

# Sustainability Evaluation of Surface Water Quality Management Options in Developing Countries: Multicriteria Analysis Using Fuzzy UTASTAR Method

Husnain Haider<sup>1</sup> · Pushpinder Singh<sup>2</sup> · Waris Ali<sup>3</sup> · Solomon Tesfamariam<sup>1</sup> · Rehan Sadiq<sup>1</sup>

Received: 17 May 2014 / Accepted: 20 March 2015 /  
Published online: 7 April 2015  
© Springer Science+Business Media Dordrecht 2015

**Abstract** The natural rivers in developing countries have not been meeting their desirable water quality objectives due to discharge of untreated wastewater from domestic and industrial sources for a long time; and thus need to implement rational water quality management (WQM) plans. Overall sustainability of proposed WQM options should not be overlooked during the planning phase due to lack or absence of data. In this research, a framework is proposed for the evaluation of different WQM options to meet the water quality objectives of natural rivers. Five main sustainability criteria (SSC) are considered, including cost (capital, land and operational), land requirements, operation and maintenance issues, environmental impacts, and socio-economic impacts. In addition, several sub-criteria (impacts) have also been included to rationally justify the assessment of SSC by the decision makers (DM). The values of cost and land requirement criteria are calculated; whereas, the other SSC are subjective in nature. However, both types possess uncertainties associated with calculation errors, inherent assumptions, and the differences in DM's opinions. Further, due to data

---

✉ Husnain Haider  
husnain.haider@ubc.ca; haider42@yahoo.com

Pushpinder Singh  
pushpindersnl@gmail.com

Waris Ali  
warisali@ucest.edu.pk

Solomon Tesfamariam  
Solomon.Tesfamariam@ubc.ca

Rehan Sadiq  
Rehan.Sadiq@ubc.ca

<sup>1</sup> School of Engineering, University of British Columbia Okanagan, 3333 University Way, Kelowna, BC V1V 1 V7, Canada

<sup>2</sup> Department of Computer Science, Palacky University, Olomouc, Czech Republic

<sup>3</sup> University College of Engineering Sciences and Technology (UCEST), Lahore Leads University, Lahore, Pakistan

limitations in developing countries, the ranking order of WQM options established by the DM should be preferred. To deal with such uncertainties and the DM preferences, the Fuzzy UTAS TAR multicriteria analysis method (based on linear programming) has been used for sustainability evaluation. To appraise the practicality of the proposed framework, it has been applied to the WQM of the Ravi River in Pakistan. The minimal difference between the DM's top ranked options affirms the effectiveness of the proposed framework.

**Keywords** Sustainability evaluation · Water quality management · Multicriteria decision analysis · Fuzzy sets · Utility method · UTASTAR

### Abbreviations

ASP	Activated sludge process
BOD	Biochemical oxygen demand
CBOD	Carbonaceous biochemical oxygen demand
CWL	Constructed wetlands
DO	Dissolved oxygen
DM	Decision makers
LP	Linear programming
MCDA	Multicriteria decision analysis
O&M	Operations and maintenance
SBC	Sub-criteria
SSC	Sustainability criteria
WSP	Waste stabilization ponds
WQM	Water quality management
WWT	Wastewater transportation

## 1 Introduction

Freshwater sources are continuously been threatened by several challenges, such as climate change, population growth, industrialization and urbanization. In developing countries, the discharge of untreated wastewater into natural water bodies is prevalent. This can cause all types of water pollution problems including, low dissolved oxygen and ammonia toxicity, particularly during low flow conditions. To conserve these limited natural resources, there is a need to adopt sustainable practices for both the water conservation, and wastewater management; however, the main focus of this paper is on the latter issue.

Municipal wastewater can be treated through different treatment options in order to attain desired water quality standards of natural rivers. The level of treatment is established based on the strength of the wastewater and dilution available in the river. For this purpose, calibrated and verified water quality models are used (Haider and Ali 2013a; Moriasi et al. 2012). The quality of treated effluent depends on the type of wastewater treatment method, for instance, some methods are more efficient in terms of ammonia removal (Haider and Ali 2010a). Simultaneously, more advanced methods are subject to high capital costs and energy consumption, and require highly skilled operators for their routine operations. Furthermore, different WQM options have different land requirements, and varying socio-economic and environmental impacts. In order to attain the most sustainable WQM option, an approach based on multicriteria decision analysis (MCDA) is needed.

Some of the recent studies for sustainability evaluation of WQM options in developing and newly industrialized countries are summarized in Table 1. To evaluate rational WQM options for a river against specific river water quality standards, there is a need of a verified water quality model. Such studies need extensive monitoring data to estimate pollutants loading, biokinetics rate coefficients, and resultant water quality in the river. Table 1 shows that all of these studies were conducted to meet regulatory effluent standards and not to meet the river water quality standards. Moreover, all of these studies evaluated conventional wastewater treatment technologies; whereas, other unconventional sustainable WQM options for developing countries e.g., wastewater transportation and natural treatment methods (such as constructed wetlands), also need to be investigated. Nevertheless, they may result in diverse environmental and socio-economic impacts, and thus need to be evaluated against all the criterions.

In general, the most sustainable WQM option is the one that is economically viable, technically feasible, environmentally sustainable and socially acceptable all over the project's planning, construction and operational phases. The most important sustainability criteria (SSC), include cost, land requirements, operation and maintenance (i.e., technical) issues, environmental impacts, and socio-economic impacts. The data is usually limited in developing countries, and thus the evaluation studies rely on the expert opinion of the decision makers (DM). In this regard, DM should adequately justify the scoring of SSC by including sub-criteria (SBC) to assess different positive and negative impacts of the selected options. Simple integration of the SSC and SBC using indexing and hierarchical based approaches may mask their individual importance.

Indeed, the uncertainties always exist in the expert opinion of the DM scoring and ranking values. Moreover, when the data is limited, it is useful to give preference to the DM's ranking of different WQM options based on their experience about the overall study area, e.g., characteristics of the drainage area, socio-economic environment, etc. Although, some of the studies in Table 1 addressed uncertainties, but their focus was only the computational aspects of the MCDA formulations, and was not the practical implications of the possible environmental and socio-economic impacts. Moreover, in most of these studies, sufficient importance has not been given to the DM preference.

The MCDA methods, based on the philosophy of preference disaggregation to infer the preference model (from a given preferential structure by the DM), are suitable in situations similar to the present study when DM's ranking is imperative. Jacquet-Lagrèze and Siskos (1982) first introduced the UTilités Additives (UTA) method aiming at inferring one or more additive value function from a given ranking on a reference set of options established by the DM. The method uses special linear programming (LP) techniques to evaluate these value functions in order to attain the rankings as close as possible to those suggested by the DM (Siskos et al. 2005). In the present work, a more recent version of UTA method, UTAS TAR, is used for sustainability evaluation WQM options. In order to deal with the above mentioned uncertainties associated, fuzzy set theory is applied in combination with UTAS TAR. The method thus known as fuzzy UTASTAR (i.e., first developed by Patiniotakis et al. 2011).

To the best of our knowledge, there is no comprehensive framework exists so far for developing countries, which includes: i) evaluating WQM options (both conventional and unconventional) against river water quality standards using a verified model, ii) comprehensive sustainability evaluation for WQM options under uncertainty, and iii) the preference order

**Table 1** Review of some recent WQM studies carried out in developing/ newly industrialized countries

Sr No.	Reference	Location	Study planned for		Consideration to uncertainties		Importance to DM <sup>c</sup> preferences		Remarks
			ES <sup>a</sup>	SS <sup>b</sup>	Yes	No	Yes	No	
1.	Mansouri et al. (2013)	Iran	✓			✓		✓	Site selection of wastewater treatment (WWT) plant in Iran
2.	Ilangkumaran et al. (2013)	-	✓			✓		✓	Hypothetical study
3.	Shahmoradi and Isalou (2013)	Iran	✓		✓			✓	Site selection of wastewater treatment (WWT) plant in Iran
3.	Nakhaei and Taheriyoun (2012)	Iran	✓		✓			✓	Fewer environmental and socio-economic impacts were considered for WWT options in Iran
4.	Meerholz and Brent (2012)	South Africa	✓			✓		✓	For evaluation of WWT technologies for a petrochemical industry in South Africa
5.	Deepa and Krishnareni (2012)	India	✓			✓		✓	Site selection of WWT plant in India
6.	Karimi et al. (2011)	Iran	✓		✓			✓	For selection of WWT technology for an industry in Iran
7.	Yilmaz and Harmancioglu (2010)	Turkey	✓			✓		✓	For evaluation of WWT technologies for irrigation use in Turkey.
8.	Ghaffar and ElSaadi (2007)	Egypt	✓			✓		✓	For evaluation of WWT technologies for irrigation reuse in Egypt.

<sup>a</sup> Effluent Standards<sup>b</sup> Stream Standards<sup>c</sup> Decision Makers

of WQM options by the DM. Therefore, a framework is developed in the present study based on MCDA to address all these issues. To demonstrate the practicality of the proposed framework, it is implemented on the River Ravi in Pakistan.

The remaining paper is organized as follows: section 2 describes the overall proposed framework for SE, and the potential WQM options for the River Ravi. Section 3 explains the methods used for the evaluation of SSC and SBC. Section 4 contains the results and discussions on the rationale behind the scoring of SBC and application of fuzzy UTASTAR for evaluation of WQM options for the River Ravi. Section 5 briefly summarizes the main conclusions of the study.

