Volume 4 Number 1 March 2014
ISSN 2043-9083
Journal of
Water, Sanitation and
Hygiene for
Development
IWA

  Journal of Water, Sanitation and Hygiene for Development | 07.2 | 2017

Review Paper

Decision sciences in the management of water resources: multi-criteria methods and game theory applied to the field of sanitation

Alexandre Bevilacqua Leoneti and Eduardo Cleto Pires

ABSTRACT

Due to the complexity of some managerial problems, especially those related to sanitation, academic studies have shown the need to use appropriate methods to assist in this type of decision. Within this context, this research aimed to provide a review of the literature from the field of decision sciences to the field of water resource management. It was identified in this study that the use of multi-criteria methods, including Analytical Hierarchy Process, Measuring Attractiveness by a Categorical based Evaluation Technique, Multiattribute Utility Theory, *Elimination et Choice Traduisant la Realité*, Preference Ranking Organization Method for Enrichment Evaluations, Technique for Order Preference by Similarity to Ideal Solution, and game theory, including cooperative and non-cooperative bargaining games, are useful for creation and comparison of scenarios, reducing the time needed to reach a solution for complex problems involving a large number of criteria and agents. It also demonstrated the benefits of creating greater transparency in the decision-making process, thus increasing the potential for a solution acceptable to all the parties involved. Although still little explored, discussions of sanitation problems can and should be enhanced with the use of techniques and methods of decision sciences, and multi-criteria and game theory techniques are particularly suitable for this task.

Key words | decision sciences, game theory, multi-criteria methods, sanitation, water management

Alexandre Bevilacqua Leoneti
(corresponding author)
Research Group in Decision Sciences, School of Economics, Business Administration and Accounting,
University of São Paulo,
Ribeirão Preto,
Brazil
E-mail: *ableoneti@usp.br*

Eduardo Cleto Pires
School of Engineering,
University of São Paulo,
São Carlos,
Brazil

INTRODUCTION

Due to the integration of different and conflicting aspects in solving complex problems, especially those related to sanitation, academic studies have shown the need to use appropriate methods to assist in this type of decision. Methods for this purpose were originally developed from techniques involving optimization with the help of traditional methods such as linear programming, dynamic programming, stochastic programming, and simulation techniques, most often prioritizing cost and efficiency aspects (Linkov *et al.* 2006).

According to Souza (1998), one of the first studies on techniques for the analysis of wastewater treatment systems was developed by Lynn *et al.* (1962), who used linear programming techniques and matrix algebra to propose a model for the project creation of wastewater treatment plants – WWTPs. Fraas (1984) also addressed this problem by proposing regression equations based on parameters provided by the Environmental Protection Agency in the United States, to find an adequate level of efficiency at the lowest possible cost. In turn, Vanrolleghem *et al.* (1999) and Gillot *et al.* (1999) developed simulation procedures to assist in the design of wastewater treatment plants, incorporating into the process some functions of installation and operation costs, using the results of this simulation as input to an operating cost model.

These studies mostly show economic or technical aspects that must be considered when undertaking a study

doi: 10.2166/washdev.2017.171

involving wastewater treatment systems. Among other factors, the preference given to the use of technical and economic criteria is largely due to: (i) non-divisibility of resources (e.g. river); (ii) non exclusiveness of resources (e.g. fishing in the river); (iii) intangibility of resources (e.g. contributions of wetlands to climate stabilization); and (iv) difficulty of identifying property rights (e.g. property rights of a coastal ecosystem) (Xenarios & Bithas 2007).

However, the use of just technical and economic criteria could lead the decision maker to a choice that is not the most adequate for a given environment, masking other possible arrangements that are as or more suitable when taking into consideration sustainable aspects, such as: (i) health and hygiene criteria; (ii) social-cultural criteria; and (iii) environmental criteria (Hellström *et al.* 2000).

In this sense, the models to support decision making that are based only on economic and/or technical criteria should evolve to models using more criteria and procedures appropriate to their resolution (Chen *et al.* 2008). According to Butlera & Schütze (2005), this type of modeling allows the construction of various scenarios and their impacts on the environment to be studied without having to change the system in real scale. In addition, as emphasized by Huesemann (2001, p. 283), 'in many cases, environmental science and technology appear to be successful only because attention is focused narrowly (in space and time) on specific objectives while wider, long-term impacts are ignored'. Thus, one would expect that the question of evaluation of different aspects of the problem would receive greater attention, which is only possible within a multi-criteria approach (Hajkowicz & Collins 2007; Hajkowicz & Higgins 2008).

In this scenario Huesemann (2001, p. 284) complements by saying that 'the inclusion of many different stakeholders in policy decisions might finally lead to the recognition of the enormous importance of non-technical issues and to the discovery that changes in personal and social behavior may provide the only possible solutions to many complex environmental problems.' However, when more than one individual is part of the decision-making process, the multi-criteria approach will unavoidably also require the resolution of conflicts that arise because of the different requirements for each criterion in the group. For example, for a wastewater treatment plant (WWTP) choice, some agents may prefer to meet economic criteria whereas others prefer to meet environmental criteria. That is, within a micro economic context, there is a latent conflict between treatment efficiency and cost (Fraas 1984). In this other approach, group decision making can be aided by game theory to propose a compromise solution, especially for cases where collaboration between agents is not possible or expected (Binmore 2007). Thus, the application of game theory has also been proposed to achieve greater approximation of decision-making models and the complex reality that involves sanitation problems, especially in multi-criteria scenarios with different agents acting to meet their preferences (Madani 2010).

Within this context, this research aims to present a review of the literature from the area of decision sciences to the area of water resource management. The research contributes to the literature bringing together outranking multi-criteria and game theory methods for aiding the choice of sustainable alternatives in management of water resources. Seeking to clarify the decision-making process, the intertwining of various criteria, being treated under different approaches and by different agents, may contribute to the improvement of decisions, especially those related to the sanitation sector, thus improving population quality of life.

OVERVIEW OF MULTI-CRITERIA METHODS AND GAME THEORY

Multi-criteria methods

The overall objective of the multi-criteria decision is to prioritize all decision alternatives with respect to their performance based on the criteria. Therefore, the multi-criteria decision is characterized as a situation in which a decision maker must prioritize or select, classify, or rank one or more alternatives from a finite set of possible solutions, depending on how they meet the criteria, which are generally conflicting (Wallenius *et al.* 2008).

According to Baker *et al.* (2001), the modeling of multi-criteria problems can be described in eight steps: (i) definition of the problem; (ii) determination of the minimum requirements that the solution must meet; (iii) establishing the objectives that the solution must achieve; (iv) identification of alternatives that could solve the problem; (v) defining the criteria based on objectives; (vi) selecting a method to aid in decision making; (vii) applying the method to select the most appropriate alternative; and (viii) evaluation of alternative proposals.

