DEVELOPMENT OF A FUZZY RULE BASED REMEDIAL PRIORITY RANKING SYSTEM FOR CONTAMINATED SITES

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ABSTRACT

DEVELOPMENT OF A FUZZY RULE BASED REMEDIAL PRIORITY RANKING SYSTEM FOR CONTAMINATED SITES

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Evaluation of contaminated sites based on human health and environmental hazards is an essential task for the proper management of the contaminated sites. A large number of contaminated sites have been waiting for remediation all over the World. However, contaminated site remediation is generally a difficult, time consuming and very expensive process. Ranking systems for contaminated sites are useful tools to determine the remedial priority and to manage the available remediation budget in the most efficient way before the costly remedial actions are taken.

To be able to have a reliable ranking result, accurate and sufficient amount of data on the nature of contamination and site characteristics are needed, which are usually not available at the early identification phases of contaminated sites, and the available data is mostly limited and vague in nature. If the available data are inaccurate or vague, the corresponding remedial ranking results can be questionable, as well. Most of the current ranking methodologies overlook the vagueness in the parameter values. The main objective of this study is to develop a remedial priority ranking system for contaminated sites by taking vagueness in parameter values into account. Within this context, development of the new Remedial Priority Ranking System, RPRS, aims to define and evaluate the current and possible environmental risks by using sufficiently comprehensive readily available parameters describing the fate and transport of contaminants in the environment and considering vagueness in those parameter values.

The consideration of vagueness in parameter values was included in remedial prioritization of contaminated sites by means of fuzzy set theory. A fuzzy expert system was built up for the evaluation of contaminated sites and it was developed in Microsoft Office Excel 2007 platform, with the intention of making the evaluation fast and user friendly. Hypothetical and real case study applications are presented to test ease of use and validity of the results of the developed methodology. Results of case study applications revealed that the developed RPRS can serve as an alternative method for remedial priority ranking of contaminated sites.

Keywords: Contaminated Soil and Groundwater, Ranking System, Clean up Priority, Fuzzy Logic and Fuzzy Expert System

ÖZ

KİRLENMİŞ SAHALAR İÇİN BULANIK KURALLARA DAYALI BİR TEMİZLEME ÖNCELİĞİ SIRALAMA SİSTEMİNİN GELİŞTİRİLMESİ

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İnsan sağlığını ve çevresel riskleri göz önünde bulundurarak yapılan kirlenmiş saha değerlendirmeleri düzenli bir kirlenmiş sahalar yönetim sistemi için gerekli bir araçtır. Dünya üzerinde birçok kirlenmiş saha temizlenmeyi beklemektedir. Ancak, kirlenmiş sahaların temizlenmesi genellikle zor, zaman alıcı ve pahalı bir süreçtir. Kirlenmiş sahalar sıralama sistemleri, temizleme önceliğini belirlemek ve pahalı temizleme eylemleri başlatılmadan önce mevcut bütçeyi en iyi şekilde yönetmek için faydalı araçlardır.

Güvenilir bir sıralama sonucu elde etmek için, kirlenmiş sahaların genellikle ön değerlendirme aşamalarında kullanılmayan, sahanın özelliklerine ve kirliliğin doğasına ilişkin doğru ve yeterli veriler gereklidir. Fakat elde edilebilen veriler ise genelde sınırlı ve doğası gereği belirsizdir. Eğer mevcut veriler yanlış ya da belirsiz olursa, elde edilecek sonuç da tartışmaya açık olabilir. Birçok mevcut sıralama sistemleri parametre değerlerindeki belirsizlikleri göz ardı etmektedir. Bu tez çalışmasının ana amacı kirlenmiş sahalar için parametre değerlerindeki belirsizlikleri dikkate alan bir temizleme önceliği sıralaması belirleme sistemi geliştirmektir. Bu bağlamda, geliştirilecek yeni Temizleme Önceliği Sıralama Sistemi, RPRS, kirliliğin akıbetini ve taşınımını belirleyen, kirliliği kapsayacak yeterlilikte ve kolayca elde edilebilecek parametreleri kullanarak ve bu parametre değerlerindeki belirsizlikleri dikkate alarak, kirlenmiş sahalardaki mevcut ve olabilecek çevresel riskleri belirlemeyi ve değerlendirmeyi hedeflemektedir.

Parametre değerlerindeki belirsizlikler, "bulanık küme teorisi" kullanılarak kirlenmiş sahaların önceliğinin belirlenmesinde ele alınmıştır. Bir bulanık uzman sistemi kirlenmiş sahaların değerlendirilmesi için geliştirilmiş ve değerlendirmelerin hızlı ve sistemin kullanımının kolayca yapılabilmesi için Microsoft Office Excel 2007 platformu kullanılmıştır. Varsayımsal ve gerçek örnek vakalar sistemde denenerek, sistemin kullanışlılığı ve geçerliliği test edilmiştir. Örnek vaka çalışmalarının sonuçları, geliştirilmiş sistemin, RPRS, kirlenmiş sahaların temizleme önceliği sıralamasında alternatif bir metot olarak kullanılabileceğini göstermiştir.

Anahtar Sözcükler: Kirlenmiş Toprak ve Yeraltı Suyu, Sıralama Sistemi, Temizleme Önceliği, Bulanık Mantık ve Bulanık Uzman Sistemi

To my beloved,

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ABBREVIATIONS

ADEC	: Alaska Department of Environmental Conservation
AHMR	: Alaska Hazard Ranking Method
ANFIS	: Adaptive-Network-Based Fuzzy Inference System
ANN	: Artificial Neural Network
BWM	: Baden-Wurttemberg Method
CDDP	: Constrained Differential Dynamic Programming
CMU	: Carnegie Mellon University
ConSiteRPRS	: Contaminated Sites Remedial Priority Ranking System
CSSM	: Contaminated Sites Screening Model
DC	: Direct Contact
DEQ	: Department of Environmental Quality
DNAPL	: Dense Non-Aqueous Phase Liquid
DREAM	: Dundee Risk Evaluator Assessment Model
EC	: European Commission
Eco	: Ecological Receptors
EEA	: European Environmental Agency
EPA	: Environmental Protection Agency
FIS	: Fuzzy Inference System
f_{oc}	: Fraction of Organic Carbon
GDOC	: Groundwater-Dissolved Organic Contaminant
GIC	: Groundwater-Inorganic Contaminant
GTK	: Geologian Tutkimus Keskus
GW	: Groundwater
HH	: Human Health Pathways
HRS	: Hazard Ranking System
IDEM	: Indiana Department of Environmental Management

IFA	: Initial Formal Assessment
ISM	: Indiana Scoring Model
K_d	: Soil-Water Partition Coefficient
KemI	: Swedish National Chemicals Inspectorate
K_{oc}	: Soil-Organic Partition Coefficient
LNAPL	: Light Non-Aqueous Phase Liquid
LR	: Lombardia Risorse
MDEP	: Massachusetts Department of Environmental Protection
MFE	: Ministry for the Environment
MIFO	: Methods for Inventories of Contaminated Sites
NCSCS	: National Classification System for Contaminated Sites
NRS	: Numerical Ranking System
PDP	: Pattle Delamore Partners Ltd.
PLS	: Pollutant Linkage Scores
PRAMS	: Preliminary Risk Assessment Model
Prop	: Harm to Designated Property Receptors
RASCL	: Risk Assessment for Small Closed Landfills
RISICO	: Risk of Contaminated Sites
RP	: Regione Piemonte
RPRS	: Remedial Priority Ranking System
RRSE	: Relative Risk Site Evaluation
RRSM	: Proximity Relative Risk-Screening
RSES	: Remedial Selection Expert System
RSS	: Risk Screening System
RUM	: Remediation Urgency Method
SAM	: Site Assessment Model
SAPS	: Site Assessment Prioritization System
SCSS	: Site Characterization Subsystem
SDSU	: San Diego State University

SEPA	: Swedish Environmental Protection Agency
SIS	: Site Index Score
SNVIC	: Soil-Non-volatile-Inorganic Contaminant
SOC	: Soil-Organic Contaminant
SP	: Snam Progetti
SPC	: Site Prioritisation Criteria
SPPS	: System for the Prioritization of Point Sources
S-P-R	: Source – Pathway – Receptor
SRA	: Simplified Risk Assessment
SVIC	: Soil-Volatile-Inorganic Contaminant
SW	: Surface Water
WARM	: Washington Ranking Method

CHAPTER 1

INTRODUCTION

1.1. General

Several recent studies on developing policy framework have been conducted by European Union and member counties to be able to prevent future contamination and decrease the number of existing contaminated sites. In these studies, it is claimed that special attention concerning source removal, site sampling and characterization and cleaning up contaminated soil and/or groundwater are required so as to decrease the number of contaminated sites. Further information can be found in Thematic Strategy for Soil Protection (EC, 2006) and Towards an European Environmental Agency (EEA) Europe-Wide Assessment of Areas under Risk for Soil Contamination (EEA, 2004).

