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Minimization of Freshwater Extraction by Using Treated Wastewater: A Fuzzy-Based Approach

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Abstract: The rapid growth of population, insufficient recharges of fresh water to the underground aquifers and increased agricultural and landscaping activities have stressed on the natural water systems in the Middle East countries. One of the available freshwater supply sources is the underground water system, which is commonly known as non-renewable water source. A large portion of domestic wastewater is currently discharged into the natural water bodies without primary treatment. Being contaminated by domestic use, discharged wastewater may cause serious environmental effects to the aquatic biota. Reuse of this water has dual benefit: reduction of fresh water extraction from stressed non-renewable sources and minimization of environmental effects. This study has introduced a fuzzy evaluation of treated wastewater reuse for agricultural and landscaping purposes. Fuzzy hierarchy structure has been developed to conduct this study. Fuzzy triangular membership functions have been employed to capture relevant uncertainties. The analytic hierarchy process has been incorporated to develop priority matrices for different hierarchy level attributes. The uncertainty in developing priority matrices was minimized through incorporating different experts' judgments from relevant field. Finally, a hypothetical case study was performed and future research directions were outlined.

Key words: Wastewater reuse, uncertainty, priority matrix and analytic hierarchy process.

Introduction

The population growth and expansion of agricultural and landscaping activities in the Middle East countries have increased in the recent years, so is the fresh water requirement. As a result, the authority has to mount pressure on the available sources of fresh water. The available sources for water supplies are surface and renewable water sources, underground and non-renewable water sources, harvesting of rainwater and desalination of seawater. Harvesting of rainwater is currently practiced in some countries including India. The feasibility of rainwater harvesting depends on amount of rain, which is quite low in these countries throughout the year. Desalination of seawater involves high cost and is used for supplying drinking water. Use of desalinated water for agricultural and landscaping purposes may not be economically feasible because of its high cost. In Middle East, most of the fresh water demand is supplied from underground and other non-renewable water sources (Alhumoud et al., 2003). The major portion of the fresh water is used for agricultural and landscaping purposes in the Middle East (Alhumoud et al., 2003). Use of treated wastewater for agricultural and landscaping purposes can reduce fresh water extraction from non-renewable sources and consequently the greater environmental problems can be reduced or delayed. In using treated wastewater, many factors including treatment and distribution cost, health risk, public perception and effects on agricultural products

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are involved. The information on such criteria is associated with uncertainties due to lack of proper knowledge and/or natural variability. To incorporate uncertainties of different parameter values, Monte Carlo simulation is widely used; but imprecisely informative data cannot be analyzed by Monte Carlo calculation. In Monte Carlo simulation, the less probability parameter values have fewer chances to be randomly selected; thus a portion of possibility may be ignored. On the contrary, fuzzy logic considers all possible parameter values through membership functions; thus provides better environmental protection (Guyonnet et al., 1999). Fuzzy logic can characterize the imprecisely informative data and provides rational solutions to the real life problems (Bonissone, 1977). Fuzzy logic and its application procedure are described in the following sections.

Fuzzy Evaluation Process

To analyze imprecisely informative data, Zadeh (1965) introduced fuzzy set theory. In a traditional set theory, an element is identified by Boolean logic. If the element is in set A, the membership grade is unity, otherwise zero. A fuzzy set is an extension of the traditional set theory in which an element has certain degree of membership μ in set A. A fuzzy set establishes relationship between uncertain data (x) and membership function μ, which ranges from 0 to 1. The membership function, $\mu_a(x)$, is defined as the fuzzy subset a in the universe of discourse x. The triangular membership function (TFNs) for Figure 1 can be shown as

$$\mu_a(x) = \begin{cases} \frac{x-a}{b-a} & a \le x \le b \\ \frac{x-c}{b-c} & b \le x \le c \end{cases} \quad (1)$$

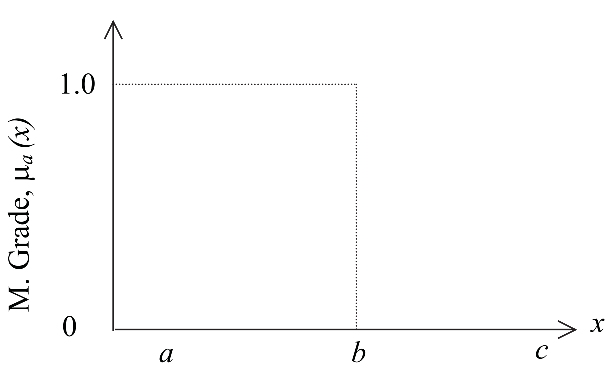

Figure 1: Construction of membership function.

