detailed criteria, and alternatives).

Table 1
Scales for pairwise comparison

Verbal judgment of preference	Intensity of importance
Equal importance	1
Moderate importance	3
Strong importance	5
Very strong importance	7
Extreme importance	9
Intermediate values between adjacent scale value	2,4,6,8

(3) Employ pairwise comparisons among decision elements and form comparison matrices.
(4) Use the eigenvalue method to estimate the relative weights of decision elements.
(5) Check the consistency property of the matrices to ensure that the judgments of decision-makers are consistent.
(6) Aggregate the relative weights of the decision elements to obtain an overall rating for the alternatives.

2.3. Identification of criteria and alternatives

Former works have shown that the selection of reuse schemes depends not only on their technical, economic, and environmental feasibility but also mainly on public support, in other words, the decision-makers who represent the interests of society [23]. Some water reuse implementation projects have failed because some other key factors, such as social awareness or associated ecological effects, were not accounted for. Thus, the consideration of regulatory, economic, technological, social, and environmental factors seems essential to successfully accomplish a reclaimed water reuse project [24].

In this study, the most important criteria for wastewater reuse were selected through reviewing different literatures and holding consultations with experts. Also we choose some sub-criteria for each of these criteria. The criteria that were chosen in our study (technical, economic, social, and environmental) were subdivided into different sub-criteria with the following:

(1) Technical criteria (quality of effluent, simple operation and maintenance, quantity of effluent, institutional cooperation, and applicability).
(2) Economic criteria (income generation, financial opportunities, capital cost, and operational cost).
(3) Social criteria (public acceptance, health risks, social benefits, and governmental support).
(4) Environmental criteria (environmental benefits, ecological risks, and water reservation).

Reclaimed water can replace freshwater in traditional practices such as agricultural and landscape irrigation, industrial applications, environmental applications (surface water replenishment, and groundwater recharge), recreational activities, urban cleaning, and firefighting, construction [25,26].

In this study, according to the case study condition, five alternatives including agricultural irrigation, landscape irrigation, industrial use, environmental uses, and groundwater recharge were selected.

2.4. Construction of hierarchy structure

The model structure for prioritizing wastewater reuse alternatives was built on the basis of hierarchical structures. Hierarchical structures break down all criteria into smaller groups (or sub-models). To break down a hierarchy into clusters, first of all, it was decided which elements to group together in each cluster. This was done according to the similarity of the elements with respect to the function they perform or the properties they share [22].

The hierarchy structure is made into four levels. The top or first level in the hierarchy represents the final goal of the MCDM analysis process, which is "to select the best alternative for using wastewater." The intermediate or second hierarchy level lists the relevant evaluation criteria which has four criteria: social, economic, environmental, and technical. The third level is made up of sixteen sub-criteria; five technical criteria, four economic criteria, four social criteria, and three environmental criteria. Finally, the lowest or fourth hierarchy level has five alternatives (agriculture, industrial, landscape, groundwater recharge, and environmental use). Fig. 1 represents the hierarchical schematic diagram for the selection of the best alternative for using wastewater as a hierarchical structure.

3. Results and discussion

For model implementation, a hierarchy structure with different levels (goal, criteria, sub-criteria, and alternatives) was made. Then, the pairwise comparison matrix was prepared, and the weights were calculated. In Fig. 2, the steps for decision-making to prioritize the alternatives for wastewater reuse are presented.

The weight for each criterion is determined according to its importance by pairwise comparisons in the context of the AHP method. The resulting weights can then be used as input for the model. The model computes the CR associated with the pairwise comparison matrix.

The pairwise comparison matrix of criteria and sub-criteria with relative importance values, and associated consistency ratios (CR) is shown in Table 2. Numbers show the rating of the row relative to the column. The CR of 0.01–0.05 for the weights are well within the ratio less than 0.10 signify that consistency is acceptable.