Additionally, it is also mentioned in those studies that most contaminated site characterization and cleanup activities are usually very costly. For example, cost estimation for site investigation process has been made for contaminated sites in Europe and a total of €31 billion is needed to complete all investigations. Moreover, for soil and groundwater remediation, €119 billion is needed according to the same estimation (EC, 2006). As a reference, it would be important to keep in mind that the US Environmental Protection Agency (EPA) has estimated the cleanup costs for the USA to be $170 - 250 billion (average $209 billion) for an estimated number of 235,000 – 355,000 sites (average 294,000) which need clean up (EC, 2006). Therefore, it is important to perform these activities in a cost effective manner considering the large number of contaminated sites waiting for cleanup. However, the most important problem is to handle at least the most seriously contaminated ones, if not all contaminated sites, because there are a huge number of contaminated sites in the world (Schafer, 1996).

Since there are a large number of contaminated sites and limited budget, the ranking of contaminated sites for remedial urgency is needed. Studies on ranking of the contaminated sites based on cleanup priority have gained close attention in the last couple of decades since soil and groundwater contamination has become an important issue. Countries dealing with soil and groundwater contamination have realized that the number of contaminated sites is very high (e.g. 60,000 in the Netherlands, 11,500 in Sweden, 11,000 in Belgium, 6,500 in Finland (EC, 2006) and taking remedial action for the existing contaminated sites is necessary.

In the meantime, the legislations and regulatory frameworks on soil and groundwater contamination have been developed in many industrialized countries that have a large number of contaminated sites. In general, the main regulatory approach is based on adapting the principle of "polluter pays". However, there are cases for which the polluter is not known (orphan sites). Nevertheless, considering remediation of all orphan contaminated sites at the same time is not possible because clean up processes are, most of the time, very expensive and sometimes may take very long time, in the order of 10 to 20 years (McCarty, 1994). Since countries that do not have sufficient budgets to clean up all contaminated sites simultaneously, ranking of contaminated sites based on cleanup priority becomes a cost effective approach.

Many of current ranking systems have generally two important tasks: ranking the contaminated sites from the most severe to the least severe one, and implementing this quickly without needing extensive field investigation studies involving sampling, monitoring, etc. Some of the existing ranking systems use several comprehensive parameters for evaluation of the sites. However, some ranking systems like EPA Hazard Ranking System (EEA, 2004) use very detailed information requiring sampling and analyzing for contaminant concentrations, identification of exact location and amounts of contamination sources, field characterization etc.

Current ranking systems use several parameters expressed in numerical values for several pathways through which the receptor is exposed to contamination such as inhalation of air and soil particles, ingestion of fish/wildlife/plants, contact with and ingestion of soil, sediment, groundwater and surface water. In almost all existing ranking systems, parameters used in site evaluation of contaminated sites for ranking purpose have a range of values with weights and scores specifying importance. For example, one parameter can take 10 points if its value is between 70 and 100, 5 points if it is between 40 and 69, and 0 points if it is between 0 and 39. Such ranking systems are prone to mistakes in the evaluation due to vague values of parameters. For example, the value of a parameter may be 39 and the score given by the ranking system should be 0 points. However, the user can use 40 instead of 39 by mistake due to the vagueness in the parameter value and the score given by the ranking system becomes 5 points. Therefore, an increase of 1 in the parameter value results in a five-point jump in the ranking score. The evaluation may be logical and reliable in existing systems but parameter values at the boundaries of the range of parameter values mapping to a given ranking score can lead to inaccurate evaluations because users can use a wrong value and make a mistake. Making a mistake in the value of the parameters can cause misevaluation of the contaminated sites. Therefore, the vagueness in parameter values introduced in the contaminated sites ranking priority systems should be considered in implementation.

Uncertainty is a term that can be considered as the reverse of information in epistemological sense. Information about a particular engineering or scientific problem may be incomplete, imprecise, fragmentary, unreliable, vague, contradictory, or deficient in some other way. The more information about a problem is acquired, the less uncertain its formulation and solution become. Problems that are characterized by very little information are said to be ill-posed, complex, or not sufficiently known. These problems are imbued with a high degree of uncertainty. Uncertainty can be manifested in many forms: it can be fuzzy (not sharp, unclear, imprecise, approximate), vague (not specific, amorphous), or ambiguous (too many choices, contradictory). It can also be of the form of ignorance (dissonant, not knowing something), or it can be a form due to natural variability (conflicting, random, chaotic, unpredictable) (Ross, 2004).

Some ranking systems (e.g. AHMR, ARGIA, HRS, ISM, NCSCS, PRAMS, SAPS and SRA, which are discussed later in Section 2) take precautions not to assign inaccurate scores due to using inaccurately obtained or highly vague parameter values for the ranking. In order to manage the vagueness in parameter values, these ranking systems may omit such parameters from the ranking process or weaken its weight on the final score by asking whether or not the user is sure about the accuracy of the parameter value. The assigned scores are decreased systematically, by decreasing or omitting the weights of the vague parameters. However, making evaluation in such a way does not make the assessment reliable since the value of the parameters thought as vague might not be vague and additional vagueness calculations might cause inaccurate evaluation. On the other hand, obtaining more accurate and reliable values for the parameters may need detailed and costly site investigations. Therefore, a comprehensive and robust system that uses easily obtained or measured parameters and takes the vagueness in parameter values into account is needed.

Many of the software of the methodologies carry out a quantitative analysis. However, the analysis made by the software is deterministic. Therefore, vagueness in the analysis is not taken into account. Some software use stochastic analysis to take vagueness into account. However, this approach is effective only if one or two parameters are taken as vague. If there are more, computation time becomes extremely long. Therefore, a new system, which considers vagueness in parameter values, should be needed.

Risk analyses should be done by human experts. However, making each evaluation by the help of the experts results in long lasting evaluations. Therefore, a software that could do what an expert can do should be developed. Since experience and expert judgment in contamination characteristics and knowledge of contaminant movement play a major role in risk assessment, using fuzzy set theory and systems may show tremendous payoff in transforming the expert's knowledge base in the form of IF-THEN rules into an engineering system in a systematic, efficient, and analyzable order. First introduced by Zadeh (1965), fuzzy logic and fuzzy set theory have been extensively used in ambiguity and uncertainty modeling in decision-making. The basic concept in fuzzy logic is quite simple: statements are not only "true" or "false". In fuzzy set theory, partial belonging to a set (a fuzzy set) is also possible (Afshar, 2007).

Several approaches have been used to apply fuzzy set theory to environmental engineering areas (e.g. contaminated soil ranking, site characterization, water resources problems), including fuzzy optimization techniques, fuzzy rule-based systems, and combination of fuzzy approaches with other techniques (Afshar, 2007). For example, Zhou et al. (1999) developed a multiobjective fuzzy pattern recognition model to assess groundwater vulnerability based on the DRASTIC parameters (Depth to water, Recharge, Aquifer media, Soil media, Topography, Impact of the vadose zone, and hydraulic Conductivity). They compared the results with those of DRASTIC in a case study, showing that the fuzzy pattern recognition model can take the fuzziness into account efficiently in a vulnerability evaluation process.

1.2. Objective of the Study

The main objective of this study is to develop a fuzzy rule based remedial priority ranking system for contaminated sites, which is alternative to the existing ranking systems. Evaluation in the system is applied by a fuzzy expert system to obtain a ranking score taking the vagueness in the parameter values into account. The developed system uses a sufficient set of parameters which play a major role in the fate and transport of the contaminants and in the description of the nature of contamination, and can be readily available or measured easily with known procedures. Fuzzy expert systems, unlike other currently used methodologies, allows assigning parameter values a degree of truth ranging from 0 to 1 rather than either 0 or 1. By this way, the negative impact of crisp sets (assigning either 0 or 1) on mapping the inputs to outcomes will be minimized. This effect will be discussed later in the thesis. Another aim of the study is to integrate the developed system into Microsoft Office Excel 2007 software to conduct ranking evaluations in a user-friendly way. Therefore, data processing can be established using the software developed in this study. Furthermore, the software is used on different case studies to test its ease of use and validity of the results.