The TFN is defined by (a, b, c), where a, b and c represent the minimum, most likely and maximum values (Figure 1). Although any shape of fuzzy data can be used, the triangular fuzzy numbers and trapezoidal fuzzy numbers are mostly used to represent linguistic scales (high, medium, low) of the managers, professionals and stakeholders (Lee, 1996; Sadiq et al., 2004).

For two fuzzy number $p(a, b)$ and $q(d, e)$, the arithmetic operations are shown as

$p + q = (a + d, b + e)$

$p - q = (a - e, b - d)$

$p.\ q = (\min(ad, ae, bd, be), \max(ad, ae, bd, be))$

$p/q = (\min(a/d, a/e, b/d, b/e), \max(a/d, a/e, b/d, b/e))$ if $0 \notin d, e$

The fuzzy assessment of risk-cost trade-off is a step-by-step procedure described in the following sections.

Step 1. Identification of Basic Attributes and Development of Hierarchy Structure

In treated wastewater reuse, the system index (SI) has two components: cost (a_1) and risk (a_2). Cost is divided into two attributes: fixed cost (a_{11}) and operation and maintenance cost (a_{12}) as shown in Figure 2. Operation and maintenance (O & M) cost (a_{12}) has been divided into two basic attributes: secondary treatment (a_{121}) and tertiary treatment (a_{122}). The risk attribute (a_2), has three sub attributes: social acceptance (a_{21}), human health risk (a_{22}) and crop growth (a_{23}). The social acceptance depends on many parameters including religious belief and traditional culture. The potential scopes of using treated wastewater are: agriculture and landscaping. The social acceptance attribute (a_{21}), is divided into two categories: agricultural (a_{211}) and landscaping (a_{212}) use. The human health risk is associated with handling treated wastewater (a_{221}) and ingestion of crop produced by applying treated wastewater (a_{222}). For both handling and crop ingestion, there are possibilities of health risk from microbial infection (a_{2211} or a_{2221}) or chemical ingestion (a_{2212} or a_{2222}) as shown in Figure 2.

Step 2. Defining Linguistic Variables

In risk assessment studies, most of the information is imprecisely defined due to unquantifiable nature of data or lack of proper knowledge. The experts (managers, stakeholders and researchers) often use linguistic scales (very good, good and bad) to express the existing scenarios. Generally 5 to 11 linguistic scales are used to incorporate the experts' judgments (Saaty, 1988). Too many scales make the evaluation process complex (Lee, 1996). In this study, five linguistic scales—bad (B), poor (P), fair (F), good (G) and excellent (E)—have been considered to capture experts' judgments. The respective spreads for the linguistic scales are shown in Figure 3.