Several methods have been proposed to assist different problematic (ranking, selecting, or classifying alternatives) in the decision-making process. The most widely used methods are: (i) Analytical Hierarchy Process (AHP), by Saaty (1980); (ii) *Elimination et Choice Traduisant la Realité* (ELECTRE), by Roy (1968); (iii) Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE), by Brans & Vincke (1985); (iv) Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), by Hwang & Yoon (1981); (v) Measuring Attractiveness by a Categorical Based Evaluation TecHnique (MACBETH), by Bana e Costa & Vansnick (1994); and (vi) Multiattribute Utility Theory (MAUT), by Keeney & Raiffa (1976), which takes into account the decision maker's preferences in the form of the utility function that is defined by a set of attributes. These methods are divided into compensatory and non-compensatory methods, the compensatory methods being the ones in which the criteria are aggregated in a manner that make it possible that a criterion with low performance can be compensated by a criterion with high performance, as is the case of sum average weighting method.

The AHP method is a compensatory multi-criteria method to support decision making developed by Thomas L. Saaty in the 1970s, which allows the modeling of unstructured problems in various areas of knowledge. Basically, this method is used to rank 'n' alternative in accordance with 'm' objectives (AHP can also be used for ranking criteria, this procedure being useful for eliciting the preferences of decision makers for further multi-criteria applications). For this purpose a numerical scale from 1 to 9 is used, where 1 is assumed when considering that the elements also influence the highest level equally, and 9 is assumed when considered that the first element influences the highest level absolutely more than the second element. From the allocation of intensities through pairwise comparisons, which is accomplished through interviews with decision makers using a judgment collection questionnaire, the next step is to create a matrix that will receive the data that were collected in these interviews. Having created the matrix, its vector of priorities is calculated. Mathematically, the principal auto-vector of the matrix, when normalized, becomes the vector of priorities. The same process is performed level by level between all the elements belonging to each level. Using all calculated priority vectors it is possible to create the matrix called 'matrix of priorities', which will be multiplied on the right by the matrix of the priority vector created at the highest level, or 'first-level matrix'. The result of this algebraic operation is a global priority vector, i.e. representing preferences of an individual as to the choice of alternatives from the defined criteria (Saaty 1980). Finally, AHP uses an index for testing the consistency of the judgments. For performing these calculations, AHP has a very well developed software package known as the Expert Choice.

MACBETH is also a technique based on pairwise comparison and has a software package for performing its calculations, which is M-MACBETH software. MACBETH is a constructivist approach to decision support because the interactivity with decision maker is one of its key advantages. According to Bana e Costa & Vansnick (1997), the procedure starts by questioning a decision maker about his/her attractiveness between any two alternatives *a* and *b* of a set of alternatives A. If for the decision maker *a* is more attractive than *b*, the decision maker should define a verbal absolute judgment about the difference of attractiveness between *a* and *b* by choosing one of six semantic categories ranging from weak attractiveness to extreme attractiveness. An index for testing the consistency of the judgments is used to review the judgments made until the semantic consistency condition is satisfied. If there is cardinal consistency, the algorithm proposed in MACBETH gives a real number for each alternative, which are then plotted in a graphic form for evaluation and concordance of the decision maker.

The ELECTRE is a family of non-compensatory methods also capable of handling different criteria, both quantitative and qualitative, and provides ranking, selection or classification of alternatives. In this type of method, the preferred alternatives are those that have a better performance for most of the criteria, and do not cause an unacceptable level of discordance to any of them, a characteristic of methods known as outranking methods (Roy 1968). The ELECTRE procedures provide for the establishment of a level of agreement, disagreement and indifference to be used in the establishment of relations between the alternatives. These indices are defined by the decision maker and vary in the range between zero and one, setting the limits for each relationship. The family of ELECTRE methods is divided into ELECTRE I, ELECTRE IS and ELECTRE IV for problems of choice (selecting), ELECTRE II, ELECTRE III and ELECTRE IV, for problems of ranking, and ELECTRE TRI for problems of classification (Figueira *et al.* 2005).

The PROMETHEE is a family of non-compensatory method that uses pairwise comparison functions in order to rank alternatives considering multiple criteria (Brans & Vincke 1985). There are basically two methods of this family, namely: PROMETHEE I, which generates a partial rank from the relationships of dominance and subdominances, which are considered from the preferences and values; and PROMETHEE II, which generates a ranking by combining both relations identified by the above method. Both methods also utilize a preference function, which is a function of the difference between two alternatives to any criteria. The other methods that belong to the family of PROMETHEE methods are PROMETHEE III, PROMETHEE IV and PROMETHEE V, for ranking alternatives, PROMETHEE VI for the human brain representation, PROMETHEE GDSS for group decision making, and the PROMETHEE TRI for dealing with classification and PROMETHEE CLUSTER for nominal classification (Behzadian *et al.* 2010).

Finally, one should note the TOPSIS and MAUT compensatory methods. TOPSIS was developed on the concept that the best alternative should be closest to the ideal alternative and have the greatest distance from the negative solution in a geometrical sense. Thus, the order of preference of the alternatives is produced by comparing the Euclidean distances (Hwang & Yoon 1981). MAUT takes into account the preference of the decision maker in the form of a utility function which is defined over a set of attributes. The utility value can be determined by utility functions followed by verification of the preferences (Keeney & Raiffa 1976).

Game theory

Widely known in various fields of science, game theory is a mathematical theory that deals with the general characteristics of competitive situations, placing particular emphasis on group decision-making processes (Luce & Raiffa 1957). The main advantages of the application of game theory are that it enables theoretical understanding of the interaction between players, and helps strategic thinking, exploring the possibilities of interaction between agents, especially in the case that the decision cannot be made in a cooperative environment. Thus, the application of the games approach allows expanding the players' view of the problem and finding new possibilities for resolution of the same, which would hardly be realized without the aid of this theory (Osborne & Rubinstein 1994).

According to Fiani (2006), to be classified as a game, the strategic interaction situation must have four characteristics: (i) allow interactions; (ii) involve more than one agent; (iii) promote rationality; and (iv) prioritize strategic behavior. In this way, any game is also a model, which should contain elements on the situation of strategic interaction between the players, especially whether or not they know the decisions of other agents. In this context, the player may be considered as any individual or organization involved in the process of strategic interaction, which has authority to make decisions.

Briefly, a game must have a finite number of players trying to achieve the best possible outcome, given their preferences. For this, players interact with an action, move, or choice at a given moment of the game, which means that each player will have their set of actions. All of these actions for a player i can be represented by the set: $A_i = \{a_j\}$. It must also be verified whether the players have made a decision at the same time or successively, in which case it should be verified whether they know the previous decisions. If the players decide at the same time, the game is known as a simultaneous game. Simultaneous games are those in which each player ignores the decisions of others when they make their own decision (Fiani 2006). The strategic form in a table format provides all possible combinations of players' actions and their results for a simultaneous game.