1.3 Organization of Thesis

The outline of this thesis is as follows. Chapter 2 provides an overview of the currently used methodologies for the evaluation of contaminated sites, information about fuzzy logic and previous studies about fuzzy logic applications. Chapter 3 presents the methodology used in the study and components of the developed methodology. In Chapter 4, the software developed in this study is introduced. Implementation of case studies in the developed system and software are given in Chapter 5. The last chapter is the summary and discussions.

CHAPTER 2

LITERATURE REVIEW

The purpose of the literature review is first to understand the motivation of this study by presenting currently used methodologies for the evaluation of contaminated sites, and deficiencies and difficulties in their implementations. In addition, brief introduction to fuzzy logic is given to conceive its use and capabilities.

2.1. Currently Used Methodologies

Many countries have their own methodologies to evaluate the risks of contaminated sites to their environment. The result of the evaluation designates the sites, which need further investigation or remedial action urgency, according to the severity of environmental risks that the contaminated sites pose.

Thirty methodologies are obtained from the literature survey. Only fourteen of them, whose documentations are available, are presented in more details in this section. Table 2.1 shows all thirty methodologies with their origin and publication date. The twenty-seven of them were reported in the study called "Towards an EEA Europe-wide assessment of areas under risk for soil contamination" (EEA, 2004). One of the other three methodologies, the Preliminary Risk Assessment Model (PRAMS) is the output of the EEA (2004) study, another one of those three is from Bulgaria and the last one is the DRASTIC from the USA, which is used for vulnerability of groundwater.

Table 2.1 Reviewed methodologies

	Methodology	Acronym	Country	Date
1	-	AGAPE	Germany	1988
2	Alaska Hazard Ranking Method	AHMR	USA	2003
3	-	ARGIA	Italy	2003
4	Baden-Wurttemberg Method	BWM	Germany	1988
5	Contaminated Sites Screening Model	CSSM	Italy	1993
6	-	DRASTIC	USA	1987
7	Dundee Risk Evaluator Assessment Model	DREAM	UK	2001
8	Geologian Tutkimus Keskus	GTK	Finland	2001
9	Hazard Ranking System	HRS	USA	1990
10	Initial Formal Assessment	IFA	Bulgaria	2001
11	Indiana Scoring Model	ISM	Indiana	1989
12	Lombardia Risorse	LR	Italy	1991
13	Method for Inventories of	MIFO	Sweden	1999
14	National Classification System	NCSCS	Canada	1992
15	Numerical Ranking System	NRS	USA	2004
16	Preliminary Risk Assessment Model	PRAMS	EEA	2005
17	Risk Assessment for Small Closed Landfills	RASCL	New Zealand	2002
18	Risk of Contaminated Sites	RISICO	Italy	2001
19	Regione Piemonte	RP	Italy	1990
20	Relative Risk Site Evaluation	RRSE	USA	1994
21	Proximity Relative Risk-Screening Model	RRSM	UK	2001
22	Risk Screening System	RSS	New Zealand	2003
23	Remediation Urgency Method	RUM	Netherlands	1995
24	Site Assessment Model	SAM	USA	1990
25	Site Assessment Prioritization System	SAPS	USA	2000
26	Snam Progetti	SP	Italy	1990
27	Site Prioritisation Criteria	SPC	Colorado	-
28	System for the Prioritisation of Point Sources	SPPS	Denmark	2003
29	Simplified Risk Assessment	SRA	France	2001
30	Washington Ranking Methods	WARM	USA	1992

2.1.1 DRASTIC

The DRASTIC (Aller et al., 1987) is a tool developed for the purpose of groundwater protection in the United States. The procedure is designed to provide for systematic evaluation of groundwater-pollution potential in any hydrogeologic setting.

DRASTIC consists of two components. The first one is the designation of mappable hydrogeologic parameters (Aller et al., 1987). There are seven parameters from which the name of the model is derived, including **D**epth to water, **R**echarge, **A**quifer media, **S**oil media, **T**opography, **I**mpact of the vadose zone, and hydraulic **C**onductivity.

The second component of DRASTIC is the numerical ranking system, which is used to assess the groundwater-pollution potential for each hydrogeologic variable. The ranking system contains three parts; weights; ranges; and ratings. Each DRASTIC parameter is assigned a relative weight between 1 and 5, with 5 being considered the most significant in regard to contamination potential and 1 being considered the least significant. Then, each variable is "sub-divided" into either numerical ranges (e.g., depth to water in meter in Table 2.2) or media types (e.g., materials making up a soil in Table 2.3) which impact pollution potential. Finally, the ratings are used to quantify the ranges/media with regard to likelihood of groundwater pollution (Aller et al., 1987).

The final result for each hydrogeologic setting (i.e., geographic area) is a numerical value obtained using the following simple equation:

$$DrDw + RrRw + ArAw + SrSw + TrTw + IrIw + CrCw \qquad (2.1)$$

where r represents the ratings and w represents the weights.

Table 2.2 Ranges and Ratings for Depth to Water

Range (meter)	Rating
0 - 1.5	10
1.5 - 4.5	9
4.5 - 9.5	7
9.5 – 15	5
15 - 22.5	3
22.5 - 30	2
30+	1

Table 2.3 Ranges and rating for Soil Media

Range	Rating
Thin or Absent	10
Gravel	10
Sand	9
Peat	8
Shrinking and/or Aggregated Clay	7
Sandy Loam	6
Loam	5
Silty Loam	4
Clay Loam	3
Muck	2
Nonshriking and Nonaggragegated Clay	1

The DRASTIC has been prepared to evaluate the relative vulnerability of sites to groundwater contamination from various sources of pollution; that is, it is not designed to provide absolute answers. According to the results of the DRASTIC, areas deserving a detailed hydrogeologic evaluation are determined.

2.1.2 Dundee Risk Evaluator Assessment Model

The Dundee Risk Evaluator Assessment Model (DREAM) (Dundee City Council Environmental & Consumer Protection Department, 2001) is based on the pollutant linkage principle, Source-Pathway-Receptor (S-P-R), adopted for the contaminated land regime in the UK. The DREAM enables scoring of the principal sources of contamination, pathways and receptors to derive individual pollutant linkage scores (PLS), which may be combined to give an overall Site Index Score (SIS). In addition, the model also assumes that if receptors or pathways are absent within a linkage, the linkage is considered incomplete and will fail to achieve a linkage score. There are 5 complete linkages to be considered: human health pathways (HH), surface water receptor proximity (SW), aquifer protection of groundwater receptors (GW), proximity to designated ecological receptors (Eco) and harm to designated property receptors (Prop) (Dundee City Council Environmental & Consumer Protection Department, 2001).

The score represents the sum of all five individual pollutant linkages as seen in Eqn. 2.2.

$$SIS = PLS_{HH} + PLS_{SW} + PLS_{GW} + PLS_{Eco} + PLS_{Prop} \qquad (2.2)$$

where	PLS	= Pollutant linkage scores
	HH	= Human health pathway
	SW	= Surface water receptor proximity
	GW	= Groundwater receptors
	Eco	= Proximity to designated ecological receptors
	Prop	= Harm to designated property receptors

Each pollutant linkage can score up to a maximum of 100, resulting in a maximum score of 500. The ability to break down a score into its individual pollutant linkage components enables to determine which linkages are significant on a particular parcel of land and which linkages present little or no threat to receptors. Pollutant linkages are reviewed individually and classified into Priority Categories in order to allow the identification of the linkages requiring priority attention. The Priority Category thresholds have been determined empirically to provide appropriate action levels. The Priority Categories are shown in Table 2.4.

Table 2.4 Priority Categories of DREAM Method (Dundee City Council Environmental & Consumer Protection Department, 2001)

Priority Category	Score	Action
1	60 - 100	Urgent action in short term
2	40 - 59	Urgent action in medium term
3	20 - 39	Action is unlikely to be needed
4	0 - 19	No action is likely to be needed

Parameters used for DREAM methodology are about hydrogeology, hydrology, geology, land use, waste and containment information, site history and management data (Dundee City Council Environmental & Consumer Protection Department, 2001).