## 2 Methodology

### 2.1 Sustainability Evaluation Framework

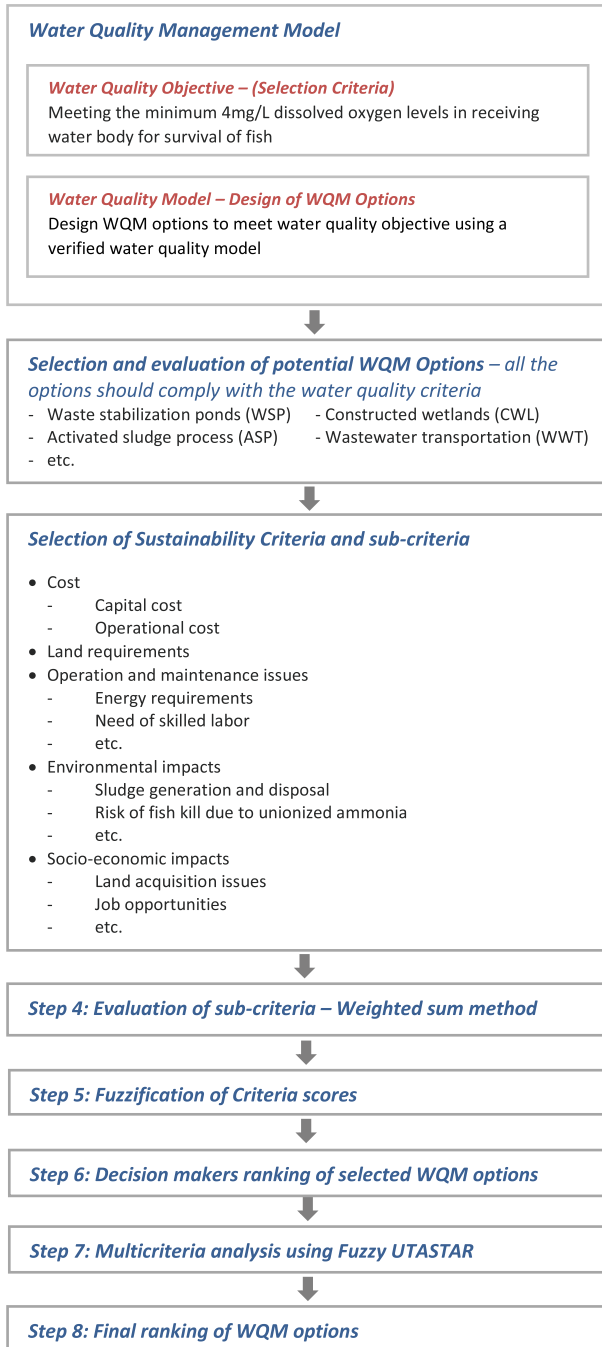
The overall sustainability evaluation framework for WQM in developing countries is shown in Fig. 1. The framework instigates by defining the water quality objectives for a specific water use of the river, e.g., survival of aquatic life, recreation, irrigation, etc. In this regard, water quality criteria values need to be established for relevant water quality parameters, such as dissolved oxygen (DO), unionized ammonia, etc. All the selected WQM options should meet the desirable water quality standards for a specific use of the river being investigated in low flow conditions. This step can be accomplished by simulating river water quality with the help of a calibrated and verified water quality model. Subsequently, the DM need to identify the most sustainable options for developing countries, followed by the selection of main SSC and SBC. For each SSC, several SBC (i.e., impacts and benefits) should also be established to facilitate the decision making process. The cumulative score of SBC need to be aggregated for further evaluation at main criteria level.

Some of the SSC such as cost and land requirements might be more objectively quantifiable than others; though, the inaccuracies (associated with inherent assumptions) certainly exist in the calculations of equipment sizing, personnel requirement, energy costs, unit cost of land, etc. In contrast, the remaining SSC (e.g., O&M issues, environmental impacts, and socio-economic impacts) would be more subjective in nature, and therefore contain uncertainties associated with expert opinion. Accordingly, the values of all the SSC need to be fuzzified to deal with such uncertainties. Finally, the MCDA method known as UTASTAR with the application of fuzzy set theory will be used to optimize the DM's ranking of the WQM options for the river under study. The framework (Fig. 1) is applied on a case study of Ravi River in Pakistan to demonstrate its practicality. The details of the MCDA methods are described in the following subsections followed by the results of case study.

### 2.2 Multicriteria Decision Analysis Approach

#### 2.2.1 Sub-criteria Evaluation

In SBC evaluation, the subjective criteria (i.e., O&M, environmental impacts, and socio-economic impacts) can be scored on ordinal scale between 1 and 10 (negligible impact to



**Fig. 1** Conceptual framework for sustainability evaluation of surface WQM options in developing countries

extremely high) by the DM. Most of the impacts are negative in nature, and thus considered as higher the worse. The corresponding weights will be allocated to each

sub-criterion in the order they are ranked. The cardinal weights have been established using the following relationship (Stillwell et al. 1981);

$$w_j = \frac{(n-r_j + 1)}{\sum_{k=1}^n (n-r_k + 1)} \tag{1}$$

where  $r_j$  is the rank of the  $j^{th}$  indicator, and  $n$  are the total number of SBC under each corresponding SSC. A rank of ‘1’ is assigned to the top ranked criteria, and  $n$  to the last one. The sum of the weights should be equal to ‘1’. The final values of each subjective SSC will be calculated by multiplying each SBC with the corresponding weight using simple additive weighting (SAW) method. As all the SBC (impacts) can be scored out of 10, there is no need of their normalization. An example of O&M criterion is shown below;

$$SSC_{O\&M} = \sum_{i=1}^n (SBC_i \times W_i) + \dots + (SBC_n \times W_n) \tag{2}$$

where  $SSC_{O\&M}$  is the calculated criteria value for O&M,  $SBC_i$  are the sub-criteria scores, and  $W_i$  are the corresponding weights. Likewise, the scores of the other SSC can be calculated.

### 2.2.2 Sustainability Evaluation Using Fuzzy UTASTAR Method

The UTA method lies in the class known as preference disaggregation in MCDA literature. In this method, a global and several partial additive utility functions are inferred from the DM ranking in the reference set of options using LP techniques. In this section, a brief introduction of UTA and UTASTAR methods is presented. The details can be seen elsewhere (Patiniotakis et al. 2011; Siskos and Grigoroudis 2010; Siskos et al. 2005; Jacquet-Lagrèze and Siskos 1982).

Conventionally, in UTA method, the set of criteria are denoted as  $\{g_1, g_2, \dots, g_N\}$ , where  $N$  is the number of criteria. The reference set, consisting of options ranked by the DM, is denoted as  $A_R$  and  $a \in A_R$  is a single option in  $A_R$ . Further,  $u$  represents the global utility function and  $u_i$  is the utility function for  $i^{th}$  criterion in utility theory. Both the marginal and the global value functions possess the monotonicity property of the true criterion. The marginal value against the criterion of an option  $a$  “ $g_i(a) \in [g_i^j - g_i^{j+1}]$ ” can be approximated by the linear interpolation as:

$$u_i[g_i(a)] = u_i(g_i^j) + \frac{g_i(a) - g_i^j}{g_i^{j+1} - g_i^j} [u_i(g_i^{j+1}) - u_i(g_i^j)] \tag{3}$$

In UTA method, for each option ‘ $a \in A_R$ ’, a single error ‘ $\sigma(a)$ ’ is needed to be minimized. The global values against the DM ranking may possess dispersion of points around the monotone curve, which cannot be efficiently minimized by using the single error function. Therefore, a double positive error function was introduced in UTASTAR method as (Siskos and Yannacopoulos 1985):

$$u'[g(a)] = \sum_{i=1}^N u_i[g_i(a)] - \sigma^+(a) + \sigma^-(a) \forall a \in A_R, \tag{4}$$

where  $\sigma^+$  and  $\sigma^-$  are overestimation and underestimation errors respectively. Furthermore, in order to address monotonicity constraints of the criteria, another modification was introduced with the help of transformation of the variables as;

$$w_{ij} = u_i(g_i^{j+1}) - u_i(g_i^j) \geq 0 \quad \forall i = 1, 2, \dots, N \quad \text{and} \quad j = 1, 2, \dots, (\alpha_i - 1) \quad (5)$$

The set of ranked options can be ordered from the most preferred option to the least preferred option. To deal with the uncertainties in present study, fuzzy set theory has been used in combination with UTASTAR method. The basic notations and definitions of fuzzy set theory and the fuzzy UTASTAR method proposed by Patriniotakis et al. (2011) are briefly described below.

Let  $X$  be the universe whose generic element are represented with  $x$ . The fuzzy set  $A$  in the universe  $X$  is a function  $A: X \rightarrow [0, 1]$ , and is characterized by its membership function,  $\mu_A: X \rightarrow [0, 1]$ , where  $\mu_A(x) \in [0, 1]$ . The value  $\mu_A(x)$  at  $x$  represents the grade of membership of  $x$  in  $A$ , and is interpreted as the degree to which  $x$  belongs to  $A$ . Thus the closer is the value of  $\mu_A(x)$  to 1; the more  $x$  belongs to the set  $A$ . Sometimes a fuzzy set  $A$  in  $X$  is denoted by listing the ordered pairs  $(x, \mu_A(x))$ , where the elements with zero degree are usually not registered. Thus a fuzzy set  $A$  in universe  $X$  can also be represented as  $A = \{(x, \mu_A(x))\}$ , where  $x \in X$  and  $\mu_A: X \rightarrow [0, 1]$ .

The arithmetic operations on fuzzy numbers can be defined by the use of Zadeh’s extension principle (Zadeh 1975). The fuzzy statements can be conceptualized by certain “appropriate” fuzzy sets in  $R$  to be termed as fuzzy numbers. Formally, a fuzzy set is defined on the set of real numbers  $R$  (i.e.,  $X = R$ ). The membership function of a fuzzy set defined as convex, normalized and piecewise continuous is called a fuzzy number, and it represents a real number interval whose boundary is fuzzy. In literature, many types of fuzzy numbers exist; however, for simplicity, the triangular fuzzy numbers are used in this study. For addition, subtraction, and multiplication, fuzzy arithmetic operations between two triangular fuzzy numbers are used (Kaufmann and Gupta 1985).