Where decisions occur in succession, the game is known as a sequential game. Sequential games are those in which players decide based on what the other players have decided in the past, that is, when decisions are made knowing the decisions of the other players, regardless of chronological order. In this game the players perform their moves in a predetermined order (Fiani 2006). The extended form, in the form of a game tree, provides all possible scenarios of the sequential game and its results.

In both cases it is necessary to determine the payoff of the players. Payoff is determined by a utility function which is a way of assigning numbers to describe preferences (Luce & Howard 1957). Thus, this utility function denotes the payoff that player i receives when player 1 adopts strategy s_1, player 2 adopts strategy s_2, and so on, including the fact that player i adopts the strategy s_i. The utility function is given by $U_i = (s_1,\ldots,s_i,\ldots,s_n)$ and must meet the inequality,

$$f(x) \geq f(y) \text{ whenever } U(x) \succsim U(y) \tag{1}$$

where $\succsim$ represents the preference of x over y.

Finally, when players cannot establish secured compromises it is said that the game is non-cooperative, otherwise it is said that it is cooperative. Therefore, the possibility of establishing guaranteed compromises is what will determine whether the game is cooperative or not (Binmore 2007). Games where the payoff of the players are inversely related, i.e. a player's gain necessarily involves the loss to another and this constitutes the so-called 'strictly competitive games' or 'zero sum game'.

Whatever the type of game, players will work with their strategies and sets of information. According to the principles identified by Neumann & Morgenstern (1944), if the individuals involved in a situation of interaction act rationally, they seek to identify alternatives that meet not only their criteria, but also to meet, at least minimally, the criteria of other individuals, being the solution an equilibrium for the game. In this sense, the strategy is an action plan that specifies the number of strategies of players at all times when searching for equilibrium solutions. The set of strategies, or space of strategies, is the set of strategies that each player has. The set of strategies is given by: $S_{ji} = \{s_{ji}\}$, and from this set, the game is analyzed by possible combinations of strategies (Fiani 2006). Each combination of strategies is given by $S = (s_1,\ldots,s_n)$, where s_1 is the strategy of player 1, s_2 of player 2 up to player 'n'.

Also, it should be considered that there are two types of situations: games with perfect information and games with imperfect information. A perfect information game is if all players know the entire history of the game before making their choices. If any player at some point in the game has to make choices without knowing the exact history of the game up to that point, the game is said to be an imperfect information game (Osborne & Rubinstein 1994).

APPLICATIONS IN SANITATION

Using qualitative variables, considering weightings for different criteria and evaluating different scenarios: the methods from the multi-criteria approach

Examples of applications using multi-criteria methods to support the decision in sanitation can be found in the literature, especially after the 1980s. For example, Duckstein *et al.* (1982), who evaluated the impact of alternative treatment plants in the Santa Cruz river basin in the United States, compare the use of ELECTRE I and ELECTRE II, compromising programming and MAUT methods. The authors used the methods for evaluating a decision matrix containing 25 alternative measures by means of 13 criteria, of which only five were quantitative. The authors provided an interesting approach for comparing multi-criteria decision making (MCDM) methods, since there are significant differences between them. The authors classified these differences into six classes, namely: (i) type of data required; (ii) nature of alternative (discrete or continuous); (iii) consistency of results; (iv) robustness of results; (v) ease of computation; and (vi) amount of interaction required between the decision maker and systems analyst. The authors concluded that: (i) ELECTRE can be used with qualitative variables, while the other methods cannot; (ii) ELECTRE cannot deal with continuous alternatives (i.e. an infinite number of reservoir systems corresponding to continuously varied reservoir sizes), while the other methods can; (iii) ELECTRE presented a minor difference in the results compared to the other methods which is due to the fact that there is a threshold value for discordance to be either satisfied or not, while with the other methods all discordances are included in the analysis; (iv) all the methodologies considered are fairly robust with respect to changes in parameter values; (v) MAUT requires the most time for learning by the analysts and for application, but analyzing its results is rather straightforward, while ELECTRE is tiresome; and finally (vi) MAUT requires an extensive amount of interaction between the decision maker and the analyst that may be impractical for certain real world cases. The authors concluded that ELECTRE I could be used to reduce the number of alternatives under consideration and ELECTRE II could be used to rank the rest of them, although they find out the compromising method the most appropriate for this case. However, it is interesting to note that from the criteria considered, eight used a subjective scale with five levels (e.g. a social criterion such as 'Creation of new opportunities' and an environmental criterion such as 'Effect of wildlife and vegetation'), which would require a method that accepts qualitative variables, which is the case in the ELECTREs methods.

In turn, Karagiannidis & Moussiopoulos (1997) used the ELECTRE III multi-criteria method to evaluate five proposals of integrated systems of urban solid waste management, to assist in planning in the Athens area of Greece. According to the authors, the ELECTRE III multi-criteria method was chosen to carry out the application because the method involves some aspects that are often overlooked by other methods, such as the preference and veto of the decision makers. Precisely, the authors criticize ELECTRE I and II methods because of the lack of possibility to set thresholds values for these preferences and indifferences, which generated unsatisfactory previous applications in solid waste management problems (Karagiannidis & Moussiopoulos 1997). The evaluation of five alternatives for integrated management of municipal solid wastes was based on 24 criteria, some of them (e.g. a social criterion such as 'Development in other sectors') were measured by an ordinal scale used according to qualitative considerations of experts. The final ranking was achieved using both ascending and descending distillation methodology, although the authors stressed that this solution cannot be seen as the 'optimum' solution, because of the process of weighting criteria. Instead, the authors state that conflicts might occur because of the divergences in the weighting given to the criteria by individuals or groups involved. Therefore, the authors suggest that different scenarios should be assessed (Karagiannidis & Moussiopoulos 1997).

The advantages of using ELECTRE methods are, therefore, the use of qualitative variables (ordinal or cardinal scales) and the ease of implementation. Qualitative variables are especially important for expanding the traditional technical-economic criteria evaluation, which is usually based on quantitative variables that are easily obtained, e.g. cost of implementation or efficiency of waste removal. These variables can be included into analysis using expert opinions in the form of Likert scales (ordinal scale), which can be calculated using ELECTRE methods. Another advantage is the ease of implementation, which allows the evaluation of several scenarios, although interpretation of the final result is not straightforward due to its distillation process. The main disadvantage in terms of application is that although threshold values being a feature that theoretically distinguishes this method from others, this brings more steps to the process. These further steps might be minimized when defined as being equal to zero the veto, indifference and preference thresholds, making the set of criteria all true criteria (Leoneti 2016a). Finally, it is important to stress that the use of a non-compensatory method would not allow a better technical-economic performance of an alternative to overcome its worse social and environmental performance and vice versa.