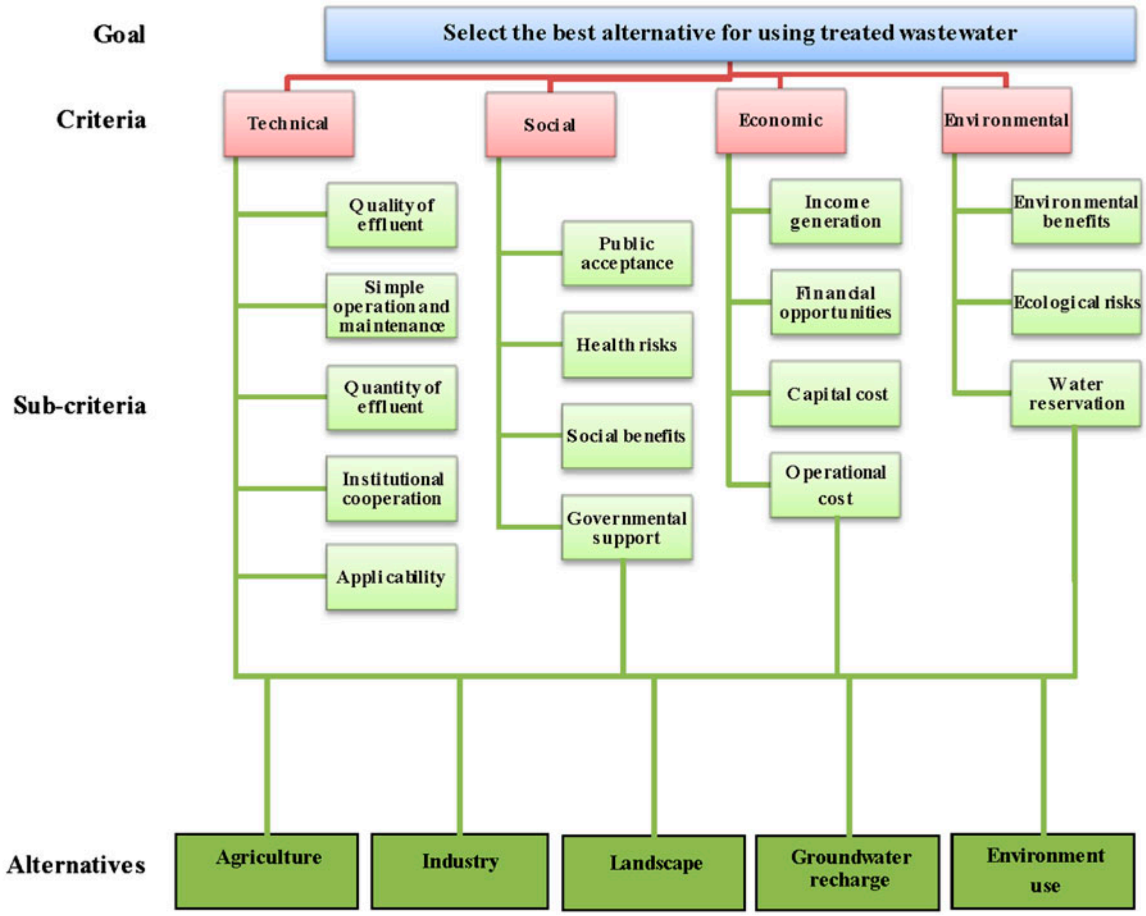

Fig. 1. Hierarchical schematic diagram for modeling the best alternative for wastewater reuse.

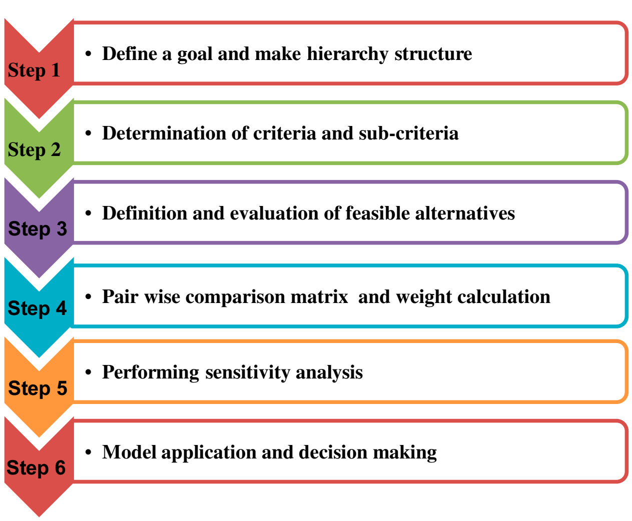

Fig. 2. Steps for decision-making to prioritize the alternatives for wastewater reuse.

To assign weights by AHP, questionnaires were used. For this purpose, some different groups of experts were involved in the process and asked to evaluate the importance of each criterion. These experts were selected from universities, research institutions, government agencies, and private companies. They were specialized in some related fields such as water resource management, wastewater engineering, environmental management, economic, civil engineering, sociology, and public health. The calculated weights of criteria that results from AHP model are presented in Table 3.

The results show that the most important criterion is technical and the least important is economic. Among the sub-criteria, environmental benefits is the most important item for environmental criteria, income generation is the most important item for economic criteria, for technical criteria, the most important one is quality of effluent, and for social criteria, public acceptance is the most weighting sub-criterion. It must be noted that the most important item in

Table 2
The pairwise comparison matrix for assessing relative importance of criteria and sub-criteria for wastewater reuse

