Development Of Fuzzy Multi-Criteria Decision Analysis Approach For Contaminated Site Management

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B.Sc., Independent University, Bangladesh, 2004

Thesis Submitted In Partial Fulfillment Of

The Requirements For The Degree Of

Master Of Science

in

Natural Resources and Environmental Studies

(Environmental Science)

The University of Northern British Columbia

March, 2008

Your file Votre référence
ISBN: 978-0-494-48803-4
Our file Notre référence
ISBN: 978-0-494-48803-4

Abstract

Selection of remediation alternative is an important task in the decision making process of contaminated site management. The number of available remediation alternatives is increasing over the years as a result of progress in scientific research. Decision makers face a confounded situation to select the best acceptable alternative by satisfying various preferences of different stakeholders. In this research, a fuzzy multi-criteria decision analysis (FMCDA) approach was developed. Since most information available in the decision making process is not deterministic, fuzzy-set theory was used to deal with such uncertainty. The developed FMCDA approach ranks the alternatives according to the utility values. Different stakeholders' opinions were effectively incorporated in the developed approach, allowing for a robust decision making for contaminated site management. The developed method was then applied to the management of a site in northern British Columbia to examine its applicability.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACKNOWLEDGEMENT

I would like to thank my supervisor Dr. Jianbing Li, for his patience and providing me all sort of supports throughout my graduate studies at the University of Northern British Columbia (UNBC). He made many efforts discussing and developing my ideas, working with me through difficulties, and reviewing my papers. His guidance and willingness to expand myself intellectually and the opportunities he afforded me are truly appreciated.

I would also like to thank my co-supervisor Dr. Jueyi Sui and committee member Dr. Liang Chen, for their guidance throughout this research. Despite busy schedules, they were more than willing to meet with me when I needed advice.

I am in debt to Dr. Michael Rutherford, Associate Professor, Environmental Science, UNBC for his valuable feedback on questionnaire survey. He also helped me to network with environmental professionals for this research.

I would like to thank Doug McMillan, Scientific Research Officer of SNC-Lavalin, Prince George for his valuable suggestions and input in my research work.

I am grateful to Bharath Reddy, Computer Science, UNBC and MA Razzaq, Senior Application Architect, Beendo Corporation, USA for their help to develop the user-friendly decision support system.

Together with, I would like to thank my brother, Muhammad Rahman and his family for providing me accommodation and all sorts of supports throughout my sojourn.

Finally, I want to acknowledge my parents for their sacrifice to let me study in Canada. Their perpetual emotional supports, and never letting me forget the bigger picture helped me to reach this far.

Consequently, I can honestly say that this research has been a group effort and I thank everyone for an amazing experience that I will carry with me throughout my life.

Chapter 1 Introduction

Numerous operations in petroleum exploration, production and transportation have been causing various environmental problems in Canada and worldwide (Amro, 2004). It is estimated that there are an excess of 10,000 contaminated sites in Canada and these sites pose significant threats to the ecosystem and human health (Siciliano and Germida, 1998; Sousa, 2001). The effective management of such contaminated sites is of critical importance and is often a liability of the federal and provincial governments as well as the industries. Thus, a solid decision making process for site management is necessary. However, the decision making of contaminated site management is complex due to the presence of many uncertainties in evaluation criteria and different stakeholder interests. Each stakeholder may define the risks and potential benefits in a remedial alternative by different (even unique) criteria, and implementation of the alternative may be prevented by raising objections that seem unnecessary to other stakeholders (Seager et al., 2007). Over the past 30 years, the concept of contaminated site management has been changed markedly (Pollard et al., 2004). In the mid-1970s the focus was on cost-centered approaches, in the mid-1980s technological feasibility was emphasized, in the mid-1990s risk based approaches were taken and in this new millennium, environmental decisions must be socially-robust (Urban Task Force, 1999; ESRC Global Environmental Change Programme, 2000). The selection of remedial alternatives requires formation of partnerships between technology developers, manufacturers, regulators, end-users and public (Seager et al., 2007). The existing decision making approaches have many limitations in a number of components, such as (a) evaluation of remedial alternatives, (b) evaluation criteria of remedial alternative, (c) stakeholder involvement, and (d) uncertainties in remedial alternative evaluation process.

Development and implementation of remedial alternatives for contaminated sites have received much attention during the past decades (Riser-Roberts, 1998; Li et al., 2001). The number of in-situ and ex-situ remedial technologies for cleaning up contaminated sites has been growing over the years due to advancements in science and technological research. Thus, decision makers face complex problems in identifying the best alternative from a wide range of remedial alternatives where none of them are dominating (Khadam and Kaluarachchi, 2003). Since most technologies are site-specific, the selection of appropriate technologies is often difficult. Being able to make these difficult decisions, with consideration to all stakeholders, is an extremely important step in successful management of contaminated sites (Khan et al., 2004). Most of the developed decision support systems provide a list of applicable remedial alternatives, but the problem remains in selecting the best alternative.

In addition, selection of a remedial alternative involves a multi-criteria evaluation process, requiring a multi-criteria analysis approach. Multi-criteria analysis refers to screening, prioritizing, ranking and/or selecting a set of remedial alternatives under independent or conflicting criteria. A wide range of criteria (e.g., flexibility, compatibility, time, cost, environmental impact, public acceptance) need to be considered in an evaluation process. These criteria may conflict with each other in terms of their trade off values. For example, some remedial alternatives might be economically feasible but require a lengthy treatment process, while other alternatives might be expensive but require shorter clean up periods.

Moreover, the management of contaminated sites is not limited to choosing the right solution solely by a decision maker or by an environmental engineer. According to Akter et al. (2005), decision on contaminated site management is no longer limited to the selection of the most preferred alternative among the non-dominated solutions; the analysis needs to be extended to account for diverse opinions of multiple decision makers. The importance of stakeholders (e.g., government, industry, regulatory agency) involvement in the decision making process can be found in many literatures (Gregory et al., 1994; Kamnikar, 2001; Balasubramaniam et al., 2007). Discussions with stakeholders are needed not only for the related model building process, but also to provide stakeholders a voice which facilitates the development of stakeholder trust in the policy-implementation process (Lind and Tyler, 1988; Lind, 1995). Borsuk et al. (2001) identified that stakeholders do not only value a particular environmental problem, they also care about how they are involved in the decision making process. In the past, the manager of a contaminated site remediation project needed to be skilled only in excavating, but now a manager must combine the skills and talents of engineer, lawyer, scientist, and negotiator (Cole, 1994). One of the recommendations Kamnikar (2001) made for contaminated site management is that one has to understand the importance of early community involvement and this will increase the acceptance of specific remediation projects, acceptance of new or alternative remediation techniques, and will establish trust and good working relationships. As a result, the decision for environmental contaminated site management needs to take into account the inputs from different stakeholders with different priorities and objectives (Linkove et al., 2006). Existing decision analysis approaches fail to address different stakeholder opinions in the process of contaminated site management and limited efforts have previously been made to address this issue (Zahedi, 1986; Juang and Lee, 1991; Cheng, 1996).

There are many uncertainties involved in the evaluation process of remediation alternatives. For example, the criteria of "cleanup cost" may vary significantly even for a particular technology ranging from \$30 per m^3 to \$300 per m^3 of soil. Similarly, the criteria (e.g., "impact on the environment", "community acceptability" etc.) without units are measured on a numeric scale (e.g., 1 to 10, 0 to 1). Generally, in a numeric scale the lower values are given to represent less preference and higher values are given to express high preference. Existing multi-criteria analysis methods assume that ratings of alternatives and the weighting factors of criteria are deterministic values. For example, rating on "clean up cost" criteria is rated as "10 = when cost is less than \$100/m^3; 5= when cost is \$100-300/m^3; and 1= when cost is more than \$300/m^3". By applying the above rating method, when a remediation alternative costs \$99/m^3, it will receive 10 points. However, if the cost is \$101/m^3 it will receive 5 points, and this significantly underestimates the remedial alternative with only slightly higher cost (e.g., when cleanup cost for 2 alternatives are \$101/m^3 and \$99/m^3 respectively, the difference in cost is only \$2/m^3). In existing rating practices, the rating value of criteria is either in or not in the crisp set. However, a rating value can partially belong to a crisp set or belong to more than one set. Therefore, it can be stated that the ratings of criteria are not best represented by only deterministic or single crisp value. These criteria ratings could be best represented by a range of values, or by linguistic terms.

Selection of criteria importance weight for remedial alternative evaluation is associated with another source of uncertainty. Different stakeholder has different preferences on each criterion. Thus the values of criteria importance can vary significantly. Most of the existing multi-criteria analysis models apply the analytical hierarchy process (AHP) (Saaty, 1994) to calculate criteria importance weight. In AHP, a decision problem is presented hierarchically and this method synthesizes various assessments for ranking alternatives in a systematic way (Yeh et al., 2000). In AHP method, stakeholders are asked to compare two criteria at a time and provide a crisp rating on the comparison. However, such approach is often criticized for inappropriateness of the crisp ratio representation and for cumbersome procedure (Zahedi, 1986; Juang and Lee, 1991; Cheng, 1996). According to Petrovic and Petrovic (2002) stakeholders with different technical and non-technical backgrounds feel more comfortable with linguistic expressions to express their opinions (e.g., high, medium, low).

There are many multi-criteria decision analysis (MCDA) methods available to support environmental decision making, such as the simple additive weighting (SAW) method, weighted product method (WPM), preference ranking organization method for enrichment evaluations (PROMETHEE), and technique for order performance by similarity to ideal solution (TOPSIS). Most of the widely used multi-criteria analysis methods are effective in dealing problems with quantitative data (Hwang and Yoon, 1981; Bana e Costa, 1990; Yeh et al., 2000). However, the applicability of existing MCDA methods are seriously reduced when dealing with situations where imprecision and subjectiveness of the decision making process are present (Chen and Hwang, 1992; Hellendoorn, 1997; Bender et al., 2000; Petrovic and

Petrovic, 2002). By neglecting these qualitative inputs, the robust capability of decision making is lost. According to Linkove et al. (2006) current decision analysis practices do not offer a comprehensive approach for incorporating the varied types of information and opinions of multiple stakeholders. The effective incorporation of multiple stakeholder perspectives within the decision making process of contaminated site management are thus of critical importance and should be a principal task of environmental professionals and regulatory agencies (Testa and Winegardner, 1991; Li et al., 2000, 2001; USEPA, 2001).

The uncertainties involved in qualitative data, qualitative criteria weights or the subjective and imprecise assessments of the decision problem can be better expressed by fuzzy logic and fuzzy set theory (Klir and Folger, 1988; Yeh et al., 2000). The application of fuzzy-set theory (Zadeh, 1965) to multi-criteria problems provide an effective way for solving decision problems in a fuzzy environment where little information is known (i.e., imprecise knowledge from descriptions of human language) and the information is subjective (Bellman and Zadeh, 1970; Carlsson, 1982; Dubois and Prade, 1994; Zimmermann, 1996; Herrera and Verdegay, 1997; Sadiq et al., 2004b; Chang et al., 2007; Li et al. 2007). It is also an effective tool to incorporate linguistic preferences from different stakeholders, and can address decision making problems under uncertainty in number of environmental management areas (Li et al., 2007). There has been much theoretical work done on the use of fuzzy-set theory in multi-criteria decision analysis (MCDA) during the last two decades, however little attention has been given to integrating these ideas and developing a fuzzy multi-criteria decision support (FMCDS) system (Cheng, 2000). Particularly, few efforts have been made to apply this approach to address the hydrocarbon impacted site management issues. In this thesis a hybrid method, fuzzy multi-criteria decision analysis (FMCDA) will be developed and applied to evaluate and rank applicable remediation alternatives for oil contaminated site by considering various stakeholder preferences and uncertainties.

Consequently, there are 3 main objectives in this research including (a) to identify the criteria for remedial alternative selection and determine the criteria importance weight according to stakeholder preference, (b) to integrate and address uncertainty issues in remediation alternative evaluation process (e.g., cost, time, and stakeholder preferences) into a general decision analysis framework, and (c) to develop an effective fuzzy multi-criteria approach for evaluating and ranking remediation alternatives by comprehensively considering various independent and/or seemingly conflicting criteria.

This thesis is organized as follows. In Chapter 2, a review on different component of contaminated site management issues are discussed. As well, existing practices of decision making and their limitations are discussed in this chapter. Also, literature review on the proposed fuzzy multi-criteria approach is presented. In Chapter 3, the overall methodology of developing a fuzzy multi-criteria approach is described. Moreover, acquisition of criteria importance weight, development of fuzzy membership functions, and development of a user-friendly decision support system is described in this chapter. In Chapter 4, the results of a case study site using the developed method is presented. A comparison of results from fuzzy multi-criteria and the existing multi-criteria methods are also presented. Besides, results of various sensitivity analyses are discussed. In Chapter 5, conclusion of the research work is drawn, while future direction of the research is discussed.

Chapter 2 Literature Review

2.1 General background of contaminated sites

Contaminated land is primarily a post-1800s problem worldwide in terms of cause but a post 1970s phenomenon in terms of risk management (Petts et al., 1997; Sousa, 2001). Significant industrialization has occurred over the past years in many developed nations (e.g., Canada, United States, and United Kingdom). Particularly, in Canada the oil and gas industries play an important role in its economy. It is expected that this industry will continue to expand in the future. However, a number of environmental concerns (e.g., soil and groundwater contamination) are associated with such development and expansion (Dowd, 1985; Newton, 1991). It is estimated that there are 200,000 underground storage tanks (USTs) in Canada. The leakage from these USTs causes contamination to the surrounding environment and significant economic losses to the petroleum industries (CCME, 1993). In general, the number of suspected/known contaminated site in USA is 384,400 and 20,000-30,000 in Canada (NRTEE, 1997; Simons, 1998).

2.2 Remediation technologies for contaminated site management

A great number of remediation technologies have been developed and implemented for contaminated site management during the past years, and more remediation alternatives will be available in the future due to continued competition among environmental service companies, technology developers and development in technology researches (Vranes et al., 2000). The existing remediation technologies can be divided into two categories of in-situ and ex-situ. For in-situ remediation, no excavation is required, while ex-situ technologies require the removal, usually by excavation, of contaminated soils. Some of the common remediation alternatives can be further divided into biological, physical/chemical and thermal treatment methods (Fig. 2.1).

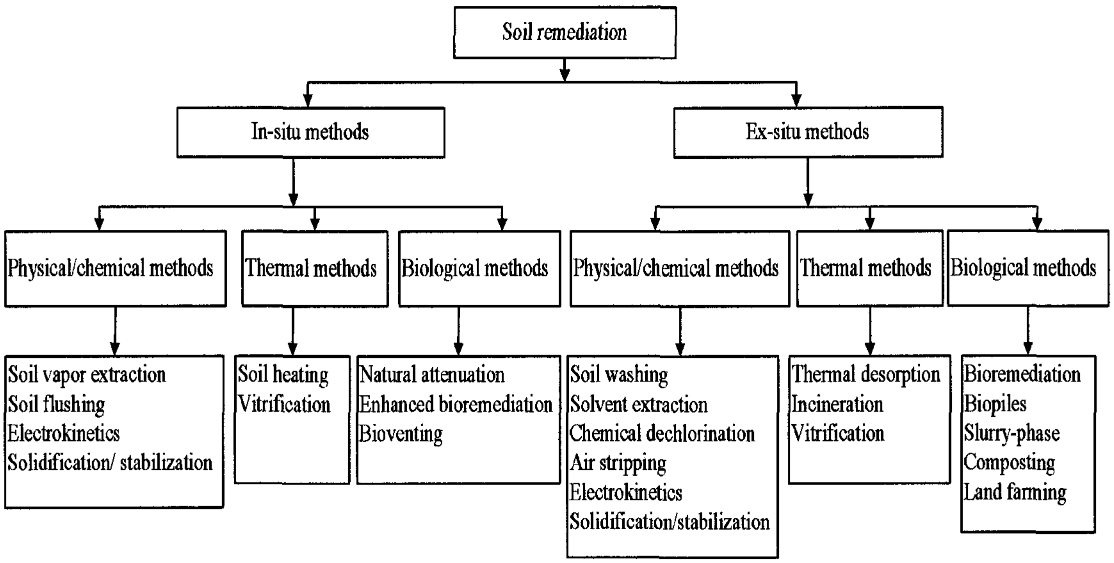


Fig. 2.1. Common soil remediation technologies (from Reddy et al., 1999)

2.2.1 In-situ methods

In-situ remediation methods treat the contaminated soil and/or water without being excavated or transported. In-situ methods are advantageous because they are often cost effective, make little site disruption, and possess increased safety due to a lessened risk of accidental contamination exposure to both on-site workers and the general public (Reddy, 1999). However, in-situ methods generally require a longer time period, and there is less certainty about the uniformity of treatment because of the variability in soil and aquifer characteristics. A comparison of some in-situ soil remediation approaches is listed in Table 2.1.

Different in-situ technologies have some strengths and limitations in their applications. For example, soil vapor extraction is a well developed technology for remediation of hydrocarbon contaminated sites. However, this technology becomes less effective when the soil characteristic is heterogeneous and there is low hydraulic conductivity. Similarly, there are differences in technology availability and cleanup cost. The contaminated site manager needs to have clear idea about such characteristics of each alternative under evaluation.

Table 2.1 Comparative assessment of in-situ soil remedial technologies (from Reddy et al., 1999)

Technology	Strengths	Factors affect the treatment	Cost range	Commercial availability
Soil vapor extraction	It is a proven technology	Not effective for heterogeneous and low hydraulic conductivity soils	<$100/ton	Widespread
Soil flushing	It is effective for residual contaminant reduction	Flushing solution may trap in soil; not effective for low conductivity soils	$80-$165/ton	Very limited
Electrokinetics	Useful for low hydraulic conductivity soils and mixed contaminants	Not effective for metallic contaminants	$90-$130/ton	Very limited
Bioremediation	This technology converts contaminants into non hazardous substance; it requires low cleanup cost	It requires lengthy treatment time; not effective for low hydraulic conductivity soils	$27-$310/ton	Widespread
Soil heating	Hydrocarbon can be easily recovered by this technology	Not effective for metallic contaminants and low hydraulic conductivity soils	$50-$100/ton	Limited
Vitrification	Effective for treatment of mixed contaminants	It converts contaminated soil into glassy structured soil; not effective for metallic compounds	$350-$900/ton	Limited
Solidification /stabilization	It is a proven technology	Not effective for low hydraulic conductivity soils	$100-$150/ton	Widespread
Phytoremediation	It produces less secondary waste and it has capability of treating broad range of contaminants	Applicable to limited to shallow depths and low concentration levels; it requires lengthy treatment time and there is risk of food chain contamination	<$100/ton	Very limited

2.2.2 Ex-situ methods

Ex-situ methods treat contaminated soils and/or groundwater after excavation. They often require shorter cleanup time period as compared to in-situ methods. Another advantage of ex-situ methods is that they provide more certainty about the uniformity of treatment because of the ability to homogenize and continuously mix the soil. Excavated soil can be treated on site or off-site depending on the site-specific conditions. Ex-situ treatments require excavation of soils, resulting in increased costs. Moreover, the urban settings characteristics, including neighboring buildings and narrow streets, often limit the use of onsite treatment facilities. Therefore, off-site treatment, requiring transport of contaminated materials to a treatment facility, is often necessary at urban contaminated sites. Ex-situ treatment methods are attractive because consideration does not need to be given to subsurface conditions. Ex-situ treatments also offer greater control and monitoring during remedial activity implementation (Reddy et al., 1999). A comparison among ex-situ remediation technologies is shown in Table 2.2.

Table 2.2 Comparative assessment of ex-situ soil remedial technologies (from Reddy et al., 1999)

Technology	Strengths	Factors affect the treatment	Cost range	Commercial availability
Soil washing	Volume of contaminated soil is reduced significantly	It is not effective in fine textured soil	$100-$300/ton	Widespread
Solvent extraction	It has capability of treating broad range of contaminants	Not effective in clays	$100-$500/ton	Limited
Chemical dechlorination	It reduces toxicity of contaminants; it can be used with other technologies	Not applicable in the sites with inorganic pollutants	$300-$500/ton	Limited
Electrokinetics	Applicable for low hydraulic conductivity soils and mixed contaminants	Not effective for remediation of metal contaminated soils	$90-$130/ton	Very limited

Thermal desorption	It requires lower cost than incineration	Not effective in clays	\$74-\$184/ton	Widespread
Incineration	It has capability of treating broad range of contaminants	The cleanup cost is high	\$500-\$1500/ton	Widespread
Vitrification	Effective for treatment of mixed contaminants	The cleanup cost is high	\$90-\$700/ton	Very limited
Bioremediation	It is a simple technology to apply; it is cost effective	Different environmental factors affect the effectiveness of this technology	\$27-\$310/ton	Widespread
Solidification	It is a proven technology; it has capability of treating broad range of contaminants	Not applicable for organic soils	\$50-\$250/ton	Widespread

2.3 Multi-criteria decision analysis (MCDA) for environmental management

Multi-criteria decision analysis (MCDA) methods have been applied to aid environmental managers to ensure better decision by selecting the best alternative. MCDA provides a systematic way to clarify the problems in a decision making process, and helps to evaluate the alternatives based on the decision maker's values and preferences. Conventional decision methods, including cost-benefit analysis, fixed target approach, and single objective linear programming, dominated to solve multi-criteria problems until the end of the 1960s (Nijkamp et al., 1990). These methods mainly considered cost criterion, and failed to address the issue of multiple criteria and trade-offs among criteria. Since the early 1970s, MCDA was introduced in order to cope with this problem. The MCDA method is a simple and intuitive approach that helps to address potential areas of conflicts among stakeholders (Cheng 2000; Linkov et al. 2006). According to Hwang and Yoon (1981), MCDA tools fall into a group of 17 methods based on the type and salient features of information received from decision makers (Fig. 2.2).

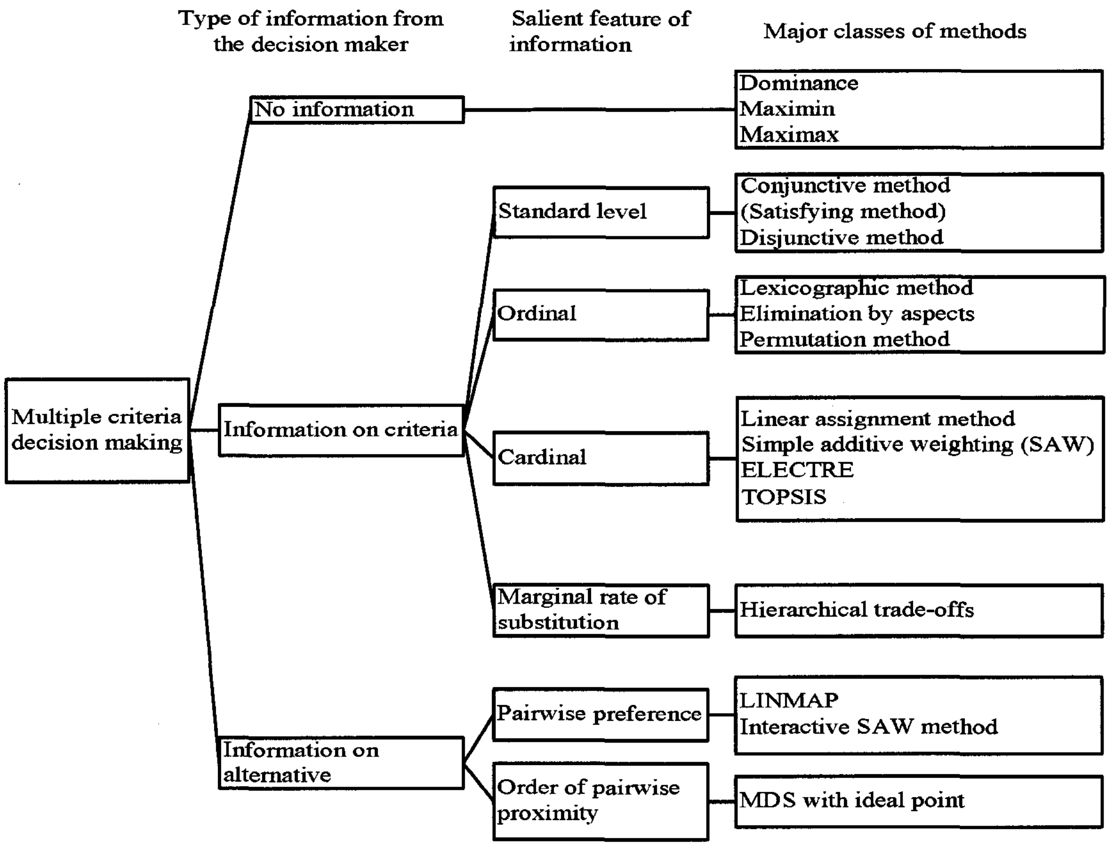


Fig. 2.2. Taxonomy of classical MCDA methods (from Cheng, 2000)

However, these MCDA methods were modified by Hwang (1987). Three new methods were added and six methods were removed from the list. The new added methods are lexicographic semi order method; weighted product method (WPM) and distance from target method. The methods permutation, hierarchical trade-offs, analytical hierarchical process (AHP), the linear programming techniques for multidimensional analysis of preference (LINMAP), the interactive simple additive weighting method and the multidimensional scaling (MDS) were removed from the previous taxonomy.

Depending on criteria information characteristics, the information is divided into three categories, a) Standard data: decision maker provides the minimum acceptable value for each criterion. Either conjunctive method or disjunctive method is used at this level; b) Ordinal data: decision maker provides ordinal data (position of the data in a series) on the criteria weights. At this level the methods that can be applied are lexicographic, elimination by aspects and Lexicographic Semiorder methods, and c) Cardinal data: cardinal data (opinion on relation between criteria) on the criteria weights is provided by the decision makers. In such cases many methods are applicable including linear assignment (LA), simple weighted addition (SWA), elimination and choice expressing the reality (ELECTRE), technique for order performance by similarity to ideal solution (TOPSIS), weighted product method, and distance-from-target (DT) methods.

There is a plethora of references regarding application of various MCDA tools in environmental management projects and related areas. For example, the allocation of Jordan River Basin water among bordering nations was determined by ELECTRE (Bella et al., 1996). Joubert et al. (1997), Ning and Chang (2002), Gregory and Failing (2002), and Gregory and Wellman (2001) applied the multi-attribute utility theory (MAUT) for water and coastal resources management projects. Al-Rashdan et al. (1999) used outranking method preference ranking organization method for enrichment evaluations (PROMETHEE) for prioritization of wastewater projects in Jordan. Rogers et al. (2004) used the same method to select novel technological alternatives for sediment management. There have been numerous applications of MAUT in environmental management projects. For instance, MAUT was applied by Arvai and Gregory (2003) for identifying radioactive waste cleanup priorities at the Department of Environment (DOE) sites. Prato (2003) also applied MAUT for selection of management alternativeS for Missouri River. In addition to MAUT, Ganoulis (2003) applied outranking method (e.g., ELECTRE) for evaluating alternative strategies for wastewater recycling and reuse in the Mediterranean. Mardle et al. (2002) applied AHP for analyzing priorities in fishery management. The application of AHP can also be found in the works of Fernandes et al. (1999), Soma (2003), Yurdakul (2004), Al-Ahmari (2007), Moran et al., (2007) and Wong et al. (2008).

The MCDA approaches have also been combined with many other decision support techniques to develop a number of decision support systems (DSS). For example, Hong et al. (1991) designed a spreadsheet-based DSS integrated with SAW to perform loan approval judgments. French (1996) applied MCDA methods to build a DSS for emergency responses on nuclear accidents. Norbis et al. (1996) applied multi-objective integer programming to the DSS in order to solve resource constrained scheduling problems. For resource planning, Al-Shemmeri et al. (1997) developed an effective monitoring system using an outranking method (PROMETHEE) to deal with the use of water resources. Qin et al. (2006) developed a DSS for the management of petroleum contaminated sites. Again, Hajkowicz and Higgins (2008) applied different MCDA methods (i.e., weighted summation, range of value, PROMETHEE II, evamix and compromise programming methods) for water management decision making problems.

2.3.1 Process of MCDA

MCDA is a process of making decisions in the presence of multiple, usually conflicting criteria (Chen et al., 1992, Figueira et al., 2005). A typical MCDA problem can be solved by the following steps (Fig. 2.3):

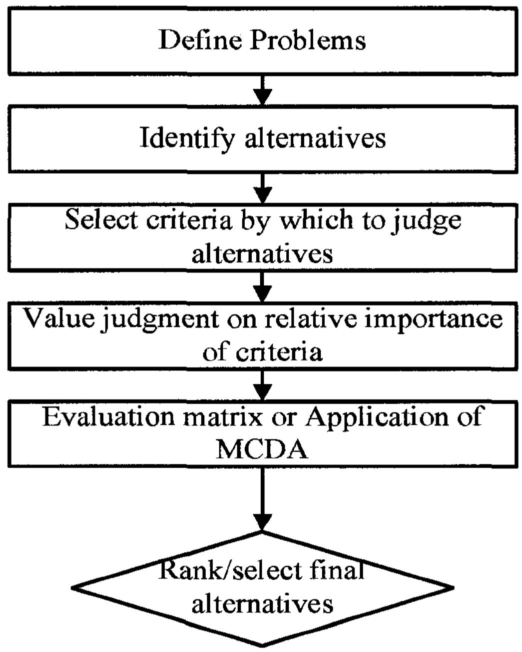


Fig. 2.3. Overall procedure of typical MCDA application (from Cheng, 2000)

In MCDA process the decision maker needs to define the problem at the beginning. Then he/she has to identify a number of alternatives applicable to solve the problem. The next step is to define the criteria to evaluate these alternatives. Many references indicate that defining criteria for a problem is a difficult and time-consuming task (Hwang et al., 1981; Chen et al., 1992 and Yoon et al., 1995). To identify the criteria representing a desired purpose, Chen et al. (1992) suggests that the analyst should use either a deductive or an inductive approach to build a hierarchy tree of criteria. A number of criteria are listed at the top level for a decision making problem. In the next stage the criteria are divided into sub-criteria. The process is continued at the bottom of a branch where information about the criteria is known or it is measurable. According to Cheng (2000) such criteria hierarchy tree has several advantages to deal with decision making problems, including (a) clarification of the intended meaning of the criteria at higher levels; (b) enabling to consider the criteria as independent entities among which appropriate trade-offs can be made later on, and (c) preventing undesirable double-counting of the same criterion. For example, Bonano et al. (2000) applied a hierarchy tree of criteria for evaluating remediation technologies by considering six major criteria (Fig.2.4). The criteria are programmatic issues, cost, socioeconomic issues, cultural resources, environment and human health. The programmatic issues can be divided into four-sub-criteria including time, type of waste generated, availability of technology and reliability of technology. Similarly, other criteria can be divided into various sub-criteria. The criteria are divided into sub-criteria until a criterion is measurable.

After defining the criteria for the problem, the next step is data acquisition on criteria importance. To solve a multi-criteria problem with uniform parameters or uniform data (e.g., only crisp data or only linguistic data) the classical multi-attribute decision making (MADM) methods can be used. The MADM methods should be modified when mixed input parameters are present (Chen et al., 1992).

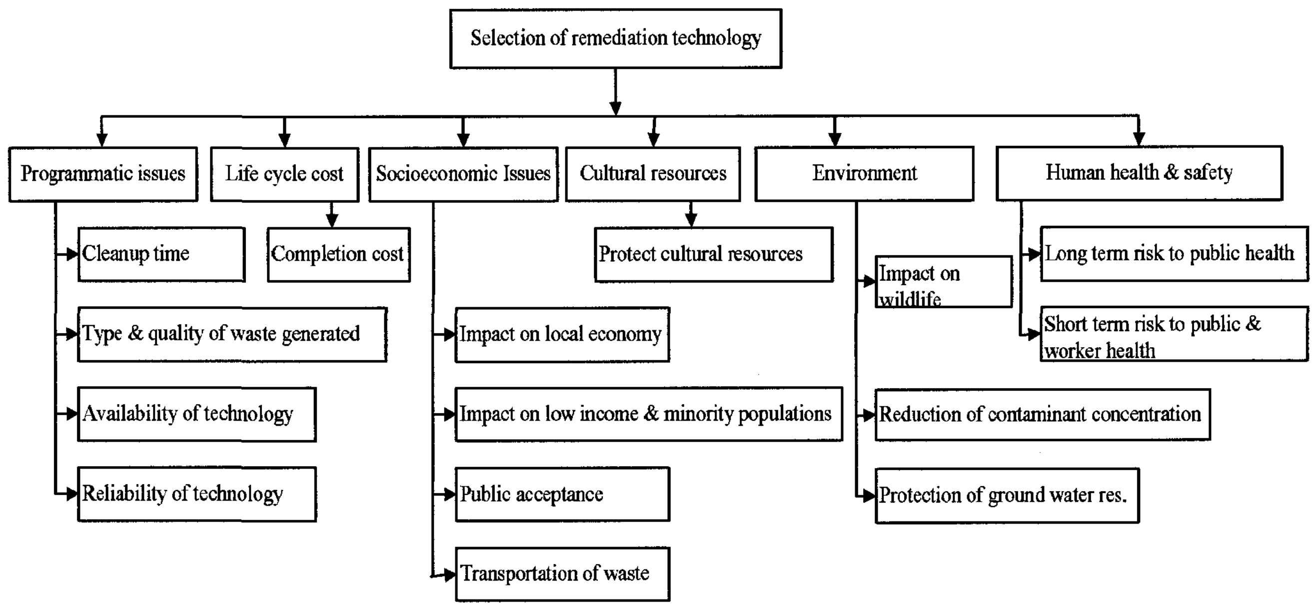


Fig. 2.4. A hierarchy of criteria for remediation alternative selection (from Bonano et al., 2000)

2.4 Description of three MCDA methods

The last step of MCDA process is to rank/select final alternatives through establishing the evaluation matrix by various methods. Three existing MCDA tools will be introduced here.

2.4.1 Simple additive weighting method (SAW)

The SAW is the simplest and widely used MCDA method. In this method the overall score of an alternative is computed as the weighted sum of the criteria values (Yoon and Hwang, 1995).