Kalbar *et al.* (2012), in choosing a wastewater treatment plant, proposed to use the TOPSIS method as the multi-criteria decision-making technique to assist in the decision of the most appropriate technology for a given installation site. The criteria used were: (i) global warming potential (kg CO_2-Eq/p.e.-year); (ii) eutrophication potential (kg PO_4-Eq/p.e.-year); (iii) life cycle costs net present worth (Rs. Lakh/MLD); (iv) land requirement (m^2/MLD); (v) manpower requirement for operation (number for operation of medium scale plant); (vi) robustness of the system (reliability, durability and flexibility); and (vii) sustainability (acceptability, participation, replicability and promotion of sustainable behavior). The latter criteria (robustness of the system and sustainability) were measured using a cardinal scale of 0–100 (0 being the worst score and 100 the best score), with scores given by the authors based on their experience with these technologies in India. The former criteria were obtained from a primary data source collected from field-scale municipal WWTPs in India. Given that the 'TOPSIS algorithm can easily be implemented computationally and can be made available as a decision support tool for the end users' (Kalbar *et al.* 2012, p. 160), the authors proposed a scenario-based decision-making procedure, being the scenarios made by each set of criteria's weightings for a given decision-making situation, addressing the technology options for wastewater treatment in India. The authors stressed that TOPSIS effectively identifies the WWTP alternative best suited to scenarios proposed (Kalbar *et al.* 2012).

The advantages of TOPSIS are the use of qualitative variables (cardinal scale), the ease of implementation and the low complexity for calculations. It should be mentioned also that the mathematical basis of TOPSIS (the Euclidian distance) is one of the most outstanding mathematical concepts (see the calculation of the hypotenuse in a triangle rectangle), what makes its interpretation easy. However, it should be noted also that precisely due to the distance-based calculation, the use of ordinal variables such as Likert scales would not be recommended. For instance, the paper of Kalbar *et al.* (2012) used qualitative variables (robustness and sustainability) such as cardinal variables, even those being collected from experts' opinions. A notorious disadvantage is that this method is highly sensitive to ranking reversal problems (Leoneti 2016a).

Simon *et al.* (2004) show the evaluation of water management strategies in the German cities of Berlin and Potsdam, using the PROMETHEE II method for obtaining the ranking of more favorable alternatives for water management. The authors state that water management represents an area of conflict between economic, ecological and social issues, and that the trade-off between these three issues is necessary to support sustainable development. Nine different scenarios were evaluated for 14 sections of a river, being evaluated by four criteria which were: (i) reduction of the discharge in a river section; (ii) difference of phosphorus from target concentration; (iii) concentration of total nitrogen; and (iv) short-term pollution. The AHP for eliciting the weights preferences was used. Although in this specific application PROMETHEE II did not perform well, PROMETHEE II is the most used method among the family of PROMETHEE methods (Behzadian *et al.* 2010).

The advantage of using PROMETHEE methods is the possibility of using different preference functions for modeling each criterion of the decision problem. PROMETHEE also makes possible the use of qualitative variables, including ordinal and cardinal variables, as in the case of ELECTRE methods. However, as with the ELECTRE cases, for some of the preference functions the definition of a preference and indifference threshold is necessary, which requires additional effort of the decision maker. The same advantage of being a non-compensatory method makes its advantages similar to ELECTRE methods.

Bottero *et al.* (2011) applied AHP and its variant analytic network process to evaluate different sewage treatment plants to the problem of waste water in the alpine environment. The alternatives considered were: composting, anaerobic digestion, and phytoremediation, which were evaluated based on 24 criteria, some of them being social criteria, such as 'public opinion' and others environmental criteria (e.g. 'use of natural resources') among the traditional technical-economic criteria. Some of the non-technical-economic criteria were evaluated on a binary scale, e.g. 'yes' or 'no'. Bottero *et al.* (2011) concluded that AHP is suitable for dealing with complex decision-making problems because they allow the analysis of several criteria that may be considered and compared systemically. In this sense, the authors claim that the more complex the problem, the more necessary is an analysis of the decision problem with sophisticated decision methods (Bottero *et al.* 2011).

The advantage of AHP, as with the other MCDM methods, is the possibility to consider quantitative and qualitative variables into the evaluation of decision problems. In the case of AHP, these variables can be on a binomial, ordinal or cardinal scale, which is its greatest advantage over other methods. It should be noted that its mathematical structure is very robust, since it uses linear algebra for calculation of the final ranking. As a consequence, AHP is the currently most applied MCDM method in all areas of knowledge. However, the possibility of using every kind of variable is at the same time AHP's notorious disadvantage, because the AHP method derives relative priority scales from the original variables into a process of $(c.(c-1)/2)+(c.n.(n-1)/2)$ pairwise comparisons, n and c being the number of alternative and criteria respectively, that should be performed by the decision maker (Harker 1987). Herva & Roca (2013, p. 360) also state that 'the main drawbacks of the AHP method are potential internal inconsistency and the questionable theoretical basis of Saaty's scale. Alternative methods, such as MACBETH, have been developed to overcome some of these objections.' However, no application of MACBETH method for water management problems was found in the literature.

The main strength from multi-criteria methods applied to the sanitation problem was the possibility to incorporate qualitative variables that assess several aspects of sustainability, using subjective analysis of decision makers. The papers presented here showed different ways of estimating qualitative variables (mainly regarding the social and environmental aspect of sustainability), which are based on binomial, ordinal or cardinal scales, which is a notorious advantage of using this method over the traditional methods, e.g. linear programming and statistic approaches. Consequently, although none of the MCDM methods guarantees an optimal solution, the advantage is the scenario construction and the comparison of different solutions, which is a constructive way of decision makers solving problems.

Nevertheless, none of the MCDM methods presented in this section allows for the consideration of risk and uncertainty. Other possible concerns regarding the use of MCDM methods can be found in Leoneti (2016a) and Roy & Słowiński (2013).

Dealing with uncertainty using the multi-criteria approach

A proper MCDM method for dealing with uncertainty is the MAUT method. Loetscher & Keller (2002) proposed a decision support system for selecting sanitation systems in developing countries with the use of the MAUT technique. This research consisted of two steps. First, the elimination of technically unfeasible alternatives is performed by means of the evaluation of criteria. Subsequently, 24 criteria were used to calculate the indexes of 'practicability' and 'sustainability' for each of the remaining alternatives using the MAUT method. Finally, the software performs financial cost estimates to propose a ranking of the alternatives in local currency. Loetscher & Keller (2002) stated that the MAUT technique was compared with the AHP, but the latter was sidelined due to the significant amount of pairwise comparisons.

Actually, there is a great debate between the practitioners of AHP and MAUT (Gass 2005). Among MCDM methods, MAUT has the most solid scientific basis because it is based on the principle of utility functions, which are mathematical models whose goal is to translate material goods into an ordinal scale that satisfactorily represents an individual's satisfaction with their choices (Luce & Howard 1957). However, MAUT depends on the creation of these utility functions with the decision makers, which could be impractical for certain real world cases (Duckstein *et al.* 1982). The great advantage of MAUT is to incorporate uncertainty into the model, which is not allowed in any other MCDM method, without a fuzzy approach.

