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Fuzzy synthetic evaluation of treated wastewater reuse for agriculture

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Abstract Reuse of treated wastewater (TWW) for agriculture is in practice in many countries. TWW reuse requires wastewater collection, treatment and recycling, which is associated with cost as well as risk to human and ecological systems. In contrast, it can increase agricultural production and reduce environmental risks by reducing wastewater discharge into the natural environment. In Saudi Arabia, where available water resources are extremely limited, TWW reuse can save significant amount of non-renewable groundwater used in agricultural development, which is a strategic goal for the country. In this paper, a multicriteria decision-making approach was developed where cost, risk, benefits and social acceptance of TWW reuse were considered to be the main criteria. A multistage hierarchy risk management model was constructed for this evaluation. Fuzzy synthetic evaluation technique was incorporated where fuzzy triangular membership functions were developed to capture uncertainties of the basic criteria. The analytic hierarchy process was used to determine the relative importance of various criteria at different hierarchy levels. This study indicated that TWW reuse could have positive impact on agriculture, risk reduction and groundwater conservation.

Keywords Treated wastewater reuse · Fuzzy multistage hierarchy framework · Agricultural production · Environmental risk · Saudi Arabia

1 Introduction

Mathematical precise solutions are generally insufficient to represent real-life problems where data are imprecise. To analyze uncertainties in the real-life problems, a widely used approach is the Monte Carlo (MC) simulation; however, the imprecise information can

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rarely be analyzed by MC simulation (Lee 1996). On the contrary, the imprecisely informative data can be fairly analyzed by fuzzy logic; thus, it has become popular in the field of real-life problems. The MC simulation mostly characterizes uncertainties through statistical distributions, where the low probability parameter values have fewer chances to be randomly selected (Guyonnet et al. 1999; Chowdhury et al. 2009); thus, a portion of extreme possibility might be ignored. In contrast, fuzzy logic combines all possible parameter values (Guyonnet et al. 1999) through membership grades. Moreover, environmental data are sometimes very limited that no statistical distribution could be developed (Chowdhury 2012). In such cases, the use of MC simulation may result in detrimental effects. To achieve a rational solution in these situations, there is a need to use a fuzzy concept. Introduction to fuzzy sets in the multicriteria decision making (MCDM) has made the decision-making process more rational in the fields of real-life problems. Fuzzy logic is a generalized form of interval analysis, which provides a language for imprecise, qualitative and vague knowledge into numerical reasoning (Bonissone 1997). The rational solutions to the imprecisely informative data can also be obtained by using probabilistic reasoning, neural networks and generic algorithms (Bonissone 1997).

In evaluating the reuse of treated wastewater (TWW) in agriculture, many factors must be considered. These include the cost of wastewater collection, treatment and recycling, human and ecological risks, benefits of reuse and social acceptance. Cost and risk are possibly the most significant factors involved in decision making for many scenarios (Lee 1992; Connor et al. 1995; USEPA 1998). Direct cost can be assessed using the economic analysis for TWW reuse, while risk can be predicted using several models, which often have poorly characterized and/or correlated and simplified parameters, leading to inherent model uncertainties (Ferson 1996; Guyonnet et al. 1999). The benefits of TWW reuse can be measured by three main indicators: (1) increase in agricultural productions; (2) reduction in environmental (human health and ecological) risks by reducing wastewater discharges; and (3) conservation of freshwater sources, such as non-renewable groundwater. The social acceptance of TWW reuse can be evaluated through a survey in the area where the TWW is intended for reuse. Obtaining precise information on the relevant parameters is often difficult, which can transfer uncertainties to the assessment (Khadam and Kaluarachchi 2003). To capture uncertainties, some techniques, such as Dempster–Shafer theory of evidence (DST), possibility theory, fuzzy set theory, interval analysis, have been employed in the past (see Khadam and Kaluarachchi 2003; Chowdhury et al. 2009). In the recent years, use of fuzzy sets in the analysis of imprecise data and its application to environmental problems has been demonstrated with an acceptable degree of confidence (Chen and Hwang 1992; Klir and Yuan 1995; Chowdhury 2012). Fuzzy risk-cost trade-off approaches have been employed in diverse fields, including nitrate-contaminated groundwater supplies (Lee 1992), risk-based indexing system (Sadiq and Rodrı́guez 2004), irrigation intensification or extensification (Chen et al. 2008) and software development (Lee 1996). The fuzzy synthetic evaluation (FSE) technique has recently been applied in evaluating water treatment system evaluation (Chowdhury et al. 2007).

To date, research has addressed some issues necessary to evaluate TWW reuse. Pescod (1992) investigated few case studies for wastewater and TWW reuse, recycle and their effects on soil, human health, and crop yield and production. Al-Aama and Nakhla (1995) investigated the cost of TWW reuse for landscape irrigation in Jubail, Saudi Arabia. Crook and Surampalli (1996) compared the criteria of TWW reuse in several States in the USA. Kajenthira et al. (2011) demonstrated that water conservation, reuse and recovery measures in the natural gas and crude oil sectors alone had the potential to conserve up to 222 MCM/