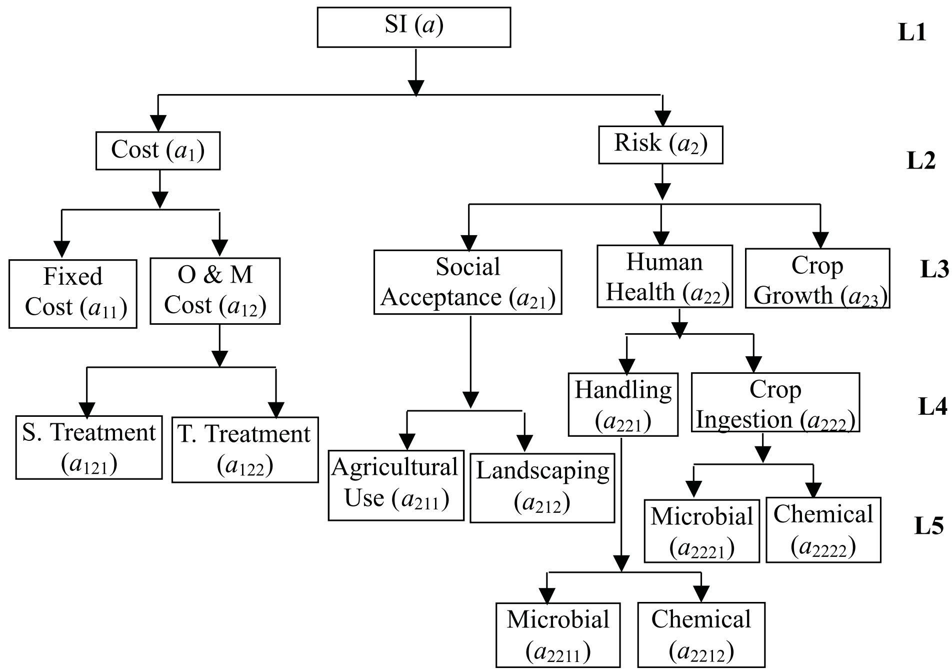

Figure 2: Hierarchy structure of wastewater treatment evaluation.

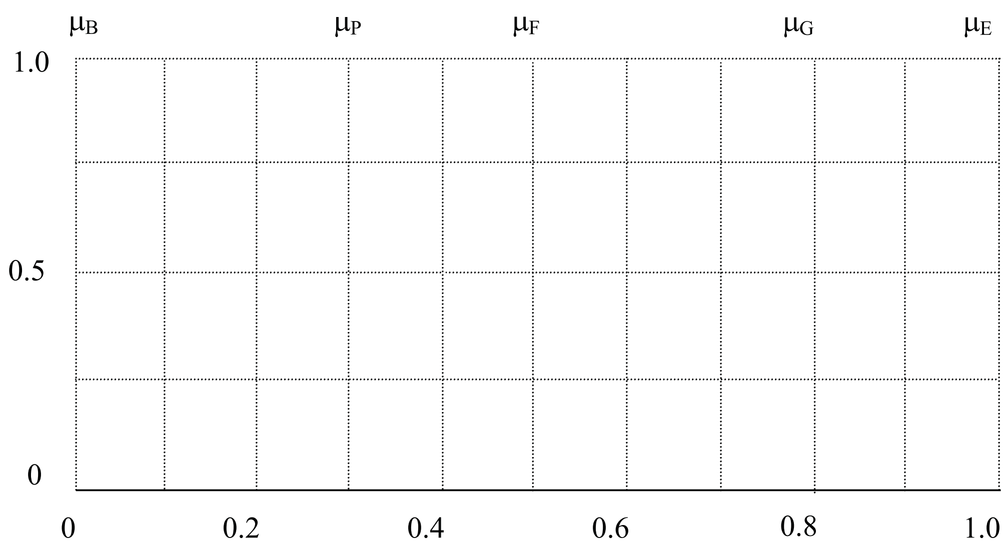

Figure 3: Membership spreads of the linguistic variables (B: (0,0,0.3), P: (0,0.3,0.5), F: (0.3,0.5,0.7), G: (0.5,0.7,1.0), E: (0.7,1,1)).

Step 3. Obtaining Fuzzy Data and Membership Functions

The different attributes like social acceptance, risk from contaminated crop ingestion and operation and maintenance cost are ambiguous or imprecise in nature; thus obtaining data for those attributes is very difficult. To overcome these difficulties, the experts in the relevant field are generally requested to provide their judgments (Chow and Liang, 2001). In case of more than one expert, the average of all judgments on any particular attribute is considered (Chow and Liang, 2001). Similar approach has been undertaken in this study. Initially, three experts were requested to provide their judgments on different basic attributes and are shown in Table 1. The average values of the three experts' judgments are also shown in Table 1. These fuzzy data were mapped on Figure 3 to

Table 1: Experts Judgments for Different Attributes of Wastewater Treatment Evaluation

Sub criteria	*Expert*			*Average fuzzy data*
	E1	*E2*	*E3*	
Fixed cost	G	F	G	0.433, 0.633, 0.9
S. Treatment	F	F	F	0.3, 0.5, 0.7
T. Treatment	P	F	P	0.1, 0.367, 0.567
Agricultural use of water	F	F	F	0.3, 0.5, 0.7
Landscaping use of water	F	E	F	0.433, 0.667, 0.8
Microbial risk-handling	P	F	P	0.1, 0.367, 0.567
Chemical risk-handling	P	P	F	0.1, 0.367, 0.567
Microbial risk-crop ingestion	G	F	G	0.433, 0.633, 0.9
Chemical risk-crop ingestion	G	G	G	0.5, 0.7, 1.0
Crop growth	F	E	F	0.433, 0.667, 0.8

obtain the membership functions. The membership functions are shown in Table 2. The details about obtaining membership functions from fuzzy data can be found elsewhere (Chowdhury and Husain, 2005; Lee, 1996). For the more generalized attributes in subsequent hierarchy level, the membership functions were evaluated based on the membership functions of the basic attributes and priority matrix following hierarchy aggregation.