In this sense, Simonovic & Verma (2008) considered the uncertainty associated with subjective values relative to the decision-making process of water resources management. The authors classify the uncertainty as one of the main sources of complexity in this process, namely: (i) the joint consideration of economic, environmental, social and technical aspects, (ii) the difficulty in quantifying the consequences in the selection of an alternative, and (iii) uncertainties about the global impact of alternatives. Consequently, the authors proposed a new multi-criteria method based on TOPSIS principles and fuzzy values using positive (more optimistic) and negative (pessimistic) ideals, because, as in the decision of water resources, the weightings associated with criteria are not always certain due to the subjectivity of decision makers. Therefore, the authors suggested that if the adopted weightings are fuzzy, the multi-criteria decision also becomes fuzzy. Thus, the weightings assigned to criteria were fuzzy weightings in a triangular form and represent a set of values (p, m, o), where 'p' was the pessimistic value 'm' the average value and 'o' the optimistic value (Simonovic & Verma 2008). To solve the problem of a proposed fuzzy multi-criteria decision, Simonovic & Verma (2008) considered the fuzzy objective function also with a triangular form. The proposed methodology was tested for the case taken from the literature on planning of sewage treatment in a municipality. As a result, the authors came to a methodology that generates a set of Pareto solutions for multi-criteria decision making in water resource problems, with varying degrees of adherence to diffuse weightings. The region of the solution is also fuzzy and triangular in form. The best decisions are those that provide the highest possible gain, avoiding the risks as much as possible (Simonovic & Verma 2008).

Other examples of fuzzy variations for MCDM methods applied to sanitation problems can be seen in Chen &

Chang (2002), who applied three methods of estimation of construction costs: a conventional method of least square regression, a linear regression method using fuzzy logic, and a regression method using fuzzy logic; in Gumus (2009), who evaluated waste transportation firms by using fuzzy-AHP and TOPSIS methodology; in Afshar *et al.* (2011), who used fuzzy TOPSIS for evaluating reservoirs systems; in Hatami-Marbini *et al.* (2013), who used a fuzzy ELECTRE method for assessment of hazardous waste recycling facilities; in Zhang *et al.* (2009), who used a fuzzy PROMETHEE method for comparing contaminated sites based on the risk assessment paradigm, among others. Also observed in the literature is a variant application of fuzzy theory, which is the grey-numbers theory (Kuang *et al.* 2015).

Group decision using multi-criteria methods

Due to different factors, most decisions, especially those involving complex problems such as environmental, occur in the presence of several agents who decide from a well defined number of viable alternatives in a committee (Maaser 2010). Following the same line of research, according to Kocher & Sutter (2005), many types of decisions, such as monetary policy or business strategies of companies, are usually made in groups rather than just by an individual. As an illustration, they cite family meetings to committee meetings, as well as reminders of decisions made by corporate directors and legislators.

According to Srdjevic (2007), three different methodologies can be used to model these decisions, including: (i) multi-criteria methods; (ii) social choice theory; and (iii) game theory. The first requires aggregation of the individual preferences of decision makers into a single group decision. The second is used when information is minimal or highly qualitative for the group, including the voting procedures: the Hare system, the Borda's score, majority voting, and approval voting (Srdjevic 2007).

According to Srdjevic (2007), in multi-criteria applications, the size of a group may become critical because most multi-criteria methods are based on the assumption that the principle of homogeneity between agents is valid (that they have similar preferences). On the other hand, when considering the applications of social choice theory, the most important questions are the fairness and the manipulation of the voting system used. In a decision-group context, multi-criteria methods and social choice have different performances with respect to issues such as fairness, transparency, or manipulation at various stages of implementation. Several authors report that the use of one or another type of method can easily declare different winners (Srdjevic 2007). In turn, Srdjevic (2007) proposed a methodology to combine the multi-criteria method with the theory of social choice in group decision making. Another example of joint application can be seen in Laukkanen *et al.* (2002).

The third possibility for the evaluation of alternatives in the presence of more than one actor, mainly for situations where each decision maker evaluates the criteria based on their divergent preferences (not existing homogeneity among the agents), is game theory.

Solving conflicts between agents, creating compromise solutions, and improving politic and negotiation process: the game theory approach

The application of game theory to solve environmental problems is not new. Szidarovszky *et al.* (1984) demonstrated how a multi-criteria model representing a regional problem of a groundwater system of an aquifer in Hungary could be solved by game theory. The main idea of the study was to provide a joint analysis of the exploitation of mineral resources, water supply, and environmental protection. These three views were represented by three objective functions, which would be difficult to be expressed in measurable units, and for which the best solution to a goal generally produces far from ideal values for other purposes. As a result, the authors proposed not finding a global overall solution for the entire system, but a solution that was satisfactory in meeting all objectives considered in conflict with each other. As a result of this work, Szidarovszky *et al.* (1984) concluded that game theory concepts could be used to develop a methodology for solving a particular class of multi-objective problems, based on certain axioms that the solution must satisfy. They also stated that the Nash equilibrium point is a minimal solution point, or the result of the subjective choice of the decision maker.

Tecle *et al.* (1988) also presented the resolution of a multi-criteria problem using game theory and the ELECTRE

I method. The case study was based on the sewage treatment project of the city of Nogales in the United States, dealing with wastewater from the twin cities of Nogales in the United States and Nogales in Mexico. The two techniques selected to support decision making (game theory and ELECTRE I) were used to analyze the problem separately. Tecle *et al.* (1988) identified differences in the modeling of wastewater management, taking into account the complexity to satisfy a number of constraints and meet a number of objectives. Therefore, the best solution is only determined once the decision maker accepts the axioms of the methodology (Tecle *et al.* 1988).

Another application example can be seen in the work of Krawczak & Zicsakowski (1985), who emphasized the control of water quality of a system containing three subsystems, namely: distribution control, water retention control, and water quality control. The authors applied game theory together with the Nash equilibrium concepts to propose a solution to the conflict in the discharge of sewage by polluters into a reservoir. In this article, Krawczak & Zicsakowski (1985) considered the reservoir of a river and several polluters around it. The reservoir was in the flow of the river and each polluter was treated as a player. Decay functions proposed by Streeter & Phelps (1958) and concepts of game theory were used in order to propose strategies for each polluter. For this, it was considered that the main objective in the control of water quality would be to keep the final levels of BOD and COD as close as possible to pre-set levels (Krawczak & Zicsakowski 1985). Based on Nash equilibrium concepts, Krawczak & Zicsakowski (1985) were able to devise strategies to control pollution in the reservoir, which provided a satisfactory solution to the conflict between the players. Thus the authors concluded that game theory could also be a tool for dealing with optimization problems.