2.1.3 Hazard Ranking System

The Hazard Ranking System (HRS) (EPA, 2009) is a scoring system developed by US EPA and used to assess the relative threats associated with contaminant releases from different sites. The HRS combines various characteristics of the site, wastes, and surrounding environment to compute an overall score. As part of the calculations, separate scores are computed for each of four exposure pathways: groundwater, surface water, soil, and air as seen in equation 2.3.

$$HRS\ Score = \sqrt{\left(\frac{(S_{gw})^2+(S_{sw})^2+(S_a)^2+(S_s)^2}{4}\right)} \qquad (2.3)$$

where S_{gw} = Ground water migration score

S_{sw} = Surface water migration score

S_a = Air migration score

S_s = Soil exposure score

The HRS score, ranging from 0 to 100, is a screening mechanism for determining whether a proposed site is included in the Superfund National Priority List (NPL). The NPL is the list of national priorities among the known releases or threatened releases of hazardous substances, pollutants, or contaminants throughout the United States and its territories. The NPL is intended primarily to guide the EPA in determining which sites warrant further investigation (EPA, 2009).

Sites with an HRS score of 28.50 or greater are taken in the NPL. This score does not represent a specified level of risk. It shows that the sites with scores 28.50 or over have priority over others to be further investigated (EPA, 1990).

2.1.4 Bulgaria Initial Formal Assessment

In Bulgaria, a ranking system called Initial Formal Assessment (IFA) (Bulgaria Ministry of Environment and Water, 2001) is used for old contaminated sites and old landfills. IFA is carried out on the basis of a small number of readily available data, which corresponds to the level of investigation and the assessment objective. These are data about the sources of harmful substances (volume, area and class of hazard), pathways (distance between contamination bottom and groundwater level and permeability) and distance to the protected objects under impact (distance to drinking water withdrawal, drinking water sanitary-protection zone 3, planned for drinking water area, protected area around mineral water springs, kindergarten/play ground, agricultural land/orchards, residential area/sports ground/school, flooding area, surface water bodies and nature/landscape protected areas/objects). Figure 2.1 shows the evaluation system for old sites in IFA.

Matrix: Source of harmful substances							
Surface area class, [m²]		Class of hazard, r_0					
		1	2	3	4	5	
small	1 – 9	0	5	15	35	40	m_I
	10 – 49	0	6	17	36	41	
	50 – 99	0	7	19	37	42	
average	100 – 199	0	10	23	40	44	
	200 – 499	0	12	26	41	45	
	500 – 999	0	15	32	43	46	
large	1 000 – 4 999	0	18	36	46	48	
	≥ 5 000	0	20	40	49	50	

Matrix: Pathway				
Distance between contamination bottom and groundwater level	Permeability, [m/s]			
	$K_f \leq 10^{-6}$	$10^{-4} \geq K_f > 10^{-6}$	$K_f > 10^{-4}$	
> 10 m	0,5	1,0	1,0	m_{II}
2 – 10 m	0,7	1,1	1,2	
0 – 2 m	0,9	1,4	1,6	
In the groundwater	1,8			

Matrix : Distance to the protected objects under impact							
Distance to:	No connection	>1 000 m	< 1 000 m	< 500 m	< 100 m	Inside	
Drinking water (DW) withdrawal	0,9	1	1,2	1,4	1,6	1,7	a_I
DW sanitary-protection zone 3	0,9	1	1	1,2	1,5	1,7	a_{II}
Planned for DW area	0,9	1	1	1	1,1	1,2	a_{III}
Protected area around mineral water springs	0,9	1	1	1,2	1,5	1,7	a_{VI}
Kindergarten / play ground	0,9	1	1	1,2	1,6	2	b_I
Agricultural land / orchards	0,9	1	1	1,1	1,3	1,5	b_{II}
Residential area / sports ground / school	0,9	1	1	1,4	1,6	1,7	b_{III}
Flooding area	0,9	1	1	1	1,1	1,2	c_I
Surface water bodies	0,9	1	1	1,1	1,2	1,2	c_{II}
Nature / landscape protected areas/objects	0,9	1	1	1	1,1	1,2	c_{III}

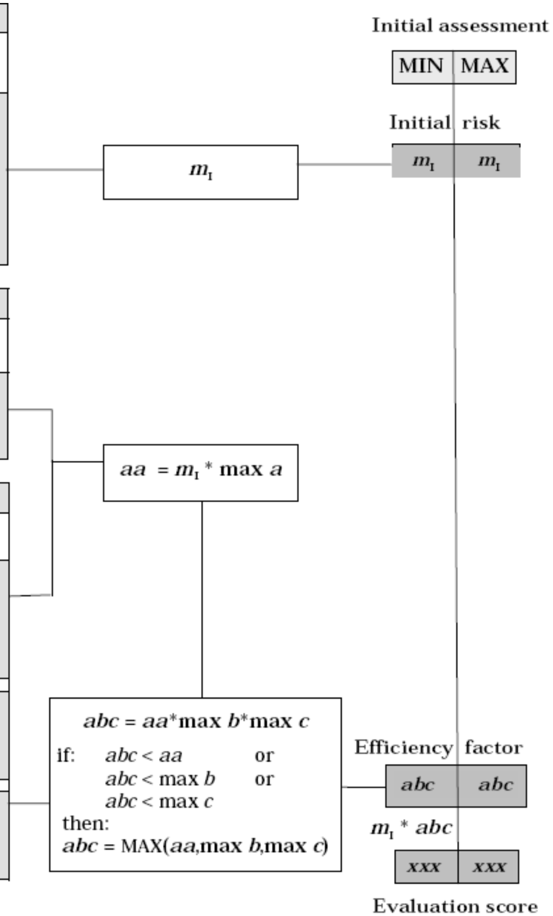


Figure 2.1 Method of Bulgaria Initial Formal Assessment (Bulgaria Ministry of Environment and Water, 2001)

The parameters used in IFA have numerical value ranges and each numerical range interval corresponds to a score according to known rules. For example, in the “Pathway” section in Figure 2.1, it is given that if the distance between contamination bottom and groundwater level is smaller than 2 m and the permeability of soil is higher than 10^{-4} m/s, the score becomes 13 for that part. Other rules and corresponding scores are given in Figure 2.1. According to the final score obtained from IFA process, contaminated old sites or landfills are assessed according to Table 2.5 (Bulgaria Ministry of Environment and Water, 2001).

Table 2.5 Assessment criteria of Bulgaria Method

Recommended Ranking of Treatment Needs	**Evaluation Numeric Score, Mean Value**	
	Old landfills	Old sites
First level of urgency	≥ 90	≥ 200
Second level of urgency	70 - 89	140 - 199
Possibility for postponing the	30 - 69	30 - 139
Currently, no treatment is required	0 - 29	0 - 29

2.1.5 Indiana Scoring Model

Indiana Scoring Model (ISM) (IDEM, 1987) uses information gathered during assessments/research to calculate a score for the site, which indicates whether the site may be placed on the Commissioner's List of sites, which qualify for state-funded remedial actions. The ISM is a less-rigorous scoring model than the HRS (IDEM, 1987). It is based upon the U.S. EPA Hazard Ranking System, but has been modified to take additional factors into consideration (EEA, 2004).

In order for a site to be placed on the Commissioner's List, the total site score must be at or above 10 (IDEM, 1987). This method applies to hazardous substance response sites, which are not in the NPL and for which an action taken by the Commissioner may be required to:

- prevent the release of a hazardous substance or contaminant;
- control, contain, isolate, neutralize, remove, store, or dispose of any hazardous substance or contaminant already released into or on the air, land, or waters of this state; or
- provide another appropriate response.

This method sets forth criteria and procedures for establishing a priority ranking by the Commissioner of Hazardous Substance Response Sites in order that those sites believed to pose the most significant threat to human health or environment are scheduled first for response and for allocation of department resources (IDEM, 1987).

The ISM combines three different scores assigned to a hazardous substance response site as follows:

(1) SM reflects the potential for harm to humans or the environment from migration of a hazardous substance away from the facility by routes involving groundwater, surface water, or air. It is a composite of separate scores for each of the three routes (groundwater, surface water and air).
(2) SFE reflects the potential for harm from substances that can explode or cause fires.
(3) SDC reflects the potential for harm from direct contact with hazardous substances at the facility, i.e., no migration needs to be involved.

The score for each hazard mode (migration, fire and explosion, and direct contact) or route is obtained by considering a set of factors that characterize the potential of the facility to cause harm. Each factor is assigned a numerical value (on a scale of 0 to 3, 5, or 8) according to prescribed guidelines. This value is then multiplied by a weighting factor yielding the factor score. The factor scores are then combined and scores within a factor category are added. Then the total scores for each factor category is multiplied together to develop a score for ground water, surface water, air, fire and explosion, and direct contact (IDEM, 1987).