An efficient approach for comparing fuzzy numbers is the use of a ranking function  $\mathfrak{R}: F(R) \rightarrow R$ , where  $F(R)$  is a set of fuzzy numbers defined on the set of real numbers. For any triangular fuzzy number  $A = (a_1, a_2, a_3)$ , the ranking function is defined as (Kumar et al. 2011a);

$$\mathfrak{R}(A) = \frac{a_1 + 2a_2 + a_3}{4} \quad (6)$$

The real numbers  $a_1$ ,  $a_2$ , and  $a_3$  in Eq. (11), correspond to minimum, average, and maximum scores of the SCCs given by the DM. According to Patriniotakis et al. (2011), the input data (scores) can be either crisp or fuzzy numbers or a mix of them, depending on the nature of the problem. In fuzzy UTASTAR algorithm, the fuzzy numbers are marked with a symbol ‘ $\sim$ ’ above the letters to distinguish them from crisp numbers; for example  $\tilde{A}$  is fuzzy, whereas  $A$  is a crisp one. The step-by-step procedure of Fuzzy UTASTAR method is given below:

- Step 1: Reorder the reference set options from the best to worst. The consecutive options can be ranked equal, when there is no preference exists for one over the other. However, too many such indifference cases can affect the quality of results.
- Step 2: Express the fuzzy global value of reference actions  $\tilde{u}[g(a_k)]$ ,  $k = 1, 2, \dots, m$ , first in terms of fuzzy marginal value  $\tilde{u}_i(g_i)$ , and then in terms of fuzzy variable  $\tilde{w}_{ij}$  using Eq. [5] as:

$$\tilde{u}_i[g_i(a)] = \sum_{k=1}^{q-1} w_{ij} + \frac{\tilde{g}_i(a) - g_i^j}{g_i^{j+1} - g_i^j} w_{iq} \quad \forall i = 1, 2, \dots, N \quad (7)$$

- Step 3: Further, in order to deal with fuzzy numbers, two fuzzified error functions  $\tilde{\sigma}^+$  and  $\tilde{\sigma}^-$  in  $A_R$  are included by writing for each pair of consecutive actions in ranking the analytic expressions as;



$$\tilde{\Delta}(a_k, a_{k+1}) = \tilde{u}[g(a_k)] - \tilde{\sigma}^-(a_k) + \tilde{\sigma}^+(a_k) - \tilde{u}[g(a_{k+1})] + \tilde{\sigma}^-(a_{k+1}) - \tilde{\sigma}^+(a_{k+1}) \quad (8)$$

Step 4: In this step, the method proposed by Kumar et al. (2011a) was used to solve the following fuzzy LP problem;

$$\left\{ \begin{array}{l} [\min] \tilde{F} = \sum_{k=1}^m \tilde{\sigma}^+(a_k) + \tilde{\sigma}^-(a_k) \\ \text{subject to} \\ \tilde{\Delta}(a_k, a_{k+1}) \geq \delta \text{ iff } a_k > a_{k+1} \\ \tilde{\Delta}(a_k, a_{k+1}) = 0 \text{ iff } a_k \sim a_{k+1}, \\ \sum_{i=1}^N \sum_{j=1}^{\alpha_i-1} w_{ij} = 1 \\ w_{ij} \geq 0, \tilde{\sigma}^+(a_k) \geq 0, \tilde{\sigma}^-(a_k) \geq 0 \forall i, j, k \end{array} \right. \quad (9)$$

Step 5: Perform stability analysis by testing the presence of multiple or near optimal solutions for the LP problem formulated in Step 4. If more than one optimal solution is found then the mean optimal utility function should be chosen. The stability analysis involves the check of optimal solutions from step 4 that maximize the following function:

$$\tilde{u}_i [g_i^*] = \sum_{j=1}^{\alpha_i-1} \tilde{w}_{ij} \forall i = 1, 2, \dots, N \quad (10)$$

with the following additional constraint:

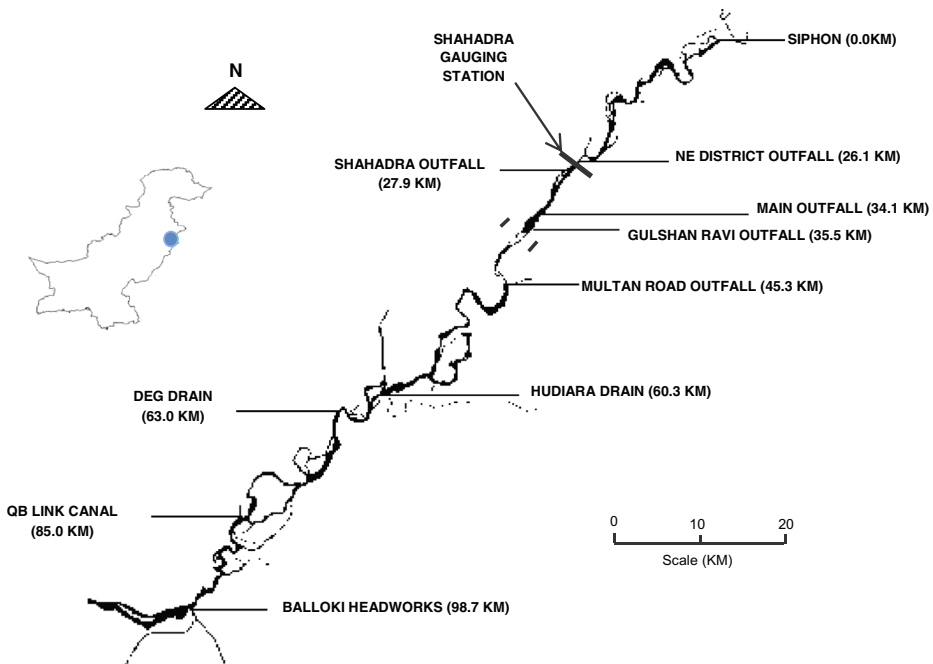
$$\sum_{k=1}^m \tilde{\sigma}^+(a_k) + \tilde{\sigma}^-(a_k) \leq z^* + \varepsilon \quad (11)$$

where,  $z^*$  is the optimal value of the linear programming problem in Step 4, and  $\varepsilon$  is a very small positive number. *LINGO* software is used to solve the LP formulations in this study.

### 3 Results and Discussions

#### 3.1 Study Area

To demonstrate the pragmatic application of the sustainability evaluation framework developed in this study, the Ravi River is selected as a case study (Fig. 2). The Ravi River is one of the most polluted rivers in Pakistan with extreme flow variations between 10 and 10,000 m<sup>3</sup>/s. It receives an average of 40 m<sup>3</sup>/s untreated municipal and industrial wastewater from the city of Lahore through five wastewater outfalls and two surface drains (Fig. 2). This flow is expected to increase up to 56 m<sup>3</sup>/s in the year 2025. According to Haider and Ali (2013a), about 60Km between North East District Outfall to QB-Link Canal shown in Fig. 2 becomes anaerobic under low flow conditions. Hence, this valuable resource needs a sustainable WQM plan for coming back to life again.



**Fig. 2** Study area, the Ravi River in Pakistan

Both the low DO concentration and ammonia toxicity, have been recognized as the main water quality problems in the River Ravi (Haider and Ali 2013a). Conventionally, minimum 4 mg/L DO should be available at all times in a river for survival of fish and overall ecological balance (Thomann and Mueller 1987; Chapra 1997). In the absence of stream water quality standards in Pakistan, the same value has been used as the desired water quality objective for the River Ravi. For unionized ammonia, 0.02 mg/L is the criteria value (FDEP 2005).

### 3.2 Water Quality Management Model

The River Ravi will be receiving 2394 tons/day of ultimate biochemical oxygen demand (UBOD) loads (i.e., sum of carbonaceous biochemical oxygen demand ‘CBOD’ and nitrogenous biochemical oxygen demand ‘NBOD’) by the year 2025 (Haider and Ali 2013b). Conventionally, WQM studies of rivers are carried for the minimum average seven consecutive days (MA7CD) flow once in 10 years also known as 7Q10. Haider (2010) estimated MA7CD value of 9.2 m<sup>3</sup>/s using cumulative probability analyses of the flow records from 1967 to 2004.

Haider and Ali (2010b) developed a hydrodynamic model coupled with Modified Streeter-Phelps model including nitrification to simulate DO in the Ravi River. Long term BOD analyses were conducted for all the wastewater outfalls and surface drains to estimate bottle rate coefficients, CBOD and NBOD. For model development, a river monitoring survey for the 100 km river length (Fig. 2) was conducted at 481.5 m<sup>3</sup>/s. Later, the model was calibrated and verified with two different monitoring data sets for the river flows of 431.5 and 52.6 m<sup>3</sup>/s, respectively. Close agreements were observed between the measured DO levels in the River Ravi and the model’s simulation results. In the same study, Haider and Ali (2013a) developed

and calibrated the nitrification model to control un-ionized ammonia in the River Ravi. Based on the pH and temperature in the Ravi River, nitrification modeling revealed that 90 % ammonia removal is required to meet conventional unionized ammonia standards of 0.02 mg/L. For details of the model development, calibration, and verification results, interested readers are referred to Haider and Ali (2010b, 2013a). Moreover, Haider and Ali (2010a) found that the rate coefficients for CBOD and NBOD reduced to 5 and 3 times respectively from settled wastewater samples to biologically treated effluents. Such consideration has also been taken into account in simulations while evaluating different WQM options for the River Ravi.