2.4.1.1 Procedure

(1) For each alternative, a score is computed by multiplying the scale rating of each criteria by its importance weight and summing these products over all criteria;

(2) The alternative with the highest score is selected. Mathematically, the value of an alternative can be selected as:

$$V(A_i) = V_i = \sum_{j=1}^{n} w_j v_j(x_{ij}), \quad i = 1,........,m; \quad j = 1,........,n \tag{2.1}$$

Where, $V(A_i)$ is the value function of alternative A_i, and w_j and $v_j(\cdot)$ are weight and value functions of criteria $_j$, respectively. x_{ij} is the outcome of the i^{th} alternative about the j^{th} criterion. However, Yoon and Hwang (1995) suggest that the value of alternative A_i can be rewritten as:

$$V_i = \sum_{j=1}^{n} w_j r_{ij}, \quad i = 1,.......m; \quad j = 1,........,n \tag{2.2}$$

Where r_{ij} is the normalized rating of x_{ij}. This procedure (calculation of r_{ij}) divides the rating of each criterion by its norm, so that each normalized rating of x_{ij} can be calculated as below (Yoon and Hwang, 1995).

r_{ij} for benefit criteria (the greater the criteria value the more its preference):

$$r_{ij} = \frac{x_{ij} - x_j^{\min}}{x_j^* - x_j^{\min}} \tag{2.3}$$

r_{ij} for cost criteria (the greater the criteria value the less its preference):

$$r_{ij} = \frac{x_j^* - x_{ij}}{x_j^* - x_j^{\min}} \tag{2.4}$$

Where x_j^* is the maximum value of j^{th} criteria and $x_j^{\min}$ is the minimum value of j^{th} criteria. By applying the above equations, the scale of measurement varies precisely from 0 to 1 for each criterion. The worst outcome of a certain criteria implies $r_{ij} = 0$, and the best outcome implies $r_{ij} = 1$.

2.4.2 Technique for order preference by similarity to ideal solution (TOPSIS)

According to Hwang and Yoon (1981) the chosen alternative should have the shortest distance from the ideal solution and the farthest distance from the negative-ideal solution. The following steps are followed to apply this method (Yoon and Hwang, 1995).

2.4.2.1 Procedure

(1) In TOPSIS vector normalization is used for calculation of r_{ij} :

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}}, \quad i = 1,.....,m; \quad j = 1,........,n \tag{2.5}$$

Where r_{ij} is normalized rating of criterion for each alternative, i is the index related to the alternatives, j is the index related to the criteria, and x_{ij} is rating of each criterion for each alternative;

(2) Then the weighted normalized decision matrix is calculated. The weighted value (v_{ij}) is calculated as:

$$v_{ij} = w_j r_{ij}, \quad i = 1,.....,m; \quad j = 1,........,n \tag{2.6}$$

Where w_j is the weight of the j^{th} criterion;

(3) Then the positive-ideal (A^*) and negative–ideal solutions (A^-) are calculated. The positive-ideal solution is the composite of all best criteria ratings attainable, and is calculated as:

$$A^* = \{v_1^*, v_2^*, ..., v_j^*, ..., v_n^*\} \tag{2.7}$$

Where v_j^* is the best value for the j^{th} criterion among all alternatives.

The negative-ideal solution is the composite of all worst criteria ratings attainable, and is calculated as:

$$A^- = \{v_1^-, v_2^-, ..., v_j^-, ..., v_n^-\} \tag{2.8}$$

Where v_j^- is the worst value for the j^{th} criterion among all alternatives;

(4) Then the separation or distance of each alternative from the positive-ideal solution (A^*) is calculated as:

$$S_i^* = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^*)^2}, \quad i = 1, \ldots\ldots\ldots, m \tag{2.9}$$

Similarly, the separation from the negative-ideal solution is calculated as:

$$S_i^- = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^-)^2}, \quad i = 1, \ldots\ldots\ldots, m \tag{2.10}$$

(5) Then the relative closeness (C_i^*) to the positive-ideal solution is calculated. For example, the relative closeness of an alternative A_i with respect to A^* is calculated as:

$$C_i^* = S_i^* / (S_i^* + S_i^-), \text{With}, 0 \le C_i^* \le 1 \text{ and } i = 1, \ldots\ldots\ldots, m \tag{2.11}$$

(6) Finally the alternatives are ranked according to C_i^* in descending order.

2.4.3 Weighted product method (WPM)

In weighted product method a product instead of a sum of the values is made across the criteria to penalize alternatives with poor criteria values (Easton, 1973).

2.4.3.1 Procedure

In this method, the scale rating of each criterion of each alternative is raised to a power equal to the importance weight of the criteria. Then the resulting values are multiplied over all criteria. The alternative with the highest product is selected. Mathematically, the most preferred alternative A_i can be calculated as:

$$V(A_i) = V_i = \prod_{j=1}^{n} x_{ij}^{w_j}, \quad i = 1, \ldots, m \tag{2.12}$$

Where x_{ij} is the outcome of the i^{th} alternative about the j^{th} criterion, with a numerically comparable scale, and w_j is the normalized importance weight of the j^{th} criterion.

Alternative values obtained by this method do not have a numerical upper bound (Yoon et al. 1995). Therefore, it is convenient to compare each alternative value with the value of ideal alternative. The value ratio between an alternative and the ideal alternative can be shown as (Yoon et al.1995):

$$R_i = \frac{V(A_i)}{V(A^*)} = \frac{\prod_{j=1}^{n} x_{ij}^{w_j}}{\prod_{j=1}^{n} (x_j^*)^{w_j}}, \quad i = 1,\ldots,m \tag{2.13}$$

Where x_j^* is the most favorable value for the j^{th} criterion. And the preference of A_i increases when R_i approaches 1.

2.5 Fuzzy-set theory

The conventional MCDA approaches are challenged by the uncertainties existing in various environmental management systems. Many data on criteria might not only be in numeric form. For example, in remediation technology selection problem, it is difficult to determine the public acceptance level of a technology. The information about these criteria could be numeric or linguistic (e.g., high, medium, low). The fuzzy-set theory is a powerful mathematical tool used for modeling and controlling uncertain systems. Fuzzy MCDA methods act as facilitator for approximate reasoning in decision making in the absence of complete and precise information (Gutierrez et al., 1995). Lotfi Zadeh introduced a simple and intuitive concept of a fuzzy-set in his seminar paper 'Fuzzy-Sets' in 1965; according to him fuzzy-set theory was developed and extensively applied in previous decade (Zadeh, 1965). A fuzzy-set is an extension of the traditional set theory (in which x is either a member of set A or not) and it is defined by membership function. An example of fuzzy sets is adapted here from Kucheva et al. (2000). If U is an ordinary set with elements $u_1, u_2, u_3, \ldots\ldots\ldots, u_m$, a fuzzy set A on U is defined by assigning a degree of membership between 0 and 1 to each $u_i \in U$, usually with regard to a linguistic term. For example, let U be the set of integers from 1 to 100 denoting the age of a person and let A be 'middle aged'. We can define a (subjective) function that assigns to each u_i a degree of membership $\mu_A(u_i) \in [0,1]$. Degree 0 denotes non-membership and degree 1 denotes full membership. A plausible model of "middle aged" will be obtained by using a function (membership function) that yields high values between, say 40 and 55 and gradually decreases towards the two edges of the scale. Thus, the degree of membership of 37, $\mu_A(37)$, can be 0.75, and of 82, $\mu_A(82)$ =0.1. In Fuzzy method, vagueness and imprecision associated with qualitative data can be represented more logically. Wang (1997) classified fuzzy theory into five major branches (Fig. 2.5), including (1) fuzzy mathematics: classical mathematics concepts are extended by replacing classical sets with fuzzy-sets; (2) fuzzy logic and artificial intelligence: approximations to classical logic are introduced and expert systems are developed based on fuzzy information and fuzzy reasoning; (3) fuzzy systems: include fuzzy control and fuzzy approaches in signal processing and communications; (4) uncertainty and information: different kinds of uncertainties are analyzed; and (5) fuzzy decision-making: considers optimization or satisfaction problems with soft constraints.

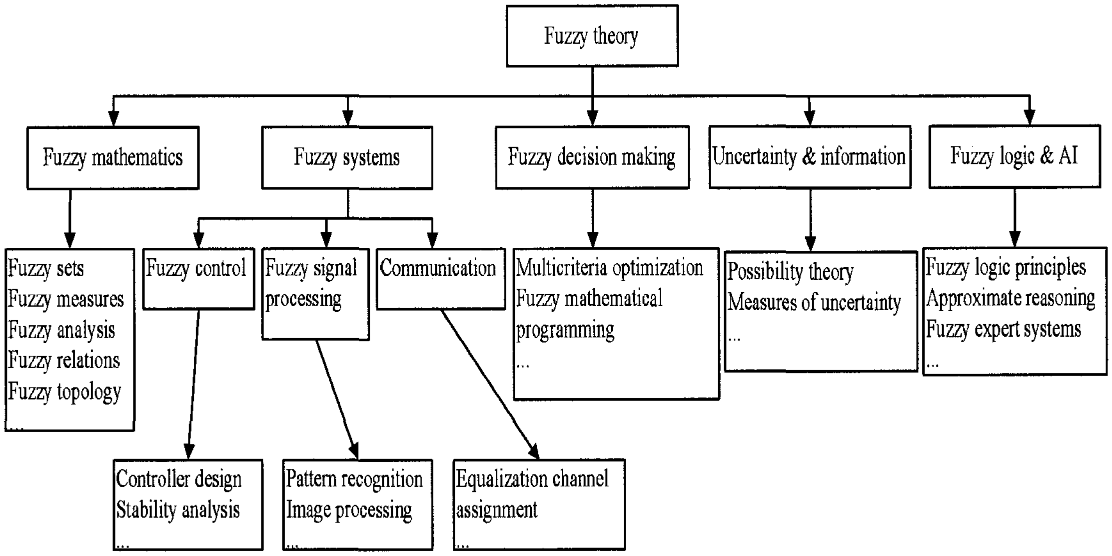


Fig. 2.5. Classification of fuzzy theory (from Wang, 1997)

These branches of fuzzy-set theory are dependent on each other and there are strong interconnections among them. For example, multi-criteria decision support system (MCDSS) is in the class of fuzzy decision-making that deals with satisfaction problems and it uses the concept from fuzzy mathematics (i.e., fuzzy-sets).

2.5.1 Handling uncertainty through fuzzy-set theory

The fuzzy-set theory can be applied to solve decision making problems with uncertainties described by linguistic variables (Chen et al., 1992). The linguistic terms are mostly encountered in the data acquisition of MCDA methods. Studies have shown that among the weightings techniques the decision makers are most comfortable with ordinal (linguistic) rankings of criteria importance (Hajkowicz et al., 2000). In the remediation technology selection problem the criteria (e.g., technology availability, public acceptance, etc.) can be adequately expressed in linguistic terms (i.e., "high", "medium", "low"). When such linguistic terms need to be counted in alternative evaluation process, the analyst needs to consider a fuzzy MCDA method. Nijkamp et al. (1990) suggests that input parameters containing fuzzy information can be converted into crisp values before applying any MADM methods.

Application of fuzzy-set theory for fuzzy input transformation includes two steps. First, the linguistic-term conversion is performed to convert the verbal terms into a fuzzy-set (Fig.2.6).

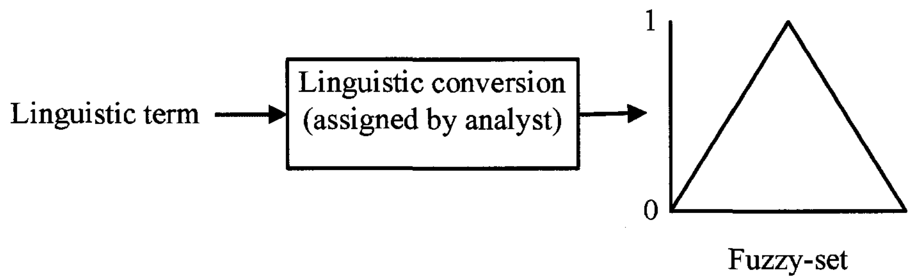


Fig. 2.6. Linguistic term conversion into fuzzy-set (adapted from Cheng, 2000)

A fuzzy-set is a class of objects with a continuation of membership grades (Zadeh, 1965). A membership function is assigned for the input value. Usually, the membership grades are [0,1]. When the grade of membership for a value in a set is one, this object is absolutely in that set; when the grade of membership is zero, the value does not convey any absolute significance (Hwang et al.1992).

2.5.2 Conversion of linguistic criteria preferences

A numerical approximation system was proposed by Chen and Hwang (1992) to systematically transform linguistic terms to their corresponding fuzzy-sets. A schematic diagram of the transformation process is shown in Fig.2.7.

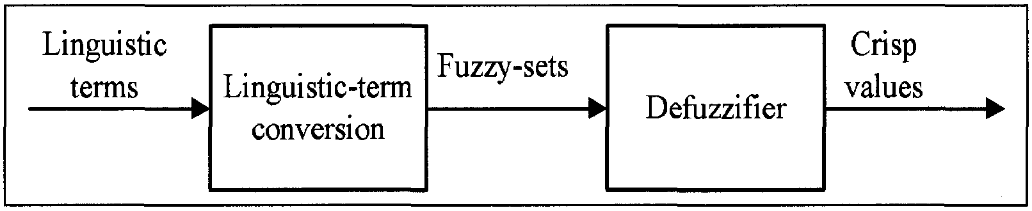
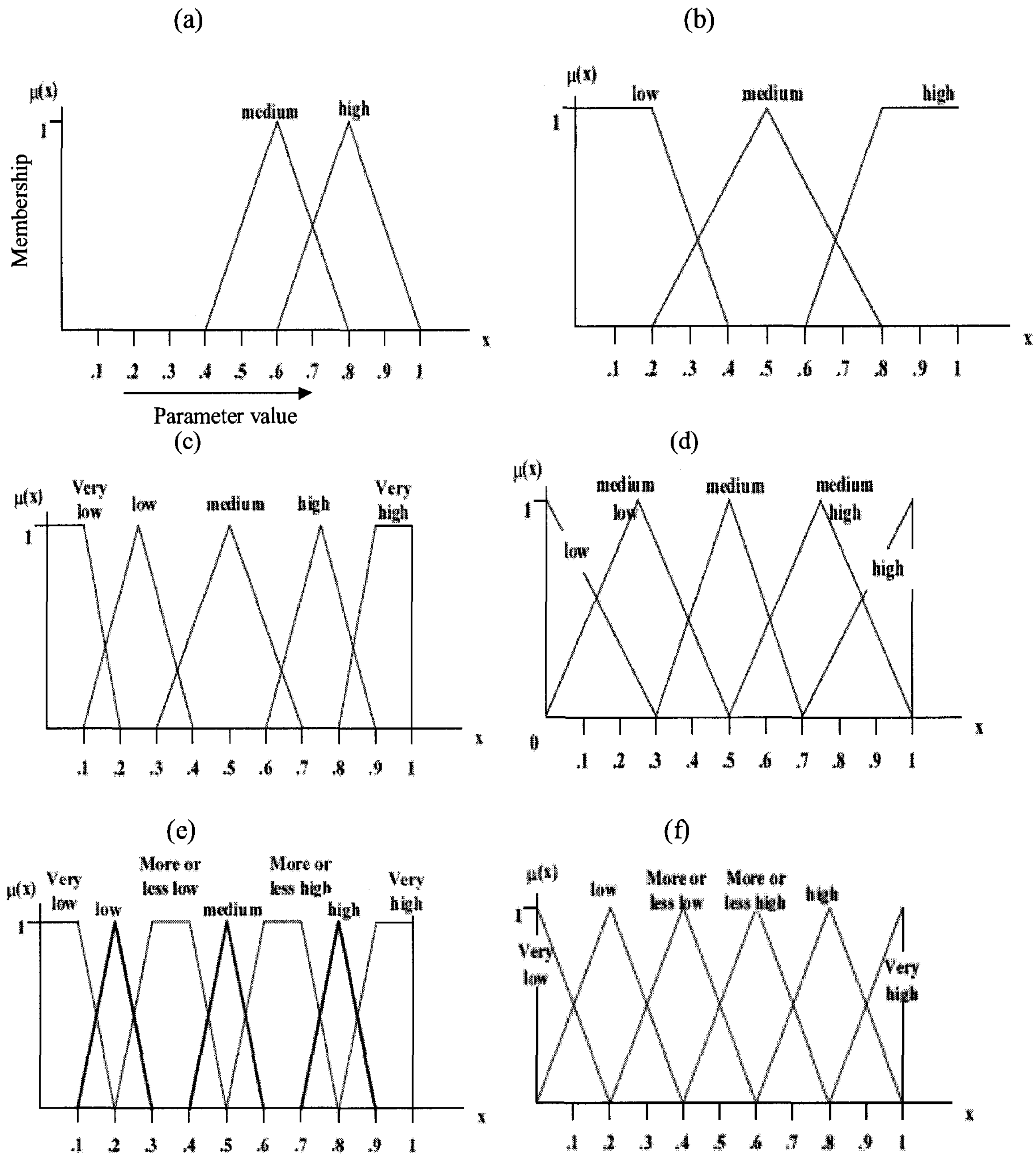


Fig. 2.7. Conversion of linguistic term into crisp values

According to them, the transformation requires eight conversion scales (Fig.2.8). These conversion scales are proposed by synthesizing and modifying previous works (Baas et al., 1977; Bonissone, 1982; Efstathiou et al., 1979; Efstathiou et al., 1982; Wenstop, 1976). It is assumed that the given figures can cover the universe of expressing the given terms "high" vs "low". One of the figures was applied when certain linguistic terms were provided. The determination of the number of conversion scales is intuitive. Miller (1965) suggested that "seven plus or minus two" of linguistic variables represent the greatest amount of information that an observer can give about the objects based on their preference and judgment. Miller's theory was also adopted by Chen and Hwang (1992) to develop their linguistic conversion scales (Fig. 2.8).


(a)
μ(x)
1
Membership
medium
high
x
.1 .2 .3 .4 .5 .6 .7 .8 .9 1
Parameter value
(b)
μ(x)
1
low
medium
high
x
.1 .2 .3 .4 .5 .6 .7 .8 .9 1
(c)
μ(x)
1
Very low
low
medium
high
Very high
x
.1 .2 .3 .4 .5 .6 .7 .8 .9 1
(d)
μ(x)
1
0
medium low
medium
medium high
low
high
x
.1 .2 .3 .4 .5 .6 .7 .8 .9 1
(e)
μ(x)
1
Very low
low
More or less low
medium
More or less high
high
Very high
x
.1 .2 .3 .4 .5 .6 .7 .8 .9 1
(f)
μ(x)
1
Very low
low
More or less low
More or less high
high
Very high
x
.1 .2 .3 .4 .5 .6 .7 .8 .9 1

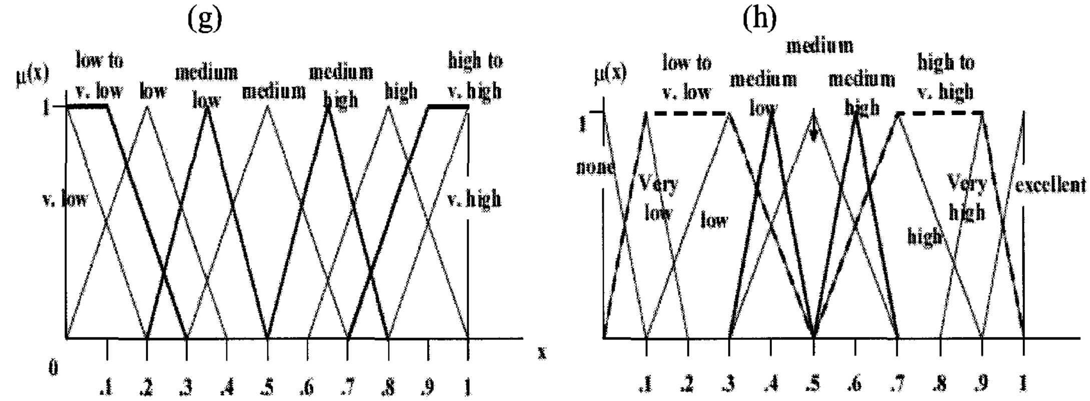


Fig. 2.8. Linguistic terms conversion scales

In the linguistic term conversion procedure, a scale figure is selected that contains all the verbal terms given by the decision-maker. Then the membership functions of those verbal terms are calculated to represent the meaning of those verbal terms. If the provided verbal terms exist in more than one figure, the simplest one should be considered. The verbal terms used in the above eight scales are in the universe: U = { "excellent", "very high", "high to very high", "high", "more or less high", "medium", "more or less low", "low", "low to very low", "very low" and "none" }. This universe of verbal terms is suitable to describe technology selection criteria like cost, maintenance, availability and community acceptability. But this universe of verbal terms is not applicable for clean up time criteria. Because to describe the clean up time the possible universe of linguistic terms will be U= {"extremely long", "very long",……, "extremely short"}. This universe and the proposed universe are different. Chen and Hwang (1992) suggest that the latter universe can be adjusted according to the nature of the criteria used in the decision problem. Therefore, "very long" cleanup time can be treated as "very high", and "very short" as "very low", respectively. A pair of words that represents extreme meanings can always be found for evaluation of any type of criteria. Eight pairs of opposite words are listed in Table 2.3. More examples on pairs of words can be found in Osgood (1975).

Table 2.3 Examples of linguistic universes

General	Price	Size	Distance	Weight	Hazard	Technique	Experience
high	expensive	large	far	heavy	danger	advanced	good
low	cheap	small	local	light	safe	basic	poor

2.5.3 Conversion of fuzzy-sets into crisp weights

In order to determine a crisp score for a fuzzy-set M, it is necessary to compare the fuzzy-sets with a maximizing fuzzy-set (fuzzy max, μ_{max}) and a minimizing fuzzy-set (fuzzy min, μ_{min}) (Chen and Hwang ,1992). The membership values of these two fuzzy-sets are calculated by equation (2.14) and (2.15).

$$\mu_{\max}(x) = \begin{cases} x, & 0 \le x \le 1 \\ 0, & otherwise \end{cases} \tag{2.14}$$

$$\mu_{\min}(x) = \begin{cases} 1-x, & 0 \le x \le 1 \\ 0, & otherwise \end{cases} \tag{2.15}$$

As well, the following Fig.2.9 shows the procedure of determining crisp values. This figure is similar to Chen and Hwang's (1992) conversion scale, Fig.2.8 (b).

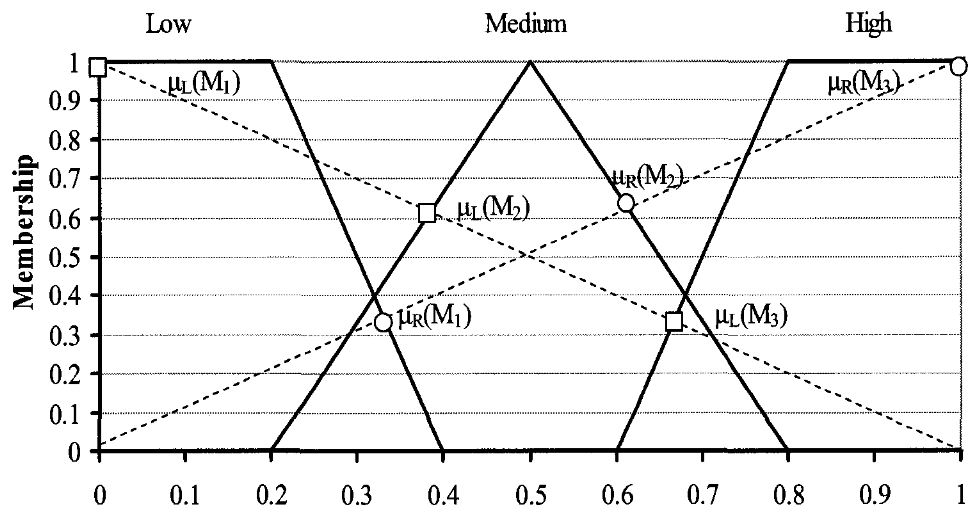


Fig. 2.9. Illustration of determining crisp value

In Fig.2.9 the maximum membership function (μ_{max}) and minimum membership function (μ_{min}) are computed and presented as two-diagonal dashed lines respectively. The right score [$\mu_R(M)$] refers to the intersections of the fuzzy-set M with the fuzzy max. The right score of M can be determined using:

$$\mu_R(M) = \sup[\mu_M(x) \wedge \mu_{\max}(x)] \tag{2.16}$$

Likewise, the left score [$\mu_L(M)$] of M can be determined using:

$$\mu_L(M) = \sup[\mu_M(x) \wedge \mu_{\min}(x)] \tag{2.17}$$

Given the left and right scores of M, the total score [$\mu_{T(M)}$] of M, can be calculated using:

$$\mu_T(M) = [\mu_R(M) + 1 - \mu_L(M)]/2 \tag{2.18}$$

The membership functions of M_1, M_2, M_3 are (Fig.2.9):

$$\mu_{M_1}(x)=\begin{cases}1, & 0\le x<0.2\\ \dfrac{0.4-x}{0.2}, & 0.2\le x<0.4\end{cases} \tag{2.19}$$

$$\mu_{M_2}(x)=\begin{cases}\dfrac{x-0.2}{0.3}, & 0.2\le x<0.5\\ \dfrac{0.8-x}{0.3}, & 0.5\le x<0.8\end{cases} \tag{2.20}$$

$$\mu_{M_3}(x)=\begin{cases}\dfrac{x-0.6}{0.2}, & 0.6\le x<0.8\\ 1, & 0.8\le x<1\end{cases} \tag{2.21}$$

The set of total score $[\mu_T(M)]$ can substitute the original linguistic terms.

2.6 Application of fuzzy-set approach in environmental problems

Fuzzy-set theories have been applied to a number of areas including the environmental sciences e.g., soil, forest air pollution, meteorology and water resources (Kuncheva et al., 2000). Kuncheva et al. (2000) proposed a fuzzy model of heavy metal loadings in Liverpool Bay. Bender et al. (2000) applied a fuzzy compromise approach in water resource systems planning under uncertainty. Vranes et al. (2000) developed a DSS to evaluate remedial alternatives considering technical, financial, environmental and social criteria. The system requires input of the numeric weight for criteria and technology performance information, thus their system fails to incorporate uncertainty in the evaluation process. van Moeffaert (2003) used fuzzy outranking method for choosing a sustainable wastewater treatment system in

Surahammar, Sweden. Li et al. (2003b) developed an integrated fuzzy-stochastic model to examine the fate of petroleum contaminants in groundwater and risk assessment. Hu et al. (2003) developed another rule based fuzzy expert system for hydrocarbon contaminated site characterization. Sadiq et al. (2004a) applied an analytical hierarchy process with a technique called fuzzy synthetic evaluation to determine the best management alternatives in a case of petroleum drilling waste discharge scenario. Sadiq et al. (2004b) developed a fuzzy based method to evaluate soil corrosiveness. To obtain diversified opinions of a large number of stakeholders and to deal with uncertainties in flood management problems, Akter el al. (2005) proposed fuzzy-set theory and fuzzy logic approaches. A risk based prioritization of air pollution monitoring using a fuzzy synthetic evaluation technique was proposed by Khan et al. (2005) to incorporate exposure frequency and potential hazard. Fuzzy classification combined with spatial prediction was used to assess the state of soil pollution by Amini et al. (2005). Najjaaran et al. (2006) developed a fuzzy expert system to assess corrosion of cast/ductile iron pipes from backfill properties. Li et al. (2006) developed a fuzzy-set approach for addressing uncertainties in health risk assessment of hydrocarbon-contaminated sites. The fuzzy-set approach was also used to evaluate different alternatives against different criteria due to a lack of crisp data. Fuzzy concepts in ranking were introduced by Baas and Kwakernak (1977), they assumed that criteria values and the relative importance of criteria were fuzzy numbers and the final evaluation of alternatives was computed by membership functions. Application of fuzzy multi-criteria method (FMCM) involves the evaluation of alternative actions with respect to multiple criteria given either in numeric or linguistic form (Altrock and Krause, 1994). The applications of FMCM found in literature have demonstrated a number of advantages in handling qualitative, unquantifiable criteria (Baas and Kwakernak, 1977; Altrock and Krause, 1994; Teng and Tzeng, 1996; McIntyre and Parfitt, 1998; Tang et al., 1999). For example, FMCM was applied by Chang et al. (2007) for ranking different landfill sites of Harlingen city of Texas, USA.

2.7 Summary of literature review

There are a number of contaminated sites in Canada. As well, a number of remediation alternatives are available in the market for remediation of contaminated sites. Meanwhile, perpetual progress in research and competition among technology developers has created a trend of more remediation alternatives in the future. As a result, it is difficult for a decision maker to select the most appropriate remediation option for a site. Besides, various stakeholders with different interests require to be involved in the decision making process of contaminated site management. Thus, there are many uncertainties (e.g., differences in stakeholder opinion, conflict among evaluation criteria) to be dealt with in a contaminated site decision making process. Though there are many decisions making tools available to aid the decision managers in their decision making process, most of these tools fail to deal with the uncertainty issues and to consider stakeholder opinions. Incorporation of fuzzy-set theory concept with existing multi-criteria decision analysis approach has been found to be the best way to deal with such problems. Application of fuzzy multi-criteria approach in various environmental decision making process has proven to be successful. However, there are limited applications of fuzzy multi-criteria approach particularly in contaminated site management. Though there is a plethora of literature and applications of fuzzy multi-criteria approach into different decision making problems, practical application of this idea into contaminated site management is still lacking. Considering this, in this study a fuzzy multi-criteria decision analysis (FMCDA) approach was developed for contaminated site management. The developed method was then applied to a case study site in northern British Columbia.

Chapter 3 Methodology

3.1 Overview of methodology

The following flow chart (Fig. 3.1) shows the steps that were followed to develop the fuzzy multi-criteria decision analysis approach in this research.

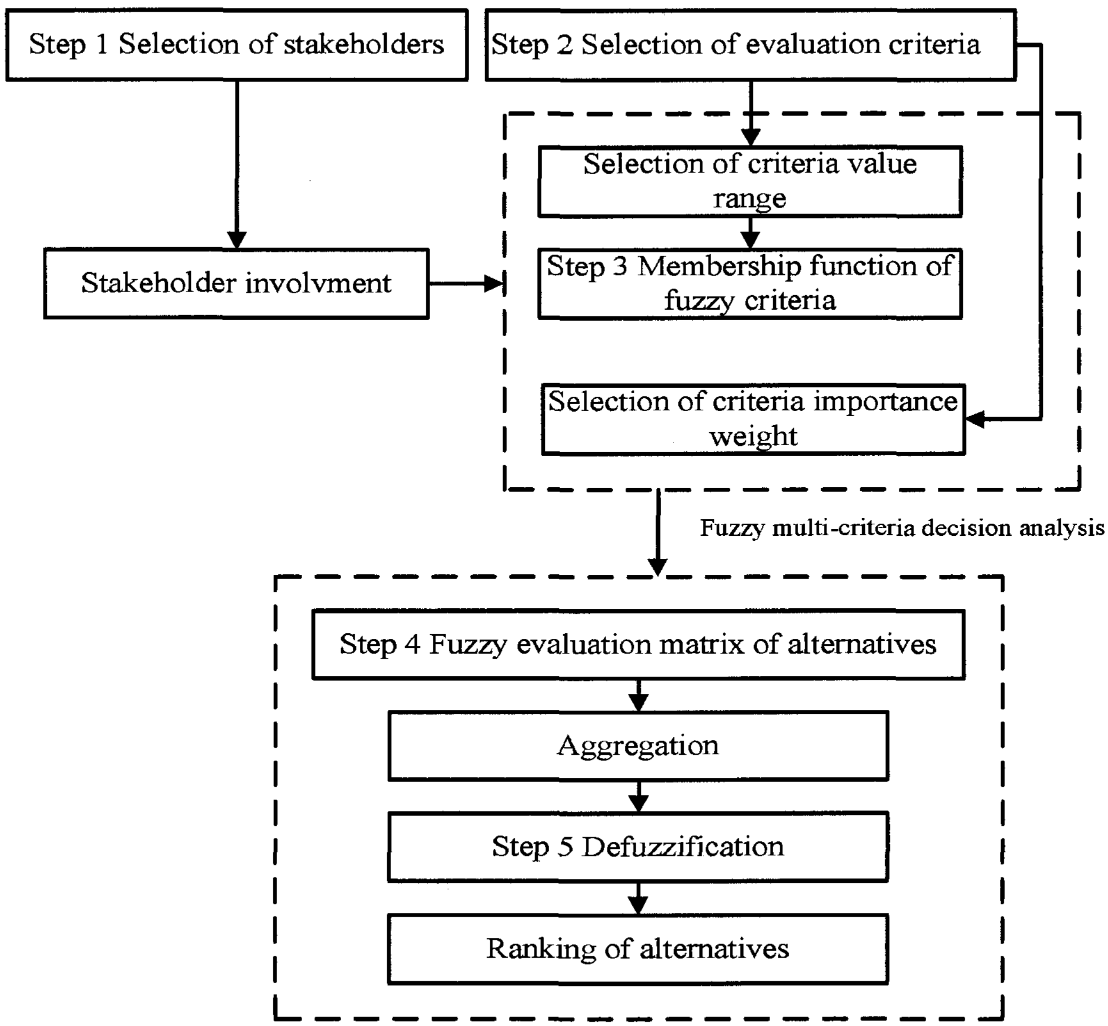


Fig. 3.1. Overall methodology of the developed fuzzy-multi criteria decision analysis approach

3.2 Step 1 Stakeholder selection

The management of a contaminated site may involve a number of stakeholders, and different stakeholders have different perspectives, priorities and concerns. Table 3.1 presents the common concerns of stakeholders regarding contaminated sites.