SM is a composite of the scores for the three possible migration routes and calculated by below equation:

$$SM = \frac{1}{1.73} \times \sqrt{\left(S_{gw}\right)^2 + (S_{sw})^2 + (S_a)^2} \qquad (2.4)$$

Where S_{gw} = ground water route score

S_{sw} = surface water route score

S_a = air route score

The effect of this means of combining the route scores is to emphasize the primary (highest scoring) route in aggregating route scores while giving some additional consideration to the secondary or tertiary routes if they score high. The factor 1/1.73 is used simply for reducing SM scores to a one hundred (100) point scale.

2.1.6 Methods for Inventories of Contaminated Sites

Methods for Inventories of Contaminated Sites (MIFO) (SEPA, 2002), the Environmental Quality Criteria Guidance for Data Collection prepared by Sweedish Environmental Protection Agency, is a guidance showing the details of how to classify the contaminated sites in Sweden. According to the MIFO, the exposure pathways are considered four levels: Hazard assessment (H), contamination level (C), potential for migration, and sensitivity (S) and protection value (P) (SEPA, 2002).

Environmental quality criteria (Figure 2.2) are used to assess individual contaminated sites, which may range in size from a petrol station to a large industrial complex or part of a groundwater system that has been polluted by a point source.

The purpose of the criteria is to permit a comprehensive assessment of the risks associated with specific contaminated sites, even in cases for which available data are limited. The results are intended to provide a basis for the setting of priorities and for decisions concerning additional investigations, remediation, and the declaration of a hazardous site or other measures.

There is no limit to the number of parameters that may be used in connection with environmental quality criteria for contaminated sites. It should be possible to assess all kinds of contaminants that may be present in a contaminated site.

Questions about the site	Questions concerning risk to man and the environment and scale on which answers are placed
Hazard assessment	
Which contaminants are present?	Level of hazard? Low <—————————> Very high
Contamination level	
Level of contaminants in each of the media in which they occur?	What is the current conditions? (How serious are the effects?) Slight <————> Very serious Deviation from reference value, i.e. degree of influence from point source? None <—————————> Very large
Total amount of each pollutant?	Small <—————————> Very large
Total volume of contaminated material?	Small <—————————> Very large
Migration potential	
How rapidly does the pollutant spread through various media?	Slow <—————————> Very rapid
Sensitivity/Protective value	
Potential exposure of humans, present and future?	Sensitivity of exposed groups? Low <—————————> Very high
Potential risk to the environment, present and future?	Level of protection required for exposed environment? Low <—————————> Very high
Comprehensive risk assessment	
	Overall risk of the site to humans and to the environment? Low <—————————> Very high

Figure 2.2 Questions concerning risk classification of contaminated sites (SEPA, 2002)

This criterion is used to classify contaminated sites according to the level of risk. The area is assigned to one of the four risk classes as the result of the evaluation: very high risk, high risk, moderate risk, and low risk.

Hazard assessment is concerned with the assessment of the risk associated with the hazardous properties at the site, which are defined either during the preliminary site investigation or as a result of the previous investigations performed on the site. These hazardous substances are classified by the assignment of each substance to one or several hazard classes (Harmful to health, harmful to environment, irritating, etc.) with associated risk phases describing the nature of the health or environmental hazard according to the Swedish National Chemicals Inspectorate (KemI), which covers a broad range of chemicals, procedure.

For the contamination level, assessment of the risks associated with the amounts and concentrations of the contaminants is necessary to determine. It is also needed to know how quickly contaminants spread within different media and this is investigated in the potential for migration. For this phase, it is enough to determine if the contaminants spread currently or are likely to spread in the future.

The sensitivity and protection value is objected to determine the severity of the contamination by considering the degree or potential of exposure to which humans and the environment is exposed.

For the comprehensive assessment and risk classification, the risk levels obtained from the four levels are inserted into the graph shown in Figure 2.3. A model has been developed in two steps. The main importance was given to cost effectiveness in these steps. After the first step, the most critical sites are selected for further investigation in the second one.

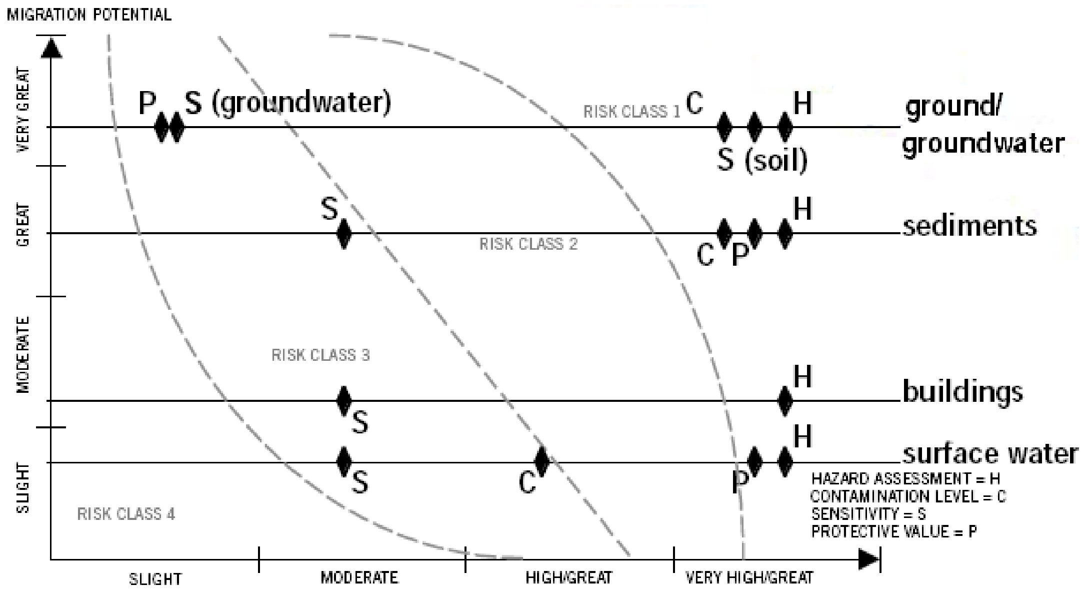


Figure 2.3 Comprehensive Assessment - Risk Classification (SEPA, 2002)

The horizontal lines from the vertical axis of the diagram in Figure 2.3 indicate the potential for migration for all media at the site: soil and groundwater, surface water, sediments, and buildings and other constructions. Represented by points along the horizontal axis are the hazards assessment (H), contamination level (C), sensitivity (S) and protection value (P).

The completed diagram thus includes one to four horizontal lines. The placement of the various points on the lines determines the risk class to which the site is assigned. If all points on all lines fall within the same class range, the site is assigned to that class. If, however, the points are distributed among two or more classes, it is necessary to decide which class best describes the site. Important factors in this regard are the impressions of the assessor, the size of the site and the number of different contaminants involved. The greater the number of contaminants, the greater the risk is assumed to be (SEPA, 2002).

2.1.7 Canadian National Classification System for Contaminated Sites

The Canada National Classification System for Contaminated Sites (NCSCS) (Canadian Council of Ministers of the Environment, 1992) is a tool to aid in the evaluation of contaminated sites according to their current or potential adverse impacts on human health and the environment. Its purpose is to provide scientific and technical assistance in the identification and prioritization of sites, which may be considered to represent high, medium, or low risk. The system classifies contaminated sites into these general categories of risk in a systematic and rational manner, according to their current or potential adverse impact on human health and/or the environment

The NCSCS is not designed to provide either a qualitative or quantitative risk assessment, but rather is a tool specifically for the classification and prioritization of contaminated sites. The system screens sites with respect to the need for further action (e.g., characterization, risk assessment, remediation, etc.) to protect human health and the environment.

Sites must be classified on their individual characteristics in order to determine the appropriate classification (Class 1, 2, 3, or N) according to their priority for further action, or Class INS (for sites that require further information before they can be classified) (Canadian Council of Ministers of the Environment, 1992).

The NCSCS uses S-P-R indicators to assess the contaminated sites. Each indicator score is obtained by summation of the scores assigned for each value of parameter in the indicators. The overall score for a site is obtained by summation of the results coming from indicators, maximum of 33 points are from Contaminant Characteristics, 33 points are from Exposure Pathways and 34 points are from Receptors. The classification groupings are shown in Table 2.6.

Table 2.6 Priority categories of NCSCS Method (Canadian Council of Ministers of the Environment, 1992).