### 3.3 Water Quality Management Options

During most of the year, the river attains low flows, and thus requires high degrees of treatment to meet aforementioned water quality standards. On the other hand, during monsoon period, the river spans over a wide flood plain and the flood protection works are used to safely direct large flows away from the city. In order to meet the required water quality standards, Haider and Ali (2013b) used the verified model to simulate DO for different WQM options, including waste stabilization ponds (WSP), constructed wetlands (CWL), activated sludge process (ASP), and wastewater transportation (WWT). These options are presented in Fig. 3a–d, and the DO simulation results corresponding to these options for MA7CD flow are shown in Fig. 4.

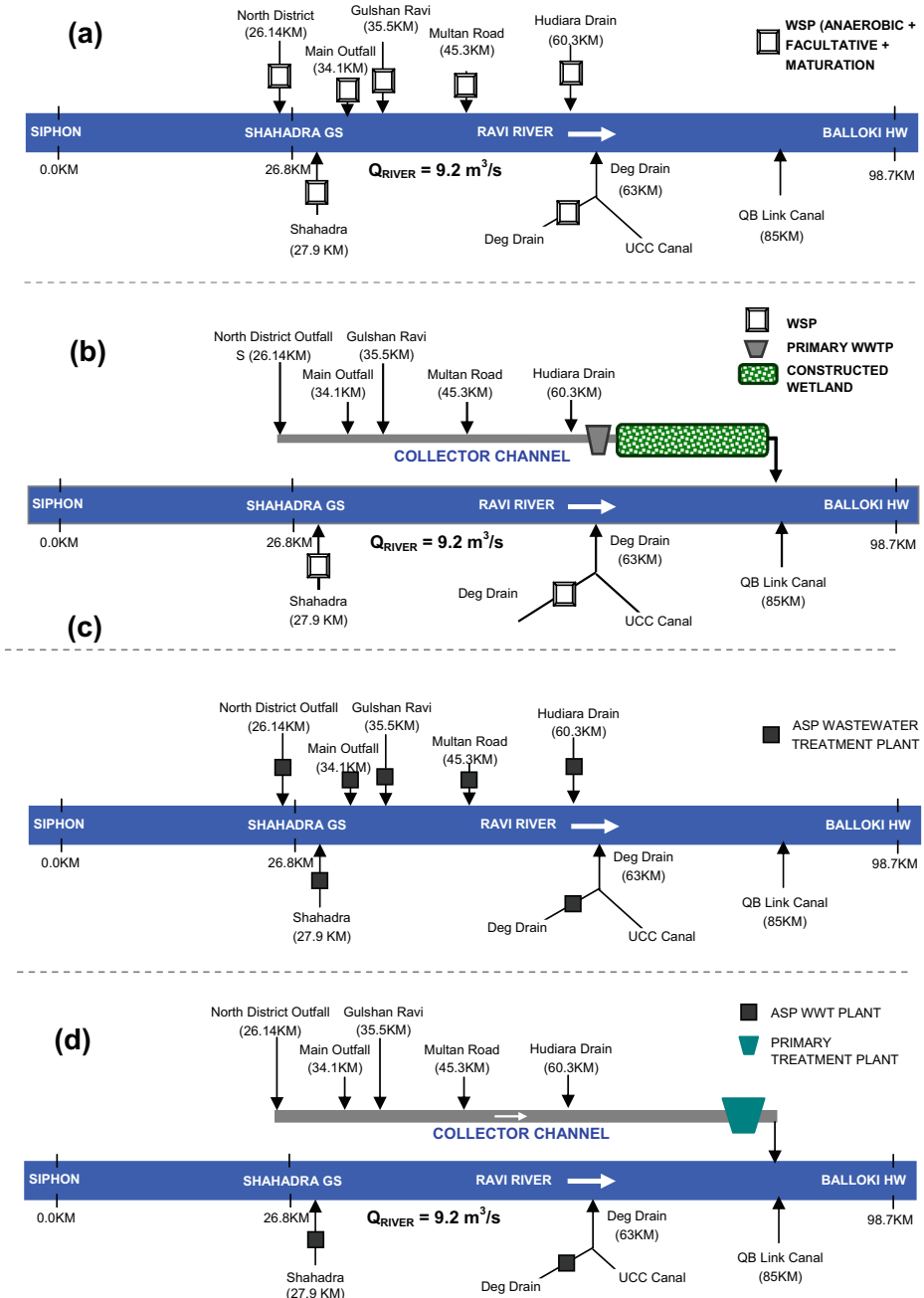
For sustainability evaluation, it is appropriate to recognize the environmental setting of these WQM options. In this regard, two cross-sections of the River Ravi are shown in Fig. 5a and b to describe the impact of land use variations (urban and rural areas). Figure 5a demonstrates that a large flood plain exists outside the main city; whereas, the river's cross-section is narrower in proximity to the urban areas (Fig. 5b). Along the part of river passing through the urban areas, the city is bounded by an elevated highway for flood protection. Therefore, the WQM options planned outside the flood plain shown in Fig. 5b (i.e., ASP) do not need additional flood protection works. However, the options with large land requirements (i.e., WSP) can only be planned within the flood plain, and thus need to be protected against floods. Furthermore, the impacts of agricultural watershed on river water quality should not be overlooked (Carlos et al. 2015). A brief description of these options is presented in the subsequent sections, and further details are in Haider and Ali (2013b).

#### 3.3.1 Waste Stabilization Ponds

The WQM option using WSP (anaerobic, facultative and maturation) in series is shown in Fig. 3a. Around 85 % of CBOD and 75 % of NBOD removal can be achieved in the treated effluent from WSP. The finally treated effluent from maturation ponds is suitable for irrigation use. Such reuse of wastewater in developing countries is a sustainable practice towards water conservation and has potential economic benefits as well (Kim et al. 2015; Azad et al. 2015). Simulation results for this option show that if 50 % of the treated effluent is reused for irrigation, the DO standards of 4 mg/L can be achieved (Fig. 4). Balfours (1987) proposed the location for WSP in the flood plain.

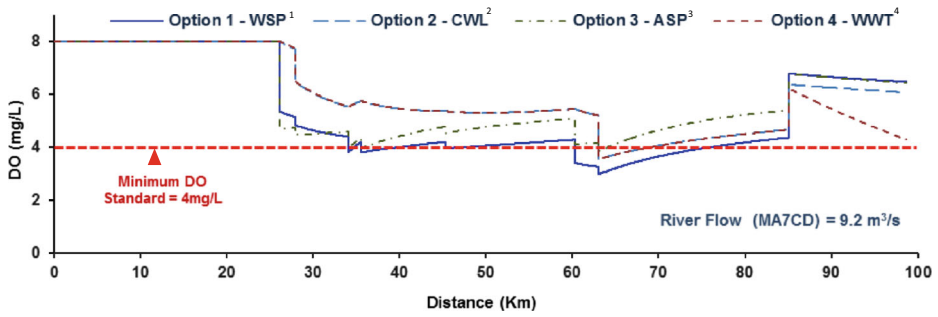
#### 3.3.2 Constructed Wetlands

The CWL option presented in Fig. 3b is based on the perception of utilizing large flood plain available downstream of Hudiara drain by transporting the wastewater (from the outfalls



**Fig. 3** Potential options for sustainability evaluation for WQM of the River Ravi; **a)** Option-1, waste stabilization ponds; **b)** Option-2, constructed wetlands, **c)** Option-3, activated Sludge Process; and **d)** Option-4, wastewater transportation (Source: Haider and Ali 2013b)

located along the left bank of the river) through a collector channel. The simulation results shown in Fig. 4 depict that the required DO standards can be achieved with this option.



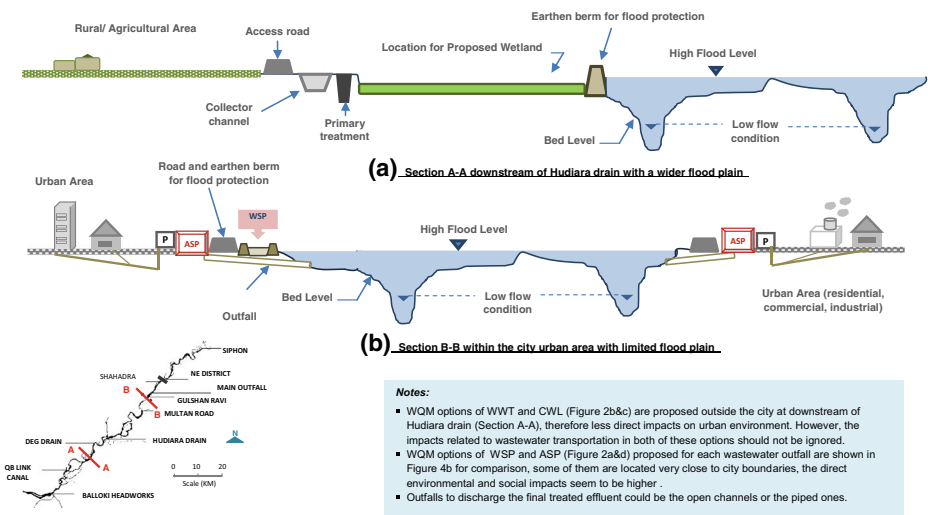
<sup>1</sup>Waste stabilization ponds; <sup>2</sup>Constructed wetlands; <sup>3</sup>Activated sludge process; <sup>4</sup>Wastewater transportation

**Fig. 4** Dissolved oxygen profiles for all the options to meet minimum standards of 4 mg/L

Transported wastewater with the help of a collector channel to the CWL can achieve up to 80 % CBOD removal, and 60 % NBOD removal; however, the influent for CWL needs to be pre-treated with settling basins. Recently, Haydar et al. (2015) evaluated the use of a wetland plant ‘Reed’ (*Phragmites*), using a lab scale wetland model, to treat the wastewater of Lahore and found similar results as shown in Fig. 4.