Table 3.1 Examples of typical stakeholder interests (adapted from USEPA, 2005)

Stakeholder	Interests
Facility owner	a) achieve regulatory compliance b) utilize risk-based techniques c) minimize/eliminate disruption of operations d) minimize costs e) reduce long-term treatment and liabilities
Regulatory agencies	a) protect human health and the environment b) protect groundwater resources c) achieve regulatory compliance d) eliminate off-site impacts to receptors e) involve stakeholders f) maintain reasonable schedule g) obtain reimbursement for oversight costs
Other stakeholders (Local/county agencies, property owners, special interest group, etc.)	a) optimize zoning b) maximize tax revenues c) accelerate schedule d) protect human health and the environment e) maximize quality of life f) protect groundwater resources

From the above table, it can be seen that a wide range of interests are existing among different stakeholders for contaminated site management. The interest of the facility owner lies in minimizing costs; however, regulatory agencies would emphasize stakeholder involvement or environmental resources protection. Again, people within the community may have concerns about quality of life.

Therefore, the owner of a site is not the only stakeholder to be considered in the decision making process of cleaning up a contaminated site. The principal stakeholders in the remediation decision making process include those who have interests in the land, its redevelopment, and impact on the environment. Bardos et al. (1999, 2000) identified the following potential stakeholders to be considered in a contaminated site management decision making process, including (a) site owners; (b) regulatory and planning authorities; (c) site users, workers, visitors; (d) financial community (banks, insurers); (e) site neighbors (tenants, dwellers, visitors); (f) advocacy organizations and local pressure groups; (g) consultants, contractors and technology vendors; and (h) researchers.

In this research, a number of written sources related to environmental projects were consulted to select potential stakeholders in the contaminated site management process. The following stakeholders were contacted for their input in developing fuzzy multi-criteria decision analysis (FMCDA) approach for contaminated site management, including (a) institution (i.e., universities); (b) site owner (i.e., oil and gas industries); (c) federal government; (d) provincial government; (e) research organizations; (f) non-governmental / non-profit organizations; (g) environmental consulting firms; (h) first nation community; (i) general public, and (j) other.

3.3 Step 2 Criteria selection

Selection of evaluation criteria is an important task in environmental decision making problems. This is also true in case of remedial alternative evaluation for contaminated sites.

According to Susan (2003), the most appropriate remediation option must meet the general criteria including practical design, feasible implementation, low impact on the landscape and reasonable cost. The author also provided a complete list of criteria for technology selection. Vranes et al. (2000) developed a decision analysis tool to select appropriate remediation technologies for different contaminants. In their developed system a wide range of criteria was applied, including overall cost, minimum achievable concentration, clean up time, public acceptability, reliability and maintenance. Again, Bonano et al. (2000) considered six criteria for evaluation, ranking and selection of remediation alternatives for Chromium (Cr) and Trichloroethylene (TCE) contaminated soil. These criteria included programmatic assumptions, cost, socio-economics, cultural, human health and archeological/historic resources. Janikowski et al. (2000) considered time, cost, effectiveness, social acceptance and feasibility criteria to select an alternative for pollutant management in agricultural lands.

3.3.1 Remediation alternative evaluation criteria

The following criteria were selected to develop the remediation alternative evaluation system. These criteria were selected after surveying pertinent references, literatures, previous case studies, professional experts and technology selection matrix of US Environmental Protection Agency (EPA). The criteria applied in the developed approach are: (a) clean up time (in-situ/ ex-situ); (b) overall cost (in-situ/ ex-situ); (c) minimum achievable concentration/ ability to reduce contaminant concentration; (d) community acceptability/public acceptability; (e) availability of the technology; (f) regulatory permitting acceptability; (g) development status; and (h) maintenance requirement.

3.3.2 Description of criteria

A. Cleanup time (in-situ and ex-situ)

The criterion of "time to complete cleanup" refers to the period of time required for completion of remedial activities, including site closure time. Required clean up period is an important criterion for technology selection. A lengthy cleanup process will increase the cost of the operation. It will also pose a negative impact on the public's opinion around a contaminated site. In general, the remedial alternative that requires less time for cleanup are more likely to be selected compared to other alternatives that require a longer period of time.

B. Overall cleanup cost (in-situ and ex-situ)

Cleanup cost is the most important deciding factor in the selection of a remedial alternative (Kamnikar, 2001). In this research, the criterion of "overall cleanup cost" includes design, construction, operations and maintenance (O and M) costs of a remedial alternative. Conversely, it excludes the cost of mobilization, demobilization, and pre- and post- treatment.

C. Minimum achievable concentration

"Minimum achievable concentration" criterion refers to the degree to which the technology is able to meet remediation objectives. It can be measured by capability of contaminant concentration reduction or efficiency of a remedial alternative.

D. Community acceptability

"Community acceptability" criterion refers to the level of technology acceptability by members of the general public that live or work near the contaminated site. Acceptability of a remedial technology in a community is an important concern in contaminated site management problem. Therefore, it is important to consult the affected community about the type of remedial strategy that is going to be applied to remediate a site.

E. Availability

The criterion of "availability of a remediation alternative" refers to the numbers of vendors which can design, construct, and maintain the technology. Availability of a remedial alternative depends on location of the contaminated site. In general, commercially available technologies are preferred over other emerging technologies.

F. Regulatory permitting acceptability

"Regulatory permitting acceptability" for a technology affects the acceptance of a remedial technology as part of a remediation plan. The level of acceptance can be expressed as a degree of existing regulatory and permitting acceptability of the technology. If regulators are reluctant to support a particular technology, it may be less attractive than those technologies that have more support.

G. Development status of a technology

"Development status" criterion refers to the current status of the technology, (i.e., laboratory scale, pilot scale, full scale). Remedial alternatives which are in a lower state (i.e. laboratory state), have a lower chance of being selected. However, these technologies should not be discounted. These alternatives can attain commercial status, if applied appropriately with alternatives in demonstrated status.

H. Technology maintenance requirement

The criterion of "technology maintenance requirement" refers to the level of complexity of the technology and how easy it is to maintain. If high maintenance is required for a technology, this will indicate that the technology has low reliability.

3.4 Step 3 Establishing membership functions of fuzzy criteria

Development of membership function is an important step in the application of fuzzy theory (Turksen, 1991). There are many approaches for generating fuzzy membership functions. However, triangular membership function is applied by many researchers to describe vagueness, ambiguity and uncertainties in the real-world system (Civanlar and Trussel, 1986; Lee 1996; Dou et al., 1997; Freissinet et al., 1999; Mohamed and Cote, 1999; Cheng and Lin, 2002; Li et al., 2003a; Mikhailov and Tsvetinov, 2004; Sadiq et al., 2004b; Chang et al., 2007, Li et al., 2007).

3.4.1 Triangular fuzzy numbers (TFNs)

A triangular fuzzy number (TFN) can be defined by specifying three numbers: (1) the most credible value, (2) the lowest possible value, and (3) the highest possible value. Fig.3.2 presents an example of a triangular fuzzy-set. The most credible value is assigned a membership value of 1, and any number that falls short of the lowest possible value or exceeds the highest possible value will get a membership grade of 0. The intermediate membership grades can be obtained by linear interpolation.

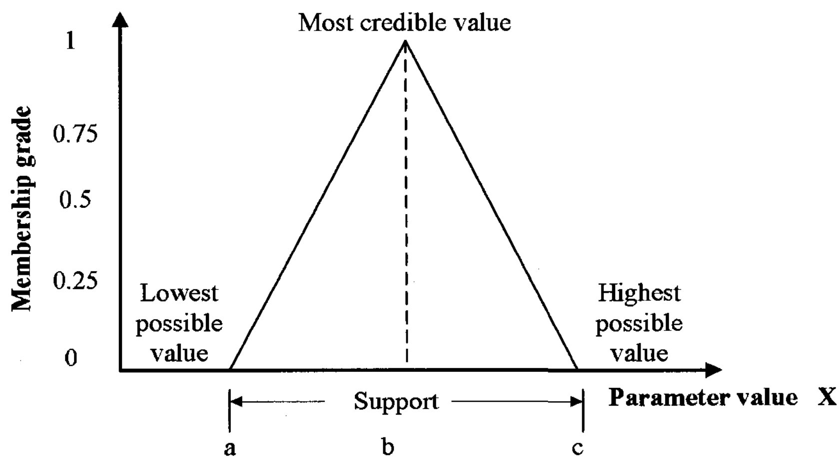


Fig. 3.2. Example of a triangular fuzzy-set

For example, a triangular fuzzy number $\tilde{N}$ can be defined by a triplet $a \leq b \leq c$, where b, a and c are the most credible value, the lowest possible value and the highest possible value, respectively. Then, the membership function ($\mu_{\tilde{N}}(x)$) can be defined as (Kaufmann et al., 1985; Mikhailov and Tsvetinov, 2004; Fenton and Wang, 2006):

$$\mu_{\tilde{N}}(x) = \begin{cases} (x-a)/(b-a), & a \leq x \leq b, \\ (c-x)/(c-b), & b \leq x \leq c, \\ 0, & \textit{Otherwise}. \end{cases} \tag{3.1}$$

According to Khan et al. (2002) the values of alternative performance rating can be crisp, fuzzy and/or linguistic. In the developed fuzzy multi-criteria evaluation system, TFNs were used to convert the remediation alternative performance information into lowest possible value, most credible value and highest possible value.

3.4.2 Selection of criteria value range

The evaluation criteria of remediation alternative are usually associated with uncertainty. For example, the overall cleanup cost for enhanced bioremediation for a particular contaminated site could vary from $50/m^3 to $300/m^3. In this research, such uncertainty will be addressed through fuzzy-set approach. Each criterion was divided into five fuzzy-sets of "low", "low to medium", "medium", "medium to high", and "high". For example, the criterion of "overall cleanup cost" was further divided into five sets ranging from "low" cost to "high" cost. Each fuzzy set was characterized by a triangular fuzzy number (TFN), and the highest possible values and the lowest possible values were selected as a value range for each criterion to develop the TFN fuzzy membership functions. The criteria value ranges were selected from pertinent references, previous case studies, and the U.S. environmental protection agency's remediation technologies screening matrix (USEPA, 1993). Table 3.2 lists the value ranges of criteria.

Table 3.2 Criteria value range

	Criteria		Criteria value range		Indicator
			Minimum	Maximum	
A	Cleanup time	In situ	6	60	month
		Ex situ (excavation)	4	12	month
B	Overall cost	In situ	50	275	$/ m^3$
		Ex situ (excavation)	100	300	$/m^3$
C	Minimum achievable concentration		10	90	% reduced concentration
D	Community acceptability		10	90	% of community population
E	Availability		1	10	Dimensionless
F	Regulatory permitting acceptability		1	10	Dimensionless
G	Development status		1	10	Dimensionless
H	Technology maintenance requirement		1	10	Dimensionless

From the above table, it can be seen that overall cleanup cost of in-situ alternatives vary from $50/m^3 to $275/m^3. And for ex-situ alternatives the costs vary from $100/m^3 to $300/m^3. Even, cleanup time for in-situ treatment vary from 6 to 60 months and for ex-situ the cleanup period vary from 4 to 12 months. However, other criteria values, including "development status", "availability", "maintenance requirement" and "regulatory permitting acceptability" have no unit to measure. Hence, a dimensionless and numerical scale consisting of values from 1 to 10 was applied to measure these criteria, where, 1 presents the lowest possible value and 10 presents the highest possible value. For the criterion "availability" of technology a rating of 1 means low availability, 5 means average availability and 10 means high availability, respectively. As well, the intermediate values are used to rate other possibilities of technology availability. Again, for the criterion "development status" a rating of 1 means the technology is at a laboratory stage and a rating of 10 means that the technology is widely applied and it is a proven technology. In the same way, for the criterion "technology maintenance requirement" a rating of 1 means that the technology requires least maintenance and a rating of 10 means that the technology requires higher maintenance during operation.

3.4.3 Membership functions of fuzzy criteria

The existing approach of probabilistic distributions (e.g., Bayesian approach) can not quantify the uncertainties in evaluation criteria adequately. However, these uncertainties can be better explained by linguistic variables and then quantified by fuzzy-set theory (Petrovic and Petrovic, 2002; Li, 2003a). In this research, the construction of fuzzy-sets of criteria depends on experiences of the experts and stakeholders who have in-depth knowledge on site management (Fayek and Sun, 2001). The stakeholder opinions were collected through a questionnaire survey, and fuzzy membership functions of evaluation criteria were then developed based on stakeholder opinions (Appendix I). The answer with highest survey response rate for each fuzzy-set was selected as full membership (i.e. 1). Other response rates of that fuzzy-set were covered as lowest possible and highest possible value. Such process was applied to address uncertainties in a fuzzy-set. However, the representative responses were counted only to construct the corresponding fuzzy membership function.

A. Time required for cleanup

In-situ treatment

From the survey it was found that 50% of respondents indicated that the option in-situ cleanup time required by an alternative should be approximately 1 year or less to be considered as "short" cleanup time, therefore 1 year was selected as the most credible value with a membership function of 1 in "short" cleanup time fuzzy-set. Next, 26.32% of the respondents selected that the option in-situ cleanup time required should be approximately 18 months and 2 years to be accepted as "short to medium" cleanup time. As the percentage of respondents were similar, an average value of 18 months and 2 years (i.e. 1.7 years) was selected as full membership in the "short to medium" cleanup fuzzy-set. Then, 47.37% of the respondents selected that "in-situ cleanup time required by an alternative should be approximately 3 years" to be accepted as a "medium" cleanup period. Subsequently, 26.32% of the respondents also selected that "in-situ cleanup time should be approximately 3 years" to be considered as "medium to long" time period. But this response rate was similar with the response rate of "medium" cleanup time. However, similar percentage of response (18.42%) was found for 42 months and 4 years. For these reasons, an average time period of 3 years, 42 months and 4 years (i.e.3.5 years) was selected as most credible value or full membership in the "medium to long" cleanup time fuzzy-set. Lastly, fifty percent of the respondents selected that "in-situ cleanup time required should be approximately 5 years or greater" to be considered as a "long" cleanup period. For this reason, 5 years or greater cleanup period was selected as "long" cleanup time. Table 3.3 lists the values of stakeholder opinion on in-situ cleanup time.

Table 3.3 Survey on the fuzzy-sets of in-situ cleanup time

(1) Survey on short cleanup time	
Cleanup time should be approximately:	**Response percentage (%)**
6 months or less	23.68%
1 year or less	**50.00%**
18 months or less	5.26%
2 years or less	13.16%
30 months or less	0.00%
3 years or less	0.00%

42 months or less	0.00%
4 years or less	0.00%
54 months or less	0.00%
5 years or less	5.26%
No opinion	2.635
Total	100.00%

(2) Survey on short to medium cleanup time

Cleanup time should be approximately:	Response percentage (%)
6 months	2.63%
1 year	18.42%
18 months	**26.32%**
2 years	**26.32%**
30 months	5.26%
3 years	10.53%
42 months	0.00%
4 years	0.00%
54 months	0.00%
5 years	5.26%
No opinion	5.26%
Total	100.00%

(3) Survey on medium cleanup time

Cleanup time should be approximately:	Response percentage (%)
6 months	0.00%
1 year	2.63%
18 months	5.26%
2 years	23.68%
30 months	7.89%
3 years	**47.37%**
42 months	2.63%
4 years	2.63%
54 months	0.00%
5 years	5.26%
No opinion	2.63%
Total	100.00%

(4) Survey on medium to long cleanup time

Cleanup time should be approximately:	Response percentage (%)
6 months	0.00%
1 year	2.63%
18 months	0.00%
2 years	2.63%
30 months	10.53%
3 years	**26.32%**

42 months	**18.42%**
4 years	**18.42%**
54 months	2.63%
5 years	7.89%
No opinion	10.53%
Total	100.00%

(5) Survey on long cleanup time

Cleanup time should be approximately:	**Response percentage (%)**
6 months or greater	0.00%
1 year or greater	2.63%
18 months or greater	0.00%
2 years or greater	0.00%
30 months or greater	0.00%
3 years or greater	10.53%
42 months or greater	2.63%
4 years or greater	18.42%
54 months or greater	10.53%
5 years or greater	**50.00%**
No opinion	5.26%
Total	100.00%

In the following Fig. 3.3 the developed membership functions of the fuzzy-sets of in-situ cleanup time are shown. The membership functions of these fuzzy-sets (i.e., short, short to medium, medium, medium to long and long) are developed based on the above collected data.

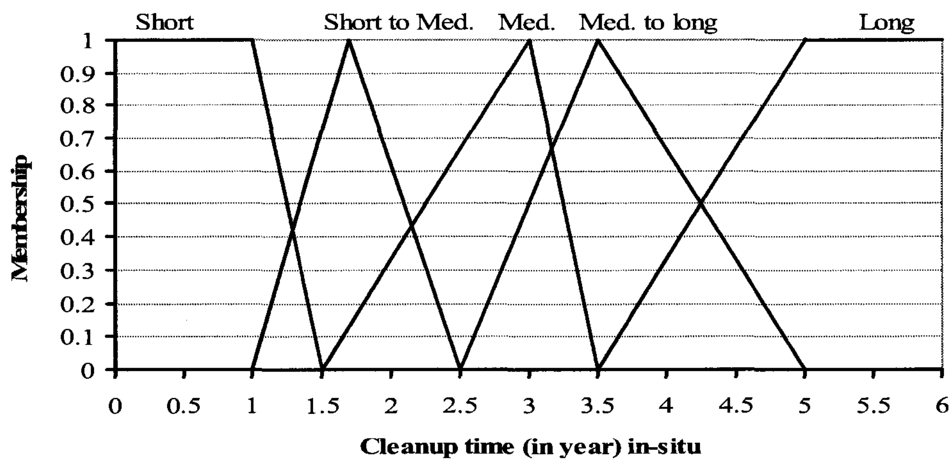


Fig. 3.3. Membership functions of fuzzy-sets "cleanup time (in-situ)" criterion

Ex-situ treatment

From the survey it was also found that 60.53% of the respondents indicated that "ex-situ cleanup time should be approximately 4 months or less" to be considered as "short" cleanup time; 52.63% of the respondents selected that "ex-situ cleanup time should be approximately 6 months" to be considered as "short to medium" cleanup time; 47.37% of the respondents selected that " ex-situ cleanup time should be approximately 8 months" to be accepted as "medium" cleanup time; 34.21% of the respondents selected that "ex-situ cleanup time should be approximately 10 months" to be considered as "medium to long"; and 60.53% of the respondents selected that "ex-situ cleanup time should be approximately 12 months or greater" to be considered as long cleanup time. Table 3.4 shows the values collected from the stakeholders on ex-situ cleanup time.

Table 3.4 Survey on the fuzzy-sets of ex-situ cleanup time

(1) Survey on short cleanup time (ex-situ)	
Cleanup time should be approximately:	**Response percentage (%)**
4 months or less	**60.53%**
5 months or less	10.53%
6 months or less	21.05%
7 months or less	0.00%
8 months or less	0.00%
9 months or less	0.00%
10 months or less	0.00%
11 months or less	0.00%
12 months or less	5.26%
No opinion	2.63%
Total	100.00%

(2) Survey on short to medium cleanup time (ex-situ)

Cleanup time should be approximately:	**Response percentage (%)**
4 months	5.26%
5 months	7.89%
6 months	**52.63%**
7 months	10.53%
8 months	7.89%
9 months	5.26%
10 months	0.00%
11 months	0.00%
12 months	0.00%
No opinion	10.53%
Total	100.00%

(3) Survey on medium cleanup time (ex-situ)

Cleanup time should be approximately:	**Response percentage (%)**
4 months	2.63%
5 months	0.00%
6 months	10.53%
7 months	2.63%
8 months	**47.37%**
9 months	10.53%
10 months	5.26%
11 months	0.00%
12 months	7.89%
No opinion	13.16%
Total	100.005

(4) Survey on medium to long cleanup time (ex-situ)

Cleanup time should be approximately:	**Response percentage (%)**
4 months	2.63%
5 months	0.00%
6 months	0.00%
7 months	7.89%
8 months	7.89%
9 months	18.42%
10 months	**34.21%**
11 months	2.63%
12 months	13.16%
No opinion	13.16%
Total	100.00%

(5) Survey on long cleanup time (ex-situ)	
Cleanup time should be approximately:	**Response percentage (%)**
4 months or greater	2.63%
5 months or greater	0.00%
6 months or greater	0.00%
7 months or greater	0.00%
8 months or greater	2.63%
9 months or greater	2.63%
10 months or greater	10.53%
11 months or greater	10.53%
12 months or greater	**60.53%**
No opinion or greater	10.53%
Total	100.00%

Fig. 3.4 shows the developed membership functions for the fuzzy-sets of ex-situ cleanup time.

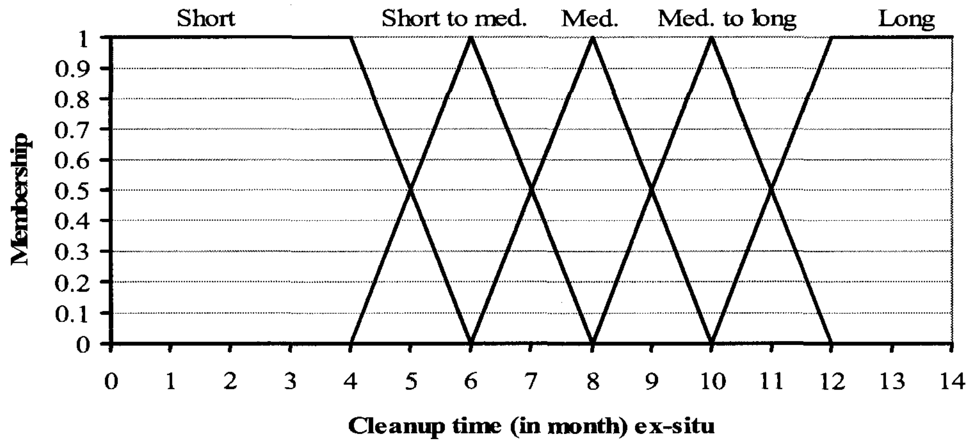


Fig. 3.4. Membership functions of fuzzy-sets of "cleanup time (ex-situ)"

B. Cleanup Cost

In-situ treatment

From the survey it was found that 57.89% of respondents selected that "in-situ cleanup cost should be approximately \$50 per m^3 or less" to be considered as "low" cleanup cost; 26.32% of the respondents indicated that "in-situ cleanup cost should be approximately \$100 per m^3" to be considered as "low to medium" cleanup cost; 36.84% of the respondents indicated that "in-situ cleanup cost should be approximately \$150 per m^3" to be considered as "medium" cleanup cost; 28.95% of the respondents selected that "in-situ cleanup cost should be approximately \$200 per m^3" to be accepted as "medium to high" cleanup cost; 28.95% of the respondents selected that " the in-situ cleanup cost should be approximately \$275 per m^3" to be considered as "high" cleanup cost. Table 3.5 shows the values for establishing membership functions of in-situ cleanup cost collected through a questionnaire survey.

Table 3.5 Survey on the fuzzy-sets of in-situ cleanup cost

(1) Survey on low cleanup cost (in-situ)

Cleanup cost should be approximately:	Response percentage (%)
\$50 per m^3 or less	**57.89%**
\$75 per m^3 or less	15.79%
\$100 per m^3 or less	10.53%
\$125 per m^3 or less	0.00%
\$150 per m^3 or less	0.00%
\$175 per m^3 or less	0.00%
\$200 per m^3 or less	0.00%
\$225 per m^3 or less	0.00%
\$275 per m^3 or less	0.00%
No opinion	15.79%
Total	100.00%

(2) Survey on low to medium cleanup cost (in-situ)

Cleanup cost should be approximately:	Response percentage (%)
\$50 per m^3	7.89%
\$75 per m^3	23.68%
\$100 per m^3	**26.32%**
\$125 per m^3	18.42%
\$150 per m^3	2.63%
\$175 per m^3	0.00%
\$200 per m^3	0.00%
\$225 per m^3	0.00%
\$275 per m^3	0.00%
No opinion	21.05%
Total	100.00%

(3) Survey on medium cleanup cost (in-situ)	
Cleanup cost should be approximately:	**Response percentage (%)**
$50 per m^3	2.63%
$75 per m^3	10.53%
$100 per m^3	13.16%
$125 per m^3	10.53%
$150 per m^3	**36.84%**
$175 per m^3	7.89%
$200 per m^3	0.00%
$225 per m^3	0.00%
$275 per m^3	0.00%
No opinion	18.42%
Total	100.00%

(4) Survey on medium to high cleanup cost (in-situ)	
Cleanup cost should be approximately:	**Response percentage (%)**
$50 per m^3	0.00%
$75 per m^3	0.00%
$100 per m^3	10.53%
$125 per m^3	13.16%
$150 per m^3	2.63%
$175 per m^3	18.42%
$200 per m^3	**28.95%**
$225 per m^3	0.00%
$275 per m^3	5.26%
No opinion	21.05%
Total	100.00%

(5) Survey on high cleanup cost (in-situ)	
Clean up cost should be approximately:	**Response percentage (%)**
$50 per m^3 or greater	2.63%
$75 per m^3 or greater	0.00%
$100 per m^3 or greater	0.00%
$125 per m^3 or greater	7.89%
$150 per m^3 or greater	13.16%
$175 per m^3 or greater	5.26%
$200 per m^3 or greater	5.26%
$225 per m^3 or greater	18.42%
$275 per m^3 or greater	**28.95%**
No opinion	18.42%
Total	100.00%

Fig. 3.5 shows the developed membership functions of the fuzzy-sets of in-situ cleanup cost.

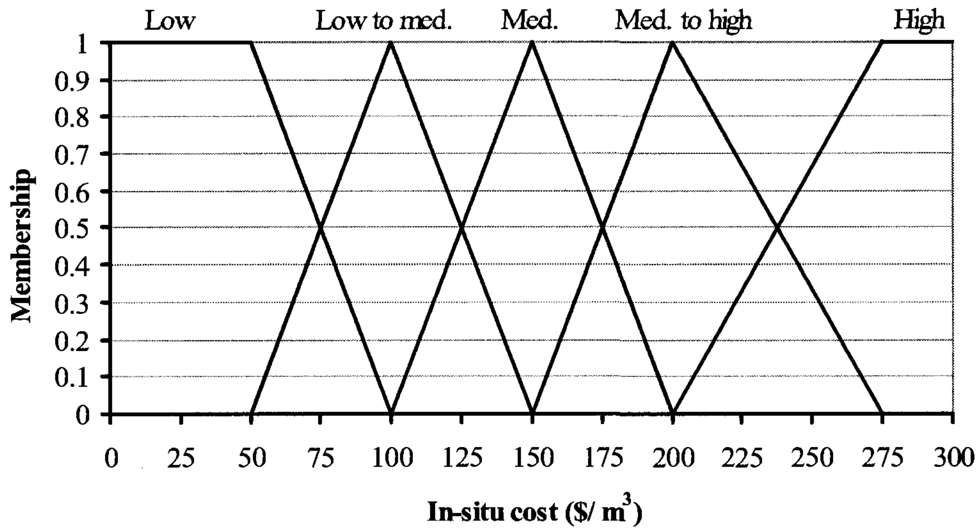


Fig. 3.5. Membership functions of fuzzy-sets of "cleanup cost (in-situ)"

Ex-situ treatment

55.26% of the surveyed respondents selected that "ex-situ cleanup cost should be approximately \$100 per m^3 or less" to be considered as "low" cleanup cost; 28.95% of the respondents selected that "ex-situ cleanup cost should be approximately \$150 per m^3" to be considered as "low to medium" cleanup cost; 31.58% of the respondents selected that "ex-situ cleanup cost should be approximately \$200 per m^3" to be considered as "medium" cleanup cost; 21.05% of the respondents selected that "ex-situ cleanup cost should be approximately \$225 per m^3" to be considered as "medium to high" cleanup cost; 36.84% of the respondents selected that "ex-situ cleanup cost should be approximately \$300 per m^3" to be considered as "high" cleanup cost. Table 3.6 shows the values collected through the questionnaire survey on ex-situ cleanup cost.

Table 3.6 Survey on the fuzzy-sets of ex-situ cleanup cost

(1) Survey on low cleanup cost (ex-situ)	
Ex-situ cleanup cost should be approximately:	**Response percentage (%)**
$100 per m^3 or less	**55.26%**
$125 per m^3 or less	26.32%
$150 per m^3 or less	5.26%
$175 per m^3 or less	0.00%
$200 per m^3 or less	0.00%
$225 per m^3 or less	0.00%
$250 per m^3 or less	0.00%
$275 per m^3 or less	0.00%
$300 per m^3 or less	0.00%
No opinion	13.16%
Total	100.00%

(2) Survey on low to medium cleanup cost (ex-situ)	
Cleanup cost should be approximately:	**Response percentage (%)**
$100 per m^3	13.16%
$125 per m^3	26.32%
$150 per m^3	**28.95%**
$175 per m^3	13.16%
$200 per m^3	2.63%
$225 per m^3	0.00%
$250 per m^3	0.00%
$275 per m^3	0.00%
$300 per m^3	0.00%
No opinion	15.79%
Total	100.00%

(3) Survey on medium cleanup cost (ex-situ)	
Cleanup cost should be approximately:	**Response percentage (%)**
$100 per m^3	2.63%
$125 per m^3	7.89%
$150 per m^3	18.42%
$175 per m^3	13.16%
$200 per m^3	**31.58%**
$225 per m^3	0.00%
$250 per m^3	10.53%
$275 per m^3	0.00%
$300 per m^3	0.00%
No opinion	15.79%
Total	100.00%

(4) Survey on medium to high cleanup cost (ex-situ)	
Cleanup cost should be approximately:	**Response percentage (%)**
$100 per m^3	0.00%
$125 per m^3	2.63%
$150 per m^3	7.89%
$175 per m^3	18.42%
$200 per m^3	5.26%
$225 per m^3	**21.05%**
$250 per m^3	13.16%
$275 per m^3	10.53%
$300 per m^3	0.00%
No opinion	21.05%
Total	100.00%

(5) Survey on high cleanup cost (ex-situ)	
Cleanup cost should be approximately:	**Response percentage (%)**
$100 per m^3 or greater	2.63%
$125 per m^3 or greater	0.00%
$150 per m^3 or greater	5.26%
$175 per m^3 or greater	5.26%
$200 per m^3 or greater	13.16%
$225 per m^3 or greater	5.26%
$250 per m^3 or greater	2.63%
$275 per m^3 or greater	15.79%
$300 per m^3 **or greater**	**36.84%**
No opinion	13.16%
Total	100.00%

By using the above data fuzzy membership function was developed for ex-situ cleanup cost. Fig.3.6 shows the developed membership functions of the fuzzy-sets of ex-situ cleanup cost criterion.

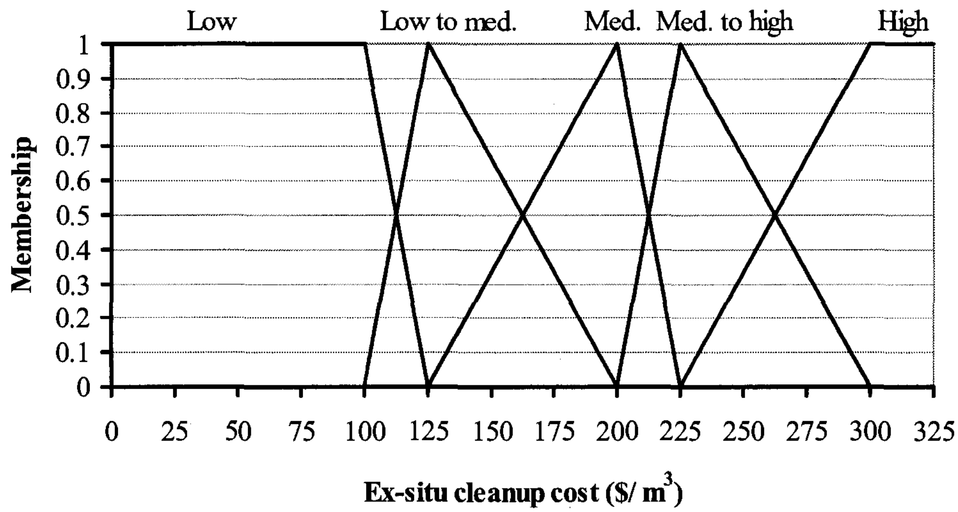


Fig. 3.6. Membership functions of fuzzy-sets of "cleanup cost (ex-situ)"

C. Minimum achievable concentration

From the survey it was found that 26.32% of respondents indicated that the option of "contaminant concentration should be reduced by approximately 10% or less" to be considered as "low" minimum achievable concentration; 31.58% of the respondents selected that "contaminant concentration should be reduced by approximately 40%" to be considered as "low to medium" category; 36.84% of the respondents selected that the option of "contaminant concentration should be reduced by approximately 50% to be considered as "medium" category; 42.11% of the respondents selected that "contaminant concentration should be reduced by approximately 70%" to be considered as "medium to high" category; and 76.32% of the respondents selected that "contaminant concentration should be reduced by approximately 90% or greater" to be accepted as "high" category. Table 3.7 shows the values on minimum achievable concentration collected from the stakeholders.

Table 3.7 Survey on the fuzzy-sets of minimum achievable concentration

(1) Survey on low minimum achievable concentration

Contaminant concentration should be reduced by approximately:	**Response percentage (%)**
10% or less	**26.32%**
20% or less	18.42%
30% or less	21.05%
40% or less	2.63%
50% or less	21.05%
60% or less	0.00%
70% or less	2.63%
80% or less	0.00%
90% or less	0.00%
No opinion	7.89%
Total	100.00%

(2) Survey on low to medium minimum achievable concentration

Contaminant concentration should be reduced by approximately:	**Response percentage (%)**
10%	5.26%
20%	0.00%
30%	18.42%
40%	**31.58%**
50%	13.16%
60%	21.05%
70%	0.00%
80%	0.00%
90%	0.00%
No opinion	10.53%
Total	100.00%

(3) Survey on medium minimum achievable concentration

Contaminant concentration should be reduced by approximately:	**Response percentage (%)**
10%	2.63%
20%	0.00%
30%	0.00%
40%	0.00%
50%	**36.84%**
60%	23.68%
70%	26.32%
80%	2.63%
90%	0.00%
No opinion	7.89%
Total	100.00%

(4) Survey on medium to high minimum achievable concentration

Contaminant concentration should be reduced by approximately:	**Response percentage (%)**
10%	0.00%
20%	0.00%
30%	0.00%
40%	0.00%
50%	0.00%
60%	10.53%
70%	**42.11%**
80%	31.58%
90%	5.26%
No opinion	10.53%
Total	100.00%

(5) Survey on high minimum achievable concentration

Contaminant concentration should be reduced by approximately:	**Response percentage (%)**
10% or greater	0.00%
20% or greater	0.00%
30% or greater	0.00%
40% or greater	0.00%
50% or greater	0.00%
60% or greater	0.00%
70% or greater	0.00%
80% or greater	15.79%
90% or greater	**76.32%**
No opinion	7.89%
Total	100.00%

The membership functions of these fuzzy sets were developed based on the collected data. Fig. 3.7 represents the developed membership functions for the fuzzy-sets of minimum contaminant concentration reduction criterion.