Table 2: Membership Functions of the Basic Attributes of Wastewater Treatment Evaluation

Sub criteria	*Membership functions*
Fixed cost	0, 0.19, 0.66, 0.83, 0.32
S. Treatment	0, 0.5, 1.0, 0.5, 0
T. Treatment	0.32, 0.81, 0.69, 0.19, 0
Agricultural use of water	0, 0.5, 1.0, 0.5, 0
Landscaping use of water	0, 0.19, 0.66, 0.80, 0.21
Microbial risk-handling	0.43, 0.94, 0.52, 0.13, 0
Chemical risk-handling	0.43, 0.94, 0.52, 0.13, 0
Microbial risk-crop ingestion	0, 0.19, 0.66, 0.83, 0.32
Chemical risk-crop ingestion	0, 0, 0.5, 1.0, 0.5
Crop growth	0, 0.19, 0.66, 0.80, 0.21

Step 4. Developing Priority Matrix

Fuzzy evaluation requires the relative weights of different attributes at each hierarchy level. The analytic hierarchy process (AHP) is a popular process to define the relative importance of each attribute. Saaty (1988) developed fundamental scales of importance ranging from 1 to 9 to construct priority matrix for different attributes through pairwise comparison. The comparative scales of importance are shown in Table 3. These are then normalized and the relative matrix is formed in such a way that

Table 3: Fundamental Scales of Importance (Source: Saaty, 1988)

Scales	*Definition*	*Description*
1	Equal importance	Both alternative are equal
3	Weakly important	Experience and judgment weakly tend to prefer one alternative
5	Strongly important	Experience and judgment strongly tend to prefer one alternative
7	Demonstratively important	Experience and judgment demonstratively tend to prefer one alternative
9	Absolutely important	Experience and judgment absolutely tend to prefer one alternative
2,4,6,8	Intermediate values	Need to judge/compromise between two

$$W = (w_1, w_2, \ldots\ldots\ldots\, w_n) \quad \text{where} \quad \sum_{k=1}^{n} w_k = 1 \qquad (2)$$

A simple example to establish the priority matrix is illustrated as: Consider the level 2 attribute: Risk (a_2). It has three sub attributes: social acceptance (a_{21}), human health risk (a_{22}) and crop growth (a_{23}). From pairwise comparison, the experts' judgments are as follows: attribute a_{21} is less important than attribute a_{22} at a ratio 3 : 4 and attribute a_{22} is more important than attribute a_{23} at a ratio 4: 3. In the priority matrix, each element of the lower triangle in the matrix is reciprocal to the upper triangle ($I_{jk} = 1/I_{jk}$). The priority matrix becomes

$$W = \begin{array}{c|ccc} & a_{21} & a_{22} & a_{23} \\ \hline a_{21} & 1 & 0.75 & 1 \\ a_{22} & 1.33 & 1 & 1.3 \\ a_{23} & 1 & 0.75 & 1 \end{array}$$

The matrix I can be formed by taking rowwise geometric mean (Saaty, 1988) of elements and normalization to unity as

$$W = \begin{bmatrix} \\ \\ \\ \end{bmatrix} \Rightarrow W = \begin{bmatrix} \\ \\ \\ \end{bmatrix} \qquad (3)$$

The weighting schemes at different hierarchy level are shown in Table 4.