### 3.3.3 Activated Sludge Process

The ASP option is proposed with individual units at each wastewater outfall just before final disposal of wastewater into the River Ravi (Fig. 3c). This option may produce relatively higher and wide-spread O&M issues, and environmental and socio-economic impacts. The simulations results with 87 % CBOD removal to achieve 4 mg/L of DO standards are shown in



**Notes:**

- WQM options of WWT and CWL (Figure 2b&c) are proposed outside the city at downstream of Hudlra drain (Section A-A), therefore less direct impacts on urban environment. However, the impacts related to wastewater transportation in both of these options should not be ignored.
- WQM options of WSP and ASP (Figure 2a&d) proposed for each wastewater outfall are shown in Figure 4b for comparison, some of them are located very close to city boundaries, the direct environmental and social impacts seem to be higher.
- Outfalls to discharge the final treated effluent could be the open channels or the piped ones.

**Fig. 5** Ravi River typical cross-section; a) applicable for constructed wetlands and wastewater transportation options shown in Fig. 3b and c; b) applicable for waste stabilization ponds and activated sludge options shown in Fig. 3a and d

Fig. 4. This option requires relatively less land and can be constructed before the flood plain as shown in Fig. 5b.

### 3.3.4 Wastewater Transportation

According to this option, the wastewater from the outfalls located along the left bank of the River Ravi will be transported to the confluence point of Qadirabad Balloki Link Canal (Fig. 3d). An average annual flow of 396 m<sup>3</sup>/s from QB Link canal will be utilized to obtain freshwater dilution (of about 1:10) for MA7CD design flow. This can be seen from DO simulation results shown in Fig. 4. However, lower level of treatment (only primary treatment) can violate un-ionized ammonia standards and can cause low DO problem during canal closure period.

## 3.4 Evaluation of Sustainability Criteria and Sub-criteria

The group of DM involved in this study possesses extensive experience of the studies related to wastewater characterization, water quality management, and social and environmental impact assessment of the Ravi River in particular, and several other studies of similar nature in general. The matrix showing minimum and maximum values of scores given by the DM for SBC along with their corresponding weights is attached as [Appendix A](#). The rationale for scoring the SBC is described in the following subsections.

### 3.4.1 Operation and Maintenance Issues

Under current energy crises in developing countries, energy consumption is the most important criterion for this criterion. WSP requires minimum energy for their operations. Although, CWL although use natural settling and biodegradation processes, for pre-treatment, the processes like desludging and plant site lighting will consume energy. Energy requirements of WWT are quite similar to CWL. ASP involves several mechanical and automated processes which require high energy inputs. In addition, the need of highly skilled staff is also higher in case of ASP than the other options for, control of oxygen, nutrients, pH, use of chemicals, recycling of mixed liquor suspended solids, and sludge handling, etc.

Sludge handling and disposal is another important O&M issues to be addressed. ASP definitely produces maximum sludge, and thus obligates higher O&M issues related to sludge handling, transportation and disposal on routine basis. Conversely, WSP have much longer desludging periods ranging from 5 to 10 years (Mara 2004). For the remaining two options, primary settling tanks are proposed as pre-treatment and primary treatment for CWL and WWT respectively. However, in these options such issues are less than ASP but certainly higher than WSP.

The requirements of flood protection for WSP and CWL are much higher than other two options (Fig. 5). Workers health and safety issues are high in ASP and CWL options as compared to WSP and WWT. In case of ASP, workers are exposed to several complex processes, including operations of heavy machinery; whereas, workers will be exposed to, different species of rodents and reptiles spread over large areas and allergies (such as pollen) during maintenance of CWL. In order to protect general public, particularly children living in the near vicinity of wastewater management facilities, strict accessibility controls (with fencing and security guards) for WSP will be required.

### 3.4.2 Environmental Impacts

Environmental impacts related to sludge generation, transportation and disposal are ranked at the first place under this criterion. Further, the use of bio-solids from sludge drying beds as fertilizer may cause health risk from the heavy metals uptake by the crops. ASP possesses the maximum such issues followed by CWL, WWT, and WSP. Under this sub-criterion, cumulative impacts are considered, e.g., increase in traffic and thus leading to high emissions; land acquisition workers health and safety issues associated with sludge drying beds; production of gases from sludge drying beds, etc.

As mentioned earlier, the unionized ammonia toxicity is another important parameter to maintain ecological balance in addition to DO in natural rivers. Different WQM options have varying efficiency against removal of ammonia. Based on the pH and temperature in the Ravi River, nitrification modeling revealed that 90 % removal is required to meet conventional unionized ammonia standards of 0.02 mg/L. In this regard, ASP was found to be the only treatment option to achieve such higher ammonia removal. Details can be seen in Haider and Ali (2013a&b). However, the actual toxicity threshold values should be established using risk analysis for the specific fish species existing in the Ravi River. The risk of un-ionized ammonia is quantified using ordinal scale defined as, very low, low, medium, high and very high, against the values of 1, 3, 5, 7 and 9, respectively. Consequently, ASP was considered as the option having lowest risk with scores varying between 1 and 3. CWL is the next with 3 and 5 scoring values, followed by WSP with values ranging between 5 and 7. Finally, WWT came out to be the option with highest risk between 7 and 9.

The land use is sub-urban with agricultural fields and farm houses in the vicinity of flood plain of the River Ravi. Therefore, reuse of treated effluent for agricultural use is a sustainable mean for its final disposal. Impact of treated effluent on natural soil seems to be higher in case of WWT due to relatively lower level of treatment (Fig. 3d). Primary treated effluent has higher BOD and coliform levels which can clog the topsoil layer, and thus affect the aerobic environment in natural soils.

Impact on groundwater due to percolation of wastewater is higher in case of WSP and CWL with the clay lined and unlined bottoms, respectively. Another significant impact is leachate generation from sludge drying beds in case of ASP. Impact on air quality will be higher through anaerobic ponds from WSP e.g., greenhouse gases emissions including CH<sub>4</sub>, N<sub>2</sub>O and CO<sub>2</sub>, etc. Photo-oxidants will also be discharged from energy consumption by various equipment operations at ASP, e.g., NO<sub>x</sub>, SO<sub>x</sub>, CO, C<sub>2</sub>H<sub>4</sub> (Ethylene), CH<sub>4</sub>, etc. (Musharrafie et al. 2011). Primary treatment in WWT and CWL options (Fig. 3b and d) will also contribute to air pollution. Increase in noise levels will be minimum with WSP and maximum in ASP option. The contributing factors to existing noise levels would be plant operations, sludge transportation vehicles, desludging of collector channel, etc.

### 3.4.3 Socio-economic Impacts

Land acquisition and resettlement are the most important components in this category. According to a study conducted by JICA (2010), about 1000 acres of land has already been acquired in lieu of the construction of wastewater treatment facilities for Lahore. This area of land is approximately 10 % of land area required for WSP and CWL. Moreover, this land has

**Table 2** Fuzzified scores of sustainability criteria for Ravi River

Water quality management options	Cost 'million Rs.' ( $g_1$ )	Land requirement 'Acres' ( $g_2$ )	O&M <sup>a</sup> Issues ( $g_3$ )	Environmental Issues ( $g_4$ )	Socio- economic Issues ( $g_5$ )	DM <sup>b</sup> Ranking
A1- Waste Stabilization Ponds (WSP)	(60,500, 71,000,82,000)	(12,000, 13,500, 15,000)	(4.11, 4.56, 5.02)	(4.11, 4.59, 5.07)	(6.53, 6.78, 7.03)	1
A2 – Constructed Wetlands (CWL)	(73,000, 86,000,99,000)	(10,000, 10,500, 11,000)	(6.35, 6.91, 7.46)	(5.24, 5.61, 5.98)	(6.06, 6.48, 6.90)	2
A3- Activated Sludge Process (ASP)	(386,000, 454,000, 523,000)	(325, 362.5, 400)	(6.52, 6.96, 7.40)	(6.07, 6.46, 6.86)	(4.49, 4.94, 5.39)	4
A4- Wastewater Transportation (WWT)	(157,000, 184,000, 212,000)	(700, 775, 850)	(4.00,4.34, 4.69)	(6.17, 6.61, 7.06)	(6.50, 6.76, 7.01)	3

<sup>a</sup> Operation and management<sup>b</sup> Decision maker



been acquired for the first four outfalls (refer to Fig. 2) along the left bank of the river. Although, land acquisition for CWL will be a new task, the proposed location (Fig. 5a) lies in flood plain with one cropping season. Therefore, it would be relatively easier to acquire land with less economic value. The already acquired land seems to be sufficient for ASP option at given locations.

Construction of such facilities can impact the value of land, due to increase in air pollution and movement of vehicles. These issues will be higher in case of ASP, except the odour problem, which would be more in the case of anaerobic ponds. Construction of WSP will disturb the existing natural landscape of the river, which can be mitigated with appropriate plant siting and artificial landscaping. Workers health and safety issues can be mitigated by implementing relevant standards, proper training, and efficient emergency response.

More or less the issues related to the reuse of wastewater are common in all options with secondary treatment; except, in case of WWT these impacts might be higher than others. Selling of crops (particularly cash crops) grown with the reused wastewater seems to be a minor consideration in developing countries due to less awareness about food and agriculture water quality standards. Due to insufficient implementation of effluent standards, industrial effluents with higher concentrations of heavy metals also join the municipal wastewaters. As the tertiary level treatment to remove these metals is difficult, the wastewater should be avoided for raw vegetables. Certainly, job opportunities will be generated during construction and operation phases of all the WQM options; ASP has highest potential due to its complex and wide-spread operational activities.