Priority Category	Score	Action
Class 1 – High Priority	> 70	Action (further site characterization, risk management or remediation) is required
Class 2 – Medium Priority	50 - 69.9	Action is likely required
Class 3 – Low Priority	37 - 49.9	Action is may be required
Class N – No Priority	< 37	Action is not likely required
Class INS – Insufficient Information	>15% of Responses are "Do Not Know"	Additional information is required

2.1.8 Preliminary Risk Assessment Model

Objective of the Preliminary Risk Assessment Model (PRAMS) (EEA, 2005) is to rank and screen contaminated sites in the European Union, based on a preliminary assessment of human health and ecological risks (EEA, 2005).

The parameters considered have been chosen after thorough analysis, comparison and harmonization of the most common parameters used in the examined methodologies and existing databases. A minimum parameter set is proposed in order to allow a wide application of the model, taking into account data availability.

A tiered two-level assessment system (Tier 1 and Tier 2) is proposed in order to allow the use of data of different accuracy and completeness. Tier 1 where the information quality is approximate and individual parameter information is generally not available: factors at this level are scored mainly on the basis of expert judgment, non site-specific literature and geo-referenced data of low resolution. Chemical characterization of soil contamination is not necessary. Tier 2 where the information quality is more accurate and parameter data are collected from both site-specific information and non site-specific literature, and from geo-referenced data of low resolution. Factors are scored based on (quantitative or qualitative) site-specific parameter values and non site-specific data. Chemical characterization of soil contamination is necessary.

The aim of Tier 1 is to have a preliminary evaluation whether a site has a potential to be of EU interest with respect to risks for human and/or ecological receptors. All sites with risk scores exceeding a certain risk threshold value in Tier 1 should be processed in Tier 2, in order to verify the results of Tier 1. For these sites, further information and data have to be gathered. Tier 2 in fact envisages a larger information basis. Some site-specific data are needed in order to characterize more specifically a number of parameters such as contamination source type, containment and extent, contaminants of concern, environmental and receptor features such as soil type, depth to groundwater and distance to urban areas (EEA, 2005).

The general framework for risk assessment adopted is the following:

- Parameters are aggregated or represented by factors, and the factors are scored on the basis of parameter quantitative or qualitative values;
- Factors, in turn, are grouped by S-P-R indicators; factors are weighted depending on the relative importance in describing the indicator; factor scores are added up in order to score each S-P-R indicator;
- S-P-R indicator scores are then multiplied for each of the following exposure routes relevant to overall risk assessment (human health): Groundwater (GW), Surface water (SW), Air (AIR), Direct contact (DC)
- Exposure route scores are calculated;

- The overall risk is scored by computing the root mean square of all exposure route scores. Risk score values are included in the range 0-100.

2.1.9 Risk Assessment for Small Closed Landfills

The aim of the Risk Assessment for Small Closed Landfills (RASCL) (MFE, 2002) is to develop a practical method to assist district and city councils to identify the environmental risk from small closed landfills. The approach taken has developed a semi-quantitative risk assessment method based on a hazard/pathway/receptor risk model. This allows individual hazards at each site to be ranked (high, medium, and low), and individual landfills to be ranked against each other (MFE, 2002).

Ranking landfill sites supplies to set priorities, target monitoring, implement appropriate management plans and improve sustainable management of the environment.

The total risk is evaluated by multiplying the values of Quantity/Size (A), Mobility (B), Toxicity (C), Lining/Containment (D), Protection of Aquifer and Effectiveness of Capping (E), Rainfall (F), Distance to Aquifer and User (G), Beneficial Use (H). The total risk is given by;

$$Total\ Risk = A \times B \times C \times D \times E \times F \times G \times H \qquad (2.5)$$

If the score is higher than 0.5, higher than 0.2, and between 0 and 0.2, the risk is high, medium, and if low, respectively (MFE, 2002).

2.1.10 Risk Screening System

The Risk Screening System (RSS) (PDP, 2001) is developed for prioritizing of contaminated sites for further investigation in New Zealand. The assessment process is based upon the hazard-pathway-receptor risk equation, so the ranking system is multiplicative rather than additive. A low score in any of the risk components (hazard, pathway or receptor) will effectively remove the risk associated with a site. While this approach has been adopted, it must be recognized that no component can be assigned a zero score, as it is considered that some degree of risk no matter how small will always apply to sites considered to be contaminated (PDP, 2001).

The RSS is based on a matrix of exposure pathways and parameters that affect the risks associated with each pathway. The exposure pathways are surface water migration, groundwater migration, and direct contact (including ingestion, dermal contact and inhalation). Each of the exposure pathways then has parameters to represent, and affect, the three parts of the risk equation: the contaminant source; the receptors; and the transport pathways and exposure mechanisms between the source and receptors. It is intended that the required information for the RSS be easily available, i.e. obtainable from maps, regional council database, phone calls, site visits, etc. The RSS should not require detailed site investigation information and the ranking is too coarse to benefit greatly from such detailed information. However, more detailed information may assist the confidence placed on the final ranking (PDP, 2001).

The three exposure pathways considered (surface water, groundwater and direct contact) are effectively independent, as each is used to assess site risk in turn, with no combination of the pathways. Therefore, the rationale for the ranking method has been to identify those sites where one pathway is "dominant", and to select this worst-case pathway to rank the site (PDP, 2001).

The site risk ranking is presented in the format "surface water rank - groundwater rank - direct contact rank". For example, if a site is identified as having a high risk for both the ground and surface water pathways, and a medium risk for the direct contact pathway, the site risk ranking would be reported as "HIGH-HIGH-MEDIUM" (PDP, 2001).

An exposure pathway is considered to have one of the following levels of risk based on the overall calculated score (i.e. the product of the individual parameter values) for that pathway as seen in Table 2.7.

Table 2.7 Risk levels and their values of range

Risk Level	**Values**
High	0.5 - 1
Medium	0.2 - 0.5
Low	0 - 0.2

2.1.11 Site Assessment Prioritization System

Site Assessment Prioritization System (SAPS) (Oregon DEQ, 2003) is a tool that Oregon Department of Environmental Quality Cleanup Program uses to determine the priority associated with further investigation or cleanup actions needed at a site. A SAPS evaluation result is a numerical ranking that translates into low, medium, or high priority for further action(s)

The SAPS includes 15 site characteristics, grouped into the following general categories:

- Environmental information about the site and surrounding area;
- Nature and quantity of hazardous substances at the site;
- Potential human and environmental receptors; and
- Evaluator assessment of the site's threat.

Adding scores from each of the 15 individually ranked items results in the total SAPS score. The method's assessment criteria are presented in Table 2.8.

Table 2.8 Assessment criteria of the SAPS (Oregon DEQ, 2003)

SAPS Score	Recommended Action
86 or above	Further Action High Priority
48 - 85	Further Action Medium Priority
21 - 47	Further Action Low Priority
0 - 20	No Further Action

2.1.12 System for the Prioritization of Point Sources

The System for the Prioritization of Point Sources (SPPS) (GEOKON, 2003) has been developed to fulfill the needs of local authorities to identify, register and deal with contaminated sites. Overall aim is to establish a prioritization system for contaminated sites about which little is known (GEOKON, 2003).

The prioritization system uses the S-P-R concept to assess risks. It is split into two stages. The Stage I assessment involves hazard ranking sites based on their historical industrial uses and the receptor's sensitivity. The Stage II procedure involves refining the assessment from Stage I by carrying out an exposure assessment.

The stage I assessment can be carried out very rapidly, providing that source and receptor information is available. The assessment produces a priority listing of sites for each type of receptor considered. The Stage II assessment involves refining the priority listing obtained from stage I, by carrying out a pathway or exposure assessment to determine whether or not a potential pollutant linkage exists. The priority listing arrived at after Stage II can be used to inform decisions as to which sites should be investigated further. In many instances the information yielded after a stage II assessment will be sufficient to decide if a site is 'contaminated' (GEOKON, 2003).

The stage I site risk scores for each individual potentially contaminative industrial site use for each receptor is then automatically calculated using the following simple algorithm:

$$SRS = IRS \times RSS \tag{2.6}$$

Where SRS = Site Risk Score

IRS = Industrial Risk Score

RSS = Receptor Sensitivity Score

When using the default scores, the maximum site risk score for land use related receptors is 30. The maximum for ground and surface water receptors is 25. Using these site risk scores, one can rapidly obtain a site by use by priority listing. However, as this listing does not include a pathway assessment, it is recommended that it is refined using the Stage II methodology.

Sites can be placed in groups based on risk using the scores obtained from the Stage I prioritization. For example, those sites with SRS's above 20 may be categorized top priority for further investigation and may constitute the initial group of sites taken further to Stage II.