Table 4: Priority Assignment of Different Hierarchy Level Attributes

$a_{ij\,k}$	W_4	W_3	*Trial 1 (T1)*		*Trial 2 (T2)*		*Trial 3 (T3)*
			W_2	W_1	W_2	W_1	
a_1							
a_{11}			0.4		0.5		
a_{12}				0.5		0.4	0.3
a_{121}		0.4	0.6		0.5		
a_{122}		0.6					
a_2							
a_{21}							
a_{211}		0.55	0.3		0.4		
a_{212}		0.45					
a_{22}							
a_{221}				0.5		0.6	0.7
a_{2211}	0.6	0.6					
a_{2212}	0.4		0.4		0.4		
a_{222}							
a_{2221}	0.6	0.4					
a_{2222}	0.4						
a_{23}			0.3		0.2		

Step 5. Aggregation through Hierarchy Structure

Fuzzy aggregation is a systematic approach starting from the basic attributes following the hierarchy structure. The aggregation is performed systematically through combinations of priority matrix and fuzzy assessment matrices formed by the membership functions. The different level calculation for evaluating treated wastewater reuse is presented as:

Level 4 (L4) calculations

The fuzzy subsets for basic attributes of human health risk associate with handling of treated wastewater (a_{221}) and ingestion of crops (a_{222}). The assessment matrices for risk from handling of treated wastewater (a_{221}) and ingestion of crops (a_{222}) are developed as

$$a_{221} = \begin{bmatrix} 0.43 & 0.94 & 0.52 & 0.13 & 0 \\ 0.43 & 0.94 & 0.52 & 0.13 & 0 \end{bmatrix} \text{ and}$$

$$a_{222} = \begin{bmatrix} 0.00 & 0.19 & 0.66 & 0.83 & 0.32 \\ 0.00 & 0.00 & 0.50 & 1.00 & 0.50 \end{bmatrix}$$

The weighting schemes for a_{221} and a_{222} are obtained from Table 4 as

$W_{4221} = [0.6 \quad 0.4]$ and

$W_{4222} = [0.6 \quad 0.4]$ respectively

The evaluation matrix A_{221} and A_{222} for handling and crop ingestion are evaluated as

$$A_{221} = [0.6 \;\; 0.4] \times \begin{bmatrix} 0.43 & 0.94 & 0.52 & 0.13 & 0 \\ 0.43 & 0.94 & 0.52 & 0.13 & 0 \end{bmatrix}$$

$$= [0.43 \;\; 0.94 \;\; 0.52 \;\; 0.13 \;\; 0.00] \quad \text{and}$$

$$A_{222} = [0.6 \;\; 0.4] \times \begin{bmatrix} 0.00 & 0.19 & 0.66 & 0.83 & 0.32 \\ 0.00 & 0.00 & 0.50 & 1.00 & 0.50 \end{bmatrix}$$

$$= [0.00 \;\; 0.114 \;\; 0.596 \;\; 0.898 \;\; 0.392]$$

Level 3 (L3) calculations

The assessment matrix for human health risk (a_{22}), social acceptance (a_{21}) and operation and maintenance cost (a_{12}) are developed as

$$a_{22} = \begin{bmatrix} 0.43 & 0.940 & 0.520 & 0.130 & 0.00 \\ 0.00 & 0.114 & 0.596 & 0.898 & 0.392 \end{bmatrix}$$

$$a_{21} = \begin{bmatrix} 0.00 & 0.50 & 1.00 & 0.50 & 0.00 \\ 0.00 & 0.19 & 0.66 & 0.80 & 0.21 \end{bmatrix}$$

$$a_{12} = \begin{bmatrix} 0.00 & 0.50 & 1.00 & 0.50 & 0.00 \\ 0.32 & 0.81 & 0.69 & 0.19 & 0.00 \end{bmatrix}$$

The weighting schemes have been developed as

$W_{322} = [0.6 \;\; 0.4]$

$W_{321} = [0.55 \;\; 0.45]$ and

$W_{312} = [0.4 \;\; 0.6]$ respectively

The assessment matrix A_{22}, A_{21} and A_{12} were developed as

$$A_{22} = [0.6 \;\; 0.4] \times \begin{bmatrix} 0.43 & 0.940 & 0.520 & 0.130 & 0.00 \\ 0.00 & 0.114 & 0.596 & 0.898 & 0.392 \end{bmatrix}$$

$$= [0.258 \;\; 0.610 \;\; 0.550 \;\; 0.437 \;\; 0.157]$$

$$A_{21} = [0.55 \;\; 0.45] \times \begin{bmatrix} 0.00 & 0.50 & 1.00 & 0.50 & 0.00 \\ 0.00 & 0.19 & 0.66 & 0.80 & 0.21 \end{bmatrix}$$