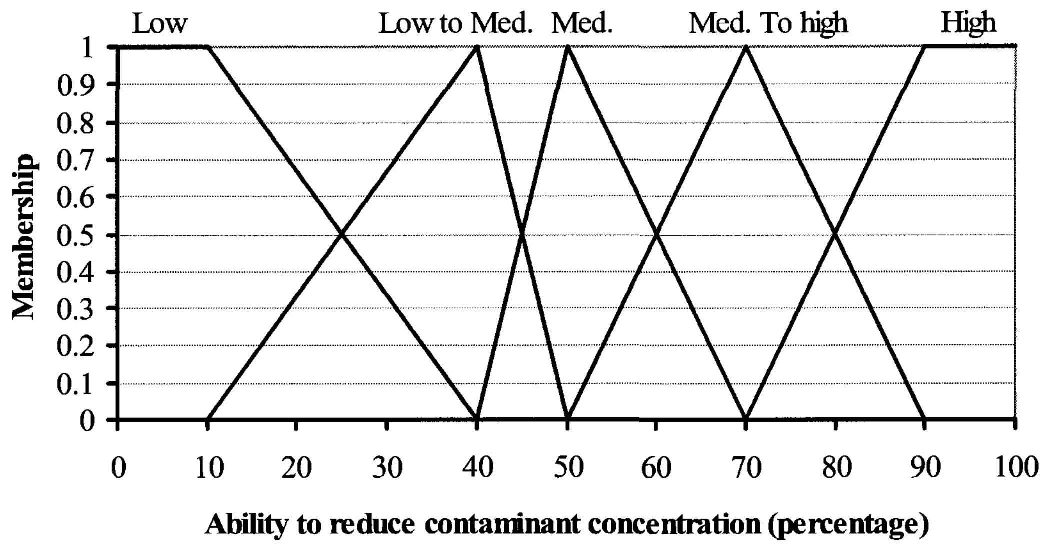


Fig. 3.7. Membership functions of fuzzy-sets of "minimum achievable concentration" criterion

D. Community acceptability

From the survey it was found that 34.21% of respondents indicated that the option of "community acceptability should be approximately 40% or less" to be accepted as "low" community acceptability; 42.11% of the respondents selected "community acceptability should be approximately 50%" to be accepted as "low to medium" community acceptability; 36.84% of the respondents selected " community acceptability should be approximately 60%" to be accepted as "medium" community acceptability; 42.11% of the respondents indicated that the option of "community acceptability should be approximately 70%" to be accepted as "medium to high" community acceptability and 42.11% of the respondents selected that "community acceptability should be approximately 90% or greater" to be accepted as "high" community acceptability. Table 3.8 shows all the values expressed by stakeholders on community acceptability criteria.

Table 3.8 Survey on the fuzzy-sets of community acceptability levels

(1) Survey on low community acceptability

Acceptance of the remedial alternative by community should be approximately:	**Response percentage (%)**
10% or less	21.05%
20% or less	7.89%
30% or less	21.05%
40% or less	**34.21%**
50% or less	10.53%
60% or less	0.00%
70% or less	0.00%
80% or less	0.00%
90% or less	0.00%
No opinion	5.26%
Total	100.00%

(2) Survey on low to medium community acceptability

Acceptance of the remedial alternative by community should be approximately:	**Response percentage (%)**
10%	0.00%
20%	7.89%
30%	15.79%
40%	10.53%
50%	**42.11%**
60%	15.79%
70%	0.00%
80%	0.00%
90%	0.00%
No opinion	7.89%
Total	100.00%

(3) Survey on medium community acceptability level

Acceptance of the remedial alternative by community should be approximately:	**Response percentage (%)**
10%	0.00%
20%	0.00%
30%	5.26%
40%	7.89%
50%	28.95%
60%	**36.84%**
70%	13.16%

80%	0.00%
90%	0.00%
no opinion	7.89%
Total No. of Respondents	100.00%

(4) Survey on medium to high community acceptability level

Acceptance of the remedial alternative by community should be approximately:	**Response percentage (%)**
10%	0.00%
20%	0.00%
30%	0.00%
40%	0.00%
50%	10.53%
60%	15.79%
70%	**42.11%**
80%	23.68%
90%	0.00%
No opinion	7.89%
Total	100.00%

(5) Survey on high community acceptability

Acceptance of the remedial alternative by community should be approximately:	**Response percentage (%)**
10% or greater	0.00%
20% or greater	0.00%
30% or greater	0.00%
40% or greater	0.00%
50% or greater	5.26%
60% or greater	5.26%
70% or greater	5.26%
80% or greater	36.84%
90% or greater	**42.11%**
No opinion	5.26%
Total	100.00%

According to Chen and Hwang (1992), the membership functions of these five fuzzy sets can be constructed based on the collected data. Fig. 3.8 shows the developed membership functions of the fuzzy-sets of community acceptability criterion. For example, if community acceptance is 80% then it could be categorized as partly (0.5) "medium to high" and partly (0.5) "high".

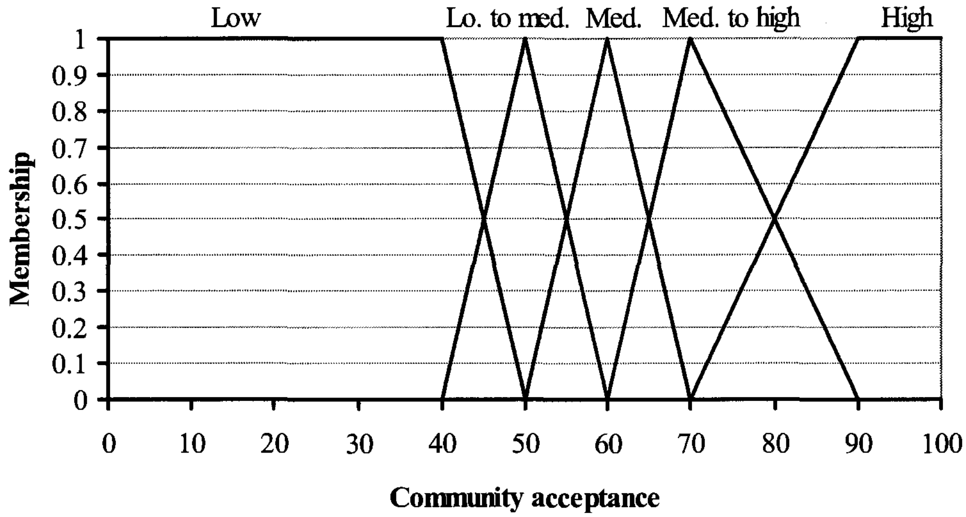


Fig. 3.8. Membership functions of fuzzy-sets of "community acceptability"

Other criteria such as technology availability, regulatory acceptability, development status and technology maintainability are mostly technical criteria. For this reason, these criteria were not included in the survey. Membership functions of these criteria were selected from references and with consultation of experts (USEPA, 1993; Soesilo, 1997).

E. Technology availability and other criteria

As rating of technology availability criteria has no unit for measurement, a dimensionless scale of 1 to 10 was adopted. The values between one and ten were divided into 5-tuple fuzzy sets. The range of "medium" category was considered from three to seven. Again, values falling below three were categorized as "low". And values above seven were categorized as "high". Fig.3.9 shows the developed membership functions for technology availability criterion. Similarly, regulatory acceptance, development status and technology maintenance criteria were fuzzified into five-tuple ("low", "low to medium", "medium", "medium to high" and "high") fuzzy-sets. Fig. 3.10, 3.11 and 3.12 shows the developed membership functions of these criteria.

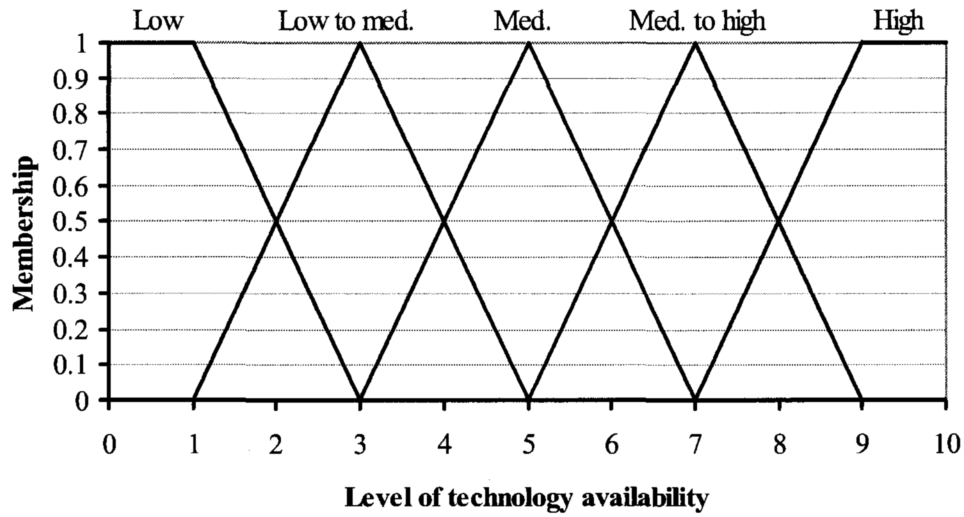


Fig. 3.9.. Membership functions of fuzzy-sets of "technology availability" criterion

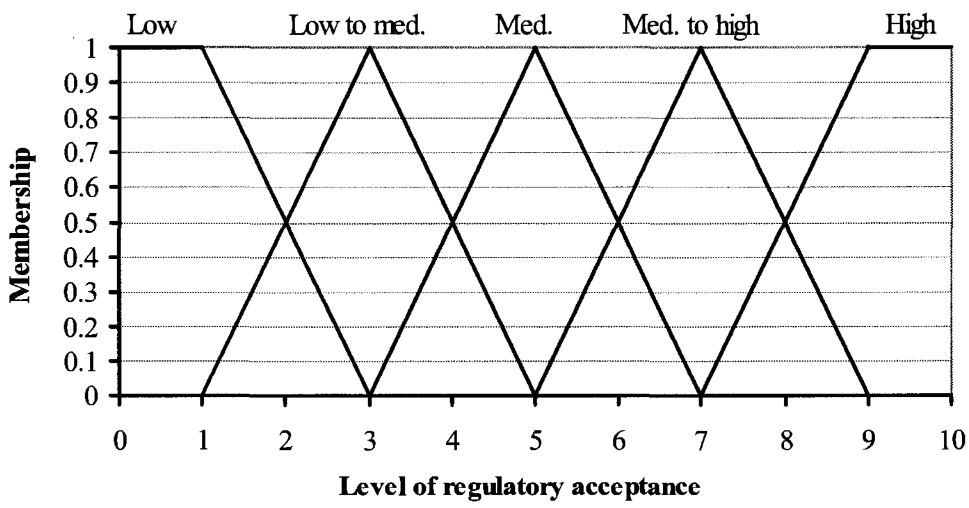


Fig. 3.10. Membership functions of fuzzy-sets of "regulatory acceptability" criterion

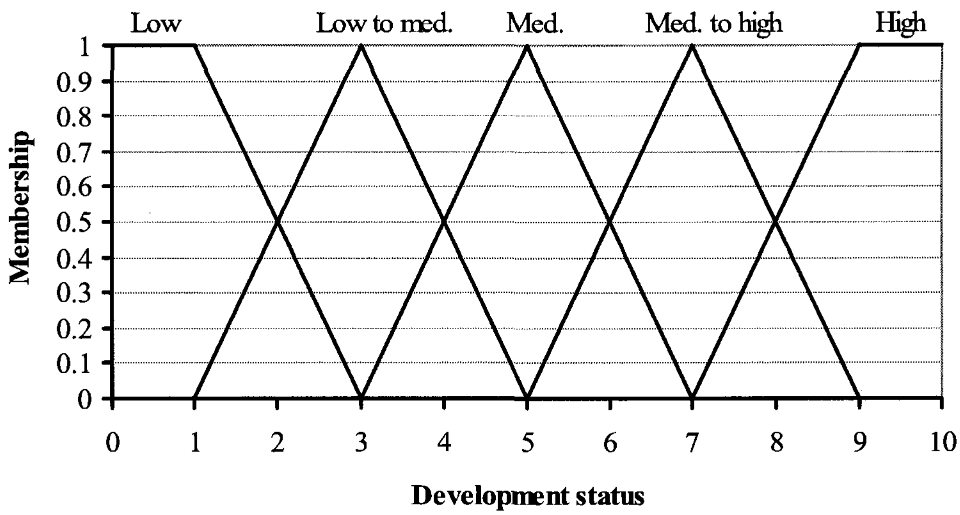


Fig. 3.11. Membership functions of fuzzy-sets of "development status" criterion

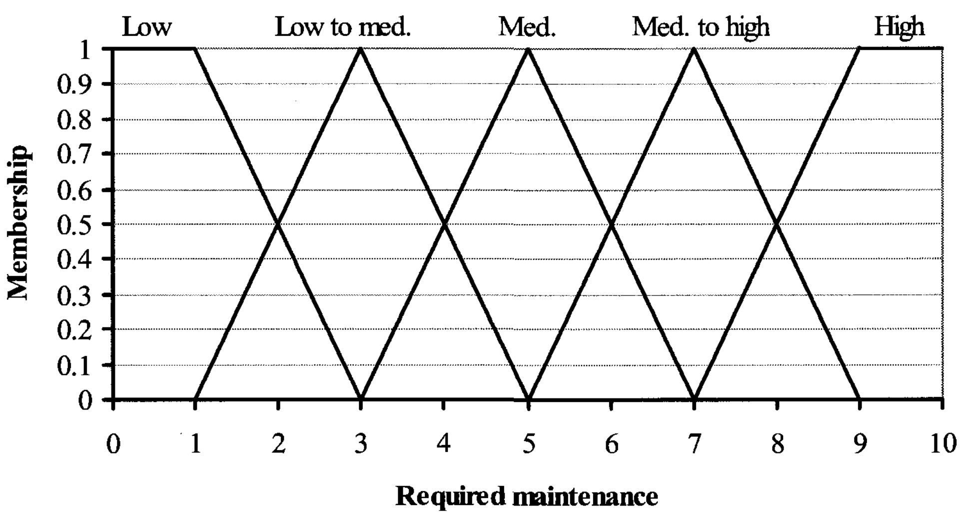


Fig. 3.12. Membership functions of fuzzy-sets of "maintenance requirement" criterion

Though different criteria uses different linguistic terms in the fuzzy performance scale figure (e.g., "low", "low to medium", "medium", "medium to high", "high", "short", "short to medium", "medium", "medium to long" and "long") all fuzzy-sets are categorized using common linguistic variables (i.e., excellent, good, fair, poor and bad). Such conversion process was developed and applied by Chen and Hwang (1992). Table 3.9 lists the values of developed membership functions for all criteria. From this table it can be observed that the fuzzfied value range of “excellent” and “bad” fuzzy-sets follow two sequences. For example, “excellent” fuzzy-set is defined by the highest values for certain criteria (e.g., technology availability, community acceptability, minimum achievable concentration). And the sequence of fuzzification for these criteria is highest values as “excellent” fuzzy-set and lowest values as “bad” fuzzy-set. On the other hand, for certain criteria “excellent” fuzzy-set is defined by the lowest values (e.g., cleanup cost, cleanup time). And the sequence of fuzzification for these criteria are opposite of the previous fuzzification sequence.

Table 3.9 Triangular fuzzy numbers (TFNs) defined for development of fuzzy membership functions of remediation alternative evaluation criteria

	Criteria	$TFN_{Excellent}$	TFN_{Good}	TFN_{Fair}	TFN_{Poor}	TFN_{Bad}
Survey based	Cleanup time (in-situ, in year)	1,1,2	1,1.7,2.5	1.5,3,3.5	2.5,5,5	3.5,5,5
	Cleanup time (ex-situ, in month)	4,4,6	4,6,8	6,8,10	8,10,12	10,12,12
	Overall cost (in-situ, $\$/m^3$)	50,50,100	50,100,150	100,150,200	150,200,275	200,275,275
	Overall cost (ex-situ, $\$/m^3$)	100,100,125	100,125,200	125,200,225	200,225,300	225,300,300
	Minimum achievable concentration (%)	90,90,70	90,70,50	70,50,40	50,40,10	40,10,10
	Community acceptability (%)	90,90,70	90,70,60	70,60,50	60,50,40	50,40,40
Literature based	Availability (0 to 10)	9,9,7	9,7,5	7,5,3	5,3,1	3,1,1
	Regulatory permitting acceptability (0 to 10)	9,9,7	9,7,5	7,5,3	5,3,1	3,1,1
	Development status (0 to 10)	9,9,7	9,7,5	7,5,3	5,3,1	3,1,1
	Technology Maintenance requirement (0 to 10)	1, 1, 3	1, 3, 5	3, 5, 7	5, 7, 9	7, 9, 9

3.5 Step 4 Developing fuzzy multi-criteria evaluation matrix

A fuzzy multi-criteria evaluation matrix was developed for remedial alternative evaluation. In a general setting, the process of fuzzy multi-criteria analysis (FMA) can be conveniently described by pointing out relationships between a collection of pattern features and their class membership vectors. A fuzzy multi-criteria decision problem with m alternatives A_i (i=1,..., m) and n criteria C_j (j=1,...,n) can be concisely expressed as: $\widetilde{D} = [\widetilde{x}_{ij}]$ and $\widetilde{W} = (\widetilde{w}_j)$, where $\widetilde{D}$ is the fuzzy decision matrix, $\widetilde{x}$ represents the fuzzy rating of alternative A_i with respect to criterion C_j, $\widetilde{W}$ is the weight vector, $\widetilde{w}$ is the fuzzy weight of criterion C_j.

3.5.1 Conversion of linguistic variables

In this research, stakeholder opinion on criteria was collected through a questionnaire survey. Each stakeholder expressed their opinion through linguistic variables. Then, the linguistic variables were converted into crisp values by using Chen and Hwang's (1992) conversion method. The conversion method of linguistic variables is discussed in details in chapter two. A scale was chosen from the eight scales (Chen and Hwang, 1992) that contained all the linguistic variables given by a respondent. For example, if a respondent preferred the variables "very low", "low medium", "high" and "very high", to rate all the criteria, scale three was selected for conversion of those linguistic variables (Fig. 3.13).

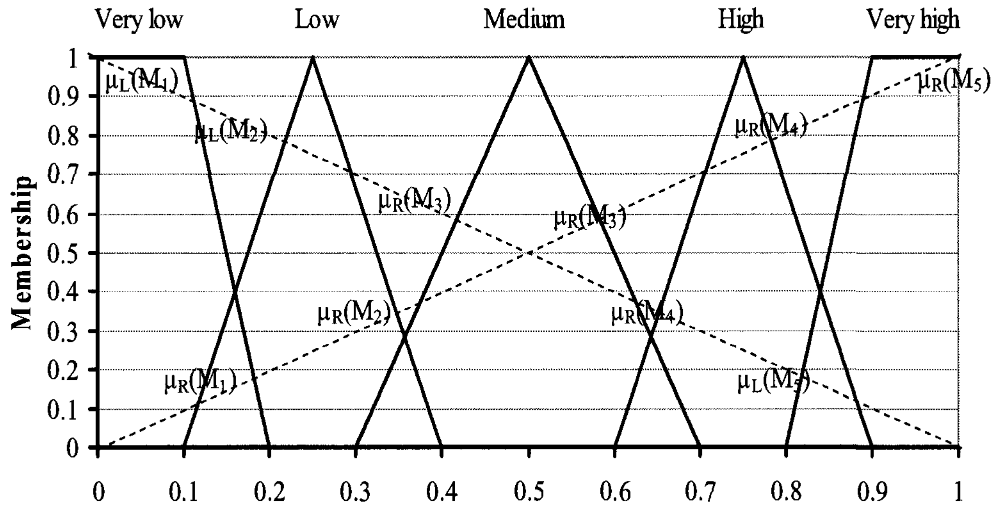


Fig. 3.13. Conversion of linguistic variables by scale three (Chen and Hwang, 1992)

In this Fig.3.13 five linguistic variables ("very low", "low", "medium", "high", and "very high") are presented as five fuzzy-sets. The membership function of each fuzzy-set is shown as a continuous line. The y axis presents the membership function values and the x axis presents the values for each fuzzy set. The left score [$\mu_L(M)$] and right score [$\mu_R(M)$] for each fuzzy-set are shown as dashed lines. Consequently, Table 3.10 represents the converted values of linguistic variables. From the table it can be seen that "very low" received numeric value of 0.0945 and "very high" linguistic variable received 0.9055.

Table 3.10 Determination of criteria value using scale three

i	Linguistic variables	$\mu_R(M_i)$	$\mu_L(M_i)$	$\mu_T(M_i)$
1	Very low	0.189	1	0.095
2	Low	0.350	0.775	0.288
3	Medium	0.588	0.588	0.500
4	High	0.775	0.350	0.713
5	Very high	1	0.189	0.906

Similarly, scale six was applied when a respondent used the linguistic variables "Very low", "Low", "Low to medium, "Medium", "Medium to high", "High" and "Very high" to rate all the criteria. Fig.3.14 shows the conversion process.

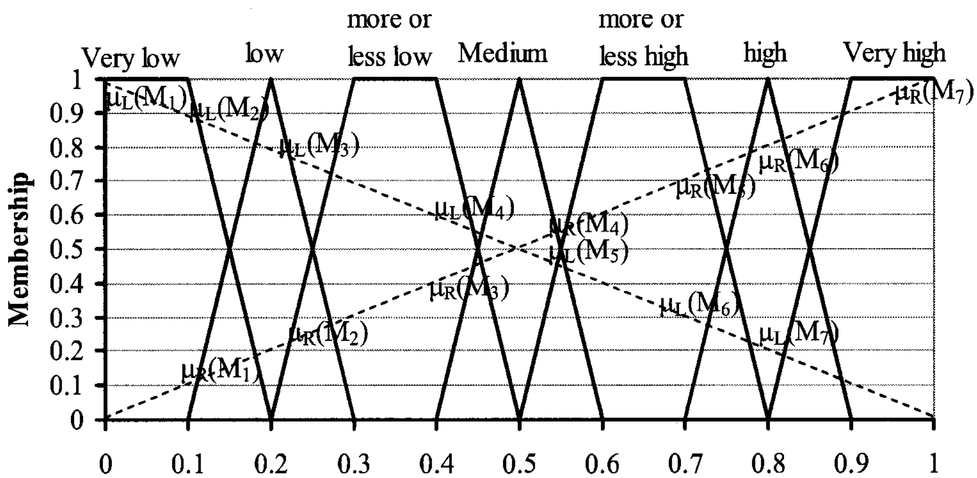


Fig. 3.14. Conversion of linguistic variables by scale six (Chen and Hwang, 1992)

The converted criteria importance weights are shown in Table 3.11. These weights were calculated by using scale six. In this scale, linguistic variable "very low" and "high" has a value of 0.0875 and 0.9125 respectively.

Table 3.11 Criteria value determination using scale six

i	Linguistic variables	$\mu_R(M_i)$	$\mu_L(M_i)$	$\mu_T(M_i)$
1	Very low	0.175	1	0.0875
2	Low	0.275	0.813	0.231
3	Low to medium	0.463	0.725	0.369
4	Medium	0.538	0.538	0.5
5	Medium to high	0.725	0.45	0.6375
6	High	0.813	0.275	0.769
7	Very high	1	0.175	0.9125

The crisp values for all the 8 conversion scales are shown in Table 3.12. According to Chen and Hwang (1992) the principle of this conversion procedure is simply to pick a figure that contains all the verbal terms given by the decision maker and then use the fuzzy membership function from the figure to represent the meaning of those verbal terms.

Table 3.12 Conversion of linguistic terms into crisp values

Scale	Linguistic variables	μ_R	μ_L	μ_T
1	Medium	0.66	0.5	0.58
	High	0.82	0.32	0.75
2	Low	0.32	1	0.16
	Med	0.62	0.62	0.5
	High	1	0.32	0.84
4	Low	0.2	1	0.1
	Med. low	0.4	0.8	0.3
	Med. low	0.6	0.6	0.5
	Med. high	0.8	0.4	0.7
	High	1	0.2	0.9
5	Very low	0.18	1	0.09
	Low	0.28	0.82	0.23
	More or less low	0.42	0.72	0.35
	Medium	0.52	0.52	0.5
	More or less high	0.72	0.42	0.65
	High	0.82	0.28	0.77
	Very high	1	0.18	0.91
7	V. low	0.18	1	0.09
	Low to very low	0.25	1	0.125
	Low	0.35	0.82	0.265
	Med low	0.42	0.7	0.36
	Med	0.58	0.58	0.5
	Med. high	0.7	0.42	0.64
	High	0.82	0.35	0.735
	High to very high	1	0.25	0.875
	V. high	1	0.18	0.91
8	None	0.09	1	0.045
	V. low	0.18	0.9	0.14
	Low to very low	0.42	0.9	0.26
	Low to very low	0.42	0.75	0.335
	Med. Low	0.45	0.62	0.415

Med. Low	0.58	0.58	0.5
Med. High	0.62	0.45	0.585
High	0.75	0.42	0.665
High to very high	0.9	0.42	0.74
Very. high	0.9	0.18	0.86
Excellent	1	0.09	0.955

From Table 3.12 it can be observed that similar linguistic variables have different values in different scale. For example, values for "medium" and "high" are 0.58 and 0.75 respectively in scale one. Again, in scale two the values for "medium" and "high" are 0.5 and 0.84 respectively.

A questionnaire survey (Apendix I) was conducted to obtain the criteria importance weights. Criteria importance weights were first collected through linguistic variables. Then, these linguistic variables were converted into crisp weights. Subsequently, an average importance weight was calculated for each of the criterion. For example, the average importance weight of criterion "overall cost" was calculated by adding all the importance weights given by each stakeholder and then the total importance weight was divided by the number of respondents. The sum of importance weights of "overall cost" given by all the stakeholders was 26.622 and total number of respondents was 38, therefore the average criterion importance weight of "overall cost" is (26.622 / 38) = 0.701. Similar procedure was applied to calculate the average criteria importance weight of other criteria. Fig. 3.15 shows the average criteria importance weights of all criteria. From this figure it can be observed that, most of the stakeholders provided high importance weight on regulatory acceptability criterion.

Such emphasis on regulatory acceptability criterion reflects that, the stakeholders are concerned that a remediation technology is implemented with in compliance with existing rules and regulations. As well, minimum achievable concentration and community acceptability criteria were rated as the next most important factors in the remediation alternative evaluation process. However, the criterion development status was rated as lowest important factor among all the criteria.

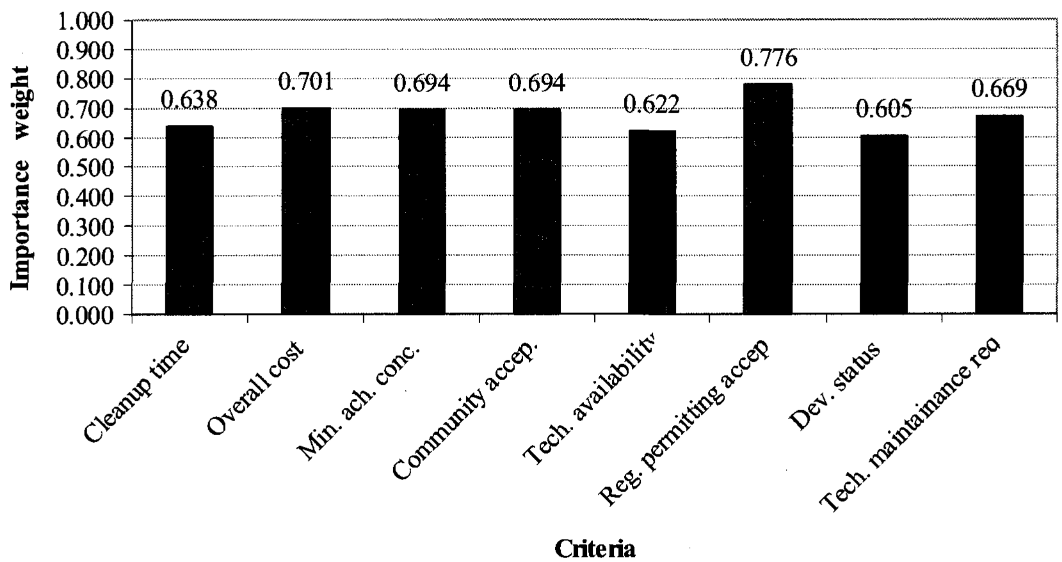


Fig. 3.15. Average criteria importance weights

To use the average criteria importance weights in the developed fuzzy multi-criteria approach the criteria importance weights were normalized. Otherwise the membership functions in the fuzzy-sets may have a membership of more than 1 in the fuzzy evaluation matrix results. The normalization procedure is conducted by dividing each criterion importance weight by the summation of all criteria importance weight. For example, the sum of all criteria importance weight is 5.399, so the normalized criterion weight of "technology availability" is

0.622 / 5.399 = 0.115. Similarly, the normalized criteria importance weights of other criteria are obtained. The normalized criteria importance weights are 0.118, 0.130, 0.129, 0.129, 0.144, 0.112 and 0.124 for "cleanup time", "overall cost", "minimum achievable concentration", "community acceptability", "regulatory permitting acceptability" and "technology maintenance requirement", respectively.

3.5.2 Fuzzy evaluation matrix

In this research fuzzy evaluation matrix was developed for each alternative. The procedure of fuzzy evaluation matrix is shown below:

Fuzzy-set (B_1) for an alternative =

$$[\,W_1 \quad W_2 \quad W_3 \quad W_4 \quad W_5 \quad W_6 \quad W_7 \quad W_8\,] \bullet \begin{bmatrix} \mu_{El,1} & \mu_{Go,1} & \mu_{Fa,1} & \mu_{Po,1} & \mu_{Ba,1} \\ \mu_{El,2} & \mu_{Go,2} & \mu_{Fa,2} & \mu_{Po,2} & \mu_{Ba,2} \\ \mu_{El,3} & \mu_{Go,3} & \mu_{Fa,3} & \mu_{Po,3} & \mu_{Ba,3} \\ \mu_{El,4} & \mu_{Go,4} & \mu_{Fa,4} & \mu_{Po,4} & \mu_{Ba,4} \\ \mu_{El,5} & \mu_{Go,5} & \mu_{Fa,5} & \mu_{Po,5} & \mu_{Ba,5} \\ \mu_{El,6} & \mu_{Go,6} & \mu_{Fa,6} & \mu_{Po,6} & \mu_{Ba,6} \\ \mu_{El,7} & \mu_{Go,7} & \mu_{Fa,7} & \mu_{Po,7} & \mu_{Ba,7} \\ \mu_{El,8} & \mu_{Go,8} & \mu_{Fa,8} & \mu_{Po,8} & \mu_{Ba,8} \end{bmatrix} \qquad (3.2)$$

Where $i = 1,2,\ldots\ldots,8$; W_i represents normalized criterion importance weight; $\mu_{El,i}$ is the membership function of the fuzzy-set "excellent" of criteria i; $\mu_{Go,i}$ is the membership function of the fuzzy-set "good" of criteria i; $\mu_{Fa,i}$ is the membership function of the fuzzy-set "fair" of criteria i; $\mu_{Po,i}$ is the membership function of the fuzzy-set "poor" of criteria i; and $\mu_{Ba,i}$ is the membership function of the fuzzy-set "bad" of criteria i.

Five membership values were generated for each alternative through the above matrix multiplication.

$$\text{Final fuzzy-set } (B_1) \text{ for an alternative} = [W \bullet A] \tag{3.3}$$
$$= [\mu_{El} \mu_{Go} \mu_{Fa} \mu_{Po} \mu_{Ba}]$$

These five membership ($\mu_{El} \mu_{Go} \mu_{Fa} \mu_{Po} \mu_{Ba}$) values are the aggregated values of an alternative.

3.6 Step 5 Defuzzification

A two step process was applied for defuzzication of final fuzzy-sets and to get a utility value of an alternative. In the first step, fuzzy-sets were normalized such that the cardinality of the fuzzy-sets was in unity. In second step, the normalized five tuple fuzzy-sets were converted into a utility value using Equation (3.4).

$$U_a = \max(\mu_{El} \mu_{Go} \mu_{Fa} \mu_{Po} \mu_{Ba}) \tag{3.4}$$

Where U_a is the predominant level that is the highest value of membership. This value decides the classification of the fuzzy-set. Again, U_a with the highest value represents the best management alternative among all.

3.7 Step 6 Development of a decision support system

A decision support system was built by using Java script computer program to make the developed fuzzy multi-criteria decision analysis approach user-friendly. There are three frames in the developed system. These three frames are used for data input, data evaluation and data presentation purposes. On the first frame the user has to select remedial technologies to be evaluated for a contaminated site. Fig. 3.16 shows a screen shot of the first frame in the developed system.