year of water in Saudi Arabia. The study showed that the increase in secondary wastewater treatment and reuse might result in substantial cost and energy savings for six inland cities, while an estimated 26 % of urban water needs could be met by such TWW (Kajenthira et al. 2011). Qadir et al. (2010) summarized the production, treatment and irrigation by TWW in the Middle East and North Africa (MENA) region. The authors have shown that the MENA region has high potential of beneficial reuse of TWW, while some of the major constraints for slow progress are as follows: (1) inadequate information on environmental and health impacts; (2) incomplete economic analysis; (3) high costs and low returns of developing collection networks; (4) lack of wastewater treatment and reuse cost recovery mechanisms; and (5) mismatch between water pricing and regional water scarcity (Qadir et al. 2010). Hussain et al. (2002) reviewed the characteristics of wastewater used for irrigation and compared the methodological issues in valuating impacts. The authors have reported increased agricultural productions from the reuse of treated and untreated wastewater, while the advanced TWW did not pose any risk to human. In contrast, use of untreated wastewater posed higher microbial risks to the farmers, children and neighborhood populations. In the context of long-term contamination, they reported that wastewater irrigation may lead to transport of heavy metals to soils and could cause crop contamination (Hussain et al. 2002). Chang et al. (2002) studied human health risks for reusing TWW in agriculture. Al-Jaloud (2010) reported the increase in crop yields by approximately 11 % through reusing TWW from the Riyadh Sewage Treatment Plant for producing wheat and alfalfa in Saudi Arabia. Fernández et al. (2009) investigated environmental effects of irrigation in arid and semi-arid regions. This study reported that the pharmaceutical compounds might emerge as pollutants when wastewater is used for irrigation without any previous treatment. Zahid (2007) performed cost analysis of TWW productions using three treatment processes in Saudi Arabia. Alhumoud et al. (2003) demonstrated that the reuse of TWW in Kuwait might be beneficial. However, studies to date have rarely performed comprehensive evaluation of TWW reuse for agriculture through combining these factors. The availability of such comprehensive evaluation study is essential to better understand the feasibility of reusing TWW in agriculture.

In this study, TWW reuse for agriculture was evaluated. Cost of wastewater collection, treatment and recycling, human health and ecological risks of TWW reuse, benefits of reusing TWW and social acceptance of TWW reuse were considered to be the main criteria of evaluation. A FSE technique was incorporated where fuzzy triangular membership functions (TFNs) characterized the uncertainties of the basic criteria. Finally, an example in the application of FSE to evaluate the reuse of TWW in Saudi Arabia is illustrated.

2 Fuzzy set theory

Zadeh (1965) introduced fuzzy set theory to analyze imprecisely informative data. This method enables the incorporation of imprecise data where information is limited, qualitative or sparse, which provides an advantage over some other uncertainty characterization approaches. A fuzzy set establishes the relationship between uncertain data and the membership function μ, which ranges from 0 to 1. In a traditional set theory, an element is identified by binary logic, where if the element is in the set (say A), the membership grade is unity; otherwise, the membership grade is zero. A fuzzy set is an extension of traditional set theory in which an element has certain degree of membership in set A. For example, the fuzzy TFN for Fig. 1 can be constructed as:

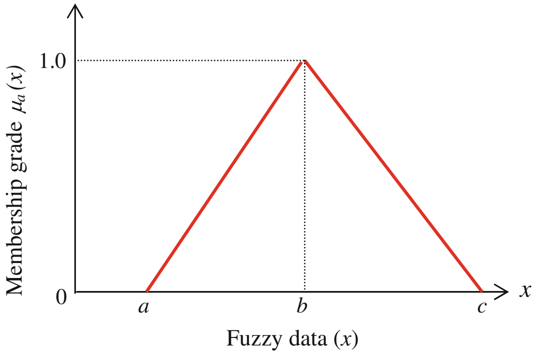

Fig. 1 Construction of membership function

$$\mu_a(x) = \begin{cases} (x-a)/(b-a), & a \le x \le b \\ (x-c)/(b-c), & b \le x \le c \\ 0, & \text{otherwise} \end{cases} \tag{1}$$

The TFNs are defined by (a, b, c), where a and c represent the minimum and maximum values and b represents the most likely value. Triangular and trapezoidal fuzzy numbers are mostly used to represent the linguistic scales (high, medium and low) employed by managers, professionals and stakeholders (Lee 1996). For two fuzzy number $p(a, b)$ and $q(d, e)$, the arithmetic operations are shown as:

$$\begin{aligned} p+q &= (a+d, b+e) \\ p-q &= (a-e, b-d) \\ p \cdot q &= (\min(ad, ae, bd, be), \max(ad, ae, bd, be)) \\ p/q &= (\min(a/d, a/e, b/d, b/e), \max(a/d, a/e, b/d, b/e) \quad \text{if } 0 \notin d, e \end{aligned} \tag{2}$$

2.1 Defining basic criteria and hierarchy framework

Defining basic criteria and construction of hierarchy framework is the first and most important step. The data for different basic criteria are obtained from experiments, literature and/or expert judgments (Chowdhury et al. 2007). The different level criteria and multistage framework are shown in Fig. 2, where a represents the overall system index of reusing TWW, while the main criteria a_1, a_2, a_3 and a_4 represent cost, risk, benefits and social acceptance of TWW reuse, respectively. The main criteria were further broken into the sub- and basic criteria. The breakdowns are as follows: a_{11}, cost of wastewater collection; a_{12}, cost of treatment; a_{13}, cost of TWW recycling for reuse; a_{121}, cost of secondary treatment; a_{122}, cost of tertiary treatment; a_{21}, human health risk; a_{22}, ecological risk; a_{211}, risk from chemicals in TWW; a_{212}, risk from microorganisms in TWW; a_{2111}, cancer risk from chemicals in TWW; a_{2112}, non-cancer risk from chemicals in TWW; a_{31}, increase in agricultural productions; a_{32}, reduction in environmental risks by reducing wastewater discharges; a_{33}, conservation of non-renewable groundwater (NGW); a_{321}, human health risk reduction; a_{322}, ecological risk reduction; a_{41}, social acceptance of reusing TWW in agriculture; a_{42}, social acceptance of reusing TWW in industry. The bottom most criteria in Fig. 2 represent the basic criteria for their respective main criteria.