The user, according to the data or on his judgment, assigns scores to every factor in the system and following final indexes are obtained:

- Final Land Use Risk Score (LU score)
- Final Groundwater Risk Score (GW score)
- Final Surface Water Risk Score (SW score)

For example, Figure 2.4 shows the method for prioritization of contaminated sites to calculate the GW.

RECEPTOR

A	GROUNDWATER CLASS?		
CLASS	Area with special groundwater interest	Area with groundwater interest	Area with borderline groundwater interest
Score	12	6	0

B	Degree of aquifer protection?		
Protection	None	Some	Good
Score	6	3	0

PATHWAY

C	Mobility?		
Class	High	Medium	Low
Score	6	3	0

F	FINAL SITE SCORE = (A+B+max(C+D+E))		
Max. Min.	32 13	26 7	20 1

D	Toxicity?		
Limit Value	< 1 µg/l	1-10 µg/l	> 10µg/l
Score	4	2	0

SOURCE

E	Degradability?		
Class	High	Medium	Low
Score	1	2	4

Figure 2.4 Method for prioritization of contaminated sites based on risks to groundwater (GEOKON, 2003).

The characterization of each site results in a Risk Score for each receptor is used to prioritize the sites in terms of the need for detailed site investigation and/or remediation. The overall final risk score is obtained from the maximum of LU score, GW score and SW score.

The prioritization system considers:

- regional prioritization of sites in terms of their requirement for detailed site investigations;
- regional prioritization of sites in terms of their requirement for remedial works;
- national prioritization of sites.

2.1.13 Simplified Risk Assessment

Simplified Risk Assessment (SRA) (The French Approach to Contaminated-land Management, 2003) is developed in France based on the information collected during the preliminary site investigations. There are 40 easily obtained parameters in the SRA. The evaluation of the SRA is not detailed, but the aim is to determine whether further investigations are needed. The SRA ranks sites in three classes as seen in Table 2.9.

Table 2.9 Ranking classes of SRA method.

Class	Sites in Class
1	Sites requiring detailed investigations.
2	Sites requiring a detailed monitoring program. If necessary, land-use restrictions may be applied.
3	Sites requiring only monitoring of the changes in site (Low-risk sites).

The SRA is a scoring method. It is based on the principle that the existence of a risk implies that a dangerous/hazardous source (D = Source), a transfer mode to and from the transfer medium (T = Pathway), and a target (C = Receptor) exist altogether. If one of these factors (D, T or C) does not exist, e.g. the absence of groundwater, the risk becomes irrelevant and a risk assessment, for this area and its planned use, is not necessary (The French Approach to Contaminated-land Management, 2003).

The evaluation of the sites is done according to the scores given in Table 2.10. The evaluation changes according to water usage aim (groundwater or surface water).

Table 2.10 Ranking criteria of the SRA Method (The French Approach to Contaminated-land Management, 2003)

	Class 1	**Class 2**	**Class 3**
1. Groundwater			
1.1. Drinking-water supply	> 55	> 27 and ≤ 55	≤ 27
1.2. Other uses of water	>60	> 37 and ≤ 60	≤ 37
1.3. Non-drinking water supply, but to	> 56	> 38 and ≤ 56	≤ 38
2. Surface water			
2.1. Drinking-water supply	> 55	> 29 and ≤ 55	≤ 29
2.2. Other uses of water	>59	> 39 and ≤ 59	≤ 39
2.3. Non-drinking water supply, but to	> 62	> 32 and ≤ 62	≤ 32
3. Soil	> 55	> 30 and ≤ 55	≤ 30

For example, the sites having scores greater than 55 are assigned as Class 1, if the water is used for drinking water supply and Class 2, if the water is used for other use of purposes. Other assessments in Table 2.10 are done similarly according to the water usage purpose.

The SRA uses easy mathematical formulas to obtain the ranking scores for the different water usage purpose for the groundwater and surface water pathways and soil pathway given in Table 2.10. Moreover, Table 2.11 shows the parameters used for the evaluation of "Groundwater-Drinking water supply" shown in Table 2.10. The ranking score for that evaluation is calculated by the equation in 2.7.

Table 2.11 Parameters chosen for the calculation for groundwater used for drinking water supply

Groundwater drinking-water supply parameters	
1.1.1	Potential hazard – groundwater
1.2	Estimated quantity of substances
2.1.1	Mobility of substances – solubility
2.1.2	Physical state of the source
2.1.3	Annual precipitation
2.1.4	Flooding potential
2.1.5	Packaging of the pollutants
2.1.6.1	Source containment - groundwater
2.2.1.3	Proximity of the groundwater
2.2.2.3	Permeability of the unsaturated zone
2.2.3.3	Permeability of the aquifer
4.1.3	Determined impact-groundwater

Ranking Score:

$$3 \times (1.1.1) \times (1.2) + (2.1.1) \times (2.1.2) + (2.1.3) + (2.1.4) + (2.1.5) + (2.1.6.1) + (2.2.1.3) \times (2.2.2.3) \times (2.2.3.3) + 9 \times (4.1.3) \qquad (2.7)$$

2.1.14 Washington Ranking Method

Washington Ranking Method (WARM) (Washington State Department of Ecology, 1992) provides an objective comparison of sites based on relative risk. Major objectives in the development of the WARM were as follows:

- to provide a consistent, objective means for assessing the relative potential risk posed by contaminated sites to human and the environment, differentiating between those sites where there may be an environment threat without a human threat;
- to provide a model which would be scientifically defensible, and yet easy to use;
- to provide a model which would maximize accuracy and reproducibility with minimum data;
- to provide relative site rankings which would adequately distinguish between potential human health and environmental risks posed by contaminated sites;
- to utilize data which would be reasonably obtainable at moderate cost;
- to provide a model which required relatively simple documentation?

A quantitative method for ranking hazardous waste sites has been developed for the state of Washington. The system relies on information available from site hazard assessment to assess the potential for risks posed by contaminated sites. The ranking of sites provides a basis for program planning and priority assessment for those sites identified as potential threats to human health or the environment (Washington State Department of Ecology, 1992).

The model has four routes: surface water, air, groundwater and marine sediment. Within each route, data elements are evaluated in three main subcategories. These are:

- Substance characteristics,
- Site characteristics or migration potential,
- Exposure targets.

Site score can be generated for seven pathways:

- Surface Water – Human Health,
- Surface Water – Environmental,
- Air – Human Health,
- Air – Environmental,
- Ground Water - Human Health
- Sediment - Human Health
- Sediment – Environmental

A multiplicative and additive algorithm combines the values from these subcategories, resulting in a numerical route score between 1 and 100. The formula given in equation 2.8 is used for the evaluation of Air – Human Health.

$$AIR_H = \left(SUB_{AH} \times \frac{60}{329}\right) \times \frac{\left[REL_A + \left(TAR_{AH} \times \frac{35}{85}\right)\right]}{24} \tag{2.8}$$

where AIR_H = Pathway Score for Air – Human Health

SUB_{AH} = (Human Toxicity Value + 5) × (Containment + 1) + Substance Quantity

REL_A = Release to Air

TAR_{AH} = Nearest Population + Population within 800 meters.

The subsequent combination of all applicable pathways scores (e.g., surface water, air, groundwater and sediment), using a simple scaling method, produces a single priority value for human health and/or for environment. The formulas 2.9 and 2.10 are used to obtain those single priority values.

$$Human\ Health\ Priority = \frac{(H^2 + 2S + 2I + L)}{10} \tag{2.9}$$

$$Environmental\ Priority = \frac{(H^2 + 2S + L)}{8} \tag{2.10}$$

where H = Highest quintile group number for a pathway score

S = Second highest quintile group number for a pathway score

I = Third highest quintile group number for a pathway score

L = Lowest quintile group number for a pathway score

These two priority values are further combined in a matrix shown in Table 2.12 to provide a final single rank for the site (Washington State Department of Ecology, 1992).

Table 2.12 The matrix to provide a final single rank for the site (Washington State Department of Ecology, 1992)

Human Health Priority	**Environment Priority**					
	5	4	3	2	1	NA*
5	1	1	1	1	1	1
4	1	2	2	2	3	2
3	1	2	3	4	4	3
2	2	3	4	4	5	3
1	2	3	4	5	5	5
NA	3	4	5	5	5	NFA**

* NA = Not Applicable

** NFA = No Further Action

The ranking method provides several types of information about the relative risks posed by a site. It provides individual exposure pathway scores and a more general overall relative risk ranking. This information can be used by the Washington State Department of Ecology, along with other established factors, in setting its priorities for cleanup actions.