$$= [0.00 \;\; 0.361 \;\; 0.847 \;\; 0.635 \;\; 0.095] \quad \text{and}$$

$$A_{12} = [0.4 \;\; 0.6] \times \begin{bmatrix} 0.00 & 0.50 & 1.00 & 0.50 & 0.00 \\ 0.32 & 0.81 & 0.69 & 0.19 & 0.00 \end{bmatrix}$$

$$= [0.192 \;\; 0.686 \;\; 0.814 \;\; 0.314 \;\; 0.00]$$

Level 2 (L2) calculations

The assessment matrix for level two attributes, cost (a_1) and risk (a_2), are developed as

$$a_1 = \begin{bmatrix} 0.00 & 0.19 & 0.66 & 0.83 & 0.32 \\ 0.192 & 0.686 & 0.814 & 0.314 & 0.00 \end{bmatrix}$$

$$a_2 = \begin{bmatrix} 0.000 & 0.361 & 0.847 & 0.635 & 0.095 \\ 0.258 & 0.610 & 0.550 & 0.437 & 0.157 \\ 0.00 & 0.190 & 0.660 & 0.800 & 0.210 \end{bmatrix}$$

The weighting schemes have been developed as

$W_1 = [0.4 \;\; 0.6]$

$W_2 = [0.3 \;\; 0.4 \;\; 0.3]$

The assessment matrix A_1 and A_2 were developed as

$$A_1 = [0.4 \;\; 0.6] \times \begin{bmatrix} 0.00 & 0.19 & 0.66 & 0.83 & 0.32 \\ 0.192 & 0.686 & 0.814 & 0.314 & 0.00 \end{bmatrix}$$

$$= [0.115 \;\; 0.488 \;\; 0.752 \;\; 0.520 \;\; 0.128]$$

$$A_2 = [0.3 \;\; 0.4 \;\; 0.3] \times \begin{bmatrix} 0.000 & 0.361 & 0.847 & 0.635 & 0.095 \\ 0.258 & 0.610 & 0.550 & 0.437 & 0.157 \\ 0.00 & 0.190 & 0.660 & 0.800 & 0.210 \end{bmatrix}$$

$$= [0.103 \;\; 0.409 \;\; 0.672 \;\; 0.605 \;\; 0.154]$$

Level 1 (L1) calculations

The assessment matrix for level one is developed as

$$a = \begin{bmatrix} 0.115 & 0.488 & 0.752 & 0.520 & 0.128 \\ 0.103 & 0.409 & 0.672 & 0.605 & 0.154 \end{bmatrix}$$

The weighting schemes for level 1 calculation are developed as

$W = [0.5 \;\; 0.5]$

The level 1 evaluation matrix was developed as

$$A = [0.5 \;\; 0.5] \times \begin{bmatrix} 0.115 & 0.488 & 0.752 & 0.520 & 0.128 \\ 0.103 & 0.409 & 0.672 & 0.605 & 0.154 \end{bmatrix}$$

$$= [0.1092 \;\; 0.448 \;\; 0.712 \;\; 0.563 \;\; 0.141]$$

The final fuzzy set for treated wastewater reuse can be expressed after normalizing to unity as

$a =$ [illegible], [illegible], [illegible], [illegible], [illegible]

The possibility mass functions for the final fuzzy sets are presented in Figure 4. The status of treated wastewater reuse is somewhere between 'Fair' and 'Good' as shown by the possibility mass function (Figure 4).

Step 6. Defuzzification

The evaluation of fuzzy sets results in fuzzy data. Comparison of fuzzy data is not straightforward. The crisp value of a fuzzy set can be obtained by many methods including Chen and Hwang (1992) and Yager (1980). The centroidal method (Yager, 1980) is one of the most widely used approaches for defuzzification. The method can be expressed as