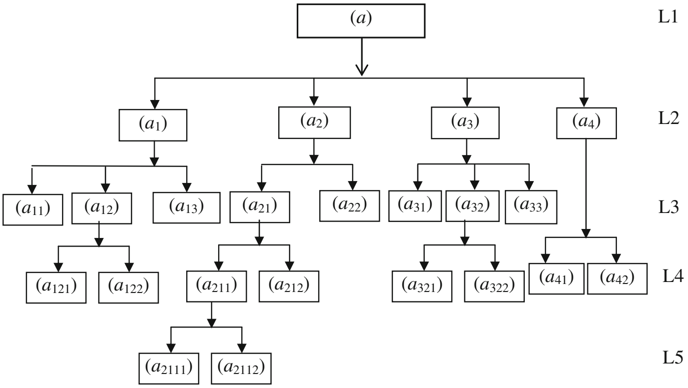

Fig. 2 Multistage hierarchy structure for evaluating TWW reuse

2.2 Parameter representation

In decision-making studies, information for few parameters may be imprecisely defined due to unquantifiable nature of data or lack of proper knowledge. Experts often use linguistic scales (e.g., very good, good and bad) to express the existing scenarios for these parameters. Generally, 5–11 linguistic scales are used to incorporate the expert judgments (Lee 1996). In this study, five linguistic scales: bad (B), poor (P), fair (F), good (G) and excellent (E) have been considered to capture expert judgments. Too many scales make the evaluation process complex (Lee 1996). The respective bases for the linguistic scales: bad (B), poor (P), fair (F), good (G) and excellent (E) are shown in Fig. 3. In the cases where parameters can be characterized by the numeric values, the numerical scales can be used to express their existing scenarios. In such cases, the lower and upper limits of the scales are defined by the boundary values, and the intermediate values for different scales are obtained. In Fig. 3, the values 0 and 1 represent the bad (B) and excellent (E) scenarios, respectively. However, for some parameters, such as cancer risks and costs, the lowest and highest values represent the excellent and bad scenarios, respectively. In these cases, 0 and 1 represent the excellent (E) and bad (B) scenarios, respectively.

2.3 Fuzzification of basic criteria

Once the fuzzy data are defined, the basic criteria are expressed with membership grades in the five predefined scales (μ_{B}, μ_{P}, μ_{F}, μ_{G} and μ_{E}) representing bad, poor, fair, good and excellent, respectively. For example in Fig. 3, an element *P* (0.3, 0.6 and 0.8) is to be fuzzified, for which the fuzzy data indicate a triangular fuzzy number in the range of 0.3–0.8 with a most likely value of 0.6. If *P* intersects any scale more than once, the maximum operator is used to define the fuzzy subsets (Yager and Filev 1994). In case of *P*, a membership grade for $\mu_{\mathrm{B}}(\text{bad}) = 0$, $\mu_{\mathrm{P}}(\text{poor}) = 0.39$, $\mu_{\mathrm{F}}(\text{fair}) = 0.81$, $\mu_{\mathrm{G}}(\text{good}) = 0.75$ and $\mu_{\mathrm{E}}(\text{excellent}) = 0.2$ would be determined (Fig. 3). As such, the fuzzy set would become (0, 0.39, 0.81, 0.75 and 0.2). If *P* were in crisp number, for example, *P* (0.4), the fuzzy set would be (0, 0.5, 0.5, 0 and 0). If *P* is assigned the linguistic judgments: say G, F and G by three experts, the average values can be calculated following Fig. 3 as $[(0.5 + 0.3 + 0.5)/3, (0.7 + 0.5 + 0.7)/3, (1.0 + 0.7 + 1.0)/3] = (0.43, 0.63, 0.9)$. The fuzzy data can be mapped on Fig. 3 to obtain the membership grades. The membership

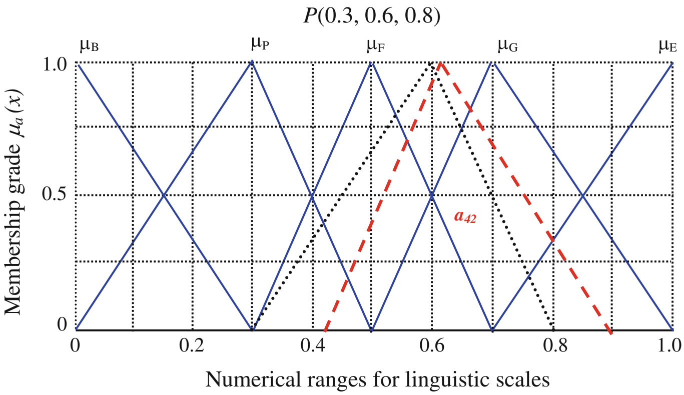

Fig. 3 Membership spread of the linguistic variables [*B* (0, 0, 0.3), *P* (0, 0.3, 0.5), *F* (0.3, 0.5, 0.7), *G* (0.5, 0.7, 1.0), *E* (0.7, 1, 1)]

grades of *P* (μ_B, μ_P, μ_F, μ_G and μ_E) are obtained as: 0, 0.19, 0.70, 0.81 and 0.32, respectively (Fig. 3).

2.4 Development of priority matrix

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

$$W = (w_1, w_2, \ldots, w_n) \quad \text{where} \sum_{k=1}^{n} w_k = 1 \tag{3}$$

As an illustration, consider three subcriteria x_{31}, x_{32} and x_{33} from the main criterion x_3. From pairwise comparison, the experts' judgments are assumed as follows: x_{31} is less important than x_{32} at a ratio 3:4 and x_{32} is more important than x_{33} 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

$$W = \begin{array}{cccc} & x_{31} & x_{32} & x_{33} \\ x_{31} & 1 & 0.75 & 1 \\ x_{32} & 1.33 & 1 & 1.33 \\ x_{33} & 1 & 0.75 & 1 \end{array} \tag{4}$$

The priority matrix *W* can be formed by taking the row-wise geometric mean (Saaty 1988) of elements and normalizing to unity.

$$W = \begin{bmatrix} 0.9086 \\ 1.2094 \\ 0.9086 \end{bmatrix} \Rightarrow W = \begin{bmatrix} x_{31} \\ x_{32} \\ x_{33} \end{bmatrix} = \begin{bmatrix} 0.3 \\ 0.4 \\ 0.3 \end{bmatrix} \tag{5}$$

Table 1 Fundamental scales of importance (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

2.5 Aggregation

Fuzzy aggregation is a systematic approach starting from the basic criteria following the hierarchy structure. The aggregation is performed systematically through combinations of a priority matrix and fuzzy assessment matrices, which are formed by the membership grades of the basic criteria. The fuzzy aggregation for any criterion (say, x_3) is obtained as:

$$A_1 = W^T \times x_3 \tag{6}$$

This procedure is continued till the final fuzzy set for the system index (L1) is obtained.