Carraro *et al.* (2005), in an article on the negotiation and non-cooperative bargaining to issues related to water, state that conflicts can arise in situations where decision makers could mutually benefit each other if they enter into an agreement, but did not establish cooperation because their interests are opposed. The authors raise the question that in general, theoretical models provide descriptions of the negotiation process and predictions of how players behave. However, the experimental evidence shows that the predictions of theoretical optimization models often do not match the actual negotiation process. Therefore, these models might not be as useful as decision support tools (Carraro *et al.* 2005). After conducting an extensive literature review on the application of game theory and negotiation in the management of water quality, Carraro *et al.* (2005) found that most of the economic literature presents the solution to these problems from the point of view of optimization, specifically economic efficiency. Alternatively, they also identified other studies using game theory to assist in finding solutions not necessarily more efficient from an economic point of view, but socially or politically feasible. Thus, the authors state that many of the environmental problems would be best treated within a game approach through game theory, for example, issues related to natural resource management. Also in this sense, Carraro *et al.* (2005) argue that a negotiated settlement is increasingly accepted as the best approach to natural resource management. In addition, they state that these negotiated solutions are more easily accepted and therefore potentially easier to be implemented. However, the negotiation process should involve not only the presentation of proposals and compromises, but also predict the preferences of players and their likely strategies.

According to Carraro *et al.* (2005), given the complexity of the processes and environmental issues involved, game theory has a high potential to help in the process of an agreement acceptable to all parties. The game theory approach can directly support the negotiation process, or indirectly, by shortening the necessary time to reach an agreement by identification (theoretical) of 'acceptability space'. That is, the proposals that have more changes of being accepted are identified and proposals that would be (almost) certainly rejected are soon discarded at the start.

Similarly, Madani (2010) also contributes to this discussion by arguing that conflicts over water issues are not just limited to costs or benefits. To Madani (2010), these conflicts can also arise from social and political aspects of the design, operation and management of environmental projects. Therefore, to analyze, operate or design a sanitation project, a decision maker should ensure that the project is not only technically, environmentally, financially and economically viable, but also socially and politically. For the author, this is a challenge for engineers who are used to measure the performance of projects only in economic, financial and physical terms. Also according to Madani (2010), optimization techniques such as linear programming can find the optimal values of the decision variables. However, if the problem is not formulated properly, it can fall short on providing more comprehensive information on the strategic behavior of decision makers who are involved in the selection process. Thus as a contribution, Madani (2010) illustrates the usefulness of non-cooperative game theory together with pure strategies in the analysis of water systems and focuses on conflict resolution through discussion of the basic concepts of game theory. He also discusses how the dynamic structure of water resource problems and the evolution of the game can affect the behavior of agents in different periods of the conflict. Three types of games were presented two by two, and their equilibria were introduced. In each game some correspondences between game theory and the management of water resources were found, which were discussed on the basis of each example. In addition, the results of the Pareto optimal type were introduced to show how the results of game theory may differ from the results of systems engineering methods (Madani 2010). In conclusion, Madani (2010) states that game theory provides a mean for understanding and resolution of water conflicts, which are often of the multi-criteria type, with multiple decision makers involved. Also according to the author, this theory could predict whether the optimal resolutions are attainable and clarify the behavior of decision makers in specific conditions (Madani 2010).

Finally, Wei *et al.* (2010) agree that the administration of water resources often involves interaction between different authors with different points of view, and must deal with the difficult task of satisfactorily meeting the wishes of all involved. The authors show conflicts between quality and quantity of water, which are usually caused by: (i) water scarcity due to uneven precipitation; (ii) multiple users and polluting sources; (iii) different degrees of pollution upstream restricting the use of water in the water basin downstream; and (iv) transfer of water between basins. To resolve these conflicts, Wei *et al.* (2010) suggested the creation of water markets, such as those existing in some countries such as Australia, USA, Chile, India and Spain, together with game theory, as an appropriate approach to model and propose solutions to address these conflicts. To create this game, Wei *et al.* (2010) proposed regression functions that were used to define the players' payoff, and four scenarios were developed to analyze the uncertainties of the simulation. From this, Wei *et al.* (2010) defined the game on two levels, with a main game and four subgames. In conclusion, Wei *et al.* (2010) show that the game would hardly be solved without cooperation between the players, even under an optimistic scenario, and also identified that cooperation with other players is the dominant strategy of the game. The study also proved that cooperation brings some losses for some players, but produces more collective benefits. However, players are not usually willing to cooperate, because they will face the risk of loss, a similar result to the prisoner dilemma game (Wei *et al.* 2010).

Many of the applications presented here used the concept of non-cooperative games for choosing the alternatives. One can eventually argue that these kinds of decision games more resemble a cooperative than a non-cooperative game. Actually, there are several applications assuming that these kinds of games should be modeled as cooperative games (Karmperis *et al.* 2013). Another example can be seen in Wang *et al.* (2003). On the other hand, the decision-making process for water resources planning usually has a committee instance in the process of making decisions, which usually suffer strong pressures of different players, e.g. environmentalists. Additionally, some sanitation problems involve more than one region, sometimes including different countries, which might bring to the context some different cultures and strong contrasting view points, making it harder to find pre-agreements with satisfactory outcomes. In this sense, the non-cooperative approach for modeling such as games seems to be more useful. Binmore (2007) reinforces that negotiation games should be studied without presupposing preplay bargaining, which is the principal assumption of cooperative games, strengthening the possibility of analyzing it through a non-cooperative bargaining model.

One clear difference between game theory and MCDM methods is that for the latter, there are several ways of modeling the value's function that is the core of the algorithm method. On the other hand, the utility function for the game theory approach should be designed almost as one for every situation. According to DeCanio & Fremstad (2013), 'the payoff structure depends on interpretation of the scientific evidence'. For instance, Carraro *et al.* (2005) defined the utility function in which the payoff of an individual would imply a reduction in the payoff of their opponents. Krawczak & Zicsakowski (1985), used decay functions proposed by Streeter & Phelps (1958). In turn, Wei *et al.* (2010) proposed regression functions that were used to define the players' payoff. Furthermore, some payoffs are formed on arbitrary judgment made by the decision makers based on ordinality principles. This makes game theory harder to be implemented when compared to MCDM methods. Toward a more accessible modeling of this approach, a recent contribution can be seen in Leoneti (2016b).

Apart from the implementation phase, game theory has a greater advantage for dealing with more than one decision maker in a non-cooperative situation (heterogeneity between agents), putting itself as a better approach for aiding the political or negotiation process.

CONCLUSIONS

Articles presenting different applications of MCDM methods and game theory to sanitation were found in the literature. In general, the use of multi-criteria methods and game theory proved useful to create and compare scenarios, reducing the time needed to reach a solution for complex problems involving a large number of criteria and agents. Also, they were shown to be important for creating greater transparency in the decision-making process, thus increasing the potential for a solution acceptable to the parties involved.