Criteria	Quality of effluent	Simple operation and maintenance	Quantity of effluent	Institutional cooperation	Applicability
Technical					
Quality of effluent	1	2	3	3	1
Simple operation and maintenance	1/2	1	2	2	1
Quantity of effluent	1/3	1/2	1	1	1/2
Institutional cooperation	1/3	1/2	1	1	1/2
Applicability	1	1	2	2	1
Consistency ratio (CR) = 0.01					
Economic	Income generation	Financial opportunities	Capital cost		Operation cost
Income generation	1	1	2		2
Financial opportunities	1	1	2		1
Capital cost	1/2	1/2	1		1/2
Operation cost	1/2	1	2		1
Consistency ratio (CR) = 0.02					
Social	Public acceptance	Health risks	Social benefits		Governmental support
Public acceptance	1	1	2		2
Health risks	1	1	1		2
Social benefits	1/2	1	1		2
Governmental support	1/2	1/2	1/2		1
Consistency ratio (CR) = 0.02					
Environmental	Environmental benefits		Ecological risks		Water reservation
Environmental benefits	1		2		1
Ecological risks	1/2		1		1
Water reservation	1		1		1
Consistency ratio (CR) = 0.05					
Effective criteria for wastewater reuse		Technical	Economic	Social	Environmental
Technical		1	2	1	2
Economic		1/2	1	1/2	1/2
Social		1	2	1	1
Environmental		1/2	2	1	1
Consistency ratio (CR) = 0.02					

wastewater project is quality of effluent because it is directly related to human health.

Final weights and ranking of alternatives are shown in Fig. 3. Results of model show that groundwater recharge is the best alternative for wastewater reuse application and environmental use is the second alternative. According to the water shortage problems in the study area, groundwater recharge provides storage of water resource which can be withdrawn in the future if necessary.

In this study, we perform a sensitivity analysis by changing the weight of criteria to improve the

Table 3
Weights of criteria and sub-criteria from AHP model

Criteria	Sub-criteria	Weight
Technical (0.340)	Quality of effluent	0.328
	Simple operation and maintenance	0.210
	Quantity of effluent	0.110
	Institutional cooperation	0.110
	Applicability	0.242
Economic (0.140)	Income generation	0.340
	Financial opportunities	0.281
	Capital cost	0.140
	Operational cost	0.239
Social (0.281)	Public acceptance	0.340
	Health risks	0.281
	Social benefits	0.239
	Governmental support	0.140
Environmental (0.239)	Environmental benefits	0.413
	Ecological risks	0.260
	Water reservation	0.327

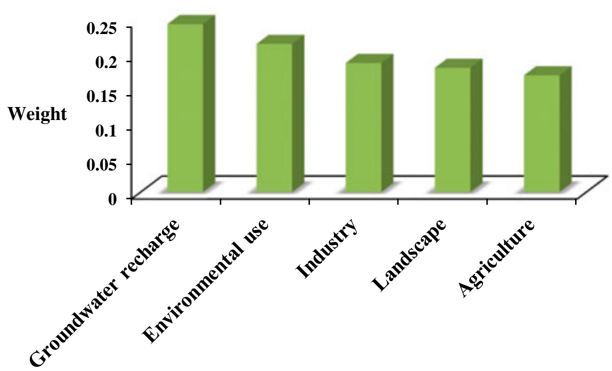

Fig. 3. Final weights and ranking of alternatives using AHP model.

reliability of the model results. Sensitivity analysis studies on how the variation of weights influence the output model and how the given model depends upon the information fed into it. By changing the criteria weigh, the results of AHP model are changed as well. The results of increasing the criteria weigh are described in four steps as follows:

In the first step, by increasing the economic criteria weight from 0.14 to more than 0.4, the initial priority was changed so that the groundwater recharge use was substituted by industrial use, and if this increase to be continued up to 0.7, the groundwater recharge use become as the last priority. In the second phase, by increasing the technical criteria weight from 0.34 to more than 0.5, the agriculture use which had the last priority among all alternatives replaced as third alternative use. In the third stage, when we increased the social criteria weight from 0.281 to 0.5, the environmental use alternative decreased dramatically and placed it in the fourth priority, while the industrial weight criteria increased and ranked as a second priority use. Finally, in the fourth stage, from observing the results, we found that by increasing the weight of environmental criteria from 0.239 to 0.7, the prioritization of groundwater recharge and environmental use alternative are increased. The industrial use alternative fell into fourth rank, and landscape use alternative went to the third rank.

4. Conclusion

In this study, an MCDM model has been applied to find the best alternative for wastewater reuse application in the central region of Iran with arid climate. The model including the AHP is effective approach for sustainable wastewater reuse management and can be applied to other regions with some modification. This model calculates the inconsistency index which is the ratio of the decision-makers inconsistency. Results can be useful for policy makers and decision-makers in water resource management to make better decisions.

It was found on the basis of technical, environmental, social, and economic criteria that groundwater recharge is the best alternative for wastewater reuse and environmental use is the second alternative. The final score of alternatives is approximately close to each other, and it is better to take into account political criteria for final decision-making.

The results of the sensitivity analysis show that the results are vigilant to the weights applied and change in weight coefficients can have a significant effect on the results of the model.

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