2.6 Defuzzification

Decision making is generally performed by comparing the crisp values. In fuzzy set theory, these crisp values are obtained through defuzzification, which can be performed using a number of available methods (Chen and Hwang 1992). For example, Cheng and Lin (2002) used a maximum operator to determine the classification of fuzzy subsets from a final fuzzy set. Different weights assigned to the membership grades are generally employed for FSEs (Lu et al. 1999). The following equation represents the highest value of membership, which determines the classification of fuzzy sets.

$$U_a = \max(\mu_1, \mu_2, \mu_3, \mu_4, \mu_5) \tag{7}$$

where U_a = utility function

An optimistic attitude focuses more on the more positive memberships of a qualitative scale, where higher weights are assigned to the more positive outcomes of qualitative scales (Cheng and Lin 2002). A similar optimistic attitude is employed in this case study, and the utility function can be derived as:

$$U_a = 0.5\mu_1 + \mu_2 + 2\mu_3 + 4\mu_4 + 6\mu_5 \tag{8}$$

It should be noted that this ‘optimistic attitude’ issue is quite subjective to the selection of the decision makers and that the values of the coefficients are arbitrary. These can be refined through inclusion of expert judgments in the respective relevant fields, when available, at which point guidelines can be established (Lu et al. 1999).

3 Case study

The Kingdom of Saudi Arabia has low annual rainfall in most of its parts (FAO 2009; Chowdhury and Al-Zahrani 2013a). The total water demands in Saudi Arabia were

18,507 million cubic meters (MCM) in 2009 (domestic: 2,330 MCM; industrial: 713 MCM; agricultural: 15,464 MCM). These demands were satisfied by the NGW sources (11,551 MCM), renewable surface and groundwater (RGSW) sources (5,541 MCM), desalinated water (DW) (1,048 MCM) and TWW (367 MCM) (MOEP 2010). The Ministry of Water (MAW) in Saudi Arabia reported that the proven, probable and possible groundwater reserves in the non-renewable aquifers were 259.1, 415.6 and 760.6 billion cubic meters (BCM), respectively (MAW 1984; FAO 1998; Water Atlas 1995). FAO (1998) reported that approximately 42 % of the MAW estimated that proven reserves might have been consumed by 1996. As such, it is important to understand the current state of reserves to offer water resources management strategy (Chowdhury and Al-Zahrani 2013a). The water reserves and withdrawal rates indicate that the available resources may not be enough to provide support for all sectors on long-term basis (MAW 1984; Water Atlas 1995; FAO 1998; Chowdhury and Al-Zahrani 2013b). The reuse of TWW, as a non-conventional resource, can have significant role in conserving groundwater. In 2008, approximately 730 MCM/year of domestic wastewater is treated in 70 sewage treatment plants from which 325 MCM/year is recycled for reuse (Chowdhury and Al-Zahrani 2013b; FAO 2009). However, generation of domestic wastewater is likely to be much higher than the treated amount (MOEP 2010; FAO 2009). The remaining untreated and partially or secondary TWW are discharged into the Arabian Gulf, Red Sea, wadies, land and sand dunes. Discharge of TWW into the marine system might contaminate seafood, which is used for human consumptions. On the other hand, discharge of TWW on land surface, wadies and sand dunes might contaminate groundwater. Groundwater is generally mixed with DW for domestic water supply (e.g., drinking and house-hold activities). Consequently, there might be a risk to human health from TWW discharges. Therefore, reuse of TWW would minimize environmental impacts and lessen groundwater quality degradation. However, better understanding is warranted to predict such risks.

3.1 Parameter characterization

3.1.1 Cost

Cost of treating wastewater varies depending on the source, type and quantity of wastewater, treatment approaches and geographical location (Lee et al. 2001). The USEPA summarized the costs for wastewater treatment processes serving for 40,000 populations (USEPA 2004). The life cycle costs of stabilization ponds, activated sludge, activate sludge + filtration + UV radiation, additional cost for full tertiary treatment, additional cost of disinfection, lime treatment + reverse osmosis after secondary treatment and microfiltration + reverse osmosis after secondary treatment were US $0.18, 0.34, 0.42, 0.24, 0.07, 0.75 and 0.54/m^3, respectively. In these estimates, costs of lands were not included, while it can be significant depending on the location of the project. For example, Zahid (2007) reported that the total cost for three treatment process in Riyadh, Saudi Arabia, was in the range of US $200.4–239.2 million, while the cost of the land was in the range of US $109.9–111.8 million (i.e., 46–54 % of the total cost). A case study on the Jubail wastewater treatment plant in Saudi Arabia showed that the overall cost for reusing TWW was US $2.03/m^3 (Al-Aama and Nakhla 1995). The capital cost was US $1.33/m^3, and the running cost was US $0.70/m^3. The costs of operation and maintenance for tertiary treatment, collection and distribution were US $0.16, 0.3 and 0.07/m^3, respectively. Alhumoud et al. (2003) reported that the costs of TWW effluents in Kuwait were US $0.42 and US $0.50/m^3 for the secondary and tertiary TWW, respectively. However, the capital cost and collection were not included in their study. Depending on effluent quality (secondary or tertiary treated), cost of wastewater treatment can vary in the range of US \$0.46–0.74/m^3 with an average of US \$0.53/m^3 (Lee et al. 2001). The costs included capital (US \$0.10–0.16/m^3), operation (US \$0.25–0.40/m^3), maintenance (US \$0.08–0.15/m^3) and miscellaneous (US \$0.03/m^3). However, collection, distribution and storage costs were not reported in their study. Zahid (2007) investigated the cost of treating municipal wastewater for three treatment processes (trickling filters, complete mix activated sludge and oxygen ditch activated sludge plants) in Saudi Arabia. The cost was in the range of US \$0.27–0.33/m^3. The estimates included capital cost US \$0.25–0.28/m^3, and operation and maintenance costs US \$0.03–0.05/m^3. However, tertiary treatment, collection of wastewater and distribution of TWW were not included in this study (Zahid 2007). A recent study by Kajenthira et al. (2011) reported that the cost of secondary and tertiary TWW was in the ranges of US \$0.13–0.63 and US \$1.19–2.03/m^3, respectively (2009 value). This study reported that TWW reuse might need little or no transportation. Following the historical information, this study will use the following data:

$$\text{Cost of secondary TWW}\,(\text{US\$}/\text{m}^3) : 0.34, 0.55, 0.75.$$

$$\text{Cost of tertiary TWW}\,(\text{US\$}/\text{m}^3) : 1.19, 1.61, 2.03$$

$$\text{Cost of wastewater collection}\,(\text{US\$}/\text{m}^3) : 0.15, 0.3, 0.5.$$

$$\text{Cost of treated wastewater distribution for reuse}\,(\text{US\$}/\text{m}^3) : 0.1, 0.25, 0.4$$

3.1.2 Risk

Risk of TWW reuse has been a concern for the last few decades (Ayres and Mar 1996; Ursula and Peasey 2002; WHO 2006). Appropriate treatments must be achieved prior to reusing TWW for agriculture. In Saudi Arabia, tertiary treatment is required to reuse TWW to satisfy the regulatory limitations (Saudi Council of Ministers 2000). Information on possible risks from TWW reuse in Saudi Arabia is limited. Past studies in different countries demonstrated that the tertiary TWW may be almost free of pathogens (Feachem et al. 1983). When applied to the crop, normal survival periods for fecal coliforms in soils and/or crops were reported to be less than 30 days (Feachem et al. 1983), while some pathogens can survive for longer periods (Feachem et al. 1983; Pescod 1992). A number of past studies reported no increased risk of microbial contamination to human from reusing TWW in agriculture (Constantina and Yanko 1994; Hass and Rose 1995; Friis et al. 1996; Hussain et al. 2002; Vigneswaran and Sundaravadivel 2004).

Reuse of TWW in agriculture might be associated with food-borne contaminants ingestion, which might have risks to human health. TWW may contain complex mixture of toxic chemicals, including heavy metals, pharmaceutically active compounds (PhAC), endocrine disrupting compounds (EDC) and disinfection byproducts (DBPs). Some of these chemicals are potentially of concern. In Saudi Arabia, studies on PhAC, EDC and DBPs in TWW have not been reported to date. Past studies have reported higher concentrations of few heavy metals in the TWW produced crops. Al-Jaloud (2010) reported higher concentrations of Zn and Fe and lower concentrations of Cu, Pb and Co in wheat and alfalfa produced with TWW in Saudi Arabia. Hussain et al. (2002) reported that wastewater irrigation may lead to transport of heavy metals to soils and can cause crop contamination. Assadian et al. (1998) investigated crop irrigation in Mexico using mixture of wastewater and river water. They reported up to 31 % of soil surface metal accumulation and heavy metal uptake by alfalfa. In the context of ecological risks from TWW reuse, Kruse and Barrett (1985) reported that a number of heavy metals might bio-accumulate in soil, while others (e.g., Cd and Cu) might be redistributed by soil fauna. Pescod (1992) reported deposition of salinity in the field cultivated with TWW, which might impose ecological risks. In order to better understand human health and ecological risks from TWW reuse in agriculture, long-term accumulation of heavy metals and other contaminants in irrigation lands, its transfer to plant tissue, bio-accumulation and human exposure through food chain needs to be comprehensively investigated. In absence of reliable data on risks, experts in the relevant fields are generally requested to provide their linguistic judgments (based on the five scales) on different risk components in Fig. 2. The average values from several experts can minimize the subjective bias.

3.1.3 Benefits of using TWW

Reuse of TWW can have several benefits, such as increase in agricultural productions, reduction in environmental risks by reducing wastewater discharges and conservation of NGW, the main water source for agriculture in Saudi Arabia. Past study demonstrated that 2,318–2,430 m^3 of water is required to produce 1 ton of wheat in the Kingdom (FAO 1998), while the value for 1 ton of wheat was approximately US $266.9 (FAO 2012); this indicates that 1 m^3 of water may produce the wheat of approximately US $0.11–0.12 value. In Saudi Arabia, well over 1,500 MCM/year of municipal wastewater production is anticipated, which can have the return of US $165–180 million/year through wheat production. Further to that, Al-Jaloud (2010) reported that wheat yield could be increased by 11 % as a result of additional nutrients in TWW. As such, financial returns may be increased by this percentage.

Moreover, TWW reuse can protect the environment by reducing discharge of contaminants into the natural environment. Secondary TWW from Riyadh, Saudi Arabia, was disposed into wadies, which created a permanent stream of about 50 km long. Increased pollution to groundwater and risks to human and ecology were anticipated from such discharge (Al-Mogrin 2003). However, in recent years, this discharge has been discontinued, while the effects of past contamination are yet to be comprehensively investigated. Past study reported an incident of typhoid breakout in the northern city of Tabuk, which was attributed to land disposal of sewage to a depression area overlying an aquifer (Al-Mogrin 2003). Alaa El-Din et al. (1994) reported that septic tank seepage was a major cause of chemical and microbiological contamination of groundwater and rise of groundwater tables in areas without sewerage systems in Saudi Arabia. Significant number of wells could not produce drinkable water due to such contamination (Al-Mogrin 2003; Alaa El-Din et al. 1994). In the western and eastern coasts of the country, much of the TWW is discharged into the Arabian Gulf and Red Sea. Ecological and human health risks through food chain have not been adequately investigated in these coasts. A bioassay study on sediments near the disposal sites in the Red Sea revealed significant decrease in *Faraminfera* organisms (unpolluted water species) and increase in *Rotalina* and *Millionlinera* (polluted water species) (Al-Mogrin 2003). Discharge of wastewater might contaminate seafood (fish, shellfish, etc.), which can pose increased risks to human health through food chain (Chowdhury et al. 2004). Reduction in TWW discharges might reduce human health and ecological risks considerably. Collection of domestic wastewater and TWW reuse might be able to reduce groundwater and marine environmental contaminations greatly. Comprehensive understanding of environmental quality protection, in particular, human and ecological risk reductions and lowering groundwater contamination is essential for evaluating the status of TWW reuse. In addition to pollution control, TWW reuse can conserve equal amounts of NGW sources in agriculture. Economic value of such conservation can be estimated in the context of strategic goals of management and/or priority setting. In Saudi Arabia, conservation of NGW reserves is a strategic goal. Better understanding is warranted on the relevant basic criteria to assess the TWW reuse comprehensively.