$$R(x) = \frac{\int_a^b x A`x' dx}{\int_a^b A`x' dx} \qquad (4)$$

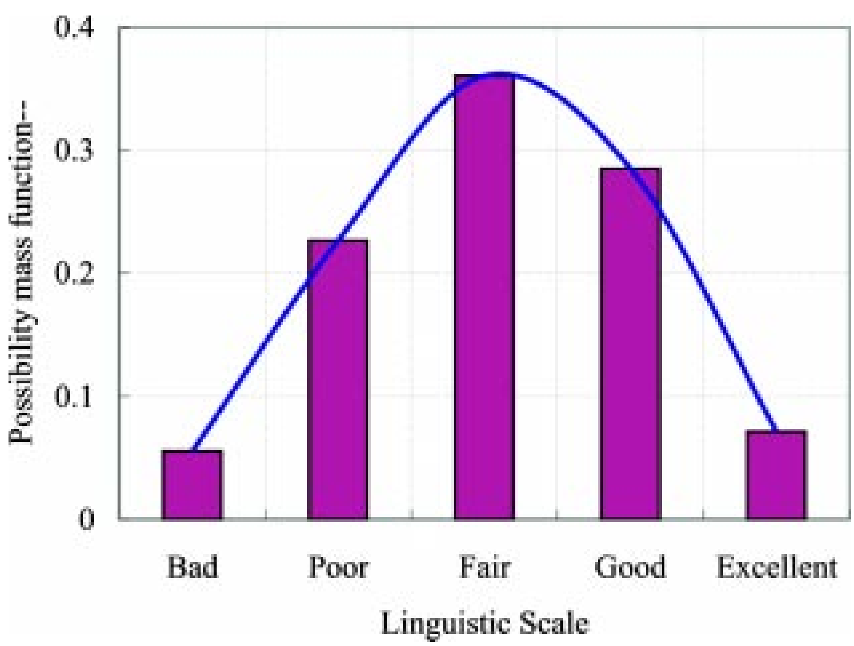

Figure 4: Possibility mass functions for wastewater treatment.

where *a* and *b* are the intervals of integration. The details of the procedure can be found elsewhere (Cheng and Hwang, 1992; Yager, 1980).

The centroid was determined as 0.522, which indicates the final status within 'Fair' and 'Good'.

Summary and Discussions

The evaluation of treated wastewater reuse has been performed through a systematic approach using fuzzy aggregation. This approach includes (1) identification of the attributes at different hierarchy level associated to treated wastewater reuse (Figure 2); (2) evaluation of fuzzy data for each of the basic attributes and fuzzification using linguistic variables (Figure 3); (3) determination of relative importance for basic attribute through pairwise comparison using analytic hierarchy process; (4) aggregation of the basic attributes using hierarchy structure in Figure 2 to obtain final fuzzy sets; and (5) defuzzification of the final fuzzy sets to evaluate the final status of treated wastewater reuse.

The annual rainfall is insufficient to satisfy the basic needs in Middle East countries (Alhumoud et al., 2003). To cope with this deficiency, the authority is extracting huge amount of fresh water from the non-renewable sources, which may induce severe environmental problems in the near future. To avoid or minimize these effects, there is a need to think about using treated wastewater for agricultural and landscaping purposes. Throughout the Middle East countries, small-scale use of treated wastewater has begun; but the amount is very small in comparison to the wastewater produced. Approximately, 1800 million cubic metres domestic wastewater is generated in Saudi Arabia while only 180 million cubic metres is treated for reuse. Use of treated wastewater reduces contaminated water discharge into the sea; thus a better environmental scenario is expected in the marine environment. At the same time, stress on non-renewable water sources can be reduced; consequently, greater environmental consequences may be delayed or avoided.

The weighting scheme for each level attributes was performed through pairwise comparisons. The human health risk was given equal and higher importance than cost (Table 4). The centroid values were determined as 0.522, 0.530 and 0.528 for trial 1, trial 2 and trial 3 respectively. The status was evaluated between 'Fair' and 'Good' in all trials (Figure 3).

This study presents a framework for assessment of using treated wastewater. This technique captures uncertainties by assigning triangular membership functions to the basic attributes. This study includes transformation of linguistic scales (bad, poor, fair, good and excellent in this study) into numerical quantities with ranges, so that the biases and imprecision from different experts in defining linguistic scales can be minimized. The generic nature of the framework may be extended to evaluate other environmental scenario.

The basic attributes need to be investigated in case of site-specific study. The future research will focus on

- determination of unit cost for secondary and tertiary treatments of wastewater,
- evaluation of social acceptance of using treated wastewater for agricultural and landscaping purposes,
- development of human health risk assessment models from handling of treated wastewater and crop ingestion, and
- development of models for typical effects on yields of crops produced by using treated wastewater.

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