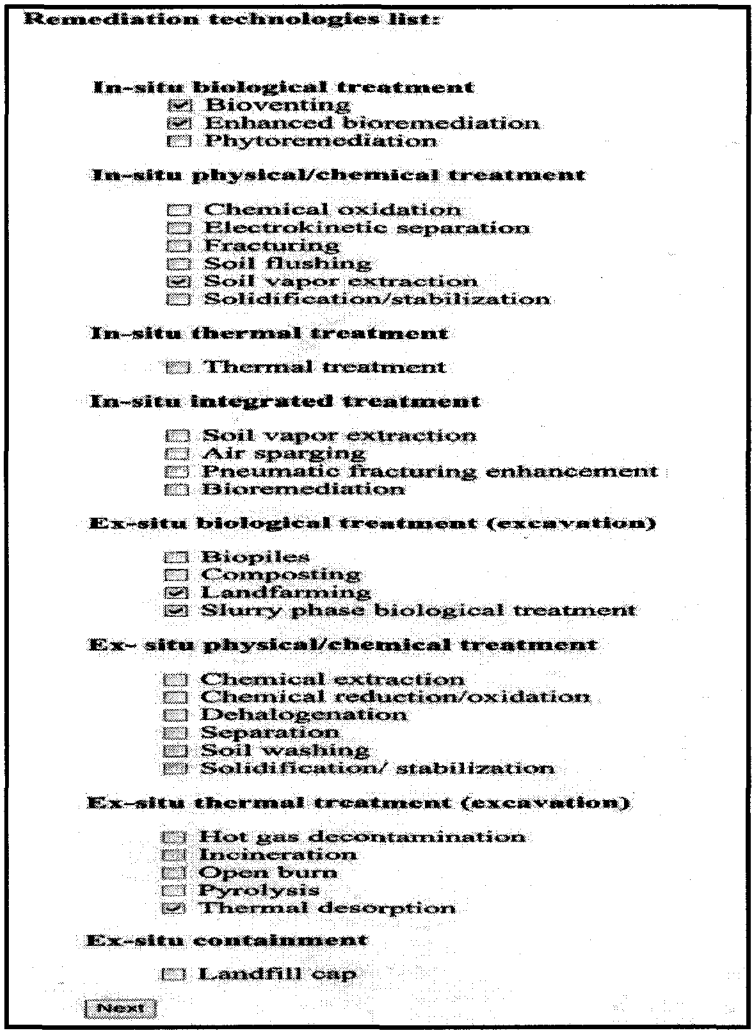


Fig. 3.16. Selection of remedial alternatives

Then the user needs to input information on all criteria for each technology. Fig. 3.17 shows the process of criteria value input.

Remidial Alternatives	Development status of technology	Required maintenance	Technology availability	Community acceptance	Regulatory acceptance	Ability to reduce contaminant concentration	Cost	Time
Bioventing	8,9,10	1,2,3	6,7,10	80,90,100	5,6,7	80,90,100	25,70,80	1,2,3
Enhanced bioremediation	8,9,10	5,6.5,7	6,7.5,10	80,90,100	1,2.5,3	50,65,70	50,1250,150	0.5,2,3
Soil vapor extraction	8,9,10	1,2,3	6,7.5,10	80,90,100	8,9,10	50,60,70	50,125,150	0.5,0.9,1
Landfarming	8,9,10	1,2,3	6,7.5,10	50,60,70	5,6,7	50,60,70	75,100,125	6,9,12
Slurry phase biological treatment	8,9,10	5,6,7	6,7,10	50,60,70	8,9,10	50,60,70	200,250,300	6,9,12
Thermal desorption	8,9,10	5,6,7	6,7,10	50,60,70	5,6,7	80,90,100	200,250,300	6,9,12

Next

Fig. 3.17. Criteria data input in the system

On the third screen the results for all alternatives are shown in a ranking order (Fig. 3.18).

Final Results

Remidiation Technology	Utility	Rank
Thermal desorption	0.277	6
Slurry phase biological treatment	0.278	5
Enhanced bioremediation	0.299	4
Landfarming	0.345	3
Soil vapor extraction	0.505	1
Bioventing	0.473	2

Fig. 3.18. Ranking order of remedial alternatives

In summary, the overall computation process by the developed system can be viewed in the following flow chart (Fig.3.19). The first task in the system is to gather site information. The site information is stored in the system as a database and for future references. Then, a list of potential remediation alternatives is prepared for the site. As well, information on each alternative is collected from expert opinion, pertinent references and case studies for evaluation and ranking of these alternatives. Since, there are 8 evaluation criteria in the developed system the user has to provide information on those criteria for evaluation and ranking.

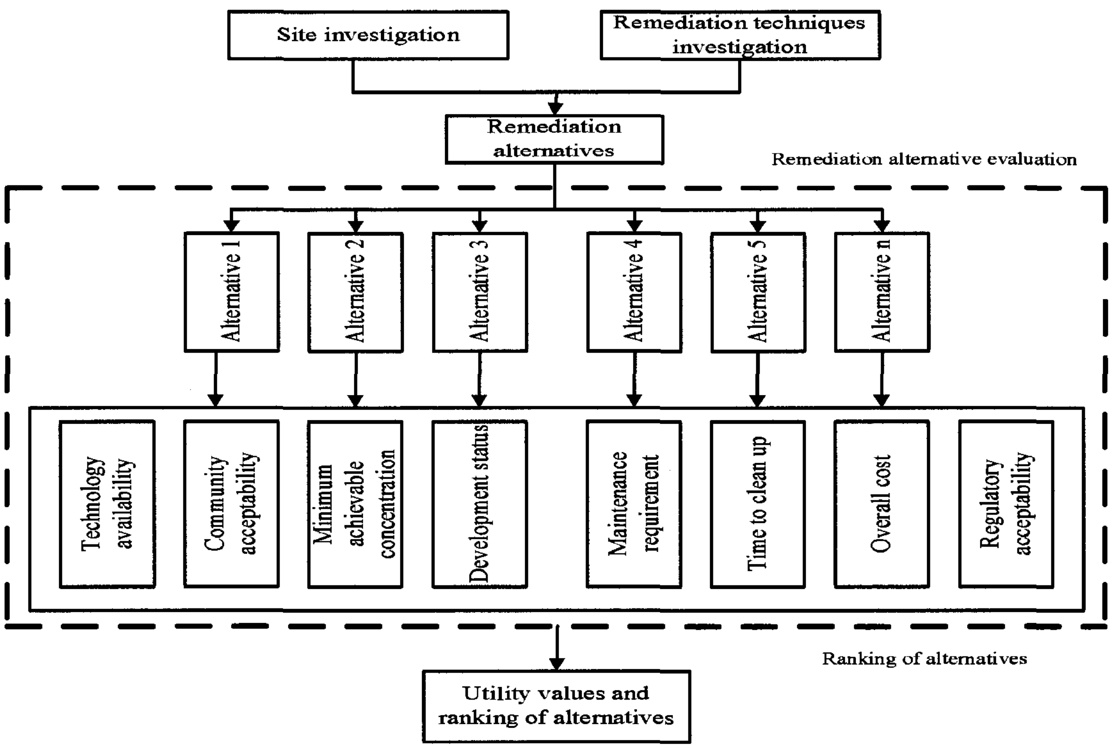


Fig. 3.19. Remediation decision process by the system

Chapter 4 Case Study, Results and Discussions

A contaminated site was selected to apply the developed method. The obtained results were compared with three existing MCDA methods, including SAW, TOPSIS and WPM.

4.1 Description of study site

The study site is located about 150 km north of Fort St.John in northern British Columbia. An oil leak was discovered in May, 2002. The leaked volume of crude oil was recorded about 200 m^3. Crude oil spilled over an area of approximately six hectares. The site is surrounded by agricultural land. This spill area is within the traditional use area of First Nations and approximately 80 kilometer from the Doig Reserve. The volume of contaminated soil was estimated to be 10,000 m^3 (13,080 yd^3). Contaminant concentration was measured higher than the provincial guideline value of Total Petroleum Hydrocarbon (TPH) level. Identified contaminants were Benzene, Ethylbenzene, Toluene and Xylene (BTEX). After primary site investigations and site characterization a list of potential remedial alternatives were selected to recover the contaminated soil. After screening out the list of available remedial alternatives, the following alternatives were selected for the above case, including (a) enhanced bioremediation (in-situ); (b) bioventing (in-situ); (c) soil vapor extraction (SVE; in-situ); (d) landfarming (ex-situ); (e) slurry phase treatment (ex-situ), and (f) low temperature thermal desorption (LTTD, ex-situ). There are three in-situ and three ex-situ alternatives in the potential alternative list. The site manager has to evaluate these alternatives to select the most appropriate remediation alternative from this list by considering stakeholder involvement and other uncertainties.

4.2 Description of remedial alternatives in the system

A brief description on remedial technologies was stored in a database as a source of reference and to assist the users of the developed system (Appendix II). The remedial alternatives were divided into two categories, ex-situ and in-situ. The user can refer to this database for background information on technology and technology evaluation criteria. This reference will help the users to measure the performance of each alternative for each criterion and then decide the input values.

4.2.1 Information about remedial alternatives

Information on these alternatives was collected based on previous application results, case studies and from remedial alternative evaluation matrix. Table 4.1 lists information on remedial alternative used for the case study site.

Table 4.1 Information on remedial alternatives

Criteria	In-situ			Ex-situ		
	A	B	C	D	E	F
Technology availability (1-10)	More than 4 vendors	More than 4 vendors	More than 4 vendors	More than 4 vendors	More than 4 vendors	More than 4 vendors
Community acceptability (10-100%)	Better	Better	Better	Average	Average	Average
Min.ach.concentration (10-100%)	Average	Better	Average	Average	Average	Better
Development status (1-10)	Full	Full	Full	Full	Full	Full
Maintenance req. (1-10)	Average	Low	Low	Low	Average	Average
Time to clean up (month or year)	0.5-3 years	1-3 years	0.5-1 year	0.5-1 year	0.5-1 year	0.5-1 year
Overall cost ($/ton)	Average	Low	Average	Low	High	High
Reg.acceptability (1-10)	Worse	Average	Better	Average	Better	Average

A= in-situ enhanced bioremediation, B= in-situ bioventing, C= in-situ soil vapor extraction (SVE), D= ex-situ landfarming, E= ex-situ slurry phase, F= ex-situ low temperature thermal desorption (LTTD)

Most of the remediation alternative information was in linguistic form. Therefore, this information is required to be processed before applying in the developed system.

4.3 Fuzzy processing of criteria information

As the developed fuzzy multi-criteria approach is capable of dealing with a range of values, it was not mandatory to input a single crisp value for each criterion. Triangular fuzzy numbers (TFNs) are an effective way to represent uncertain values. Table 4.2 represents the converted criteria values.

Table 4.2 Input values of remedial alternatives

	Criteria	In-situ												Ex-situ					
		Enhanced bio remediation			Bioventing			Soil vapor extraction			Landfarming			Slurry phase			Low temperature thermal desorption		
		Min	MLV	Max	Min	MLV	Max	Min	MLV	Max	Min	MLV	Max	Min	MLV	Max	Min	MLV	Max
A	Cleanup time (month/year)	0.5yr	2yr	3.5yr	1yr	2yr	3yr	0.5yr	0.9yr	1yr	6m	9m	12m	6m	9m	12m	6m	9m	12m
B	Overall cost ($/m^3)	$50	$125	$150	$25	$70	$80	$50	$125	$150	$75	$100	$125	$200	$250	$300	$200	$250	$300
C	Min.achievable concentration (10-100%)	50%	65%	70%	80%	90%	100%	50%	60%	70%	50%	60%	70%	50%	60%	70%	80%	90%	100%
D	Community acceptability (10-100%)	80%	90%	100%	80%	90%	100%	80%	90%	100%	50%	60%	70%	50%	60%	70%	50%	60%	70%
E	Availability (1-10)	6	7.5	10	6	7	10	6	7.5	10	6	7.5	10	6	7	10	6	7	10
F	Regulatory acceptability (1-10)	1	2.5	3	5	6	7	8	9	10	5	6	7	8	9	10	5	6	7
G	Dev.status (1-10)	8	9	10	8	9	10	8	9	10	8	9	10	8	9	10	8	9	10
H	Maintenance requirement (1-10)	5	6.5	7	1	2	3	1	2	3	1	2	3	5	6	7	5	6	7

Min=Minimum, MLV=Maximum Likely Value, Max=Maximum, yr=year, m=month.

4.4 Processing of input data

The input data processing of in-situ enhanced bioremediation is described below.

A. Cleanup time

The possible values of cleanup time for in-situ enhanced bioremediation are 0.5, 2 and 3.5 years. This array refers to a Triangular Fuzzy Number (TFN) which has most credible value 2 and lowest and highest possible values are 0.5 and 3.5. When the TFN is plotted on Fig. 4.1, the memberships of cleanup time to the five fuzzy-sets (0.5, 0.89, 0.69, 0.4, 0.0) are obtained (Fig. 4.1), where these five fuzzy-sets include "short", "short to medium", "medium", "medium to long" and "long" cleanup time, respectively.

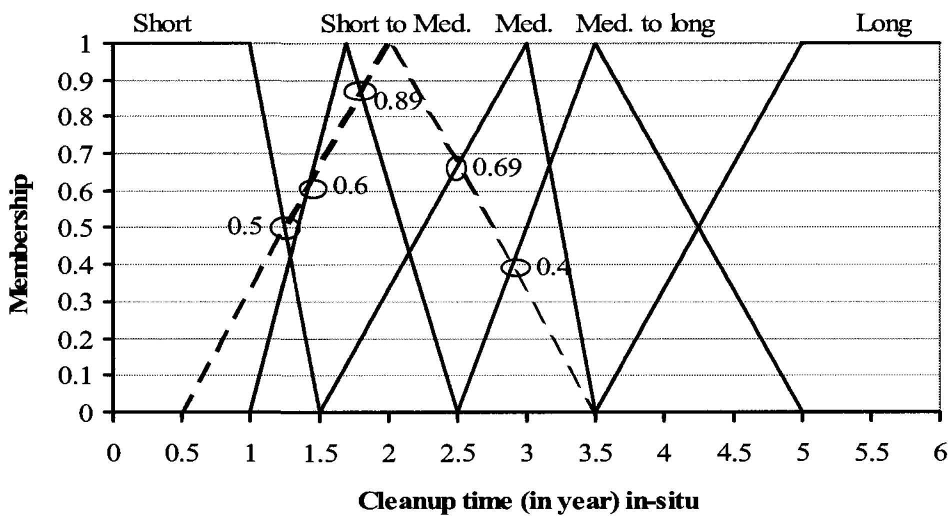


Fig. 4.1. Data input for in-situ cleanup time

Fig. 4.1 shows that the TFN intersected the fuzzy-sets of "short", "short to medium", "medium" and "medium to long" with a certain membership, i.e. short (0.5), short to medium (0.6 & 0.89), medium (0.69), medium to long (0.4) and long (0.0). The TFN intersected, the fuzzy-set "short to medium" at 0.6 and 0.89 (Fig. 4.1), therefore, the maximum operator is used to determine the membership to fuzzy-set "short to medium", which is 0.89 (Yager and Filev, 1994). Likewise, the other criteria input data is processed similarly. Fig. 4.2 to 4.8 presents the processing of input data for enhanced bioremediation.

B. Overall cost

The estimated cleanup cost by in-situ enhanced bioremediation is \$50 per m^3 to \$150 per m^3. The maximum possible value for this criterion is \$125 per m^3. And, the lowest possible and highest possible values are \$50 and \$150 per m^3 respectively. Therefore, the vertex of TFN of this criterion is leaned towards the "medium cost" fuzzy-set (Fig. 4.2). After interpolation of the TFN the memberships obtained for this criterion regarding in-situ enhanced bioremediation alternative are 0.4, 0.8, 0.68, 0.0 and 0.0 to "low", "low to medium", "medium", "medium to high", and "high" cleanup cost fuzzy-sets, respectively .

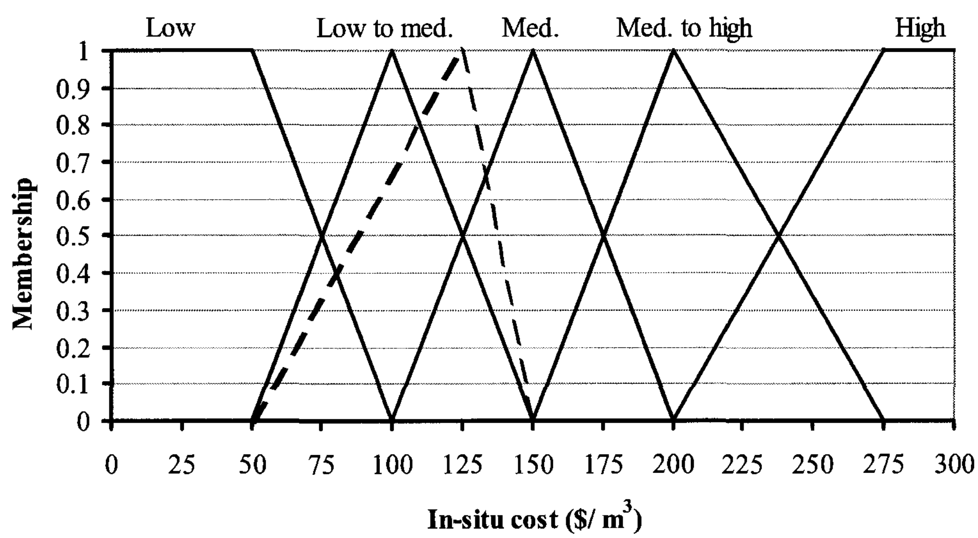


Fig. 4.2. Data input for in-situ cleanup cost

C. Minimum achievable concentration

The value of ability to reduce contaminant concentration of in-situ enhanced bioremediation criterion varies from 50% to 70%. The most credible likely value was 65% for this criterion. The vertex of the TFN of the criterion was leaned towards "medium to high" category (Fig. 4.3).

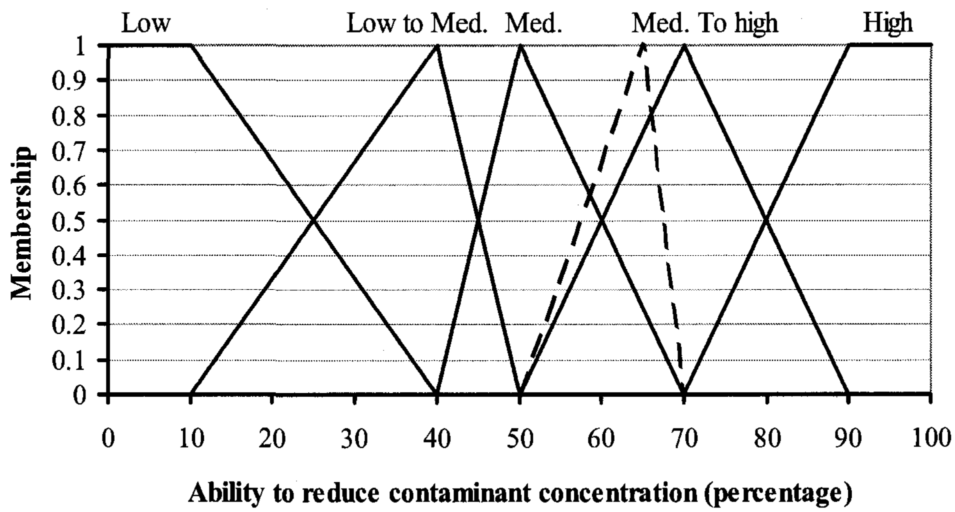


Fig. 4.3. Data input for ability to reduce contaminant concentration

D. Community acceptability

Again, community acceptability of the in-situ enhanced bioremediation alternative is within 80% to 100%. The TFN for this alternative is 80, 90 and 100. Five membership values (1.0, 0.32, 0.0, 0.0, 0.0) are obtained after plotting the TFN in the fuzzy performance scale (Fig. 4.4).

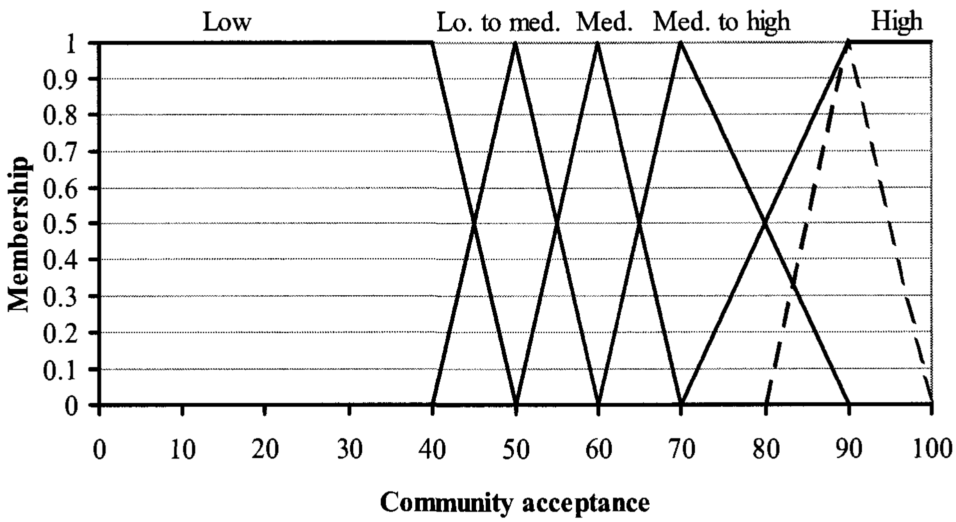


Fig. 4.4. Data input for community acceptance

Since the most likely value is 90, the vertex of the TFN is leaned toward "high" fuzzy-set.

E. Availability

Availability of in-situ enhanced bioremediation alternative varies from 6 to 10. The TFN for this criterion is 6, 7.5, and10. Since, the most credible value is 7.5 the vertex of TFN is leaned towards "good" fuzzy-set (Fig.4.5).

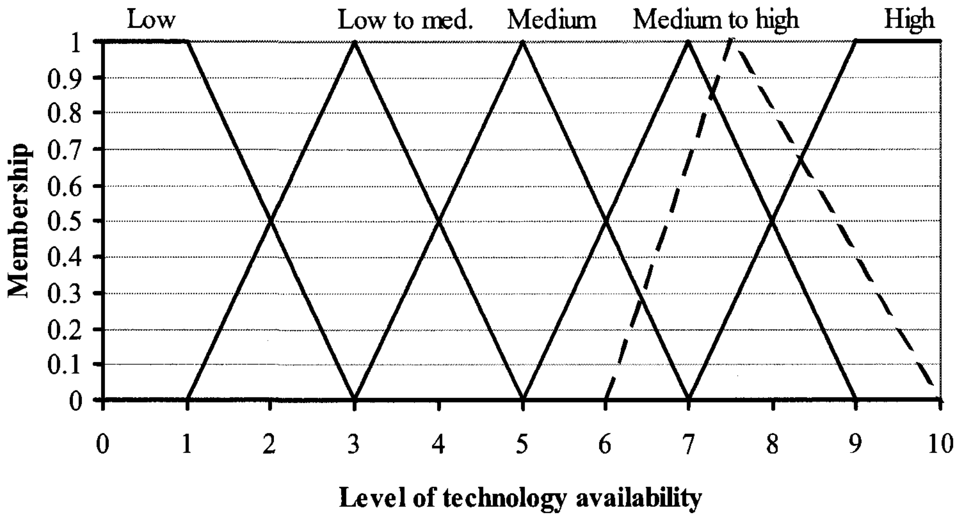


Fig. 4.5. Data input process of technology availability criterion

The memberships obtained for this criterion are 0.67,0.85, 0.28, 0.0, and 0.0. That means the TFN has a membership of 0.67 to "high", 0.85 to "medium to high", 0.28 to "medium" and no membership to "low to medium" and "low" fuzzy-sets.

F. Regulatory permitting acceptability

The regulatory permitting acceptability value of in-situ enhanced bioremediation varies from 1 to 3, and the most credible value is 2.5. Therefore, the vertex of the TFN is leaned towards the "low to medium" fuzzy-set (Fig. 4.6).

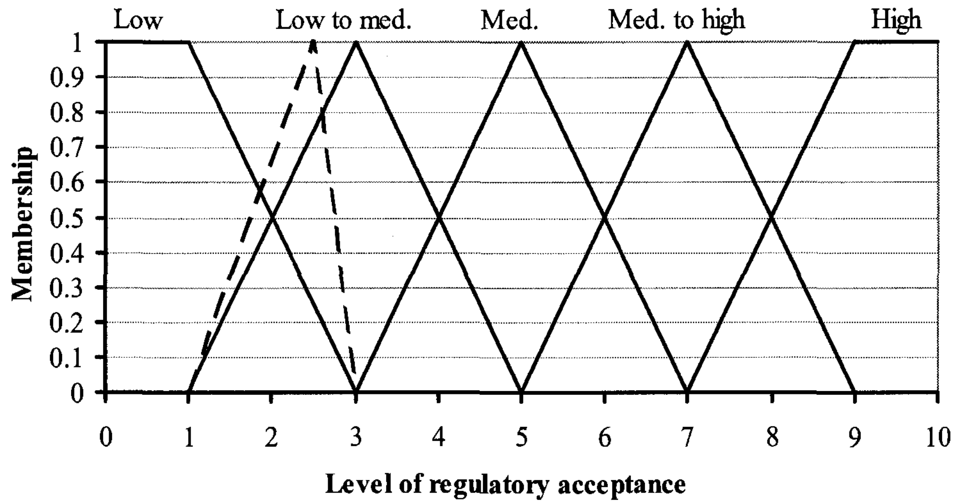


Fig. 4.6. Data input for regulatory acceptance criterion

G. Development status

The numeric scale value of development status of in-situ enhanced bioremediation technology varies from 8 to 10. The most credible value of this criterion is 9. Therefore, the vertex of TFN of the criterion intersected the vertex of the "high" fuzzy-set (Fig. 4.7).

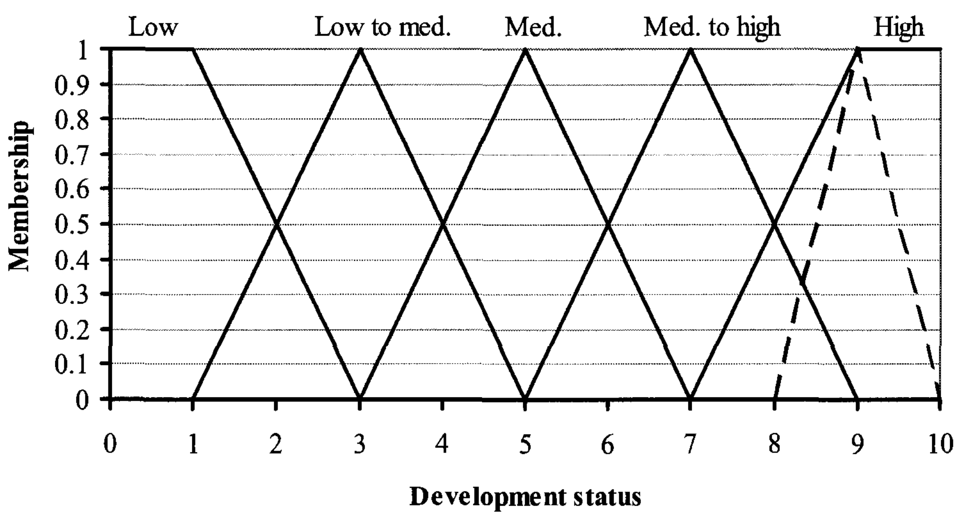


Fig. 4.7. Data input for development status

H. Maintenance requirement

The possible values of maintenance requirement criterion of in-situ enhanced bioremediation alternative are 5, 6.5 and 7. This array refers to a triangular fuzzy number (TFN) which has most credible value 6.5. The lowest and highest possible values are 5 and 7 respectively. Five membership values (0.0, 0.0, 0.6, 0.8 and 0.0) are obtained for "low", "low to medium", "medium", "medium to high", and "high" maintenance requirement, respectively (Fig. 4.8).

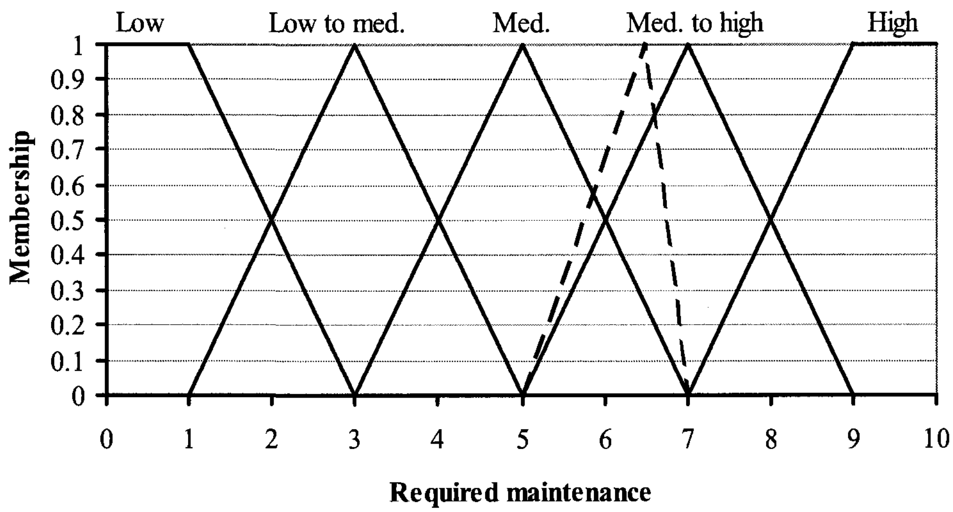


Fig. 4.8. Fuzzification of input data for required maintenance criterion

In the same way, the input data of other remediation alternatives are handled, and the membership values to the fuzzy-sets of each criterion are then obtained. Table 4.3 lists the results after converting different linguistic terms to common linguistic variables of "excellent", "good", "fair", "poor", and "bad", respectively.

Table 4.3 Fuzzification of remediation alternative criteria

Remediation alternative	**Criteria**	μ_{El}	μ_{Go}	μ_{Fa}	μ_{Po}	μ_{Ba}
Enhanced bioremediation (in-situ)	Cleanup time	0.5	0.89	0.69	0.4	0.0
	Overall cost	0.4	0.8	0.68	0.0	0.0
	Minimum achievable concentration	0.0	0.8	0.59	0.0	0.0
	Community acceptability	1.0	0.32	0.0	0.0	0.0
	Technology availability	0.67	0.85	0.28	0.0	0.0
	Regulatory permitting acceptability	0.0	0.0	0.0	0.82	0.58
	Development status	1.0	0.32	0.0	0.0	0.0
	Technology maintenance requirement	0.0	0.0	0.6	0.80	0.0
Bioventing (in-situ)	Cleanup time	0.32	0.85	0.6	0.25	0.0
	Overall cost	0.88	0.35	0.0	0.0	0.0
	Minimum achievable concentration	1.0	0.35	0.0	0.0	0.0
	Community acceptability	1.0	0.32	0.0	0.0	0.0
	Technology availability	0.6	1.0	0.32	0.0	0.0
	Regulatory permitting acceptability	0.0	0.5	0.5	0.0	0.0
	Development status	1.0	0.32	0.0	0.0	0.0
	Technology maintenance requirement	0.5	0.5	0.0	0.0	0.0
	Technology availability	0.6	1.0	0.32	0.0	0.0
Soil vapor extraction (in-situ)	Cleanup time	1.0	0.0	0.0	0.0	0.0
	Overall cost	0.4	0.8	0.68	0.0	0.0
	Minimum achievable concentration	0.0	0.69	0.69	0.0	0.0
	Community acceptability	1.0	0.32	0.0	0.0	0.0
	Technology availability	0.67	0.85	0.28	0.0	0.0
	Regulatory permitting acceptability	1.0	0.32	0.0	0.0	0.0
	Development status	1.0	0.32	0.0	0.0	0.0
	Technology maintenance requirement	0.5	0.5	0.0	0.0	0.0

Table 4.3 Fuzzification of remediation alternative criteria (continued)

Remediation alternative	Criteria	μ_{El}	μ_{Go}	μ_{Fa}	μ_{Po}	μ_{Ba}
Landfarming (ex-situ)	Cleanup time	0.0	0.4	0.8	0.8	0.4
	Overall cost	1.0	0.5	0.0	0.0	0.0
	Minimum achievable concentration	0.0	0.69	0.69	0.0	0.0
	Community acceptability	0.0	0.5	1.0	0.5	0.0
	Technology availability	0.67	0.85	0.28	0.0	0.0
	Regulatory permitting acceptability	0.0	0.5	0.5	0.0	0.0
	Development status	1.0	0.32	0.0	0.0	0.0
	Technology maintenance requirement	0.5	0.5	0.0	0.0	0.0
Slurry phase (ex-situ)	Cleanup time	0.0	0.4	0.8	0.8	0.4
	Overall cost	0.0	0.0	0.32	0.81	0.6
	Minimum achievable concentration	0.0	0.69	0.69	0.0	0.0
	Community acceptability	0.0	0.5	1.0	0.5	0.0
	Technology availability	0.6	1.0	0.32	0.0	0.0
	Regulatory permitting acceptability	1.0	0.32	0.0	0.0	0.0
	Development status	1.0	0.32	0.0	0.0	0.0
	Technology maintenance requirement	0.0	0.0	0.5	0.5	0.0
Low temperature thermal desorption (ex-situ)	Cleanup time	0.0	0.4	0.8	0.8	0.4
	Overall cost	0.0	0.0	0.32	0.81	0.6
	Minimum achievable concentration	1.0	0.35	0.0	0.0	0.0
	Community acceptability	0.0	0.5	1.0	0.5	0.0
	Technology availability	0.6	1.0	0.32	0.0	0.0
	Regulatory permitting acceptability	0.0	0.5	0.5	0.0	0.0
	Development status	1.0	0.32	0.0	0.0	0.0
	Technology maintenance requirement	0.0	0.0	0.5	0.5	0.0

From Table 4.3 it can be observed that each technology has different membership functions in fuzzy-sets. For example, membership functions of overall cleanup cost of in-situ enhanced bioremediation are 0.4, 0.8, 0.68, 0.0, and 0.0 for the fuzzy-sets of "excellent", "good", "fair", "poor", and "bad", respectively. Again, membership functions of overall cleanup cost of in-situ bioventing are 0.88, 0.35, 0.0, 0.0 and 0.0 for the fuzzy-sets of "excellent", "good", "fair", "poor", and "bad", respectively.