3.1.4 Social acceptance of TWW reuse

In 1979, the Islamic Council of Research and Consultation stated that properly TWW can be considered clean if it poses no health hazard and meets health standards and criteria set for that purpose. It is assumed that properly TWW returns to its natural form, free from impurities that caused it to be banned in the first place (Al-Mogrin 2003). Several community level surveys in various States of Australia during early 1990s indicated that the public is not averse to the concept of wastewater recycling within the community (Vigneswaran and Sundaravadivel 2004). In one survey, less than 15 % readily agreed for potable reuse (Vigneswaran and Sundaravadivel 2004). While non-potable use was a technically accepted option, concerns about possible health risks were frequently raised by the public. In Saudi Arabia, TWW reuse has been increasing since 1990. In 1990, 1992 and 1997, TWW effluents were 110, 185 and 185 MCM, respectively (Abderrahman 2000). In 2000, TWW effluent was 475 MCM (Elhadj 2004), while in 2004 and 2008, TWW effluents were 511 and 730 MCM, respectively (MOEP 2010). In 2004 and 2009, approximately 260 and 325 MCM of TWW effluents were reused. The increasing trends of domestic wastewater treatment and TWW reuse could indicate that the public may not be averse to the concept of wastewater recycling for agriculture and/or industrial reuse in Saudi Arabia. In Saudi Arabia, no known study reported quantitative evaluation of social acceptance for TWW reuse. As such, this study depends on experts view on this issue. However, through a comprehensive sampling program, social evaluation can be quantitatively determined in the future. Upon availability of such information, the evaluation of TWW reuse can be updated.

3.2 Data processing

The values of different basic criteria for a typical scenario are presented in Table 2. The basic criteria for cost were adopted from past literature. However, the data for the basic criteria of risks, benefits of reusing TWW and social acceptance of TWW reuse were not adequately explained in the literature. Three experts in the relevant fields assigned three qualitative levels for these basic criteria. The experts followed the scaling system presented in Fig. 3. The average values for these linguistic levels were determined and presented in Table 2. The basic criteria for risks, benefits of reusing TWW and social acceptance of TWW reuse were mapped on Fig. 3, and the corresponding membership grades were determined (Table 2). For the basic criteria of cost, a scaling system was developed by considering the ranges of cost (US \$0–2/m^3) for different components of TWW reuse (Fig. 4). The cost data (Table 2) are mapped in Fig. 4, and the membership grades were determined (Table 2). In the next step, pairwise comparisons were performed following Table 1, and the priority matrices are presented in Table 3. The basic criteria were aggregated following the hierarchy structure to obtain the final fuzzy set for the main criteria and the system index (a).

4 Results and discussions

The basic criteria in the framework (Fig. 2) are the input variables for evaluating TWW reuse. The basic criteria and pairwise importance of different level criteria from Tables 2 and 3 were synthesized following the procedure described earlier in this paper. The fuzzy sets for the main criteria were obtained as:

$$\begin{aligned}\mathrm{Cost}(a_1) &= (0.120, 0.158, 0.104, 0.538, 0.445)\\ \mathrm{Risk}(a_2) &= (0.168, 0.681, 0.819, 0.321, 0.00)\\ \mathrm{Benefits\,of\,reusing\,TWW}(a_3) &= (0.00, 0.00, 0.248, 0.728, 0.617)\\ \mathrm{Social\,acceptance}(a_4) &= (0.00, 0.076, 0.382, 0.684, 0.578)\end{aligned}$$

The normalized fuzzy data for the main criteria are shown in Fig. 5. The cost criterion (a_1) had the highest membership grade for ‘good’ (0.39) followed by ‘excellent’ (0.33), while risk (a_2) had the highest membership grade for ‘fair’ (0.41). Benefits of TWW reuse (a_3) and ‘social acceptance’ (a_4) had the highest membership grades for ‘good’ with values of 0.46 and 0.4, respectively. The highest membership grade of criterion ‘benefits of TWW reuse’ for the status ‘good’ indicates that the ‘benefits of TWW reuse’ might be significant. Figure 5 demonstrates that the status of cost might be between ‘good’ and ‘excellent.’ The status of risk might be between ‘fair’ and ‘poor.’ The status of ‘benefits of TWW reuse’ and ‘social acceptance’ might be between ‘good’ and ‘excellent.’ To better understand the overall status of TWW reuse, it is essential that decision makers, managers and/or stakeholders assign their preference for different criteria. To understand the implications of such preference, seven different scenarios were assessed though assigning various combinations of relative importance for the main criteria (Table 3). Using the seven sets of relative importance (Table 3), the final fuzzy sets of the system index (a) for seven scenarios (S1–S7) were obtained as:

$$\begin{aligned}\mathrm{Scenario\,1}\,(a) &= (0.0985\;0.2789\;0.3818\;0.5232\;0.3573)\\ \mathrm{Scenario\,2}\,(a) &= (0.0937\;0.2266\;0.3103\;0.5449\;0.4018)\\ \mathrm{Scenario\,3}\,(a) &= (0.1081\;0.3836\;0.5248\;0.4797\;0.2683)\\ \mathrm{Scenario\,4}\,(a) &= (0.0721\;0.2288\;0.3883\;0.5676\;0.4101)\\ \mathrm{Scenario\,5}\,(a) &= (0.1153\;0.3433\;0.4322\;0.4846\;0.2975)\\ \mathrm{Scenario\,6}\,(a) &= (0.0577\;0.1830\;0.3602\;0.5996\;0.4516)\\ \mathrm{Scenario\,7}\,(a) &= (0.0528\;0.1231\;0.2754\;0.6258\;0.5000)\end{aligned}$$