Specifically, in this research it can be seen that the use of MCDM methods allows a significant increase in the number of criteria for evaluation. The increase in the criteria was often associated with sustainability criteria, covering the social, economic and environmental aspects of the alternatives. More importantly, although not appropriate for finding optimal solutions, MCDM has the advantage of making it possible to include qualitative variables into water management resources modeling. Being different to all other traditional techniques, except the ones based on non-parametric techniques which do not require that the variables be quantitative, some holistic concepts of sustainability can be taken into account in this approach.

Associated with the increase of the criteria, the inclusion of a greater number of participants in the decision-making process was also mentioned as important. However, in the multi-criteria approach, different preferences in meeting the criteria would lead to conflicts that make harder the adoption of one alternative as the solution for the group. In this context, game theory approach, with its utility functions and its equilibrium-based solutions, has been suggested as a solution that would be suitable for situations of non-cooperation or conflict among individuals. This allows the inclusion of objectives other than the technical-economic objectives, thus also taking into account of social, political and environmental objectives in the decision making process. In this sense, the solutions would be more readily accepted by the decision makers who, instead of a Pareto-optimal solutions, would have a consensus solution formulated based on equilibrium.

Although applied studies have been identified for each of the main multi-criteria methods and game theory, the number of studies by technique was very low in the literature, when filtered by the sanitation area, mainly regarding water management. On the other hand, it was found that in both theoretical developments and real life applications MCDM methods are significantly more used than game theory. This is probably due to the fact that MCDM is more understandable to decision makers and therefore in many cases easier to implement. Moreover, there is the possibility of using MCDM methods in group contexts combining those methods with game theory or social choice theory methods, including the voting procedures.

In conclusion, although still little explored, discussions of sanitation problems can and should be enhanced with the use of techniques and methods of decision science, and MCDM methods and game theory are particularly suitable for this task.

ACKNOWLEDGEMENTS

The authors are grateful to FAPESP for doctoral fellowship (2009/07598) and to the two anonymous reviewers for their insightful comments and suggestions.

REFERENCES

Afshar, A., Mariño, M. A., Saadatpour, M. & Afshar, A. 2011 Fuzzy TOPSIS multi-criteria decision analysis applied to Karun reservoirs system. *Water Resour. Manage.* **25** (2), 545–563.

Baker, D., Bridges, D., Hunter, R., Johnson, G., Krupa, J., Murphy, J. & Sorenson, K. 2001 *Guidebook to Decision-Making Methods*. Department of Energy, USA. Available from: http://ckmportal.eclacpos.org/caribbean-digital-library/industrial-development/xfer-949.

Bana e Costa, C. A. & Vansnick, J. C. 1994 MACBETH – an interactive path towards the construction of cardinal value functions. *Int. Trans. Oper. Res.* **1**, 489–500.

Bana e Costa, C. A. & Vansnick, J. C. 1997 Applications of the MACBETH approach in the framework of an additive aggregation model. *J. Multi-Criteria Decis. Anal.* **6** (2), 107–114.

Behzadian, M., Kazemzadeh, R. B., Albadvi, A. & Aghdasi, M. 2010 PROMETHEE: a comprehensive literature review on methodologies and applications. *Eur. J. Oper. Res.* **200** (1), 198–215.

Binmore, K. 2007 *Playing For Real: A Text on Game Theory*. Oxford University Press, Oxford, UK.

Bottero, M., Comino, E. & Riggio, V. 2011 Application of the analytic hierarchy process and the analytic network process for the assessment of different wastewater treatment systems. *Environ. Model. Software* **26** (10), 1211–1224.

Brans, J. P. & Vincke, P. H. 1985 A preference ranking organization method. *Manage. Sci.* **31** (6), 647–656.

Butlera, D. & Schütze, M. 2005 Integrating simulation models with a view to optimal control of urban wastewater systems. *Environ. Model. Software* **20**, 415–426.

Carraro, C., Marchiori, C. & Sgobbi, A. 2005 *Applications of Negotiation, Theory to Water Issues*. World Bank Policy Research Working Paper. World Bank, Washington, DC.

Chen, H. W. & Chang, N. B. 2002 A comparative analysis of methods to represent uncertainty in estimating the cost of constructing wastewater treatment plants. *Journal of Environmental Management* **65** (4), 383–409.

Chen, S. H., Jakeman, A. J. & Norton, J. P. 2008 Artificial intelligence techniques: an introduction to their use for modelling environmental systems. *Math. Comput. Simul.* **78**, 379–400.

DeCanio, S. J. & Fremstad, A. 2013 Game theory and climate diplomacy. *Ecological Economics* **85**, 177–187.

Duckstein, L., Gershon, M. & McAniff, R. 1982 Model selection in multiobjective decision making for river basin planning. *Adv. Water Resour.* **5** (3), 178–184.

Fiani, R. 2006 *Game Theory*, 2nd edn. Elsevier, Rio de Janeiro.

Figueira, J., Mousseau, V. & Roy, B. (eds). 2005 ELECTRE methods. In: *Multiple Criteria Decision Analysis: State of the Art Surveys*. Springer, New York, pp. 133–153.

Fraas, A. G. 1984 Municipal wastewater treatment cost. *J. Environ. Econ. Manage.* **11**, 28–38.

Gass, S. I. 2005 Model world: The great debate – MAUT versus AHP. *Interfaces* **35** (4), 308–312.

Gillot, S., de Clercq, B., Defour, D., Simoens, F., Gernaey, K. & e Vanrolleghem, P. A. 1999 Optimization of wastewater treatment plant design and operation using simulation and cost analysis. In: *Proceedings of the 72nd Annual WEF Conference and Exposition*, New Orleans, USA, October, 9–13.

Gumus, A. T. 2009 Evaluation of hazardous waste transportation firms by using a two step fuzzy-AHP and TOPSIS methodology. *Expert Systems with Applications* **36** (2), 4067–4074.

Hajkowicz, S. & Collins, K. 2007 A review of multiple criteria analysis for water resource planning and management. *Water Resour. Manage.* **21** (9), 1553–1566.

Hajkowicz, S. & Higgins, A. 2008 A comparison of multiple criteria analysis techniques for water resource management. *Eur. J. Oper. Res.* **184** (1), 255–265.

Harker, P. T. 1987 Incomplete pairwise comparisons in the analytic hierarchy process. *Math. Model.* **9** (11), 837–848.

Hatami-Marbini, A., Tavana, M., Moradi, M. & Kangi, F. 2013 A fuzzy group Electre method for safety and health assessment in hazardous waste recycling facilities. *Saf. Sci.* **51** (1), 414–426.

Hellström, D., Jeppsson, U. & Kärrman, E. 2000 A framework for systems analysis of sustainable urban water management. *Environ. Impact Assess. Rev.* **20** (3), 311–321.

Herva, M. & Roca, E. 2013 Review of combined approaches and multi-criteria analysis for corporate environmental evaluation. *J. Clean. Prod.* **39**, 355–371.

Huesemann, M. H. 2001 Can pollution problems be effectively solved by environmental science and technology? An analysis of critical limitations. *Ecol. Econ.* **37**, 271–287.