4.4.1 Aggregation of membership values and criteria weights

In the next step, the membership values of all criteria are multiplied by the criteria weights for aggregation. Since, there are 8 criteria weights and 5 fuzzy-sets for each criterion the multiplication provides the membership values to the five fuzzy-sets for each alternative. For example, equation (3.2) is applied to aggregate the criteria importance weights and in-situ remediation alternative performance values. The calculation process is shown below:

$$[\ 0.118, 0.130, 0.129, 0.129, 0.115, 0.144, 0.112, 0.124\ ] \bullet \begin{bmatrix} 0.5, & 0.89, & 0.69, & 0.4, & 0.0 \\ 0.4, & 0.8, & 0.68, & 0.0, & 0.0 \\ 0.0, & 0.8, & 0.59, & 0.0, & 0.0 \\ 1.0, & 0.32, & 0.0, & 0.0, & 0.0 \\ 0.67, & 0.85, & 0.28, & 0.0, & 0.0 \\ 1.0, & 0.32, & 0.0, & 0.0, & 0.0 \\ 0.6, & 0.94, & 0.68, & 0.5, & 0.0 \\ 0.0, & 0.0, & 0.0, & 0.82, & 0.58 \end{bmatrix}$$

$$= [0.429 \quad 0.487 \quad 0.353 \quad 0.264 \quad 0.084]$$

Similar procedure is followed to aggregate the criteria importance weight and remediation alternative performance values of all remediation alternatives. Table 4.4 shows the aggregated results of each alternative. In this table, it can be seen that, in-situ enhanced bioremediation has an aggregated membership value of 0.429 in "excellent", 0.487 in "good", 0.353 in "fair", 0.264 in "poor" and 0.084 in "bad" fuzzy-sets, respectively.

Table 4.4 Membership values of each alternative after aggregation

Remediation alternatives	μ_{El}	μ_{Go}	μ_{Fa}	μ_{Po}	μ_{Ba}	**Cardinality**
Enhanced bioremediation (in-situ)	0.429 **0.265**	0.487 **0.301**	0.353 **0.218**	0.264 **0.164**	0.084 **0.052**	1.617
Bioventing (in-situ)	0.653 **0.474**	0.517 **0.375**	0.180 **0.130**	0.030 **0.021**	0.000 **0.000**	1.379
SVE (in-situ)	0.694 **0.503**	0.476 **0.345**	0.210 **0.152**	0.000 **0.000**	0.000 **0.000**	1.380
Landfarming (Ex-situ)	0.381 **0.248**	0.533 **0.347**	0.417 **0.271**	0.159 **0.103**	0.047 **0.031**	1.537
Slurry phase (Ex-situ)	0.325 **0.200**	0.398 **0.244**	0.453 **0.278**	0.326 **0.201**	0.125 **0.077**	1.627
Low temperature thermal desorption (ex-situ)	0.310 **0.197**	0.380 **0.241**	0.436 **0.276**	0.326 **0.207**	0.125 **0.079**	1.577

* Normalized values are in bold

4.5 Defuzzification and ranking of alternatives

In this step, the membership values are normalized. The normalization process is done by dividing each membership value with cardinality of an alternative. According to Sadiq et al. (2004) the term "cardinality" is referred as the sum of all the membership values of all of its fuzzy sets (i.e., $\mu_{El}, \mu_{Go}, \mu_{Fa}, \mu_{Po}, \mu_{Ba}$). For example, the cardinality for five fuzzy-sets of in-situ enhanced bioremediation is 1.617 and the normalized membership functions are 0.265, 0.301, 0.218, 0.164, and 0.052 in "excellent", "good", "fair", "poor" and "bad" fuzzy-sets, respectively. Similar procedure is followed to obtain normalized membership functions of other alternatives. Table 4.4 shows the normalized values of each alternative in bold. Afterwards, the alternatives are ranked by using the maximum normalized value (within five fuzzy-sets) of an alternative.

Final membership functions of alternatives are shown in Fig. 4.9 in form of a possibility mass function. The height of the bars in the figure represents normalized memberships to 5 fuzzy-sets. These are "excellent", "good", "fair", "poor" and "bad". These memberships represent the overall fuzzy multi-criteria score for each alternative after aggregating all the criteria. From Fig. 4.9 it can be seen that in-situ soil vapor extraction (SVE) and in-situ bioventing technology has higher membership in "excellent" fuzzy-set. In-situ enhanced bioremediation also has a higher membership in "excellent", "good" and "fair" fuzzy-sets.

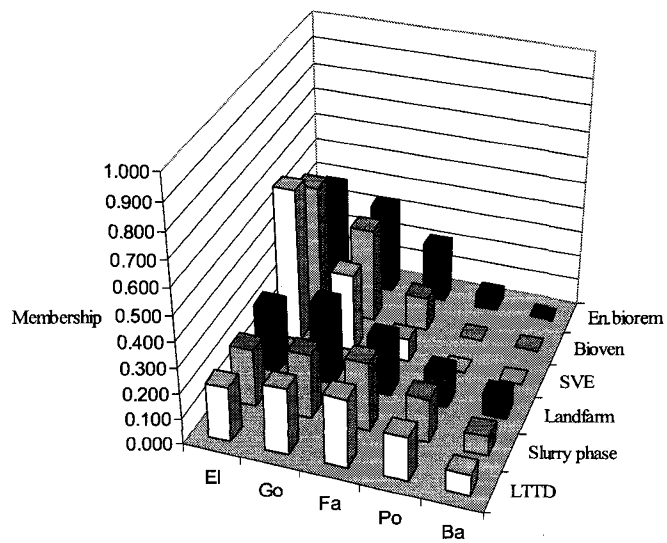


Fig. 4.9. Final membership functions of remediation alternatives

4.6 Ranking of alternatives

Each of the fuzzy-sets was divided by the cardinality for all fuzzy sets. Then the maximum utility value within 5-tuple fuzzy-sets was selected for ranking of the alternatives. Fig. 4.10 shows the ranking order of the remedial alternatives.

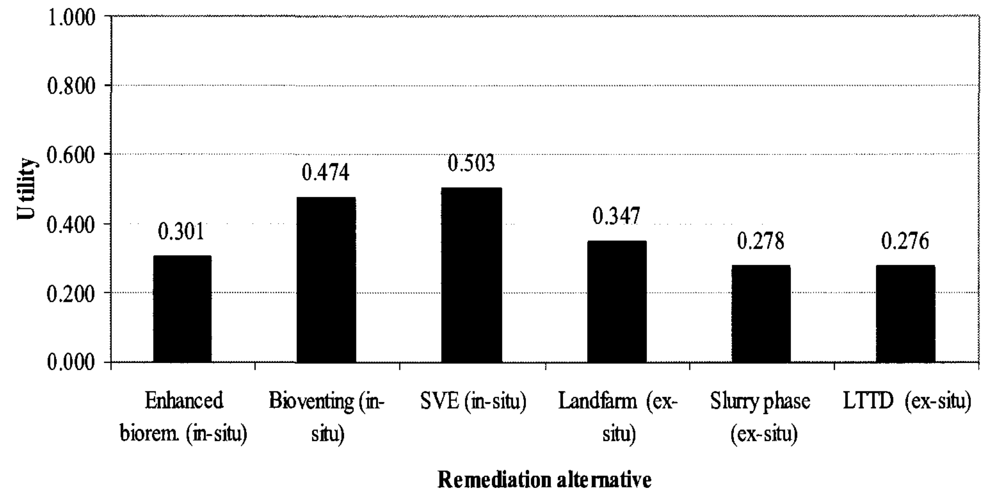


Fig. 4.10. Ranking of remediation alternatives by fuzzy multi-criteria method

It was observed that in-situ soil vapor extraction alternative scored 0.503 and became the most preferred alternative according to the developed fuzzy multi-criteria approach. Again, in-situ bioventing became the second most preferred option with a score of 0.474. In-situ enhanced bioremediation and ex-situ landfarming alternatives were third and fourth preferable options, respectively. From the remedial alternative input data in Table 4.2, it was observed that criteria values of "technology availability", "community acceptability", "overall cost" and "regulatory acceptability" of in-situ SVE alternative contributed mostly for its top preference. For example, the cost range of in-situ SVE is \$50-\$150/m^3 and the cost range of low temperature thermal desorption is \$200-\$300/m^3. Similar observations were made for other criteria values of other alternatives.

4.7 Comparison of results of MCDA techniques for the same case study site

Different multi-criteria decision analysis (MCDA) techniques (i.e., SAW, TOPSIS, and WPM) techniques were applied for the same case study site for analysis of results. A description of these MCDA tools is given in Chapter 2. Since existing MCDA methods can deal with only crisp rating values, the collected criteria information needed to be converted into single crisp values before using in these MCDA methods. The conversion process of selecting crisp values was done in reference with existing rating system and USEPA (1993), remediation alternative screening matrix. According to USEPA the criteria of "overall cost", "minimum achievable concentration", "cleanup time", "required maintenance" and "community acceptability" are rated by means of linguistic terms of "better", "average" and "worse". These linguistic ratings are then divided into representative numerical values such as1= better, 2= average, and 3= worse (ICS-UNIDO, 2000; UNECE, 1997). Assigning numerical values to the linguistic terms is dependent on the decision maker's preference. Table 4.5 lists the remediation alternative evaluation criteria information in linguistic and crisp form. In this table the values in bold represent the single crisp values for each criterion. It should be mentioned here that, the applied numerical rating scale has a value range of 1 to 10 and 10 to100 for certain criteria (e.g., technology availability and minimum achievable concentration).

Table 4.5 Criteria input value for MCDA methods

Criteria	**En.bio[a] rem. (in-situ)**	**Bioventing (in-situ)**	**SVE[b] (in-situ)**	**Landfarming (ex-situ)**	**Slurry phase (ex-situ)**	**LTTD[c] (ex-situ)**
Cleanup time (months)	1-3yrs **24m**	1-3yrs **24m**	0.5-1yr **9m**	0.5-1yr **9m**	0.5-1yr **9m**	0.5-1yr **9m**
Overall cost ($\$/m^3$)	Average **$100m³**	Low **$50/m³**	Average **$100/m³**	Low **$100/m³**	High **$250/m³**	High **$250/m³**
Minimum achievable concentration (10-100%)	Average **60%**	Better **90%**	Average **60%**	Average **60%**	Average **60%**	Better **90%**
Community acceptability (10-100%)	Better **90%**	Better **90%**	Better **90%**	Average **60%**	Average **60%**	Average **60%**
Availability (1-10)	More than 4 vendors **8**	More than 4 vendors **8**	More than 4 vendors **8**	More than 4 vendors **8**	More than 4 vendors **8**	More than 4 vendors **8**
Regulatory permitting acceptability (1-10)	Worse **2**	Average **6**	Better **9**	Average **6**	Better **9**	Average **6**
Development status (1-10)	Full **9**	Full **9**	Full **9**	Full **9**	Full **9**	Full **9**
Technology maintenance requirement (1-10)	Average **6**	Low **2**	Low **2**	Low **2**	Average **6**	Average **6**

*values in bold are single crisp values

a. En.bio= Enhanced bioremediation, b. SVE= Soil vapor extraction, c. LTTD= Low temperature thermal desorption.

4.7.1 Simple additive weighting (SAW) method

Simple additive weighting method was applied for the case study site. The calculations are shown in Table 4.6. Performance weights of each alternative were calculated by using equation (2.1). Then these performance weights were converted into utility values.

Table 4.6 Calculations using SAW method

Criteria	CW	A		B		C		D		E		F	
		Perf.	**U**	**Perf.**	**U**	**Perf.**	**U**	**Perf.**	**U**	**Perf.**	**U**	**Perf.**	**U**
Technology availability (1-10)	0.115	0.144	9.052	0.119	9.050	0.145	9.052	0.116	9.052	0.149	9.052	0.138	9.052
Community accep. (10-100%)	0.129	0.164	11.714	0.136	11.710	0.104	7.321	0.132	11.714	0.106	7.321	0.0986	7.321
Min. ach.concen (10-100%)	0.129	0.103	7.113	0.136	11.380	0.104	7.113	0.083	7.113	0.106	7.113	0.158	11.380
Dev.status (1-10)	0.112	0.164	10.279	0.136	10.280	0.166	10.279	0.132	10.279	0.170	10.279	0.158	10.279
Maintenance req. (1-10)	0.124	0.082	5.431	0.136	10.860	0.166	10.863	0.132	10.863	0.0849	5.431	0.0789	5.431
Time to cleanup (months)	0.118	0.138	8.800	0.115	8.800	0.070	4.400	0.149	11.733	0.0716	4.400	0.0665	4.400
Overall cost ($/yd3)	0.130	0.185	12.277	0.139	11.190	0.140	9.208	0.123	10.095	0.1432	9.208	0.204	14.119
Reg.acceptability (1-10)	0.144	0.021	1.621	0.085	8.100	0.104	8.103	0.132	12.965	0.170	12.965	0.0986	8.103
Total			61.938		82.468		69.408		83.268		59.631		59.037
Normalized utility			0.131		0.203		0.188		0.190		0.140		0.148

CW= criteria weight, Perf.= performance, U= utility, A= in-situ enhanced bioremediation, B= in-situ bioventing, C= in-situ soil vapor extraction, D= ex-situ landfarming, E= ex-situ slurry phase, F= ex-situ low temperature thermal desorption

4.7.2 Technique for order performance by similarity to ideal solution (TOPSIS)

Another MCDA technique TOPSIS was applied for ranking of these remediation alternatives. The procedure of TOPSIS method is discussed in Chapter 2. Since, each evaluation criterion has a different measurement value; a criterion normalization process was applied (equation 2.5). The normalized criteria rating values are shown in Table 4.7 and Table 4.8. Next, these normalized criteria rating values were multiplied with the criteria importance weights (equation 2.6) to calculate the weighted normalization values (Table 4.8).Then, the positive ideal and negative ideal solutions were calculated by using equation (2.7) and equation (2.8). Table 4.9 shows the calculated values of positive ideal and negative ideal solutions. Subsequently, the values of separation measures from positive ideal and negative ideal alternatives were calculated using equation (2.9) and equation (2.10). Finally, the values of similarities to ideal solutions (C_j) were calculated by using equation (2.11) and the calculated values are shown in Table 4.10.

Table 4.7 Normalized criterion ratings

		R (normalized criteria values) =							
	Remediation alternative	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
A	Enhanced biorem. (In-situ)	0.4083	0.4804	0.3430	0.4083	0.5472	0.6118	0.2520	0.1208
B	Bioventing (in-situ)	0.4083	0.4804	0.5145	0.4083	0.1826	0.6118	0.1260	0.3625
C	Soil vapor extraction (in-situ)	0.4083	0.4804	0.3430	0.4083	0.1826	0.3059	0.2520	0.5437
D	Landfarming (ex-situ)	0.4083	0.3203	0.3430	0.4083	0.1826	0.2294	0.2520	0.3625
E	Slurry phase (ex-situ)	0.4083	0.3203	0.3430	0.4083	0.5472	0.2294	0.6299	0.5437
F	LTTD (ex-situ)	0.4083	0.3203	0.5145	0.4083	0.5477	0.2294	0.6299	0.3625

C1: Technology availability; C2: Community acceptability; C3: Minimum achievable concentration; C4: Development status; C5: Maintenance requirement; C6: Time to clean up; C7: Overall cost; C8: Regulatory acceptability.

Table 4.8 Weighted normalized values of criteria

		V(weighted normalized values) =							
	Remediation alternative	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
A	Enhanced biorem. (In-situ)	0.0474	0.0634	0.0439	0.0474	0.0668	0.0716	0.0310	0.0176
B	Bioventing (in-situ)	0.0474	0.0634	0.0659	0.0474	0.0223	0.0716	0.0155	0.0529
C	Soil vapor extraction (in-situ)	0.0474	0.0634	0.0439	0.0474	0.0223	0.0358	0.0310	0.0794
D	Landfarming (ex-situ)	0.0474	0.0423	0.0439	0.0474	0.0223	0.0268	0.0310	0.0529
E	Slurry phase (ex-situ)	0.0474	0.0423	0.0439	0.0474	0.0668	0.0268	0.0775	0.0794
F	LTTD (ex-situ)	0.0474	0.0423	0.0659	0.0474	0.0668	0.0268	0.0775	0.0529

Table 4.9 Positive ideal and negative ideal solutions

Positive Ideal solution							
C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
0.0474	0.0634	0.0659	0.0474	0.0223	0.0268	0.0310	0.0794
Negative ideal solution							
0.0474	0.0423	0.0439	0.0474	0.0668	0.0716	0.0775	0.0176

Table 4.10 Separation measure from positive and negative ideal solutions and calculated value function of each alternative

	Alternatives	S+	S-	Normalized C_j
A	Enhanced bioremediation (in-situ)	0.0910	0.0511	0.104
B	Bioventing (in-situ)	0.0542	0.0894	0.181
C	Soil vapor extraction (in-situ)	0.0237	0.0984	0.234
D	Landfarming (ex-situ)	0.0404	0.0860	0.198
E	Slurry phase (ex-situ)	0.0712	0.0763	0.150
F	Low temperature thermal desorption (ex-situ)	0.0728	0.0611	0.133

S+: Separation measure from positive ideal solution; S-: Separation measure from negative ideal solution; C_j: Value function (similarities to positive ideal solutions).

4.7.3 Weighted product method (WPM)

In WPM method, the normalized performance index of each alternative was calculated initially by using available criteria information. Then, utility value of an alternative was calculated by using equation (2.12). Subsequently, the value ratio (R_i) for each alternative was calculated by applying equation (2.13). The calculated value ratio is then used for ranking of the alternatives. Table 4.11 shows the calculated normalized R_i values.

Table 4.11 Calculations of weighted product method

Criteria	Criteria weight	A	B	C	D	E	F	$V(A^*)$
Technology availability (1-10)	0.115	1.274	1.274	1.274	1.274	1.274	1.274	1.274
Community acceptability (10-100 %)	0.129	1.809	1.809	1.809	1.715	1.715	1.715	1.809
Minimum achieveable concentration (10-100%)	0.129	1.684	1.774	1.684	1.684	1.684	1.774	1.774
Development status (1-10)	0.112	1.289	1.289	1.289	1.289	1.289	1.289	1.289
Maintenance requirement (1-10)	0.124	0.803	0.919	0.919	0.919	0.803	0.803	0.919
Time to cleanup (month)	0.118	0.689	0.689	0.747	0.773	0.773	0.773	0.747
Overall cost ($/yd3)	0.130	0.568	0.619	0.568	0.568	0.508	0.508	0.619
Regulatory acceptability (1-10)	0.144	1.106	1.298	1.37756	1.298	1.378	1.298	1.378
$V(A_i)$		**1.741**	**2.679**	**2.689**	**2.485**	**2.060**	**2.045**	**3.083**
Normalized R_i		**0.127**	**0.196**	**0.181**	**0.196**	**0.150**	**0.149**	

A= Enhanced bioremediation (in-situ); B= Bioventing (in-situ); C= Landfarming (in-situ); D= Soil vapor extraction (SVE; ex-situ); E= Slurry phase; F= Low temperature thermal desorption; $V(A^*)$= value of an ideal alternative; $V(A_i)$= value of an alternative; R_i= the normalized value ratio between an alternative and the ideal alternative.

4.8 Results from MCDA methods

It was observed that in-situ soil vapor extraction (SVE) alternative was the first preference both by TOPSIS and WPM methods. In these methods the utility values of SVE is 0.234 and 0.196 (Table 4.10 and Table 4.11). As well, in-situ bioventing alternative became first preference by SAW method. In this method, the utility value of in-situ bioventing is 0.203 (Table 4.6). As, SVE scored highest ranking order by two methods, this alternative remained the top preference to remediate the site in hand. Subsequently, enhanced bioremediation became the least preferable by all the three MCDA methods. The results from existing MCDA tools of remediation alternatives are shown in Fig. 4.11. In this figure, the X-axis represents the name of the alternatives, and the Y-axis represents the utility values for each alternative. From the remediation alternative input data (Table 4.5) it can be observed that criteria value of cleanup time, and regulatory acceptability of SVE alternative mostly influenced the ranking order comparing with the criteria value of in-situ enhanced bioremediation.

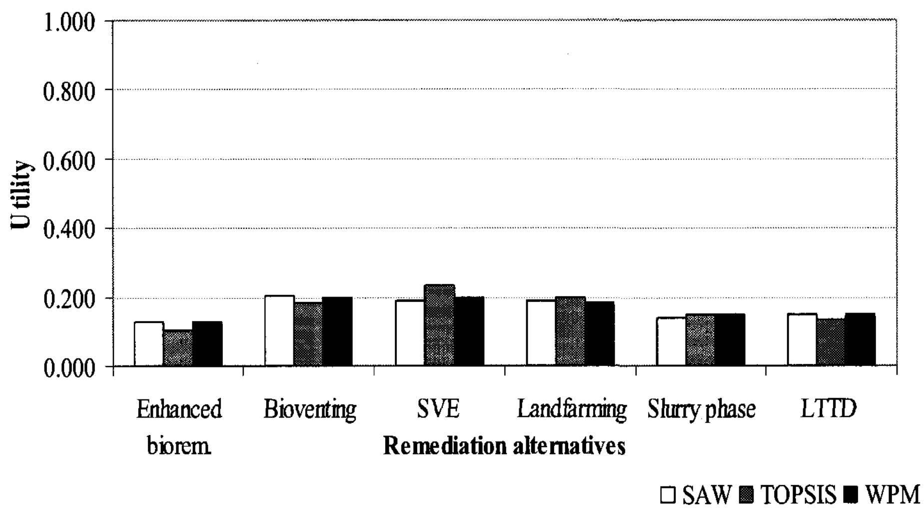


Fig. 4.11. Utility values of alternatives obtained from MCDA methods

4.9 Comparison of results

The average ranking order of each alternative was calculated by dividing each utility value with the total of three utility values obtained from three MCDA methods. Then, this ranking order was compared with the ranking order of fuzzy multi-criteria approach. Fig. 4.12 shows the comparison of results between fuzzy multi-criteria and MCDA methods. In this figure, the Y-axis represents the ranking order of remedial alternatives and the X-axis represents the list of remedial alternatives.

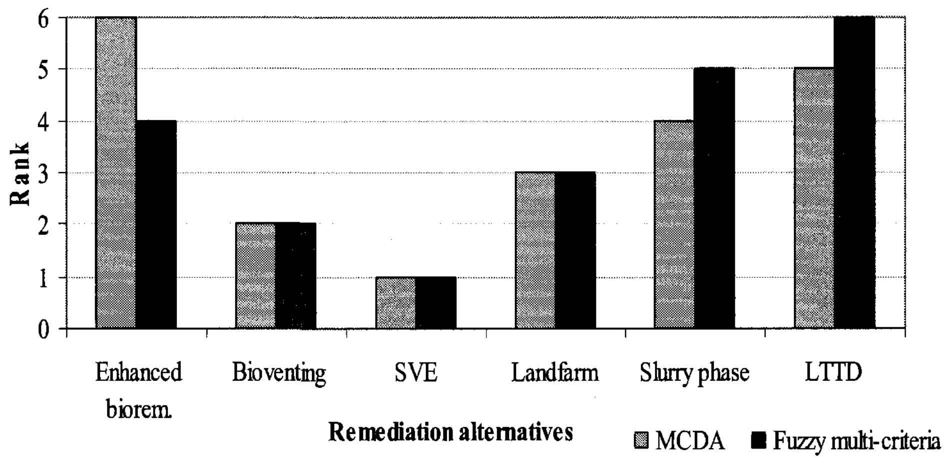


Fig. 4.12. Ranking order of remedial alternatives by MCDA and fuzzy multi-criteria and methods.

From Table 4.2 and Table 4.5 it was observed that the maximum likely values (MLVs) of the criteria in fuzzy multi-criteria method and single values of the criteria in MCDA methods were mostly similar. Such similarities in input values were also reflected between the ranking orders of both methods. In-situ soil vapor extraction (SVE) and in-situ bioventing alternatives became first and second preference, respectively by both MCDA and fuzzy multi-criteria methods. Again, the ranking order for ex-situ land farming became fifth in MCDA method and sixth in fuzzy multi-criteria method.

In fuzzy multi-criteria method the ranking order of in-situ enhanced bioremediation was fourth. However, in MCDA method it became sixth. This difference is observed due to the variation of criteria values including “minimum achievable concentration”, “technology availability” and “regulatory permitting acceptability”. For example, in fuzzy multi-criteria method the criterion value of “minimum achievable concentration” was 50% to 70% and maximum likely value was 65%. But in MCDA method the value was 60%.

4.10 Sensitivity analysis

Several sensitivity analyses were conducted to find the effect of parameter value changes on the remedial alternative ranking order.

4.10.1 Single input value

The remedial alternative performance values were applied as a single crisp value in the developed fuzzy multi-criteria approach. Table 4.12 lists the input values used in the fuzzy multi-criteria approach. These input values are similar with respect to the values used in MCDA methods.

Table 4.12 Single input value used in the fuzzy multi-criteria approach

Criteria	En.bio[a] (in-situ)	Bioventing (in-situ)	SVE[b] (in-situ)	Landfarming (ex-situ)	Slurry phase (ex-situ)	LTTD[c] (ex-situ)
Technology availability (1-10)	8	8	8	8	8	8
Community acceptability (10-100 %)	90	90	90	60	60	60
Minimum achieveable concentration (10-100 %)	60	90	60	60	60	90
Development status (1-10)	9	9	9	9	9	9
Maintenance requirement (1-10)	6	2	2	2	6	6
Time to cleanup (month or year)	24m	24m	9m	9m	9m	9m
Overall cost ($\$/m^3$)	100	50	100	100	250	250
Regulatory acceptability (1-10)	2	6	9	6	9	6

*values in bold are single crisp values

a. En.bio= Enhanced bioremediation, b. SVE= Soil vapor extraction, c. LTTD= Low temperature thermal desorption.

A comparison was conducted between the results of uncertainty consideration and the results of no uncertainty consideration (single input value) in the developed fuzzy multi-criteria method. It was found that there was no influence of uncertainty consideration in the ranking order of in-situ bioventing, in-situ soil vapor extraction, ex-situ landfarming and ex-situ slurry phase remediation alternatives. In both cases (i.e., uncertainties were considered, uncertainties were not considered) the ranking order of these alternatives remained the same. On the other hand, the ranking order of in-situ enhanced bioremediation became fourth when uncertainties were considered and it became sixth when uncertainties were not considered. However, the ranking order of ex-situ low temperature thermal desorption (LTTD) became sixth when uncertainties were considered and this alternative became fourth when uncertainties were not considered. The differences between the ranking order of in-situ enhanced bioremediation and ex-situ LTTD without uncertainty consideration were due to the differences in remediation alternative performance values of "minimum achievable concentration", "cleanup time", and "regulatory acceptability". For example, "Minimum achievable concentration" by in-situ enhanced bioremediation was 60% whereas, "minimum achievable concentration" by ex-situ LTTD was 90%; "cleanup time" by in-situ enhance bioremediation was 24m and by ex-situ LTTD was 9m; "regulatory acceptability" of in-situ enhanced bioremediation was 2, and "regulator acceptability" of ex-situ LTTD was 6 (Table 4.12).

The differences between ranking order of in-situ enhanced bioremediation and ex-situ LTTD with uncertainty consideration were due to the differences in remediation alternative performance values of "overall cost" and "community acceptability". For example, the uncertainties involved in the "overall cost" criterion of in-situ enhanced bioremediation varied from \$50m^3 to \$150/m^3 and the uncertainties of "overall cost" criterion of ex-situ LTTD varied from \$200/m^3 to \$300/m^3 and the uncertainties involved in the "community acceptability" criterion of in-situ enhanced bioremediation varied from 80% to 100% and the uncertainties in "community acceptability" criterion of ex-situ LTTD varied from 50% to 70% (Table 4.2). The overall comparison results between uncertainty consideration and without uncertainty consideration are shown in Fig. 4.13.

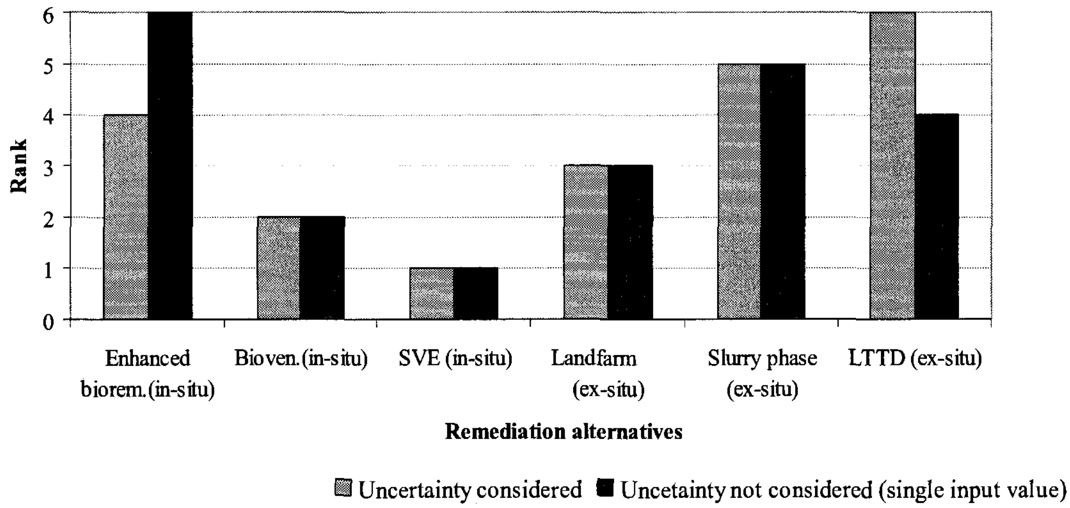


Fig. 4.13. Comparison of results when uncertainty is considered in the evaluation

4.10.2 Change in criteria importance weight

The criteria importance weights were changed to determine the sensitivity of remedial alternative ranking order. In trial 1 the importance weight of "overall cost" criterion was set to 0.26. As the total of all criteria importance weight needed to be 1 (normalized), the weights of other criteria (i.e., "technology availability", "community acceptability", "minimum achievable concentration", "development status", "maintenance requirement", "cleanup time" and "regulatory acceptance") were set to 0.106. From the results of trial 1 it was observed that in-situ bioventing became the first preferred alternative and in-situ soil vapor extraction (SVE) became the second preferred alternative. The ranking order of other alternatives remained similar to the original ranking order of alternatives for the case study site. In trial 2 the importance weight of "overall cost" was set to 0.52 and the importance weights of other criteria were set to 0.069. Likewise in trial 1, in-situ bioventing alternative remained the first preferred alternative in this trial. Though, the rank order of ex-situ landfarming was third in the original rank order of case study site and it became the second preferred alternative in trial 2. This difference was due to the increment of importance weight of "overall cost" criterion from 0.130 to 0.52. In trial 3 the importance weight of "overall cost" criterion was set to 0.85 and the importance weight of al other criteria were set to 0.022. Though ex-situ landfarming remained second preferred alternative in trial 3 in-situ SVE became the fifth preferred alternative. The rank order of in-situ SVE was third in trial 2. However, such difference in the rank order was due to the difference between the performance values of "overall cost" criterion of these two alternatives. From Table 4.2 it was observed that the maximum likely value (MLV) of in-situ and ex-situ landfarming were $\$125/m^3$ and $\$100/m^3$, respectively. Fig. 4.14 shows the utility values and the ranking order of remediation alternatives obtained from trial 1, trial 2 and trial 3.

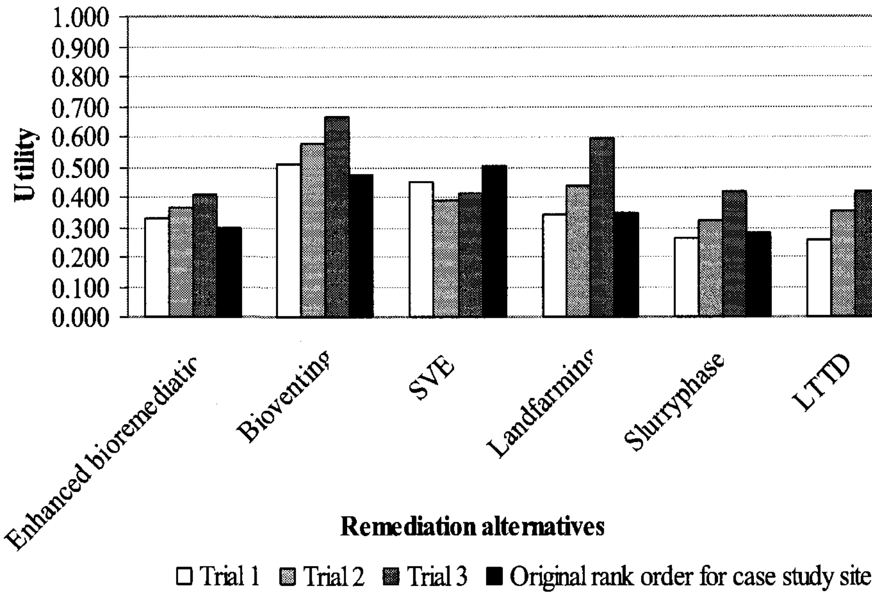


Fig. 4.14. Sensitivity analysis of remediation alternatives by changing "overall cost" criterion importance weight

In trial 4, criteria importance weights of both "overall cost" and "cleanup time" criteria were set to 0.45 and criteria importance weight of all other criteria (i.e., "technology availability", "community acceptability", "minimum achievable concentration", "development status", "maintenance requirement", and "regulatory acceptance") were set to 0.017. In this trial, in-situ SVE became the first preferred alternative whereas, in-situ SVE was fifth preferred alternative in trial 3. It was observed that the lower importance weight of "overall cost" criterion played an important role for higher ranking order of in-situ SVE in trial 4 because the importance weight of this criterion was 0.85 in trial 3. In addition, trial 5 was conducted by setting the criteria importance weights of "overall cost", "cleanup time" and "community acceptability" as 0.250. The importance weights of all other criteria were set to 0.05. In-situ SVE remained the first preferred alternative in this trial and overall there were no significant differences in the ranking order of trial 5 compared to the ranking order of trial 4. The results of trial 4 and trial 5 of sensitivity analysis are shown in Fig. 4.15.