It is not straightforward to compare the fuzzy data of the system index. The comparisons among different trials are generally performed using the crisp values. Using Eq. (8), the utility function for the system index (a) was obtained to be 5.33, 5.48, 5.02, 5.77, 4.99, 6.04 and 6.2 for S1, S2, S3, S4, S5, S6 and S7, respectively. The higher value of $U(a)$ indicates the positive attitude toward TWW reuse.

The utility function demonstrates some interesting aspects in TWW reuse. In trial 1 (S1), cost was given the highest priority (0.4), followed by risk (0.3), benefits (0.15) and social acceptance (0.15). The utility function was 5.33. When the priority of cost was increased to 0.5 and risk was decreased to 0.2, the utility function was increased to 5.48, indicating positive attitude toward reusing TWW. However, when risk was given the highest priority (0.5), followed by cost (0.2), the attitude toward reusing TWW was reduced ($U_a = 5.02$). When each of the main criteria was given equal priority, U_a was increased to 5.77, indicating that increase in importance of ‘benefits of reusing TWW’ and

Table 2 Fuzzy data for the basic criteria in the framework

Name	Basic criteria	Experts			Average data	Membership grades
		E1	E2	E3		
a_{11}	Cost of wastewater collection (US\$/m^3)[a]				0.15, 0.3, 0.5	0, 0, 0, 0.63, 0.6
a_{121}	Cost of secondary treatment[a]				0.34, 0.55, 0.75	0, 0, 0.27, 0.95, 0.32
a_{122}	Cost of tertiary treatment[a]				1.19, 1.61, 2.03	0.6, 0.79, 0.25, 0, 0
a_{13}	Cost of TWW recycling[a]				0.1, 0.25, 0.4	0, 0, 0, 0.53, 0.67
a_{2111}	Cancer risk from chemicals in TWW	F	F	F	0.3, 0.5, 0.7	0, 0.5, 1.0, 0.5, 0
a_{2112}	Non-cancer risk from chemicals in TWW	P	F	P	0.1, 0.367, 0.567	0.33, 0.81, 0.69, 0.21, 0
a_{212}	Risk from microorganisms in TWW	F	F	P	0.2, 0.433, 0.633	0.19, 0.71, 0.79, 0.29, 0
a_{22}	Ecological risk	F	P	F	0.2, 0.433, 0.633	0.19, 0.71, 0.79, 0.29, 0
a_{31}	Increase in agricultural productions	G	E	G	0.567, 0.80, 1.0	0, 0, 0.27, 0.81, 0.6
a_{321}	Human health risk reduction	G	F	E	0.5, 0.733, 0.90	0, 0, 0.48, 0.98, 0.17
a_{322}	Ecological risk reduction	E	G	G	0.567, 0.80, 1.0	0, 0, 0.27, 0.81, 0.6
a_{33}	Conservation of non-renewable groundwater	E	G	E	0.633, 0.9, 1.0	0, 0, 0.17, 0.6, 0.75
a_{41}	Social acceptance of TWW reuse in agriculture	E	G	E	0.633, 0.9, 1.0	0, 0, 0.17, 0.6, 0.75
a_{42}	Social acceptance of TWW reuse in industry	G	F	G	0.43, 0.63, 0.9	0, 0.19, 0.70, 0.81, 0.32

E1, E2, E3: Experts 1, 2, 3, respectively; [reflected in Fig. 3; 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)]

[a] Cost reflected in Fig. 4

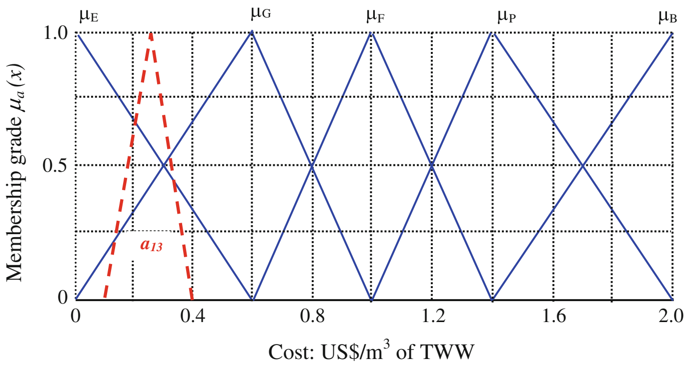

Fig. 4 Fuzzification for cost data for different linguistic scales [*E* (0, 0, 0.6), *G* (0, 0.6, 1.0), *F* (0.6, 1.0, 1.40), *P* (1.0, 1.4, 2.0), *B* (1.4, 2.0, 2.0)]

Table 3 Priority assignment of different level criteria

Name	S1				S2	S3	S4	S5	S6	S7
	W_{L5}	W_{L4}	W_{L3}	W_{L2}	W_{L2}	W_{L2}	W_{L2}	W_{L2}	W_{L2}	W_{L2}
a_1										
a_{11}			0.3	0.4	0.5	0.2	0.25	0.4	0.2	0.3
a_{12}										
a_{121}		0.5	0.4							
a_{122}		0.5								
a_{13}			0.3							
a_2										
a_{21}			0.67	0.3	0.2	0.5	0.25	0.4	0.2	0.1
a_{211}		0.4								
a_{2111}	0.67									
a_{2112}	0.33									
a_{212}		0.6								
a_{22}			0.33							
a_3										
a_{31}			0.3	0.15	0.15	0.15	0.25	0.1	0.4	0.5
a_{32}			0.2							
a_{321}		0.67								
a_{322}		0.33								
a_{33}			0.5							
a_4										
a_{41}			0.60	0.15	0.15	0.15	0.25	0.1	0.2	0.1
a_{42}			0.40							