Hwang, C. L. & Yoon, K. 1981 *Multiple Attribute Decision Making: Methods and Applications*. Springer, New York, NY, USA.

Kalbar, P. P., Karmakar, S. & Asolekar, S. R. 2012 Selection of an appropriate wastewater treatment technology: a scenario-based multiple-attribute decision-making approach. *J. Environ. Manage.* **113**, 158–169.

Karagiannidis, A. & Moussiopoulos, N. 1997 Application of ELECTRE III for the integrated management of municipal solid wastes in the Greater Athens Area. In: *Multiple Criteria Decision Making* (C. Zopounidis, ed.). Springer, Berlin Heidelberg, pp. 568–578.

Karmperis, A. C., Aravossis, K., Tatsiopoulos, I. P. & Sotirchos, A. 2013 Decision support models for solid waste management: review and game-theoretic approaches. *Waste Manage.* **33** (5), 1290–1301.

Keeney, R. & Raiffa, H. 1976 *Decision with Multiple Objectives: Preferences and Value Tradeoffs*. Wiley, New York.

Kocher, M. & Sutter, M. 2005 The decision maker matters: individual versus group behaviour in experimental beauty contest games. *Econ. J.* **115**, 200–223.

Krawczak, M. & Zicsakowski, A. 1985 Nash model of water reservoir pollution. *Ann. Rev. Auto. Prog.* **12** (2), 181–184.

Kuang, H., Kilgour, D. M. & Hipel, K. W. 2015 Grey-based PROMETHEE II with application to evaluation of source water protection strategies. *Info. Sci.* **294**, 376–389.

Laukkanen, S., Kangas, A. & Kangas, J. 2002 Applying voting theory in natural resource management: a case of multiple-criteria group decision support. *J. Environ. Manage.* **64** (2), 127–137.

Leoneti, A. B. 2016a Considerations regarding the choice of ranking multiple criteria decision making methods. *Pesqui. Operac.* **36** (2), 259–277.

Leoneti, A. B. 2016b Utility function for modeling group multi-criteria decision making problems as games. *Oper. Res. Perspect.* **3**, 21–26.

Linkov, I., Satterstrom, F. K., Kiker, G., Batchelor, C., Bridges, T. & Ferguson, E. 2006 From comparative risk assessment to multi-criteria decision analysis and adaptive management: recent developments and applications. *Environ. Int.* **32** (8), 1072–1093.

Loetscher, T. & Keller, J. 2002 A decision support system for selecting sanitation systems in developing countries. *Socioecon. Plann. Sci.* **36** (4), 267–290.

Luce, R. D. & Howard, R. 1957 *Games and Decisions: Introduction and Critical Surveys*. Wiley, New York, NY.

Luce, R. D. & Raiffa, H. 1957 *Games and Decisions: Introduction and Critical Surveys*. Wiley, New York.

Lynn, W. R., Logan, J. A. & Charnes, A. 1962 Systems analysis for planning wastewater treatment plants. *J. Water Pollut. Control Fed.* **34** (6), 565–581.

Maaser, N. F. 2010 *Decision-Making in Committees: Game-Theoretic Analysis*. Springer-Verlag, Berlin Heidelberg.

Madani, K. 2010 Game theory and water resources. *J. Hydrol.* **381**, 225–238.

Neumann, J. V. & Morgenstern, O. 1944 *Theory of Games and Economic Behavior*. Princeton University Press, Princeton, New Jersey.

Osborne, M. J. & Rubinstein, A. 1994 *A Course in Game Theory*. The MIT Press, Cambridge, Massachusetts.

Roy, B. 1968 Classement et choix en présence de points de vue multiples: la méthode ELECTRE. *Rev. Fr. Inf. Rech. Op.* **8**, 57–75.

Roy, B. & Słowiński, R. 2013 Questions guiding the choice of a multi-criteria decision aiding method. *Eur. J. Dec. Process.* **1** (1–2), 69–97.

Saaty, T. L. 1980 *The Analytic Hierarchy Process*. McGraw Hill, New York, NY, USA.

Simon, U., Brüggemann, R. & Pudenz, S. 2004 Aspects of decision support in water management – example Berlin and Potsdam (Germany) I – spatially differentiated evaluation. *Water Research* **38** (7), 1809–1816.

Simonovic, S. P. & Verma, R. 2008 A new methodology for water resources multi-criteria decision making under uncertainty. *Phys. Chem. Earth* **33**, 322–329.

Souza, M. A. A. 1998 Um modelo para seleção de processos de tratamento de águas residuárias municipais. (Associação Interamericana de Engenharia Sanitária e Ambiental – AIDIS, eds). Gestão Ambiental no Século XXI. Lima, APIS, pp. 1–20.

Srdjevic, B. 2007 Linking analytic hierarchy process and social choice methods to support group decision-making in water management. *Decis. Support Syst.* **42**, 2261–2273.

Streeter, H. W. & Phelps, E. B. 1958 *A Study of the Pollution and Natural Purification of the Ohio River*. US Department of Health, Education, & Welfare, Washington, DC, USA.

Szidarovszky, F., Duckstein, L. & Bogardi, I. 1984 Multiobjective management of mining under water hazard by game theory. *Eur. J. Oper. Res.* **15** (2), 251–258.

Tecle, A., Fogel, M. & Duckstein, L. 1988 Multicriterion selection of wastewater management alternatives. *J. Water Resour. Plann. Manage.* **114** (4), 383–398.

Vanrolleghem, P. A., Jeppsson, U., Carstensen, J., Carlsson, B. & Olsson, G. 1999 Integration of wastewater treatment plant design and operation – a systematic approach using cost functions. *Water Sci. Technol.* **34** (3–4), 159–171.

Wallenius, J., Dyer, J. S., Fishburn, P. C., Steuer, R. E., Zionts, S. & Deb, K. 2008 Multiple criteria decision making, multiattribute utility theory: recent accomplishments and what lies ahead. *Manage. Sci.* **54** (7), 1336–1349.

Wang, L. Z., Fang, L. & Hipel, K. W. 2003 Water resources allocation: a cooperative game theoretic approach. *J. Environ. Inform.* **2** (2), 11–22.

Wei, S., Yang, H., Abbaspour, K., Mousavi, J. & Gnauck, A. 2010 Game theory based models to analyze water conflicts in the Middle Route of the South-to-North Water Transfer Project in China. *Water Res.* **44**, 2499–2516.

Xenarios, S. & Bithas, K. 2007 Extrapolating the benefits arising from the compliance of urban wastewater systems with the Water Framework Directive. *Desalination* **211**, 200–211.

Zhang, K., Kluck, C. & Achari, G. 2009 A comparative approach for ranking contaminated sites based on the risk assessment paradigm using fuzzy PROMETHEE. *Environmental Management* **44** (5), 952.

First received 6 December 2016; accepted in revised form 22 February 2017. Available online 18 March 2017