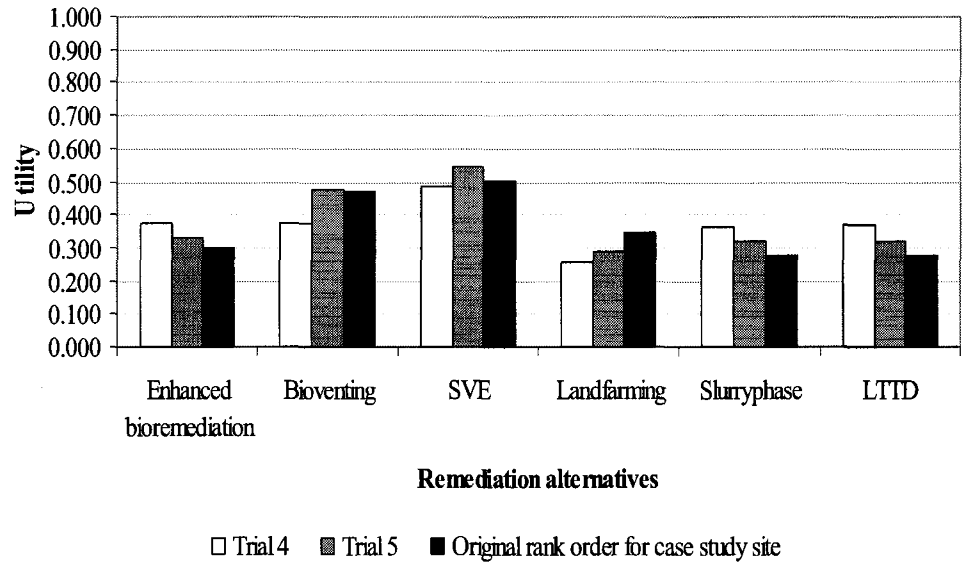


Fig. 4.15. Sensitivity analysis of remediation alternatives by changing the importance weights "overall cost", "cleanup time" and "community acceptability" criteria

In summary it can be stated that the criteria importance weights can influence the overall ranking order of the remediation alternatives. If all the criteria importance weights are close to each other then all of these criteria will influence the ranking order of the alternatives. However, if a criterion has significantly higher importance weight compared to other criteria then this criterion will influence the evaluation results of the alternatives. It was observed that the criterion "overall cost" played an important role in the ranking order of alternatives when the importance weight of this criterion was very high.

4.10.3 Change in remediation alternative performance values

Since the remediation alternative in-situ soil vapor extraction (SVE) became the best preference among other alternatives by fuzzy multi-criteria method. A sensitivity test was conducted by changing the performance values of criteria, "community acceptability", "cleanup time" and "overall cost" of in-situ SVE to observe whether performance values affect the ranking order of an alternative. The existing performance value range of criterion "community acceptability" was 80% to 100%; "cleanup time" was 0.5yr to 1yr and "overall cost" was 50$/m^3$ to 150$/m^3$. In the sensitivity analysis these performance value ranges were set to 30% to 50%, 3yr to 5yr, and 250$/m^3$ to 300$/m^3$, respectively. From the sensitivity analysis, it was observed that the rank order of in-situ soil SVE alternative became fourth from first ranking place in the original ranking order of remediation alternatives for the case study site (Fig. 4.16). However, the in-situ bioventing alternative became the first preference in this ranking order. The ranking order of in-situ bioremediation also improved from previous ranking order of fourth to third. Fig. 4.16 shows the ranking order and utility values of all the alternatives obtained from the sensitivity analysis.

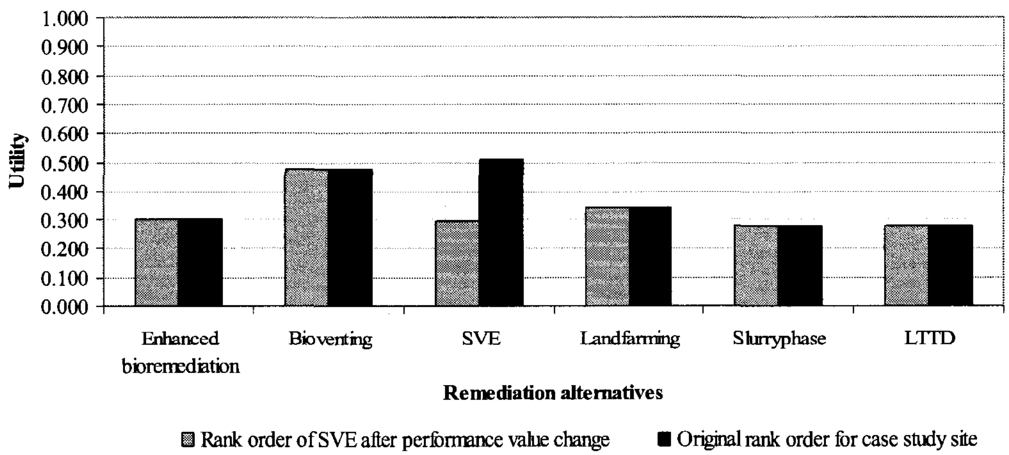


Fig. 4.16. Sensitivity analysis for SVE alternative by changing performance values of "community acceptability, "cleanup time" and "cleanup cost" criteria

In summary it can be stated that selection of remediation alternative through an evaluation process mostly depends on independent performance value (i.e., "cleanup cost", "cleanup time", "regulatory acceptance" etc.) of each alternative. From the above analysis it was observed that the in-situ SVE became less preferred option when the performance value of "community acceptability" criterion was significantly reduced and the performance value "cleanup time" and "overall cost" criteria were significantly increased.

Chapter 5 Conclusions and Recommendations

5.1 Summary

Management of contaminated sites is a complex task. Such decision making process is not limited only in selection of the best remediation alternative, but also several factors need to be considered. The factors which influence the decision making process include, involvement of various stakeholders, consideration of uncertainties, and evaluation and selection of the right remediation alternative.

Selection of remediation alternative is considered as a multi-criteria problem because a number of criteria including cleanup time, overall cost, community acceptability and regulatory acceptability need to be considered for the evaluation of remediation alternatives. There are many multi-criteria decision analysis (MCDA) tools (e.g., AHP, TOPSIS, PROMETHEE, ELECTRE, WPM, SAW) available to aid the decision making process of a contaminated site. Most of these MCDA tools require crisp values as inputs. However, the performance data of remediation alternatives are not always available in crisp form. For example, performance data on community acceptability and regulatory acceptability are expressed in linguistic terms (e.g., high, medium, low). These linguistic terms need to be converted into numerical scale value or into crisp values to use in the existing MCDA tools.

Public participation and stakeholder involvement is another important component in the decision making process of contaminated site management. Due to public concern on environment, public interest in contaminated sites and regulatory requirement, it is essential to incorporate public opinions in such decision making process. However, the existing decision making approaches have limitations to involve public and different stakeholders' opinions adequately.

Moreover, presence of a number of uncertainities in the decision making problems limit the application of existing MCDA tools. The source of uncertainties includes lack of information about a contaminated site, different opinions of different stakeholders, and a range of possible values of remediation alternative evaluation criteria.

Considering these problems, there was a need for development of a holistic approach for contaminated site management. There are many applications of fuzzy set theory available in literature, especially in the environmental decision making problems. It was found that the concept of fuzzy-set theory is appropriate to solve these problems. Fuzzy-set theory provides an intuitive and effective way for the decision makers for dealing with such linguistic preferences and uncertainties.

The fuzzy multi-criteria technique involves identification of remediation alternative selection criteria, estimating criteria weight, fuzzification, aggregation, defuzzification, and ranking remedial alternatives. In this research, a fuzzy multi-criteria decision analysis approach was developed.

First, the remediation alternative evaluation criteria were identified. Then, different stakeholders were contacted to express their opinion on the importance of the selected criteria.

Second, the criteria measurement values (e.g., overall cost/m^3, cleanup time/year) were divided into five fuzzy-sets by the stakeholders. Then, performance of each alternative was evaluated by means of these fuzzy-sets. Subsequently, the criteria importance weight and the membership functions of the fuzzy-sets were aggregated by applying fuzzy matrix multiplication. This multiplication produced the final fuzzy-sets for each alternative. Then utility values were calculated for each alternative. Finally, the alternatives were ranked according to their utility.

One of the objectives of this research was to identify the remediation alternative evaluation criteria and determine the importance weights of the criteria according to stakeholder preference. This objective was achieved by selecting the most important evaluation criteria from literature survey and by involving stakeholder in determining the criteria importance weights. Another objective of this research was to integrate the uncertainty issues in the remediation alternative evaluation process. This objective was also achieved by using fuzzy-set theory. Finally, the last objective regarding development of an effective fuzzy multi-criteria approach for evaluating and ranking remediation alternatives was met in this research. The developed fuzzy multi-criteria approach was applied to a contaminated site to solve remediation alternative selection problem and reasonable results were achieved. In the developed method, it was possible to use a range of possible values to address the uncertainties in the alternative evaluation performance data. The involved stakeholders were also satisfied with the easy process of their participation in the selection of most appropriate remediation alternative.

In addition, existing MCDA methods (i.e., SAW, TOPSIS, and WPM) were applied to solve the same problem. To apply the existing MCDA methods, remediation alternative evaluation data was required to convert into single crisp value. Much information was not counted in the overall evaluation process due to selection of single value. Though, the results by the both approach were mostly consistent, the fuzzy multi-criteria method proved to be more efficient in dealing with uncertainties. The results from the developed method are more acceptable than the results of existing MCDA methods because various stakeholder opinions were incorporated in the system.

5.2 Future extensions

Selection of remediation alternatives is one of the many challenges in contaminated site management. The developed fuzzy multi-criteria approach could be applied in the earlier stage of a decision making process of contaminated sites. For example, site characterization and risk assessment are two important steps of successful contaminated site management. However, in the developed method it is assumed that both of these two steps have already been conducted and the user faces the problem of selecting a remediation alternative. Site characterization tools and risk assessment tools should be incorporated within the developed method for more efficiency in the contaminated site management. Once site characterization and risk assessment are incorporated the method can provide a decision on the most appropriate remediation option for a contaminated site.

The list of the remediation alternative is fixed in the system. Thereby, a user can apply this system when the potential remediation alternatives match with the list. However, situation may arise that integrated remediation alternatives (e.g., bioremediation and thermal treatment) need to be considered for evaluation and ranking. The future extension of the system should incorporate the integrated remediation alternatives in the list.

In the developed method, it was assumed that different stakeholders have agreed on criteria importance weight. The average criteria importance weights were used for remediation alternative evaluation. This may not satisfy all the stakeholders involved in the decision making process. An approach should be developed to achieve consensus on a balanced criteria importance weight among the stakeholders. This can be achieved through group meetings of stakeholders and by identifying their key interests. Related researches can be found in Bose et al. (1997) and Zapatero et al. (1997).

Again, in the developed method only eight evaluation criteria were used for remediation alternative evaluation. However, a number of other criteria (e.g. environmental impact, produced waste) need to be identified and incorporated within the method. The selection of criteria should depend on contaminated site characteristics and stakeholder's objectives.

References

Akter, T., and Simonovic, S. P. 2005. Aggregation of fuzzy views of a large number of stakeholders for multi-objective flood management decision-making, *Journal of Environmental Management,* 77, 133-143.

Al-Ahmari, A. M. A. 2007. Evaluation of CIM technologies in Saudi industries using AHP. *Int.J.Adv.Manuf.Technol.* 34, 736-747.

Al-Rashdan, D., Al-Kloub, B., Dean, A., Al-Shemmeri, T. 1999. Environmental impact assessment and ranking the environmental projects in Jordan, *European Journal of Operational Research,* 118(1), 30-45.

Al-Shemmeri, T., Al-Kloub, B., Pearman, A. 1997. Computer aided decision support system for water strategic planning in Jordan, *European Journal of Operational Research,* 102(3), 455-472.

Altrock, C. V., and Krause, B. 1994. Multi-criteria decision making in German automotive industry using fuzzy logic, *Fuzzy Sets and Systems,* 63, 375-380.

Amini, M., Afyuni, M., Fathianpour, N., Khademi, H., Fluhler, H. 2005. Continuous soil pollution mapping using fuzzy logic and spatial interpolation, *Geoderma,* 124, 223-233.

Amro, M. M. 2004. Factors affecting chemical remediation of oil contaminated water-wetted soil, *Chemical Engineering Technology,* 27, 890-894.

Arvai, J., and Gregory, R. 2003. Testing alternative decision approaches for identifying cleanup priorities at contaminated sites, *Environmental Science & Technology,* 37(8), 1469-1476.

Baas, S. M., and Kwakernaak, H. 1977. Rating and ranking of multiple aspect alternative using fuzzy sets, *Automatica,* 13(1), 47-58.

Balasubramaniam, A., Boyle, A. R., Voulvoulis, N. 2007. The appropriateness of multicriteria analysis in environmental decision-making problems, *Chemosphere,* 66, 791-798.

Bana e Costa, C., ed. 1990. *Reading in Multiple Criteria Decision Aid.* Springer-Verlag.

Bardos, R. P., Martin, I. D., Kearney, T. 1999. Framework for evaluating remediation technologies, *Proc., IBC's 10th Conference- Contaminated Land,* IBC technical services Ltd.

Bardos, R. P., Mariotti, C., Marot, F., Sullivan, T. 2000. *Framework for Decision Support used in Contaminated Land Management in Europe and North America,* Environmental Management Support Inc., Maryland, USA.

Bella, A., Duckstein, L., Szidarovszky, F. 1996. A multicriterion analysis of the water allocation conflict in the upper Rio Grande basin, *Applied Mathematics and Computaion,* 77(2-3), 245-265.

Bellman, R. E., and Zadeh, L. A. 1970. Decision making in a fuzzy environment. *Management Science* 17, 141-164.

Bender, M. J., and Simonovic, S. P. 2000. A fuzzy compromise approach to water resource systems planning under uncertainty, *Fuzzy Sets and Systems,* 115, 35-44.

Bonano, E. J., Apostolakis, G. E., Salter, P. F., Ghassemi, A. 2000. Application of risk assessment and decision analysis to the evaluation, ranking and selection of environmental remediation alternatives, *Journal of Hazardous Materials,* 71(1-3), 35-57.

Bonissone, P. P. 1982. A fuzzy set based linguistic approach: theory and applications, *Approximate Reasoning in Decision Analysis,* North-Holland, 329-339.

Borsuk, M., Clemen, R., Maguire, L., Reckhow, K. 2001. Stakeholder values and scientific modeling in the Neuse River Watershed, *Group Decision and Negotiation,* 10, 355-373.

Bose, U., Davey, A. M., and Olson, D. L. 1997. Multi-attribute utility methods in group decision making: Past applications and potential for inclusion in GDSS. *Omega* 25, 691-706.

Carlsson, C. 1982. Tackling a MCDM-problem with the help of some results from fuzzy set theory. *European Journal of Operational Research* 10, 270-281.

CCME (Canadian Council of Ministers of the Environment). 1993. *Environmental code of practice for underground storage tank systems containing petroleum products and allied petroleum products.* Beauregard Printers Limited.

Chang, N., Parvathinathan, G., Breeden, J. B. 2007. Combining GIS with fuzzy multicriteria decision-Making for Landfill Siting in a Fast-Growing Urban Region, *Journal of Environmental Management.*

Chen, S. J., and Hwang, C. L. 1992. *Fuzzy Multiple Attribute Decision-Making,* Springer-Verlag, New York.

Cheng, C. H. 1996. Evaluating naval tactical missile systems by fuzzy AHP based on the grade of membership function, *European Journal of Operational Research,* 96, 343-350.

Cheng, C. H., and Lin,Y. 2002. Evaluating the best main battle tank using fuzzy decision theory with linguistic criteria evaluation. *European Journal of Operational Research* 142, 174-186.

Cheng, S. K. Y. 2000. Development of a fuzzy multi-criteria decision support system for municipal solid waste management, Masters Thesis, University of Ragina.

Civanlar, M. R., and Trussel, H.J. 1986. Constructing membership functions using statistical data. *Fuzzy Sets and Systems* 18, (1) 1-13.

Cole, G.,M. 1994. *Assessment and Remediation of Petroleum Contaminated Sites,* Lewis Publishers, USA.

Dou, C., Woldt, W., Bogardi, I. and Dahab, M. 1997. "Numerical solute transport simulation using fuzzy sets approach ". *Journal of Contaminant Hydrology* 27, no. 1:107-126.

Dowd, R. M. 1985. Leaking underground storage tanks. *Environ.Sci. & Tech.* 18, 10-15.

Dubois, J. S., and Prade, H. 1994. Fuzzy sets- a convenient fiction for modelling vagueness and possibility. *IEEE transaction on Systems, Man, Cybernetics* 2, no. 1:16-21.

Easton, A. 1973. *One-of-a-Kind Decisions Involving Weighted Multiple Objectives and Disparate Alternatives,* University of South Carolina Press, Columbia, South Carolina.

Efstathiou, J. 1982. Ranking Fuzzy Sets: A decision theoretic approach, *IEEE Transaction on Systems, Man, Cybernetics,* SMC-12, 655-659.

Efstathiou, J., and Rajkovic, V. 1979. Multiattribute decision making using a fuzzy Heurisitic approach, *IEEE Transaction on Systems, Man, Cybernetics,* SMC-9, 326-333.

ESRC Global Environmental Change Programmed. 2000. Risky choices, soft disasters: environmental decision-making under uncertainty, University of Sussex, Brighton, 25.

Fayek, A. R., and Sun, Z. 2001. A fuzzy expert system for design performance prediction and evaluation, *Canadian Journal of Civil Engineering,* 28(1), 1-25.

Fenton, N., and Wang. W. 2006. Risk and confidence analysis for fuzzy multicriteria decision making. *Knowledge based system* 19 (6),430-437.

Fernandes, L., Ridgley, M. A., van't Hof, T. 1999. Multiple criteria analysis integrates economic, ecological and social objectives for coral reef managers, *Coral Reefs,* 18(4), 393-402.

Figueira, J., Greco, S., Ehrgott, M. 2005. *Multiple Criteria Decision Analysis: State of the Art Surveys,* Springer Science, United States of America.

French, S. 1996. Multi-attribute decision support in the event of a nuclear accident, *Journal of Multi-Criteria Decision Analysis,* 5, 39-57.

Freissinet, C., Vauclin, M. and Erlich, M. 1999. Comparison of first-order analysis and fuzzy set approach for the evaluation of imprecision in a pesticide groundwater pollution screening model. *J. Contam. Hydrol* 27, 21-43.

Ganoulis, J. 2003. Evaluating alternative strategies for wastewater recycling and reuse in the Mediterranean area, *Water Science and Technology,* 3(4), 11-19.

Gregory, R., and Failing, L. 2002. Using decision analysis to encourage sound deliberation: water use planning in British Columbia, Canada, *Journal of Policy Analysis and Management,* 21(3), 492-499.

Gregory, R., and Wellman, K. 2001. Bringing stakeholder values into environmental policy choices: a community-based estuary case study, *Ecological Economics,* 39(1), 37-52.

Gregory, R., and Keeney, R. L. 1994. Creating policy alternatives using stakeholder values, *Management Science,* 40(8), 1035-1048.

Gutierrez, I., and Carmona, S. 1995. Ambiguity in multicriteria quality decision, *International Journal of Production Economics,* 38(2-3), 215-224.

Hajkowicz, S. A., McDonald, G. T. and Smith, P. N. 2000. An evaluation of multiple objective decision support weighting techniques in natural resource management. *Journal of Environmental Planning and Management* 43, no. 4:505-518.

Hajkowicz, S.A., and Higgins, A. 2008. A comparison of multiple criteria analysis techniques for water resource management. *European Journal of Operational Research* 184, 255-265.

Hellendoorn, H. 1997. After the fuzzy wave reached Europe, *European Journal of Operational Research,* 99, 58-71.

Herrera, F., and Verdegay, J. L. 1997. Fuzzy sets and operations research: perspectives. *Fuzzy Sets and Systems* 90, 207-218.

Hong, I. B., and Vogel, D. R. 1991. Data and model management in a generalized MCDM-DSS, *Decision Sciences,* 22(1), 25.

Hu, Z., Chan, C. W., Huang, G., H. 2003. A fuzzy expert system for site characterization, *Expert Systems with Applications,* 24, 123-131.

Hwang, F. 1987. An expert decision making support system for multiple attribute decision making, Ph.D. dissertation, Kansas state university.

Hwang, C. L., and Yoon, K. 1981. *Multiple Attribute Decision Making-Methods and Applications, A State-of-the-Art Survey,* Springer-Verlag, New York.

ICS-UNIDO and UNECE. 2000. *Compendium of soil clean-up technologies and soil remediation companies, second edition.* New York and Geneva.

Janikowski, R., Kucharski, R., Sas-Nowosielska, A. 2000. Multi-criteria and multi-perspective analysis of contaminated land management methods, *Environmental Monitoring and Assessment,* 60, 89-102.

Joubert, A. R., Leiman, A., de Klerk, H. M., Katua, S., Aggenbach, J. C. 1997. Fybos (fine bush) vegetation and the supply of water: a comparison of multi-criteria decision analysis and cost-benefit analysis, *Ecological Economics,* 22(2), 123-140.

Juang, C. H., and Lee, D. H. 1991. A fuzzy scale for measuring weights of criteria in hierarchical structures, *IFES,* 415-421.

Kamnikar, B. 2001. Managing petroleum contaminated soil: department of transportation perspective, *Journal of Environmental Engineering,* 127(12), 1080-1088.

Kaufmann, A., and Gupta, M. M. 1985. *Introduction to Fuzzy Arithmetic: Theory and Applications.* New York: Van Nostrand Reinhold.

Khadam, I. M., and Kalauarachchi, J. J. 2003. Multi-criteria decision analysis with probabilistic risk assessment for the management of contaminated ground water. *Environmental Impact Assessment Review* 23, 683-721.

Khan, F. I., Hussain, T., Hejazi, R. 2004. An overview and analysis of site remediation technologies, *Journal of Environmental Management,* 71, 95-122.

Khan, F. I., Sadiq, R., Husain, T. 2002. GreenPro-I: A risk-based life cycle assessment and decision-making methodology for process plant design, *Environmental Modelling and Software,* 17(8), 669-692.

Khan, F. I., and Sadiq, R. 2005. Risk based prioritization of air pollution monitoring using fuzzy synthetic evaluation technique, *Environmental Monitoring and Assessment,* 105, 261-283.

Klir, G. J., and Folger, T. 1988. *Fuzzy Sets, Uncertainty and Information.* Englewood Cliffs, NJ: Prentice Hall.

Kuncheva, L. I., Wrench, J., Jain, L. C., Al-Zaidan, A. S. 2000. A fuzzy model of heavy metal loadings in Liverpool Bay," *Environmental Modelling & Software,* 15(2), 161-167.

Lee, H. 1996. Applying fuzzy set theory to evaluate the rate of aggregative risk in software development, *Fuzzy Sets and Systems,* 79(3), 323-336.

Lehr, J. H. 2004. *Wiley's Remediation Technologies Handbook,* 1st Ed., John Wiley & Sons, Inc., Hoboken, New Jersey.

Li, J. B., Huang, G. H., Chakma, A., Chen, Z., Liu, L., Zeng, G. M. 2000. URREM: A decision support system for subsurface modeling, risk assessment and site remediation, *Proceedings of*

Critical Technologies to the World in 21st Century: Pollution Control and Reclamation in Process Industries, IAWQ Specialty Conference, Beijing, China, September 2000, 882-889.

Li, J.B. 2003. Development of an inexact environmental modeling system for the management of petroleum contaminated Sites, University of Regina, Regina, Saskatchewan.

Li, J.B., Huang, G., H., Chakma, A., Zeng, G. M., Liu, L. 2003. Integrated fuzzy-stochastic modeling of petroleum contamination in subsurface, *Energy Sources,* 25, 547-563.

Li, J.B., Huang, G., H., Zeng, G. M. 2001. An integrated decision support system for the management of petroleum contaminated sites, *Journal of Environmental Science and Health,* 36(7), 1163-1186.

Li, J.B., Huang, G., H., Zeng, G., Maqsood, I., Huang, Y. 2007. An integrated fuzzy-stochastic modeling approach for risk assessment of groundwater contamination, *Journal of Environmental Management,* 82, 173-188.

Li, J. B., Liu, L., Huang, G., Zeng, G. M. 2006. A fuzzy-set approach for addressing uncertainties in risk assessment of hydrocarbon-contaminated Site, *Water, Air and Soil Pollution,* 171(1-4), 5-18.

Lind, E. A. 1995. *Social Conflict and Social Justice: Some Lessons from the Social Psychology of Justice,* University Press, Leiden, The Netherlands.

Lind, E. A., and Tyler, T. R. 1988. *Social Psychology of Procedural Justice,* Plenum, NewYork.

Linkov, I., Satterstrom, F. K., Kiker, G., Seager, T. P., Bridges, T., Gardner, K. H., Rogers, S. H., Belluck, D. A., Meyer, A. 2006. Multicriteria decision analysis: A comprehensive decision approach for management of contaminated sediments, *Risk Analysis,* 26(1), 61-78.

Mardle, S., and Pascoe, S. 2002. Modelling the effects of trade-offs between long and short-term objectives in fisheries management, *Journal of Environmental Management,* 65(1), 49-62.

McIntyre, C., and Parfitt, M. K. 1998. Decision support system for residential land development site selection process, *Journal of Architect Engineering ASCE,* 4, 125-131.

Mikhailov, L., and Tsvetinov, P. 2004. Evaluation of services using a fuzzy analytic hierarchy process. *Applied Soft Computing* 5, 23-33.

Miller, G. A. 1965. The Magic Number Seven, Plus or Minus Seven, *Psychological Review,* 63, 81-97.

Mohamed, A. M. O., and Cote, K. 1999. Decision analysis of polluted sites-a fuzzy set approach. *Waste management* 19, 519-533.

Moran, D., A. McVittie, D. J. Allcroft, and D. A. Elston. 2007. Quantifying public preferences for agri-environmental policy in Scotland: A comparison of methods. *Ecological Economics* 63, 42-53.

Najjaran, H., Sadiq, R., Rajani, B. 2006. Fuzzy expert system to assess corrosion of cast/ductile iron pipes from backfill properties, *Computer-Aided Civil and Infrastructure Engineering,* 21, 67-77.

Newton, J. 1991. Investigating leaking underground storage tanks. *Pollution Engineering.* 23, 80-83.

Nijkamp, P., Rietveld, P., Voogd, H. 1990. *Multicriteria evaluation in physical planning,* Elsevier Science Publishers, Amsterdam, The Netherlands.

Ning, S. K., and Chang, N. B. 2002. Multi-objective, decision-based assessment of a water quality monitoring network in a river system, *Journal of Environmental Monitoring,* 4, 121-126.

Norbis, M., and Smith, J. M. 1996. An interactive decision support system for the resource Constrained Scheduling Problem, *European Journal of Operational Research,* 94(1), 54-65.

NRTEE. 1997. *Removing barriers: redeveloping national round table on the environment and the economy, Canadian mortgage and housing corporation.* Canada: Golder Associates ltd. and McCarthy Tetrault.

Osgood, C. E., Suci, G. J., Tannenbaum, P. H. 1975. *The measurement of meaning,* 9th Ed., University of Illinois Press, Urbana.

Petrovic, S., and Petrovic, R. 2002. A new fuzzy multi-criteria methodology for ranking of alternatives. *Intl. Trans. in Op. Res.* 9, 73-84.

Petts, J., Cairney, T., and Smith, M. 1997. *Risk-based contaminated land investigation and assessment.* Chichester: John Wiley & Sons.

Pollard, S. J. T., Brookes, A., Earl, N., Lowe, J., Kearney, T., Nathanail, C. P. 2004. Integrating decision tools for the sustainable management of land contamination, *Science of the Total Environment,* 325, 15-28.

Prato, T. 2003. Multiple-attribute evaluation of ecosystem management for the Missouri river system, *Ecological Economics,* 45(2), 297-309.

Qin, X. S., Huang, G. H., Huang, Y. F., Zeng, G. M., Li, J. B. 2006. NRSRM: A decision support system and visualization software for the management of petroleum-contaminated sites, *Energy Sources,* 28, 199-220.

Reddy, K. R., Adams, J. A., Richardson, C. 1999. Potential technologies for remediation of brownfields, *Practice Periodical of Hazardous, Toxic, and Radioactive Waste Management,* 3(2), 61-68.

Riser-Roberts, E. 1998. *Remediation of petroleum contaminated soil: Biologica , Physical, and Chemical Processes,* Lewis Publishers, Boca Raton, FL.

Rogers, S. H., Seager, T. P., Gardner, K. H. 2004. Combining expert judgement and stakeholder values with Promethee: A case study in contaminated sediments management, *Comparative Risk Assessment and Environmental Decision Making,* Kluwer Academic Publishers, Boston, 305-322.

Saaty, T. L. 1994. How to make a decision: The analytic hierarchy process. *Interfaces,* 24, 19-43.

Sadiq, R., Hussain, T., Veitch, B., Bose, N. 2004a. Risk-based decision making for drilling waste discharges using a fuzzy synthetic evaluation technique, *Ocean Engineering,* 31, 1929-1953.

Sadiq, R., Rajani, B., Kleiner, Y. 2004b. Fuzzy- based method to evaluate soil corrosivity for Prediction of Water Main Deterioration, *Journal of Infrastructure Systems,* 10(4), 149-156.

Seager, T. P., Lambert, J. H. and Gardner, K. H. 2007. Fostering innovation in contaminated sediments management through multicriteria technology assessment and public participation. *Risk Analysis* 27, no. 4:1043-1052.

Simons, R. 1998. *Turning brownfields into greenback.* Washington DC: Urban Land Istitute.

Siciliano, S. D., and Germida, J. J. 1998. Mechanisms of phytoremediation: biochemical and ecological interactions between plants and bacteria, *Environ. Rev.,* 6, 65-79.

Soesilo, J. A., and Wilson, S. R. 1997. *Site remediation planning and managemen.* 1st ed. USA: Lewis Publishers.

Soma, K. 2003. How to involve stakeholders in fisheries management-a country case study in Trinidad and Tobago, *Marine Policy,* 27(1), 47-58.

Sousa, D., C. 2001. Contaminated Sites: The Canadian situation in an international context, *Journal of Environmental Management,* 62(131), 154.

Susan, R. 2003. A decision tree for selecting bioremediation in cold climates, *Proc., Assessment and Remediation of Contaminated Sites in Arctic and Cold Climates,* ARCSACC, Edmonton, 183-197.

Tang, M. T., Tzeng, G. H., Wang, S. W. 1999. A hierarchy fuzzy MCDM method for studying electronic marketing strategies in the information service industry, *Journal of International Information Management,* 8(1), 1-22.

Teng, J. Y., and Tzeng, G. H. 1996. Fuzzy multicriteria ranking of urban transportation investment alternatives, *Transportation Plannig Technology,* 20(1), 15-31.

Testa, S. M., and Winegardner, D. L. 1991. *Restoration of petroleum-contaminated aquifers,* Lewis Publishers, Chelsea, MI.

Turksen, I. B. 1991. Measurement of membership functions and their acquisition. *Fuzzy sets and Systems* 40, no. 1:5-34.

UNECE, 1997. *Compendium of soil clean-up technologies and soil remediation companies,* first edition, New York and Geneva.

Urban Task Force. 1999. *Towards an urban renaissance,* E&FN Spon, London.

USEPA (U.S. Environmental Protection Agency). 1993. *Remediation technologies screening matrix and reference guide.* Washington, DC.

USEPA (U.S. Environmental Protection Agency). 2001. *Abstracts of remediation case studies,* Washington, DC.

USEPA (U.S. Environmental Protection Agency). 2005. *A decision-making framework for cleanup of sites impacted with light non-aqueous phase liquids (LNAPL).*EPA 542-R-04-011, Washington, DC.

USEPA (U.S. Environmental Protection Agency). 2008. Remediation technologies screening matrix and reference guide, version 4.0. [cited January/01 2008]. Available from http://www.frtr.gov/matrix2/top_page.html.

van Moeffaert, D. 2002. Multi-criteria decision aid in sustainable urban water management, *Masters Thesis,* Royal Institute of Technology, Stockholm, Sweden.

Vranes, E., Gonzalez, V., Lodolo, A., Miertus, S. 2000. *Decision support tool: applications in remediation technology evaluation and selection,* Environmental management support, Inc., Maryland.

Wang, L. X. 1997. *A course in fuzzy systems and control,* Prentice-Hall,Inc., USA.

Wenstop, F. 1976. Fuzzy set simulation models in a systems dynamic perspective, *Kybernetes,* 5, 209-218.

Wong, J. K. W., and Li, H. 2008. Application of the analytic hierarchy process (AHP) in multi-criteria analysis of the selection of intelligent building systems. *Building and Environment* 43, 108-125.

Yager, R. R.; Filev, D. P.1994. *Essentials of fuzzy modelling and control;* John Wiley & Sons Inc.: New York: 1994.

Yeh, C. H., Deng, H. and Chang, Y.H. 2000. Fuzzy multicriteria analysis for performance evaluation of bus companies. *European Journal of Operational Research* 126, 459-473.

Yoon, K. P., and Hwang, C. L. 1995. *Multiple attribute decision making an introduction,* Sage Publications, Thousand Oaks, California.

Yurdakul, M. 2004. AHP as a strategic decision-making tool to justify machine tool selection. *Journal of Materials Processing Technology* 146, 365-376.

Zadeh, L. A. 1965. Fuzzy Sets, *Information and Control,* 8, 338-353.

Zahedi, F. 1986. The Analytical Hierarchy Process:The Method and its application. *Interfaces,* 16, 96-108.

Zapatero, E., Smith, C. H., and Weistroffer, H. R. 1997. Evaluating multiple attribute decision support software. *Journal of Multi-criteria Decision Analysis* 6, 201-214.

Zimmermann, H. -J. 1996. *Fuzzy set theory and its applications.* Boston: Kluwer Academic Publishers.