### 3.5 Multicriteria Analysis Using Fuzzy UTASTAR

The fuzzy UTASTAR method is applied in this section for the final evaluation of main SSC of cost, land requirements, O&M issues, environmental impacts, and socioeconomic impacts. It can be seen in Appendix A that a difference of opinion exists among the DM while scoring different SBC. To incorporate these uncertainties, the main SSC values are fuzzified as minimum, average, and maximum. The fuzzified values of the SSC and the DM ranking for all the options are shown in Table 2. The steps of the fuzzy UTASTAR method described in section 2 are used to evaluate the WQM options for the Ravi River. The detailed step-by-step application and results of sustainability evaluation of all four WQM options are attached as Appendix B.

Using *LINGO* on the post-optimal solution,  $w_{12}$ ,  $w_{41}$ , and  $w_{42}$  (refer to Appendix B) came out to be the binding constraints; which shows that cost and environmental impacts, as expected, were the most sensitive sustainability criteria for the present study. The final

**Table 3** Final ranking of WQM options for the River Ravi

WQM Option	Final utilities	$\mathfrak{H}[(UA)]$	Decision makers ranking	Ranking obtained from SAW and fuzzy UTASTAR
A1 – WSP	U(A1)=(0.980, 0.990, 0.999)	0.990	1	1
A2 – CWL	U(A2)=(0.884, 0.911, 0.939)	0.911	2	2
A3 – ASP	U(A3)=(0.761, 0.796, 0.833)	0.781	3	3
A4 - WWT	U(A4)=(0.573, 0.643, 0.711)	0.642	4	4

evaluation results are presented in Table 3. The final utilities from post optimal analysis are presented in second column of Table 3. The ranking values of final utilities listed in the third column of Table 3 were subsequently calculated using the formula given in Eq. [6]. It can be seen that these crisp values have already been sorted in descending order which shows that the decision makers ranking order has been obtained, i.e.,  $U(A1) > U(A2) > U(A3) > U(A4)$ . However, the small difference in first two options (i.e., WSP and CWL) in Table 3 affirms the use of preference based decision making using the proposed sustainability evaluation framework.

The study results revealed that WSP is the most sustainable option for developing countries with minimum cost, and relatively lesser O&M, environmental and socio-economic problems. CWL was found to be the second most sustainable option. ASP came out to be the second last option primarily due to high energy requirements, high initial and O&M costs, and sludge handling and disposal issues. WWT was found to be the least sustainable option primarily due to its lower level of treatment and resulting environmental and socio-economic impacts.

## 4 Summary and Conclusions

In this research, a comprehensive sustainability evaluation framework is developed for WQM of large rivers in developing countries. The framework contains: selection of WQM options to achieve desirable water quality objectives; five main SSC including cost (capital, land and operational), land requirements, operation and maintenance issues, environmental and socio-economic impacts; and several sub-criteria. The framework is able to deal with uncertainties associated with calculation errors, inherent assumptions, and the differences in DM's opinions; it also incorporates the DM' preference order of WQM options in the evaluation process.

To demonstrate the practicality of the research, the modeling framework is implemented on a real case scenario of River Ravi in Pakistan. It was found that the water quality objectives can also be achieved by using other management options than the conventional ones, such as wastewater transportation. These options can be less expensive but may cause diverse impacts.

The minimal difference between the top ranked options (initially set by DM) in the final results demonstrates the effectiveness of the use of preference based decision making. While solving the LP formulation, cost and environmental impacts were found to be the most sensitive SSC.

The framework developed in this study is flexible enough to be implemented for studies of a similar nature in developing countries with additional sustainability criteria (and sub-criteria); it can include different WQP options other than those used in this study, depending on site specific conditions. However, this approach requires a verified river water quality model to evaluate different options against river water quality standards.

**Acknowledgments** The water quality and cost data obtained by the PhD work of first author, which was funded by the Institute of Environmental Engineering and Research, UET, Lahore, Pakistan. The sustainability evaluation part was done at University of British Columbia, Okanagan, Canada. The second author was supported by the Education for Competitiveness Operational Programme (reg. no. CZ.1.07/2.3.00/30.0004) co-financed by the European Social Fund and the state budget of the Czech Republic.

## Appendix A

**Table 4** Scoring matrix for sustainability sub-criteria evaluation

Sustainability Criteria/ Sub-criteria	Criteria Weight	Option 1: WSP <sup>a</sup>		Option 2: CWL <sup>b</sup>		Option 3: ASP <sup>c</sup>		Option 4: WWT <sup>d</sup>	
		Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
<b>Operation and management issues</b>									
Energy requirements	0.22	4.0	5.0	6.0	7.0	8.0	9.0	5.0	6.0
Need of skilled operators	0.19	3.0	4.0	7.0	8.0	8.0	9.0	3.0	4.0
Need of sophisticated equipment	0.17	2.0	3.0	5.0	7.0	8.0	9.0	3.0	3.0
Sludge handling, transportation and disposal	0.13	3.0	4.0	5.0	7.0	8.0	9.0	5.0	5.0
Maintenance of flood protection works	0.12	8.0	8.0	9.0	9.0	2.0	2.0	5.0	7.0
Workers health and safety at plant operations	0.08	4.0	5.0	6.0	7.0	5.0	7.0	3.0	3.0
Storm water drainage at plant site	0.06	7.0	7.0	9.0	9.0	2.0	2.0	4.0	4.0
Public accessibility controls required at plant site	0.03	8.0	8.0	3.0	4.0	2.0	2.0	3.0	4.0
<b>Environmental impacts</b>									
Sludge generation and disposal	0.20	1.0	3.0	7.0	7.5	9.0	9.0	6.5	7.0
Risk of fish kill due to un-ionized ammonia (ammonia removal level)	0.18	5.0	6.0	3.0	5.0	1.0	3.0	8.0	9.0
Impacts on soil (wastewater reuse for agriculture)	0.16	5.0	5.0	5.0	5.5	6.0	7.0	7.0	8.5
Impact on surface water quality (Effluent quality)	0.13	6.0	6.0	4.0	4.5	5.0	5.5	7.0	8.0
Impact on groundwater quality (percolation and leachate)	0.11	5.0	6.0	7.0	7.0	8.0	9.0	4.0	5.0
Air pollution due to exhaust gasses	0.09	7.0	7.5	6.0	6.5	8.0	8.5	5.0	5.0
Noise levels increase	0.07	1.0	2.0	3.0	4.0	9.0	9.0	4.0	5.0
Impacts on flora and fauna	0.04	2.0	5.0	7.0	7.5	5.0	6.0	4.0	5.0
Changes in existing drainage pattern	0.02	5.0	6.0	8.0	8.0	3.0	3.5	4.0	5.0
Impact on river flows	0.01	6.0	7.0	5.0	6.0	5.0	5.0	5.0	6.0
<b>Socio-economic impacts</b>									
Land acquisition issues (resettlement)	0.22	9.0	9.0	8.0	8.5	6.0	7.0	7.0	9.0
Impacts on value of land	0.19	8.0	9.0	7.0	8.5	7.5	9.0	7.5	8.0
Impacts on recreational areas and landscaping	0.17	9.0	9.0	8.0	9.0	7.0	7.0	8.5	8.5
Job opportunities (Positive Impact)	0.14	3.0	3.0	3.0	3.0	9.0	9.0	2.0	2.0
Odor generation	0.11	9.0	9.0	8.0	9.0	7.0	9.0	8.5	8.5
Workers health and safety during wastewater reuse for agriculture	0.08	7.0	9.0	7.0	8.0	5.0	6.0	9.0	9.0
Nuisance due to operations and sludge disposal vehicles	0.06	3.0	5.0	7.0	8.0	8.5	9.0	7.0	8.0
Problems with selling of crops grown from wastewater reuse	0.03	5.0	6.0	5.0	6.0	5.0	6.0	9.0	9.0

<sup>a</sup> Waste stabilization ponds

<sup>b</sup> Constructed wetlands

<sup>c</sup> Activated sludge process

<sup>d</sup> Wastewater transportation

**Appendix B: Step-by-step application of Fuzzy UTASTAR for sustainability evaluation of WQM options for Ravi River**

Step 1: First the DM ranked the available WQM options from the most preferred to the least preferred as shown in Table 2 of main text. Triangular fuzzy numbers shown in Fig. 6 are used in this study.

Step 2: Depending on the range of SSCs values, two evaluation scale intervals are considered for all the criteria, except for the environmental impacts which is segmented over three intervals. The intervals of the segments of criteria values are presented in Table 5. For instance in Table 5, the cost criterion has value ranging from 60,500 to 523,000 million Rs for different options. The minimum lower boundary is represented by the lower range boundary of all fuzzy evaluations, and the upper range value is the maximum upper boundary of all the fuzzified evaluations. The width of crisp interval was found to be 462,500 million Rs. (i.e., 523,000–60,500), which was further divided into two intervals as listed in Table 5. In the similar way, the other criteria were segmented over their corresponding intervals.