'social importance' improves the attitude toward TWW reuse. When the priority of cost and risk was similar (0.4) and 'benefits of reusing TWW' and 'social acceptance' were lowered to 0.1, the attitude toward TWW reuse was decreased ($U_a = 4.99$). In trial 6 (S6),

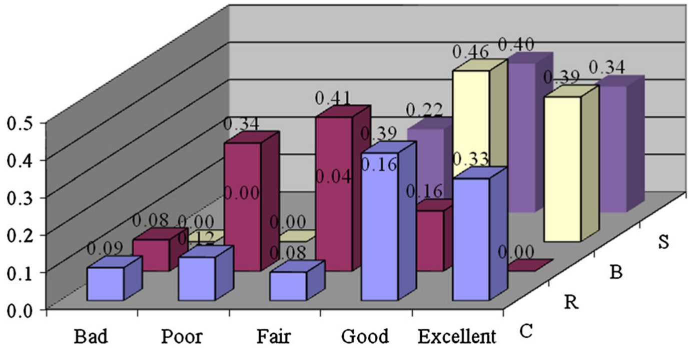

Fig. 5 Normalized fuzzy data for the main criteria (*C* cost, *R* risk, *B* benefits of reusing TWW, *S* social acceptance of TWW reuse)

‘benefits of reusing TWW’ were assigned the highest priority (0.4) and the other criteria were assigned to 0.2. The utility function was increased to 6.04. In trial 7 (S7), the weight of ‘benefits of reusing TWW’ was increased to 0.5 and cost was assigned 0.3. Risk and social acceptance were assigned 0.1 each. The attitude toward reusing TWW was improved from 6.04 to 6.2. The trials indicate that the assessments were sensitive to the relative importance of different criteria. The higher importance to the ‘benefits of TWW reuse’ improves the attitude of TWW reuse. It is to be noted that the benefits include increased wheat production, environmental pollution reduction and conservation of NGW resources. The conservation of groundwater was given the highest importance, which is consistent to the strategic water resources management in Saudi Arabia. It is to be noted that the choice of different weighting schemes is arbitrary and a guideline can be set through expert opinions (Lee 1992).

Overall, reuse of TWW for agriculture was not evaluated to have high risks, possibly due to the level of treatments. In Saudi Arabia, wastewater must be treated to tertiary level prior to making it reusable in agriculture. The high levels of treatments generally make sure that most of the harmful microorganisms are removed during the treatment process. However, possibility of accumulation of trace metals and other persistent contaminants cannot be ignored. Several studies in the Arabian region have shown that irrigation using TWW may accumulate heavy metals in soils. In many instances, pH was reported to be alkaline (e.g., >7), indicating possible tendency of immobilization. In Saudi Arabia, Al-Jaloud (2010) observed insignificant change in soil salinity between the TWW and freshwater irrigated lands. The levels of nutrients (e. g., nitrogen, phosphorus and potassium) in the TWW irrigated lands were higher. Concentrations of potassium, iron, zinc and copper were slightly higher in the TWW irrigated soil than the freshwater irrigated soil (Al-Jaloud 2010). Although, the differences in concentrations were not significant, long-term accumulation of these metals might pose threat to ecological balance and soil productivity. Comprehensive study is warranted to better understand the accumulation of metals and other harmful chemicals in soil and crops, their transfer to crops and risks to human and ecology. Further to that, many issues related to the life cycle of reusing TWW, such as quality job, sound investment, natural resources conservation, societal effects of project implementation, community well-being, environmental health and governance, could not be fully incorporated in this assessment. Incorporation of these factors requires related data, which is not easily available. Upon availability of these data, a wider scale assessment may be possible in future using the ‘Triple Bottom Line’ analysis.

5 Conclusions

In Saudi Arabia, the volume of TWW was 24.3–32 % of the domestic water demands during 2004–2008. Further, 44.5 % of the TWW (325 MCM/year) was reused in 2009. Past studies indicated that the production of domestic wastewater was approximately 1,514–1,864 MCM in 2009. Approximately 75 % of the domestic wastewater is not effectively reused in the Kingdom. In contrast, much of the domestic wastewater is discharged into the natural environment, which can pose risks to human and ecology.

The fuzzy-based evaluation through hierarchy structure involves identification and fuzzification of the basic criteria, assigning relative weights, aggregation through hierarchy structure and defuzzification. The fuzzified values of each basic criterion were grouped using hierarchy structure. The final fuzzy sets were defuzzified, and utility function values were evaluated to determine their ranking order. The weighting schemes were developed using AHP. By assigning different weighting schemes, seven trials were performed to verify the impact of different weighting schemes on the system index. The evaluation was found to be sensitive to the assignment of weighting schemes.

Human judgments are associated in the fuzzy evaluation process. Thus, there is a possibility of biases. The bias due to subjective information can be reduced through incorporation of more than one expert in the relevant field. A Delphi-type study can be performed until a consensus is achieved. The assignment of weighting schemes was performed in crisp values for simplicity, which may be in interval other than a single value. In such case, the max–min paired elimination method through fuzzy α-cut technique can be employed. The data associated with this study were imprecise in general. If precise data are available, this framework may provide a better understanding for the decision-making process. The application of fuzzy synthetic evaluation can be extended to similar types of environmental management studies, such as, water quality issues, solid waste management and produce water management. However, this application requires representative information in qualitative and/or quantitative terms from experts in the relevant fields. Despite such limitations, this study sheds light on the benefits of reusing TWW, which can be enriched through better understanding of different basic criteria and their relative importance in the future.

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