APPENDIX I Questionnaire

Part I:

1. Which best describes your age group? (Please select one)

a. Under 25	[ ]	b. 25-30	[ ]
c. 31-40	[ ]	d. 41-55	[ ]
e. 56-65	[ ]	f. Over 65	[ ]

2. Highest level of education completed? (Please select one)

a. 12th grade, no diploma	[ ]	b. High school graduate	[ ]
c. Some college credit, but less than 1 year	[ ]	d. 1 or more years of college, no degree	[ ]
e. Associate degree (i.e., AA, AS)	[ ]	f. Bachelor's degree (i.e.,BA,AB,BS)	[ ]
g. Master's degree (i.e.,MA, MS, MEng)	[ ]	h. Professional degree (i.e., MD,LLB,JD)	[ ]
i. Doctoral degree (i.e.,PhD,EdD)	[ ]	j. Other	[ ]

3. Which one of the following best describes your professional affiliation? (Please select one)

a. Institution (i.e., universities)	[ ]	b. Industry (i.e.,oil and gas industries)	[ ]
c. Federal government	[ ]	d. Provincial government	
e. Research organization	[ ]	f. Non-governmental / non-profit organization	[ ]
g. Environmental consulting firms	[ ]	h. First nation community	[ ]
i. General public	[ ]	j. Other	[ ]

4. How many years of experience do you have in your profession?

a. less than 2 years	[ ]	b. 2 -5 years	[ ]
c. More than 5 years	[ ]	d. Not applicable	[ ]

<u>Please read these important definitions, these are helpful references for the next sections:</u>

1. Community Acceptability criterion

Refers to the level of technology acceptability by members of the general public that live or work near the contaminated site.

2. Minimum Achievable Concentration Criterion

Addresses the degree to which the technology is able to meet remediation objectives.

3. Time to Complete Cleanup (in-situ and ex- situ) Criterion

Refers to the time required to complete remediation, including site closure time by a technology.

4. Overall Cost (in-situ and ex- situ) Criterion

Includes design, construction, operations and maintenance (O&M) costs of a remediation technology, exclusive of mobilization, demobilization, and pre- and post- treatment.

5. Development Status of a Technology

Refers to the current status of the technology, i.e., experimental (laboratory scale), pilot scale, full scale, or the technology is already being applied as commercially and industrially.

6. Availability of the Technology Criterion
Number of vendors that can design, construct, and maintain the technology.

7. Technology Maintenance Criterion
Refers to the level of complexity of the technology and how easy it is to maintain. If high maintenance is required for a technology this will indicate low reliability of the technology.

8. Regulatory (permitting) Acceptability Criterion
Degree of regulatory and permitting acceptability of the technology.

Part II : **Your opinion on criteria importance**

Different criteria carry different weights among decision makers to select a remediation technology.

5. Please rate the following 10 criteria in terms of their importance to you, by selecting the linguistic scale below. For explanation on criteria you may refer to the previous page.

Criteria		Linguistic scale to rate the importance of criteria							
1	**Community acceptability**	Very low	Low	Low to medium	Medium	Medium to High	High	Very high	No opinion
2	**Minimum achievable concentration**	Very low	Low	Low to medium	Medium	Medium to High	High	Very high	No opinion
3	**Time to complete clean up**	Very low	Low	Low to medium	Medium	Medium to High	High	Very high	No opinion
4	**Overall cost**	Very low	Low	Low to medium	Medium	Medium to High	High	Very high	No opinion
5	**Data requirements**	Very low	Low	Low to medium	Medium	Medium to High	High	Very high	No opinion
6	**Availability**	Very low	Low	Low to medium	Medium	Medium to High	High	Very high	No opinion
7	**Maintenance**	Very low	Low	Low to medium	Medium	Medium to High	High	Very high	No opinion
8	**Regulatory permitting acceptability**	Very low	Low	Low to medium	Medium	Medium to High	High	Very high	No opinion

<u>Part III:</u> Opinion on criteria value range

A. Community acceptability

Refers to the level of technology acceptability by members of the general public that live or work near the contaminated site.

<u>Note:</u> Provided that the technology is effective for Petroleum Hydrocarbon contaminants

6. When would you consider that acceptance of a technology is <u>low</u> in the community? (You may select more than one response)

a. If the technology is accepted by 10% or less of the community involved
b. If the technology is accepted by 20% or less of the community involved
c. If the technology is accepted by 30% or less of the community involved
d. If the technology is accepted by 40% or less of the community involved
e. If the technology is accepted by 50% or less of the community involved
f. If the technology is accepted by 60% or less of the community involved
g. If the technology is accepted by 70% or less of the community involved
h. If the technology is accepted by 80% or less of the community involved
i. If the technology is accepted by 90% or less of the community involved
j. No opinion

7. When would you consider that acceptance of a technology is <u>low to medium</u> in the community? (You may select more than one response)

a. If the technology is accepted by aprox. 10% of the community involved
b. If the technology is accepted by aprox. 20% of the community involved
c. If the technology is accepted by aprox. 30% of the community involved
d. If the technology is accepted by aprox. 40% of the community involved
e. If the technology is accepted by aprox. 50% of the community involved
f. If the technology is accepted by aprox. 60% of the community involved
g. If the technology is accepted by aprox. 70% of the community involved
h. If the technology is accepted by aprox. 80% of the community involved
i. If the technology is accepted by aprox. 90% of the community involved
j. No opinion

8. When would you consider that acceptance of a technology is <u>medium</u> in the community? (You may select more than one response)

a. If the technology is accepted by aprox. 10% of the community involved
b. If the technology is accepted by aprox. 20% of the community involved
c. If the technology is accepted by aprox. 30% of the community involved
d. If the technology is accepted by aprox. 40% of the community involved
e. If the technology is accepted by aprox. 50% of the community involved
f. If the technology is accepted by aprox. 60% of the community involved
g. If the technology is accepted by aprox. 70% of the community involved
h. If the technology is accepted by aprox. 80% of the community involved
i. If the technology is accepted by aprox. 90% of the community involved
j. No opinion

9. When would you consider that acceptance of a technology is <u>medium to high</u> in the community? (You may select more than one response)

a. If the technology is accepted by aprox. 10% of the community involved b. If the technology is accepted by aprox. 20% of the community involved
c. If the technology is accepted by aprox. 30% of the community involved
d. If the technology is accepted by aprox. 40% of the community involved
e. If the technology is accepted by aprox. 50% of the community involved
f. If the technology is accepted by aprox. 60% of the community involved
g. If the technology is accepted by aprox. 70% of the community involved
h. If the technology is accepted by aprox. 80% of the community involved

i. If the technology is accepted by aprox. 90% of the community involved
j. No opinion

10. When would you consider that acceptance of a technology is high in the community? (You may select more than one response)
a. If the technology is accepted by 10% or greater of the community involved
b. If the technology is accepted by 20% or greater of the community involved
c. If the technology is accepted by 30% or greater of the community involved
d. If the technology is accepted by 40% or greater of the community involved
e. If the technology is accepted by 50% or greater of the community involved
f. If the technology is accepted by 60% or greater of the community involved
g. If the technology is accepted by 70% or greater of the community involved
h. If the technology is accepted by 80% or greater of the community involved
i. If the technology is accepted by 90% or greater of the community involved
j. No opinion

B. Minimum achievable concentration

Different remediation technologies have various level of capability to achieve expected contaminant concentration. The following questions ask about your opinion to rate a technology depending on its achieved concentration. The linguistic scale to evaluate this criteria value range includes bad, poor, average, good, and excellent.

Note: Provided that the technology is effective for Petroleum Hydrocarbon contaminants

11. When would you rate a technology as low? (You may select more than one response)
a. If contaminant concentration of interest is reduced 10% or less
b. If contaminant concentration of interest is reduced 20% or less
c. If contaminant concentration of interest is reduced 30% or less
d. If contaminant concentration of interest is reduced 40% or less
e. If contaminant concentration of interest is reduced 50% or less
f. If contaminant concentration of interest is reduced 60% or less
g. If contaminant concentration of interest is reduced 70% or less
h. If contaminant concentration of interest is reduced 80% or less
i. If contaminant concentration of interest is reduced 90% or less
j. No opinion

12. When would you rate a technology as low to average? (You may select more than one response)
a. If contaminant concentration of interest is reduced approx. 10%
b. If contaminant concentration of interest is reduced approx. 20%
c. If contaminant concentration of interest is reduced approx. 30%
d. If contaminant concentration of interest is reduced approx. 40%
e. If contaminant concentration of interest is reduced approx. 50%
f. If contaminant concentration of interest is reduced approx. 60%
g. If contaminant concentration of interest is reduced approx. 70%
h. If contaminant concentration of interest is reduced approx.80%
i. If contaminant concentration of interest is reduced approx. 90%
j. No opinion

13. When would you rate a technology as average? (You may select more than one response)
a. If contaminant concentration of interest is reduced approx. 10%
b. If contaminant concentration of interest is reduced approx. 20%
c. If contaminant concentration of interest is reduced approx. 30%
d. If contaminant concentration of interest is reduced approx. 40%
e. If contaminant concentration of interest is reduced approx. 50%
f. If contaminant concentration of interest is reduced approx. 60%

g. If contaminant concentration of interest is reduced approx. 70%
h. If contaminant concentration of interest is reduced approx.80%
i. If contaminant concentration of interest is reduced approx. 90%
j. No opinion

14. When would you rate a technology as __average to high__? (You may select more than one response)
a. If contaminant of interest concentration is reduced approx. 10%
b. If contaminant of interest concentration is reduced approx. 20%
c. If contaminant of interest concentration is reduced approx. 30%
d. If contaminant of interest concentration is reduced approx. 40%
e. If contaminant of interest concentration is reduced approx. 50%
f. If contaminant of interest concentration is reduced approx. 60%
g. If contaminant of interest concentration is reduced approx. 70%
h. If contaminant of interest concentration is reduced approx.80%
i. If contaminant of interest concentration is reduced approx. 90%
j. No opinion

15. When would you rate a technology as __high__? (You may select more than one response)
a. If contaminant concentration of interest is reduced 10% or greater
b. If contaminant concentration of interest is reduced 20% or greater
c. If contaminant concentration of interest is reduced 30% or greater
d. If contaminant concentration of interest is reduced 40% or greater
e. If contaminant concentration of interest is reduced 50% or greater
f. If contaminant concentration of interest is reduced 60% or greater
g. If contaminant concentration of interest is reduced 70% or greater
h. If contaminant concentration of interest is reduced 80% or greater
i. If contaminant concentration of interest is reduced 90% or greater
j. No opinion

C. Clean-up time (in-situ and ex-situ):

Refers to the time required to complete remediation, including site closure time. In general the technologies with high efficiency might have higher preference over technologies with low efficiency. The following questions are to survey your opinion on clean up time required for both in-situ and ex-situ remediation treatments.
In-situ treatment: contaminated soil is treated without excavation. In a general setting in-situ treatment is a slow process compared to ex-situ treatment.
__Note:__ Provided that the technology is effective for Petroleum Hydrocarbon (crude oil) contaminants, the mentioned time for in-situ treatment is based on a standard site and under favorable conditions. It is assumed that contaminated site area is 40m X 40m (1600m^2); the average depth of soil contamination is from the surface to a depth of 5m. The contaminated soil mass is approx. 20,000 tons. Only contaminated soil is considered for treatment.

16. **When using in-situ treatment, what time period would you consider as a __short__ clean-up time for the above case?** (You may select more than one response)
a. Approximately 6 months or less
b. Approximately 1 year or less
c. Approximately 18 months or less
d. Approximately 2 years or less
e. Approximately 30 months or less
f. Approximately 3 years or less
g. Approximately 42 months or less
h. Approximately 4 years or less
i. Approximately 54 months or less
j. Approximately 5 years or less
k. No opinion

17. When using in-situ treatment, what time period would you consider as a __short to medium__ clean-up time for the above case? (You may select more than one response)
a. Approximately 6 months
b. Approximately 1 year

c. Approximately 18 months
d. Approximately 2 years
e. Approximately 30 months
f. Approximately 3 years
g. Approximately 42 months
h. Approximately 4 years
i. Approximately 54 months
j. Approximately 5 years
k. No opinion

18. When using in-situ treatment, what time period would you consider as a <u>medium</u> clean-up time for the above case? (You may select more than one response)

a. Approximately 6 months
b. Approximately 1 year
c. Approximately 18 months
d. Approximately 2 years
e. Approximately 30 months
f. Approximately 3 years
g. Approximately 42 months
h. Approximately 4 years
i. Approximately 54 months
j. Approximately 5 years
k. no opinion

19. When using in-situ treatment, what time period would you consider as a <u>medium to long</u> clean-up time for the above case? (You may select more than one response)

a. Approximately 6 months
b. Approximately 1 year
c. Approximately 18 months
d. Approximately 2 years
e. Approximately 30 months
f. Approximately 3 years
g. Approximately 42 months
h. Approximately 4 years
i. Approximately 54 months
j. Approximately 5 years
k. No opinion

20. When using in-situ treatment, what time period would you consider as a <u>long</u> clean-up time for the above case? (You may select more than one response)

a. Approximately 6 months or greater
b. Approximately 1 year or greater
c. Approximately 18 months or greater
d. Approximately 2 years or greater
e. Approximately 30 months or greater
f. Approximately 3 years or greater
g. Approximately 42 months or greater
h. Approximately 4 years or greater
i. Approximately 54 months or greater
j. Approximately 5 years or greater
k. No opinion

Ex-situ treatment: contaminated soil is treated after excavation. In a general setting ex-situ treatment is a fast process compared to in-situ treatment.

<u>Note:</u> Provided that the technology is effective for Petroleum Hydrocarbon (crude oil) contaminants, the mentioned time for ex-situ treatment is based on a standard site and under favorable conditions. It is assumed that contaminated site area is 40m X 40m ($1600m^2$); the average depth of soil contamination is from the surface to a depth of 5m. The contaminated soil mass is approx. 20,000 tons. It is also assumed that the soil is excavated and treated.

21. When using ex-situ treatment, what time period would you consider as a <u>short</u> clean-up time for the above case? (You may select more than one response)

a. Approximately 4 months or less
b. Approximately 5 months or less
c. Approximately 6 months or less
d. Approximately 7 months or less
e. Approximately 8 months or less
f. Approximately 9 months or less
g. Approximately 10 months or less
h. Approximately 11 months or le
i. Approximately 12 months or less
j. No opinion

22. When using ex-situ treatment, what time period would you consider as a <u>short to medium</u> clean-up time for the above case? (You may select more than one response)

a. Approximately 4 months
b. Approximately 5 months
c. Approximately 6 months
d. Approximately 7 months

e. Approximately 8 months
f. Approximately 9 months
g. Approximately 10 months
h. Approximately 11 months
i. Approximately 12 months
j. No opinion

23. When using ex-situ treatment, what time period would you consider as a medium clean-up time for the above case? (You may select more than one response)
a. Approximately 4 months
b. Approximately 5 months
c. Approximately 6 months
d. Approximately 7 months
e. Approximately 8 months
f. Approximately 9 months
g. Approximately 10 months
h. approximately 11 months
i. Approximately 12 months
j. no opinion

24. When using ex-situ treatment, what time period would you consider as a medium to long clean-up time for the above case? (You may select more than one response)
a. Approximately 4 months
b. Approximately 5 months
c. Approximately 6 months
d. Approximately 7 months
e. Approximately 8 months
f. Approximately 9 months
g. Approximately 10 months
h. Approximately 11 months
i. Approximately 12 months
j. No opinion

25. When using ex-situ treatment, what time period would you consider as a long clean-up time for the above case? (You may select more than one response)
a. Approximately 4 month or greater
b. Approximately 5 month or greater
c. Approximately 6 month or greater
d. Approximately 7 month or greater
e. Approximately 8 month or greater
f. Approximately 9 month or greater
g. Approximately 10 month or greater
h. Approximately 11 month or greater
i. Approximately 12 month or greater
j. No opinion

D. Overall Cost

Includes design, construction, operations and maintenance (O&M) costs of the core process that defines each technology, exclusive of mobilization, demobilization, and pre- and post- treatment.

In- situ treatment: contaminated soil is treated without excavation.

Note: **Provided that the technology is effective for Petroleum Hydrocarbon (crude oil) contaminants, the mentioned cost for in-situ treatment is based on a standard site and under favorable conditions. It is assumed that contaminated site area is 40m X 40m (1600m^2); the average depth of soil contamination is from the surface to a depth of 5m. The contaminated soil mass is approx. 20,000 tons. Only contaminated soil is considered for treatment.**

26. Which value would you consider as low cost (per cubic meter) when in-situ treatment is considered for the above case? (You may select multiple or single options)
a. Approximately \$50 per m^3 or less
b. Approximately \$75 per m^3 or less
c. Approximately \$100 per m^3 or less
d. Approximately \$125 per m^3 or less
e. Approximately \$150 per m^3 or less
f. Approximately \$175 per m^3 or less
g. Approximately \$200 per m^3 or less
h. Approximately \$225 per m^3 or less
i. Approximately \$275 per m^3 or less
j. No opinion

27. Which value would you consider as low to medium cost (per cubic meter) when in-situ treatment is considered for the above case? (You may select more than one response)
a. Approximately \$50 per m^3
b. Approximately \$75 per m^3
c. Approximately \$100 per m^3
d. Approximately \$125 per m^3
e. Approximately \$150 per m^3
f. Approximately \$175 per m^3

g. Approximately \$200 per m^3
h. Approximately \$225 per m^3
i. Approximately \$275 per m^3
j. No opinion

28. Which value would you consider as <u>medium cost (per cubic meter)</u> when in-situ treatment is considered for the above case? (You may select more than one response)
a. Approximately \$50 per m^3
b. Approximately \$75 per m^3
c. Approximately \$100 per m^3
d. Approximately \$125 per m^3
e. Approximately \$150 per m^3
f. Approximately \$175 per m^3
g. Approximately \$200 per m^3
h. Approximately \$225 per m^3
i. Approximately \$275 per m^3
j. No opinion

29. Which value would you consider as <u>medium to high cost (per cubic meter)</u> when in-situ treatment is considered for the above case? (You may select more than one response)
a. Approximately \$50 per m^3
b. Approximately \$75 per m^3
c. Approximately \$100 per m^3
d. Approximately \$125 per m^3
e. Approximately \$150 per m^3
f. Approximately \$175 per m^3
g. Approximately \$200 per m^3
h. Approximately \$225 per m^3
i. Approximately \$275 per m^3
j. No opinion

30. Which value would you consider as <u>high cost (per cubic meter)</u> when in-situ treatment is considered for the above case? (You may select more than one response)
a. Approximately \$50 per m^3 or greater
b. Approximately \$75 per m^3 or greater
c. Approximately \$100 per m^3 or greater
d. Approximately \$125 per m^3 or greater
e. Approximately \$150 per m^3 or greater
f. Approximately \$175 per m^3 or greater
g. Approximately \$200 per m^3 or greater
h. Approximately \$225 per m^3 or greater
i. Approximately \$275 per m^3 or greater
j. No opinion

Ex situ treatment: contaminated soil is treated after excavation and excavation cost is assumed \$50/ton.
<u>Note:</u> Provided that the technology is effective for Petroleum Hydrocarbon (crude oil) contaminants, the mentioned cost for ex-situ treatment is based on a standard site and under favorable conditions. It is assumed that contaminated site area is 40m X 40m (1600m^2); the average depth of soil contamination is from the surface to a depth of 5m. The contaminated soil mass is approx. 20,000 tons. The excavation cost is \$50 per ton. Excavation cost is included in the following values.

31. Which value you consider as <u>low cost (per cubic meter)</u> when ex-situ treatment is considered for above case? (You may select more than one response)
a. Approximately \$100 per yd^3 or less
b. Approximately \$125 per yd^3 or less
c. Approximately \$150 per m^3 or less
d. Approximately \$175 per m^3 or less
e. Approximately \$200 per m^3 or less
f. Approximately \$225 per m^3 or less
g. Approximately \$275 per m^3 or less
h. Approximately \$300 per m^3 or less
i. Approximately \$325 per m^3 or less
j. No opinion

32. Which value you consider as <u>low to medium cost (per cubic meter)</u> when ex-situ treatment is considered for above case? (You may select more than one response)
a. Approximately \$100 per m^3
b. Approximately \$125 per m^3
c. Approximately \$150 per m^3
d. Approximately \$175 per m^3
e. Approximately \$200 per m^3
f. Approximately \$225 per m^3
g. Approximately \$275 per m^3
h. Approximately \$300 per m^3
i. Approximately \$325 per m^3
j. No opinion

33. Which value you consider as <u>medium cost (per cubic meter)</u> when ex-situ treatment is considered for above case? (You may select more than one response)
a. Approximately \$100 per m^3
b. Approximately \$125 per m^3
c. Approximately \$150 per m^3
d. Approximately \$175 per m^3
e. Approximately \$200 per m^3
f. Approximately \$225 per m^3

g. Approximately \$275 per m^3
h. Approximately \$300 per m^3
i. Approximately \$325 per m^3
j. No opinion

34. Which value you consider as <u>medium to high cost (per cubic meter)</u> when ex-situ treatment is considered for above case? (You may select more than one response)

a. Approximately \$100 per m^3
b. Approximately \$125 per m^3
c. Approximately \$150 per m^3
d. Approximately \$175 per m^3
e. Approximately \$200 per m^3
f. Approximately \$225 per m^3
g. Approximately \$275 per m^3
h. Approximately \$300 per m^3
i. Approximately \$325 per m^3
j. No opinion

35. Which value you consider as <u>high cost (per cubic meter)</u> when ex-situ treatment is considered for above case? (You may select more than one response)

a. Approximately \$100 per m^3 or greater
b. Approximately \$125 per m^3 or greater
c. Approximately \$150 per m^3 or greater
d. Approximately \$175 per m^3 or greater
e. Approximately \$200 per m^3 or greater
f. Approximately \$225 per m^3 or greater
g. Approximately \$275 per m^3 or greater
h. Approximately \$300 per m^3 or greater
i. Approximately \$325 per m^3 or greater
j. No opinion

APPENDIX II Introduction of Remediation Technologies

A brief description of all the remediation alternatives used in the system is given below as a reference to the users of the system. The description of the following remediation alternatives and criteria information is synthesized from Lehr (2004) and USEPA (2008).

1. Enhanced bioremediation (in-situ biological treatment)

Technology description

Bioremediation is a general term used for the destruction of contaminants in soil, including microorganisms (e.g., yeast, fungi, or bacteria), by biological mechanisms. In enhanced bioremediation, the activity of naturally occurring microbes is stimulated by circulating water-based solutions through contaminated soils to enhance *in situ* biological degradation of organic contaminants or immobilization of inorganic contaminants. Nutrients, oxygen, or other amendments may be used to enhance bioremediation and contaminant desorption from subsurface materials. Bioremediation may rely on either indigenous microorganisms (i.e., those that are native to the site) or exogenous microorganisms (i.e., those that are imported from other locations. It can take place under aerobic or anaerobic conditions. Under aerobic conditions, in the presence of sufficient oxygen and other nutrient elements, microorganisms will ultimately convert many organic contaminants to carbon dioxide, water and microbial cell mass. Under anaerobic conditions (i.e., in the absence of oxygen the organic contaminants will be ultimately metabolized to methane, limited amounts of carbon dioxide and trace amounts of hydrogen gas. The main advantage of the in situ process is that it allows soil to be treated without being excavated and transported, resulting in less disturbance of site activities. When the clean up goal can be attained in an acceptable time frame, it can save costs to the projects. This kind of process mostly requires longer time periods and there is an uncertainty about the quality of the treatment.

a) Community acceptability: Above average;

b) Minimum achievable concentration: Above average;

c) Clean up time: The length of time required for treatment can range from 6 months to 5 years and is dependent on many site-specific factors;

d) Clean up cost: Bioremediation is cost competitive. Typical costs for enhanced bioremediation range from $30 to $100 per cubic meter ($20 to $80 per cubic yard) of soil;

e) Development status: Above average (Full scale);

f) Technology availability: More than 4 vendors and commercially available;

g) Maintenance requirement: Average maintenance required. Access to the site for unexpected repairs, adjustments, and regular maintenance is likely to be limited;

h) Regulatory acceptability: Average.

2. Bioventing (in-situ biological treatment)

Technology description

Bioventing stimulates the naturally occurring soil microorganisms to degrade compounds in soil by providing oxygen. Oxygen is most commonly supplied through direct air injection into soil. Passive bioventing systems use natural air exchange to deliver oxygen to the subsurface via bioventing wells. The rate of natural degradation is generally limited by the lack of oxygen and other electron acceptors (i.e., a compound that gains electrons during Biodegradation rather than by the lack of nutrients (i.e., electron donors).

a) Community acceptability: Above average;

b) Minimum achievable concentration: All aerobically biodegradable constituents can be treated by bioventing. Bioventing techniques have been successfully used to remediate soils contaminated by petroleum hydrocarbons, nonchlorinated solvents, some pesticides, wood preservatives, and other organic chemicals. These techniques, while still largely experimental, show considerable promise of stabilizing or removing inorganics from soil;

c) Clean up time: Average, 1-3 years;

d) Clean up cost: For small site $709 to $742 per cubic yard and for large site $60 to $84 per cubic yard ($928 to $970 per cubic meter or $79 to $109 cubic meter respectively);

e) Development status: Above average (Full).

f) Technology availability: More than 4 vendors. Bioventing is becoming more common and most of the hardware components are readily available;

g) Maintenance requirement: Above average (low maintenance required);

h) Regulatory acceptability: Average;

3. Phytoremediation (in-situ biological treatment)

Technology description:

Phytoremediation is a process that uses plants to remove, transfer, stabilize, and destroy contaminants in soil and sediment. Contaminants may be either organic or inorganic.

a) Community acceptability: Below average;

b) Ability to achieve minimum concentration: Data not available;

c) Clean up time: Below average, more than 3 years. The time required to remediate a site using bioventing is highly dependent upon the specific soil and chemical properties of the contaminated media;

d) Clean up cost: For small site $479 to $1775, for large site $479 to $1775 ($626 to $2,322 and$147 to $483 per cubic meter);

e) Development status of the technology: Above average (full scale);

f) Technology availability: 2-4 vendors;

g) Maintenance requirement: Below average (high maintenance required);

h) Regulatory acceptability: Below average.

4. Soil vapor extraction (in-situ physical/chemical treatment)

Technology description

In soil vapor extraction technique a vacuum is applied to the soil to induce the controlled flow of air and remove volatile and some semivolatile contaminants from the soil. The gas leaving the soil may be treated to recover or destroy the contaminants, depending on local and state air discharge regulations. Vertical extraction vents are typically used at depths of 1.5 meters or greater and have been successfully applied as deep as 91 meters. Horizontal extraction vents (installed in trenches or horizontal borings) can be used as warranted by contaminant zone geometry, drill rig access, or other site-specific factors.

a) Community acceptability: Average;

b) Minimum achievable concentration: Average;

c) Clean up time: The duration of operation and maintenance for in situ SVE is typically medium- to long-term. In situ SVE projects are typically completed in 1 to 3 years;

d) Overall cost: Cost for SVE of contaminated soil varies from $944-$1,100 /cubic yard for a small site and for large site $300-$722/cubic yard;

e) Development status: Full;

f) Availability of the technology: Above average, more than 4 vendors;

g) Maintenance: Low maintenance and high reliability;

h) Regulatory permitting acceptability: Average;

5. Biopiles / static pile (ex- situ biological treatment)

Technology description:

Excavated soils are mixed with soil amendments and placed in aboveground enclosures. It is an aerated static pile composting process in which compost is formed into piles and aerated with blowers or vacuum pumps. Biopiles are engineered systems in which excavated soils are combined with soil amendments, formed into compost piles and enclosed for treatment. They are commonly provided with an air distribution system by blowers or vacuum pumps. The leachate must be collected and treated. Several properties of the process such as nutrients and oxygen can be controlled in order to enhance the remediation procedure. This technology is used to reduce concentrations of petroleum constituents in excavated soils. The treatment area will generally be covered or contained with an impermeable liner to minimize the risk of contaminants leaching into uncontaminated soil.

a) Community acceptability: Data not available and it is site specific;

b) Minimum achievable concentration: Data not available; Biopile treatment has been applied to treatment of nonhalogenated VOCs and fuel hydrocarbons. Halogenated VOCs, SVOCs and pesticides can also be treated;

c) Clean up time: approximate 0.5 to 1 year;

d) Clean up cost: Typical costs with a prepared bed and liner are $130 to $260 per cubic meter ($30 to $60 per cubic yard);

e) Development status of the technology: Above average (full scale). More than 4 vendors;

f) Technology availability: Above average (full scale).The technology is commercially available for treating fuel contamination;

g) Maintenance requirement: Above average (low maintenance required);

h) Regulatory acceptability: Data not available.

5. Landfarming (ex-situ biological treatment)

Technology description:

Landfarming, also known as land treatment or land application, is an above-ground remediation technology for soils. It reduces concentrations of petroleum constituents through biodegradation. Contaminated soils are mixed with soil amendments such as soil bulking agents and nutrients and then tilled into the earth. The soil is spread over an area and periodically turned to improve aeration. Turning the soil also avoids the disadvantages of having heterogeneous degradation. Soil conditions are controlled to optimize the rate of contaminant degradation. The enhanced microbial activity results in degradation of adsorbed petroleum product constituents through microbial respiration. The petroleum industry has used landfarming for many years. Contaminated soil, sediment, or sludge is excavated, applied into lined beds, and periodically turned over or tilled to aerate the waste. Landfarming is extremely simple and inexpensive. Requires no process controls. Relatively unskilled personnel can perform the technique. Certain pollutants can be completely removed from the soil.

a) Community acceptability: Average;

b) Minimum achievable concentration/ technology applicability: Average;

Land farming has been proven most successful in treating petroleum hydrocarbons and other less volatile biodegradable contaminants. Because lighter, more volatile hydrocarbons such as gasoline are treated very successfully by processes that use their volatility (i.e., soil vapor extraction), the use of aboveground bioremediation is usually limited to heavier hydrocarbons. As a rule of thumb, the higher the molecular weight (and the more rings with a PAH), the slower the degradation rate;

c) Clean up time: approximate 0.5 to 1 year;

d) Clean up cost: Costs prior to treatment (assumed to be independent of volume to be treated): $25,000 to $50,000 for laboratory studies; and less than $100,000 for pilot tests or field demonstrations. Cost of prepared bed (ex situ treatment and placement of soil on a prepared liner): Under $100 per cubic meter (under $75 per cubic yard);

e) Development status of the technology: Above average (full scale);

f) Technology availability: Above average, more than 4 vendors;

g) Maintenance requirement: Low maintenance required;

h) Regulatory acceptability: Average;

6. Slurry phase treatment (ex-situ biological treatment)

Technology description:

An aqueous slurry is created by combining soil, sediment, or sludge with water and other additives. The slurry is mixed to keep solids suspended and microorganisms in contact with the soil contaminants. Upon completion of the process, the slurry is dewatered and the treated soil is disposed of.

a) Community acceptability: Average;

b) Minimum achievable concentration: Average ;

c) Clean up time: approximate 0.5 to 1 year;

d) Clean up cost: Treatment costs using slurry reactors range from $130 to $200 per cubic meter ($100 to $150 per cubic yard). Costs ranging from $160 to $210 per cubic meter ($125 to $160 per cubic yard) are incurred when the slurry-bioreactor off-gas has to be further treated because of the presence of volatile compounds;

e) Development status of the technology: Above average (full scale);

f) Technology availability: Above average, More than 4 vendors;

g) Maintenance requirement: Average maintenance required;

h) Regulatory acceptability: Above average;

7. Low temperature thermal desorption-LTTD (ex-situ thermal treatment)

Technology description:

In LTTD, wastes are heated to between 90 and 320 °C (200 to 600 °F). Decontaminated soil retains its physical properties. Unless being heated to the higher end of the LTTD temperature range, organic components in the soil are not damaged, which enables treated soil to retain the ability to support future biological activity.

a) Community acceptability: Average;

b) Minimum achievable concentration/ technology applicability: Above average. The technology is targeted to semi volatile halogenated and non-halogenated organic compounds, as well as other organics. LTTD is a full-scale technology that has been proven successful for remediating petroleum hydrocarbon contamination in all types of soil. Contaminant destruction efficiencies in the afterburners of these units are greater than 95%.

c) Clean up time: Less than 0.5 year;

d) Clean up cost: Cleanup cost for LTTD is approximate $75-$232/cubic yard for a small site. For a large site the cost may vary from $44-$110;

e) Development status of the technology: Above average, full scale;

f) Technology availability: Above average, more than 4 vendors. Thermal desorption is a well established technology;

g) Maintenance requirement: Average;

h) Regulatory acceptability: Average.

8. Soil washing (ex-situ physical/chemical treatment)

Technology description:

Soil washing uses water to remove contaminants from soils. The process works by either dissolving or suspending contaminants in the wash solution. Contaminants which are absorbed onto soil particles are separated from soil in an aqueous based system. High pressure water can be used to aid the removal from the surface.

a) Community acceptability: Above average;

b) Minimum achievable concentration/ technology applicability: The target contaminant groups for this technology are SVOCs, fuels and heavy metals, including radionuclides. The technology can be used on selected VOCs and pesticides;

c) Clean up time: Less than 0.5 year;

d) Clean up cost: Cost for soil washing is approximately $142/cubic yard for small site and for large site approximately $53/cubic yard;

e) Development status of the technology: Above average, full scale;

f) Technology availability: The technology of soil washing is used extensively in Europe. Commercialization in the United States is not yet extensive; More than four vendors, above average

g) Maintenance requirement: Low maintenance required;

h) Regulatory permitting acceptability: Average.

9. Soil flushing (in-situ physical chemical treatment)

Technology description

Water, or water containing an additive to enhance contaminant solubility, is applied to the soil or injected into the ground water to raise the water table into the contaminated soil zone. Contaminants are leached into the ground water, which is then extracted and treated.

a) Community acceptability: Average;

b) Minimum achievable concentration/ technology applicability: Below average. The target contaminant group for soil flushing is inorganics including radioactive contaminants. The technology can be used to treat VOCs, SVOCs, fuels, and pesticides, but it may be less cost-effective than alternative technologies for these contaminant groups;

c) Clean up time: 1 to 3 years;

d) Clean up cost: The cost of soil flushing depends greatly on the type and concentration of surfactants used, if they are used at all. Rough estimates ranging from $25 to $250 per cubic yard have been reported.

e) Development status of the technology: Above average, full scale;

f) Technology availability: Above average, more than 4 vendors;

g) Maintenance requirement: Average;

h) Regulatory acceptability: Below average (worse).