The utilities of the first option (A1-WSP) were calculated by initiating with the Fuzzification of the SSCs values as follows:

$$g_1(A1) = (60500, 71000, 82000), \quad g_2(A1) = (12000, 13500, 15000), \quad g_3(A1) = (4.11, 4.56, 5.02), \\ g_4(A1) = (4.11, 4.59, 5.07), \quad g_5(A1) = (6.53, 6.78, 7.03),$$

The overall utility for option A1 can be written as:

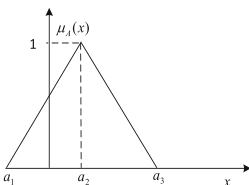
$$U(A1) = u_1[g_1(A1)] + u_2[g_2(A1)] + u_3[g_3(A1)] + u_4[g_4(A1)] + u_5[g_5(A1)]$$

For criterion  $g_1(A1)=(60500,71000,82000)$ , the interval end points are,  $g_1^1=291750$ , and  $g_1^*=60500$  (Table 5). The marginal utility function for  $g_1(A1)$  can be expressed using Eq. [7] of the main text as:

$$u_1[g_1(A1)] = (1, 1, 1)w_{11} + \frac{g_1^1 - g_1(A1)}{g_1^1 - g_1^*}w_{12},$$

or

$$u_1[g_1(A1)] = u_1[(60500, 71000, 82000)] \\ = (1, 1, 1)w_{11} + \frac{(291750, 291750, 291750) - (60500, 71000, 82000)}{291750 - 60500}w_{12} \\ = (1, 1, 1)w_{11} + (0.907, 0.955, 1.0)w_{12}$$



$$\mu_A = \begin{cases} 0, & -\infty < x \leq a_1 \\ \frac{x - a_1}{a_2 - a_1} & a_1 < x \leq a_2 \\ \frac{a_3 - x}{a_3 - a_2} & a_2 \leq x < a_3 \\ 0, & a_3 \leq x \leq \infty \end{cases} \quad \text{where } a_1 < a_2 < a_3 \text{ in fuzzy set } R$$

**Fig. 6** Triangular fuzzy number used in this study

**Table 5** Segments intervals for the criteria values

Criterion	Min	Max	Spread	Intervals	Step	Interval 1	Interval 2	Interval 3	Direction
Cost	60,500	523,000	462,500	2	231,250	[523,000, 291,750]	[291,750, 60,500]	–	Decrease
Land requirements	325	15,000	14,675	2	7338	[15,000, 7663]	[7663, 325]	–	Decrease
Operation and management issues	4.00	7.46	3.46	2	1.73	[7.46, 5.73]	[5.73, 4.00]	–	Decrease
Environmental impacts	4.11	7.06	2.94	3	0.98	[7.06, 6.07]	[6.07, 5.09]	[5.09, 4.11]	Decrease
Socio-economic impacts	4.49	7.03	2.54	2	1.27	[7.03, 5.76]	[5.76, 4.49]	–	Decrease

Similarly, we can calculate the utility marginal function for remaining SSCs. The overall utility of option (A1) comes out to be:

$$U(A1) = (1, 1, 1)w_{11} + (0.907, 0.955, 1.0)w_{12} + (0, 0.102, 0.204)w_{21} + (1, 1, 1)w_{22} \\ + (1, 1, 1)w_{31} + (0.41, 0.674, 0.939)w_{32} + (1, 1, 1)w_{41} + (1, 1, 1)w_{42} \\ + (0.026, 0.513, 1.0)w_{43} + (0.0, 0.098, 0.197)w_{51} + (1, 1, 1)w_{52}$$

Similarly the utility functions for the remaining options (A2, A3, and A4) can be computed.

Step 3: Apply error functions  $\sigma_{Ai}^+$  and  $\sigma_{Ai}^-$  for option (A1) can be calculated as:

$$U(A1) = (1, 1, 1)w_{11} + (0.907, 0.955, 1.0)w_{12} + (0, 0.102, 0.204)w_{21} + (1, 1, 1)w_{22} \\ + (1, 1, 1)w_{31} + (0.41, 0.674, 0.939)w_{32} + (1, 1, 1)w_{41} + (1, 1, 1)w_{42} \\ + (0.026, 0.513, 1.0)w_{43} + (0.0, 0.098, 0.197)w_{51} + (1, 1, 1)w_{52} + \sigma_{A1}^+ - \sigma_{A1}^-$$

Similarly the error functions for the remaining options (A2, A3, and A4) can be computed.

Express the utility equations as differences between consecutive pair of options, for instance, between options A1 and A2 in the following way:

$$\Delta U(A1A2) = U(A1) - U(A2) = (-0.04, 0.065, 0.166)w_{12} + (-0.341, -0.204, -0.068)w_{21} \\ + (0.667, 0.839, 1.0)w_{31} + (-0.59, -0.326, -0.061)w_{32} + (0.577, 0.764, 0.951)w_{42} \\ + (-0.974, 0.487, 0.0)w_{43} + (-0.383, -0.117, 0.148)w_{51} + \sigma_{A1}^- - \sigma_{A1}^+ - \sigma_{A2}^- + \sigma_{A2}^+$$

Similarly the differences between other pairs can be computed.

A1 > A2 > A3 > A4, is the preference order set by the DM. In order to insure that the difference is large enough to clearly express the preference, this difference must be greater than the threshold (i.e.,  $\delta > 0$ ). In this study, a fuzzified value of (0.05, 0.05, 0.05) was assumed for  $\delta$ . Therefore, the following inequalities can be established:

$$\Delta U(A1A2) \geq \delta, \quad \Delta U(A2A3) \geq \delta, \quad \Delta U(A3A4) \geq \delta.$$

Step 4: The equations developed in Step 2 and 3 are used in this step to formulate the fuzzy LP problem using Eq. [11] of the main text. The objective function  $\tilde{F}$  of the fuzzy LP problem needs to be minimized (subject to the given constraints) in Eq. [11]. The

additional constraint  $(\sum_{i=1}^5 \sum_{j=1}^3 w_{ij} = 1)$  has been used to satisfy the condition that the

total sum of all the upper bounds of the utility functions coefficients should be equal to a unity. The tableau form of this LP problem is presented in Table 6; the objective function can be seen in the last row. The cells with (0, 0, 0) values are shown as the empty cells. The errors  $\sigma_s$  contain the crisp values as 1 or -1. Similar is the case with the threshold  $\delta$  with a crisp value of 0.05.

Equation [11] was solved by using Kumar et al. (2011b) method, in which they transformed the fuzzy LP problem into the crisp form. The crisp form of LP problem was further solved using the conventional SIMPLEX method (Dantzig 1963). The

Table 6 Tableau form of fuzzy linear programming problem in Step 4

$W_{11}$	$W_{12}$	$W_{21}$	$W_{22}$	$W_{31}$	$W_{32}$	$W_{41}$	$W_{42}$
	$(-0.04, 0.07, 0.17)$	$(-0.34, -0.20, -0.07)$		$(0.68, 0.84, 1.00)$	$(-0.59, -0.33, -0.06)$		$(0.58, 0.76, 0.95)$
$(0.70, 0.85, 1.0)$	$(-0.17, -0.11, -0.05)$	$(-0.73, -0.69, -0.66)$	$(0.0, 0.005, 0.01)$	$(-0.27, 0.02, 0.31)$		$(0.66, 0.8, 0.93)$	$(-0.95, -0.76, -0.58)$
$(-1.0, -0.85, -0.70)$	$(0.42, 0.53, 0.65)$		$(0.04, 0.06, 0.07)$	$(-0.98, -0.85, -0.73)$	$(0.0, 0.19, 0.39)$	$(-0.23, 0.05, 0.34)$	
$(1, 1, 1)$	$(1, 1, 1)$	$(1, 1, 1)$	$(1, 1, 1)$	$(1, 1, 1)$	$(1, 1, 1)$	$(1, 1, 1)$	$(1, 1, 1)$

$W_{43}$	$W_{51}$	$W_{52}$	$\sigma_{A1}^+$	$\sigma_{A1}$	$\sigma_{A2}^+$	$\sigma_{A2}$	$\sigma_{A3}^+$	$\sigma_{A3}$	$\sigma_{A4}^+$	$\sigma_{A4}$	$\delta$
$(-0.97, -0.49, 0.0)$	$(-0.38, -0.12, 0.15)$		-1	1	1	-1				$\Delta$	0.05
	$(-1.0, -0.78, -0.62)$	$(0.0, 0.36, 0.71)$			-1	1	1	-1		$\Delta$	0.05
	$(0.79, 0.89, 0.99)$	$(-0.71, -0.36, 0.0)$				-1	-1	1	1	$\Delta$	0.05
$(1, 1, 1)$	$(1, 1, 1)$	$(1, 1, 1)$	1	1	1	1	1	1	1	=	$(1, 1, 1)$
											Min

**Table 7** Tableau form of post-optimal fuzzy linear programming problem in Step 5

$w_{11}$	$w_{12}$	$w_{21}$	$w_{22}$	$w_{31}$	$w_{32}$	$w_{41}$	$w_{42}$	$w_{43}$
$(0.70, 0.85, 1.0)$	$(-0.04, 0.07, 0.17)$	$(-0.34, -0.20, -0.07)$	$(0.0, 0.005, 0.01)$	$(0.68, 0.84, 1.00)$	$(-0.59, -0.33, -0.06)$	$(0.66, 0.8, 0.93)$	$(0.58, 0.76, 0.95)$	$(-0.97, -0.49, 0.0)$
$(-1.0, -0.85, -0.70)$	$(-0.17, -0.11, -0.05)$	$(-0.73, -0.69, -0.66)$	$(0.04, 0.06, 0.07)$	$(-0.27, 0.02, 0.31)$	$(0.0, 0.19, 0.39)$	$(-0.23, 0.05, 0.34)$	$(-0.95, -0.76, -0.58)$	
$(1, 1, 1)$	$(1, 1, 1)$	$(1, 1, 1)$	$(1, 1, 1)$	$(1, 1, 1)$	$(1, 1, 1)$	$(1, 1, 1)$	$(1, 1, 1)$	$(1, 1, 1)$
1	1	1	1	1	1	1	1	1

$w_{51}$	$w_{52}$	$\sigma_{A1}^+$	$\sigma_{A1}^-$	$\sigma_{A2}^+$	$\sigma_{A2}^-$	$\sigma_{A3}^+$	$\sigma_{A3}^-$	$\sigma_{A4}^+$	$\sigma_{A4}^-$	$\delta$
$(-0.38, -0.12, 0.15)$		-1	1	1	-1	1	1	1	1	$\Delta$
$(-1.0, -0.78, -0.62)$	$(0.0, 0.36, 0.71)$		-1	-1	1	1	-1	1	-1	$\Delta$
$(0.79, 0.89, 0.99)$	$(-0.71, -0.36, 0.0)$					-1	1	1	-1	$\Delta$
$(1, 1, 1)$	$(1, 1, 1)$									$=$
1	1									Max
										Max
										Max
										Max
										Max



following optimal solution was achieved by solving the LP problem with the help of *LINGO* program, with the fuzzy optimal value  $F^*=(0.0, 0.0, 0.0)$ :

$$w_{12} = (0.2447, 0.2447, 0.2447), w_{22} = (0.3651, 0.3651, 0.3651), \\ w_{41} = (0.2864, 0.2864, 0.2864), w_{42} = (0.1036, 0.1036, 0.1036),$$

Step 5: After finding the optimal solution of fuzzy LP problem for WQM for the Ravi River, the post-optimization has been carried out for stability check. In this regard, a new LP problem presented in Table 7 was formulated with the purpose to maximize the sum of the weight under each criterion. Simultaneously, the sum of all the error functions should be less than a value slightly higher than the previously estimate optimal value in step 4 (i.e.,  $F^* + \varepsilon$ ). Let,  $\tilde{\varepsilon} = (0.01, 0.01, 0.0)$ . The following LP problem was then solved:

$$\left\{ \begin{array}{l} [\max] \tilde{u}_i [g_i^*] = \sum_{k=1}^3 w_{ik}, \forall i = 1, 2, 3, 4, 5 \\ \text{subject to} \\ \Delta U(A1A2) \geq 0.05, \\ \Delta U(A2A3) \geq 0.05, \\ \Delta U(A3A4) \geq 0.05, \\ \sum_{i=1}^5 \sum_{j=1}^3 w_{ij} = 1, \\ \sum_{k=1}^4 \tilde{\sigma}_{Ak}^+ + \tilde{\sigma}_{Ak}^- < F^* + \tilde{\varepsilon}, \tilde{\varepsilon} > 0, \\ w_{ij} \geq 0, \tilde{\sigma}_{Ak}^+ \geq 0, \tilde{\sigma}_{Ak}^- \geq 0 \end{array} \right.$$

The post optimal analysis achieved the following results:

$$w_{12} = (0.2447, 0.2447, 0.2447), w_{22} = (0.3651, 0.3651, 0.3651), \\ w_{41} = (0.2864, 0.2864, 0.2864), w_{42} = (0.1036, 0.1036, 0.1036),$$

The final results are shown in Table 3 of main text.

## References

- Azad MAS, Ancev T, Hernández-Sancho F (2015) Efficient water use for sustainable irrigation industry. *Water Resour Manag* 29:1683–1696
- Balfours (1987) Report on Lahore Wastewater Treatment Project, Lahore, Balfours Consulting Engineers, Pakistan
- Carlos AG, Kalliola R, Kirkkala T, Lepistö A (2015) Multiscale landscape pattern affecting on stream water quality in agricultural watershed, SW Finland. *Water Resour Manag* 29:1669–1682
- Chapra SC (1997) Surface water quality modeling. McGraw Hill International, Civil Engineering Series, Singapore
- Dantzig GB (1963) Linear programming and extensions. Princeton University Press, Princeton

- Deepa K, Krishnaveni M (2012) Suitable site selection of decentralised treatment plants using multicriteria approach GIS. *J Geogr Inf Syst* 4:254–260
- FDEP (2005) Lower St. Johns Basin Lakes, Rivers, Streams, and Aquifers, Florida Department of Environmental Protection. Division of Water Resource Management, Bureau of Watershed Management, Watershed Monitoring Section, Tallahassee, Florida, USA
- Ghaffar EA, Ei Saddi A (2007) Wastewater natural treatment using multi-criteria decision analysis technique. Eleventh International Water Technology Conference, IWTC11 2007 Sharm El-Sheikh, Egypt
- Haider H (2010) Water quality management model for Ravi River. PhD Thesis, University of Engineering and Technology Lahore, Pakistan
- Haider H, Ali W (2010a) Effect of wastewater treatment on bio-kinetics of dissolved oxygen in River Ravi. *Pak Jour Engg App Sci* 6:42–51
- Haider H, Ali W (2010b) Development of dissolved oxygen model for a highly variable flow river: case study of Ravi River in Pakistan. *Environ Model Assess* 15(6):583–599
- Haider H, Ali W (2013a) Calibration and verification of a dissolved oxygen management model for a highly polluted river with extreme flow variations in Pakistan. *Environ Monit Assess* 185(5):4231–4244
- Haider H, Ali W (2013b) Evaluation of water quality management alternatives to control dissolved oxygen and un-ionized ammonia for Ravi River in Pakistan. *Environ Model Assess* 18(4):451–469
- Hayder S, Haider H, Nadeem O, Hussain G, Zahra S (2015) Proposed model for wastewater treatment in Lahore using constructed wetlands. *J Fac Eng Tech* 22(1):07–17
- Ilangkumaran M et al (2013) Optimization of wastewater treatment technology selection using hybrid MCDM. *Man Env Qual: An Int J* 24(5):619–641
- Jacquet-Lagréze E, Siskos Y (1982) Assessing a set of additive utility functions for multicriteria decision making: the UTA method. *Eur J Oper Res* 10(2):151–164
- JICA (2010) Preparatory study on Lahore water supply, sewerage, and drainage improvement Project in Islamic Republic of Pakistan. Japan International Cooperation Agency
- Karimi AR, Mehrdadi N, Hashemian SJ, Bidhendi GRN, Moghaddam RT (2011) Selection of wastewater treatment process based on the analytical hierarchy process and fuzzy analytical hierarchy process methods. *Int J Environ Sci Technol* 8(2):267–280
- Kaufmann A, Gupta MM (1985) Introduction to fuzzy arithmetic theory and applications. Van Nostrand Reinhold, New York
- Kim Y, Chung E, Jun S (2015) Iterative framework for robust reclaimed wastewater allocation in a changing environment using multi-criteria decision making. *Water Resour Manag* 29:1169–1191
- Kumar A, Kaur J, Singh P (2011a) A new method for solving fully fuzzy linear programming problems. *Appl Math Model* 35:817–823
- Kumar A, Singh P, Kaur P, Kaur A (2011b) A new approach for ranking of L-R type generalized fuzzy numbers. *Expert Sys Appl* 38:10906–10910
- Mansouri Z, Moghaddas NH, Dahrazma B, Geope J (2013) Wastewater treatment plant site selection using AHP and GIS: a case study in Falavarjan. *Geopersia* 3(2):63–72
- Mara D (2004) Domestic wastewater treatment in developing countries. Earthscan Publications, London
- Meerholz A, Brent AC (2012) Assessing the sustainability of wastewater treatment technologies in the petrochemical industry. IEEE International Technology Management Conference, Dallas, TX USA, June 25–27, 2012
- Moriasi DN, Wilson BN, Douglas-Mankin KR, Arnold JG, Gowda PH (2012) Hydrologic and water quality models: use, calibration, and validation. *Am Soc Agric Biol Eng* 55(4):1241–1247
- Musharrafie A, Güereca PL, Padilla A, Morgan JM, Noyola A (2011) Comparison of two wastewater treatment plants: stabilization ponds and activated sludge with a social perspective impacts. Instituto de Ingeniería. Universidad Nacional Autónoma de México, México
- Nakhaei M, Taheriyoum M (2012) Evaluation of wastewater treatment technologies applying fuzzy analytic hierarchy process and gray relational analysis. International Conference on Chemical, Civil and Environment engineering (ICCEE'2012) March 24–25, 2012 Dubai
- Patiniotakis I, Apostolou D, Mentzas G (2011) Fuzzy UTASTAR: a method for discovering utility functions from fuzzy data. *Expert Sys Appl* 38(2011):15463–15474
- Shahmoradi B, Isalou AA (2013) Site selection for wastewater treatment plant using integrated fuzzy logic and multicriteria decision model: a case study in Kahak, Iran. *J Adv Environ Health Res* 1(1):51–61
- Siskos Y, Grigoroudis E (2010) New trends in aggregation-disaggregation approaches. In C. Zopounidis & P. M. Pardalos (Eds.), *Handbook of Multicriteria Analysis. Applied optimization Heidelberg*: Springer-Verlag. Part 2. Berlin 103:189–214
- Siskos Y, Grigoroudis E, Matsatsinis NF (2005) Chapter 8-UTA, Methods-multiple criteria decision analysis: State of the art surveys. *Int Ser Oper Res Manag Sci* 78:297–334

- Siskos Y, Yannacopoulos D (1985) UTASTAR: An ordinal regression method for building additive value functions. *Investig Operac* 5(1):39–53
- Stillwell WG, Seaver DA, Edwards W (1981) A comparison of weight approximation techniques in multiattribute utility decision making. *Organ Behav Hum Perform* 28:62–77
- Thomann VR, Mueller AJ (1987) *Principals of surface water quality modeling*. Harper International Edition. Harper & Row, New York
- Yilmaz B, Harmancioglu NB (2010) Multi-criteria decision making for water resource management: a case study of the Gediz River Basin, Turkey. *Water SA* 36(5):563–576
- Zadeh LA (1975) The concept of a linguistic variable and its application to approximate reasoning. Part I, II, and Part III. *Inform Scien* 8(3):199–249, 8(4):301–357, 9(1):43–58