2.1.15. Overall Assessment of Current Ranking Systems

To be able to understand the general approaches and principles of currently used methodologies, fourteen of the selected systems described in sections 2.1.1 to 2.1.14 were examined closely. Table 2.1 shows all available methodologies reported in the literature, together with the closely examined methodologies.

The reviewed methodologies apply a scoring system in order to assess risks of the sites based on several selected parameters. The methods are generally applied at the national or regional level for assessment of contaminated sites based on available data and are used for planning priority of actions (i.e. further investigations or remediation) in the management of contaminated sites.

All methodologies reviewed adopt a qualitative (or semi-quantitative) approach for the assessment of site risks, describing risks in term of scores, rather than absolute estimates of health/ecological impacts. Risk scores assigned to contaminated sites allow for site ranking in order to decide on resource allocation and priorities for action in terms of detailed site investigation and, in some cases, direct remedial measures. The preliminary assessment methodologies reviewed are decision support tools quite frequently adopted at the regional or central administration level in many countries.

The majority of the methodologies analyze only human health risks, but some of them provide a ranking system including ecological receptors. Moreover, all methodologies reviewed adopt a scoring system based on Source-Pathway-Receptor (S-P-R) elements.

All methodologies need inputs related with the site hydraulic characteristics, contaminant characteristics or receptors that could be affected by the contamination. However, it is often not easy for users to specify these characteristics for the entire contaminated site. To provide the inputs, users need to deduce the soil texture, permeability, other site hydraulic properties and contaminant characteristics from the sampling data using a complex but comprehensive procedure. In this procedure, many subjective and uncertain conceptions or preferences are involved and different users will characterize a given site differently. The data available to the users are constrained by many factors such as location distribution of the obtained samples, and the time in which those specimens are obtained. Furthermore, even for a set of available data, due to the different methods for sample collection and analysis, result requirement of the samples, the time of the experiment, and human biases of the experimenter, the data may not be completely reliable and may even conflict. Therefore, a question arises regarding how the input parameters for the evaluation of a site can be derived based on a set of sampling data with inherent constraints or even contradictions (Hu et al., 2002).

One of the most important shortcomings of the existing methodologies is to ignore the vagueness in parameter values used for the evaluation of the contaminated sites. Since most of the methodologies use weights or linguistic variables for the range of values of the parameters, using vague parameter in the evaluations can cause misevaluation of the sites. For those methodologies, the score assigned for a parameter can be very different, when the value of the parameter changes slightly. For example, consider the parameter of depth to groundwater in DRASTIC in Table 2.2. When the depth to groundwater is between 9.5 and 15 meters, the rating becomes 5, and when it is between 4.5 and 9.5 meters, the rating becomes 7. In other words, if the depth to groundwater is 9.6 meters, the rating becomes 5 and if it is 9.5 meters, the rating becomes 7. Let us consider a vulnerability evaluation for a case, where the value of the parameter of depth to groundwater used in the evaluation is 9.6 meters, but the user uses 9.5 meters by mistake. The difference between the evaluation results of evaluation with 9.5 meters and evaluation with 9.6 meters becomes 10 when the corresponding ratings (7 and 5) are multiplied with the weight factor (5) of depth to groundwater (7×5 - 5×5 = 10). Besides, two cases can have the same score when the values of a parameter for these cases have significantly different values. For instance, the first case may have 4.5 meters of depth to water and the other case may have a depth to water of 9.5 meters. The scores for these cases can be the same since the corresponding ratings (7) are the same, although depths to groundwater are rather different. Therefore, methodologies that use weights or linguistic variables for value ranges of parameters would not be sufficient to establish accurate evaluations.

Another deficiency of the existing methodologies is that the evaluation procedures classify the contaminated sites for inclusion in a number of classes (i.e. sites that require; further investigation, remediation or urgent action, etc). However, they do not classify which site has more priority in a given class. Therefore, it can be said that ranking is established on a coarse precision. For the methodologies using linguistic classifications like low, medium, high or class 1, class 2, class 3, etc., the problem increases further, since the evaluation is progressed according to the final numerical results. For example, classification category of a contaminated site can change even if the resulting score changes by only 1 or less points. As in the IFA method of Bulgaria, a site can be considered in the group of “first level of urgency”, if it has 90 points and in “second level of urgency” if it has 89 points (Table 2.5). These examples show that a single weight for a range of parameter used for the evaluation can lead to a jump in the ranking decisions about contaminated sites.

Another shortcoming of the existing ranking systems is that they can tolerate missing values of parameters and assign a score to a case when some of the values of parameters are not certain, which makes the evaluation conservative rather than accurate. In general, consideration of vagueness parameter values exists in nine of the current ranking systems given in Table 2.1. The user puts a sign or a question mark for the uncertain parameter and the final score decreases using a prespecified formula. However, that value of the uncertain parameter can actually be correct. In this case, decreasing the score becomes a mistake since the user declares that parameter as uncertain because the user is not sure.

Consequently, a ranking system, considering vagueness in parameter values no to cause misevaluation of contaminated sites should be needed. In this study, a fuzzy logic based system, called Remedial Priority Ranking System, has been developed for ranking contaminated sites, which can tolerate the vague parameter.

2.2 Fuzzy Logic and Previous Studies Conducted

Fuzzy logic is a superset of conventional (Boolean) logic that has been extended to handle the uncertainty in data. Fuzzy logic provides a simple way to arrive at a definite conclusion based upon vague, ambiguous, imprecise, noisy, or missing input information. Fuzzy logic's approach to control problems mimics how a person would make decisions, only much faster (Kaehler, 1998).

Fuzzy sets and fuzzy logic was first introduced by Zadeh (1965) and was built by considering fuzzy set or membership function. Fuzzy set theory provides opportunity to handle uncertain information like true/false, yes/no, high/low, etc. by means of membership functions (Zadeh, 1965).

Fuzzy Logic provides a different way to approach a control or classification problem. This method focuses on what the system should do rather than trying to model how it works. One can concentrate on solving the problem rather than trying to model the system mathematically, if that is even possible. On the other hand, the fuzzy approach requires a sufficient expert knowledge for the formulation of the fuzzy rules, the combination of the sets and the defuzzification. In general, the employment of fuzzy logic might be helpful, for very complex processes, when there is no simple mathematical model, for highly nonlinear processes or if the processing of (linguistically formulated) expert knowledge is to be performed (Hellmann, 2001).

There are countless applications for fuzzy logic. The common applications that one may encounter in everyday life are underground time tables, temperature control (heating/cooling), auto-focus on a camera, predicting travel time and antilock braking system (Dementia, 1999). It has also been used in the area of environmental contamination assessment.

Some studies tested the superiority of fuzzy logic over classical methods. For example, a study done by Afshar et. al. (2007) explains a fuzzy-ruled based inference system on the evaluation of groundwater vulnerability. The numerical system studied in the article, which is developed to assess groundwater pollution potential in hydrogeological setting, benefits from a fuzzy engine and conscious knowledge-based DRASTIC parameters for nonlinear mapping of groundwater vulnerability concept. In order to show fuzzy model performance in the assessment results, the authors deal with the comparison of fuzzy-rule based

DRASTIC and the original DRASTIC outputs on vulnerability in the article (Afshar et. al., 2007).

In the article, 128 different cases are compared. Similar results were expected for both systems (fuzzy-rule based DRASTIC and original DRASTIC) as both of their knowledge bases are derived from the same system. However, the continuous nature of fuzzy system, which is sensitive to the variation ranges and able to account for those variations in the system outputs, makes difference. The investigations in the study show the vulnerability variation resulting from Fuzzy Inference System (FIS) and DRASTIC with respect to any single variable, keeping other parameters constant between upper and lower limits of a value range. In this case, when only one parameter changes, the results also changes in accordance with the effect of parameter for the vulnerability in the FIS; however, this does not happen in DRASTIC. Consequently, it is concluded in the article that the outputs of FIS have a continuous nature while the output of the DRASTIC have a discrete nature (Afshar et. al., 2007).

Another study, by Mohammed and Coté (1999), explains the risks associated with the migration of the pollutants of the contaminated sites and develops a decision analysis based model (DAPS 1.0, Decision Analysis of Polluted Sites). DAPS 1.0. requires a clear understanding of which pollutants are present at a site, their concentration and how they move to the receptor in the environment. Modeling all these steps is a time consuming job, therefore DAPS 1.0.supports that limitation of the effort, which would be spend, can be achieved by the use of stochastic analysis. In the article, fuzzy set theory and fuzzy logic are utilized as the alternatives of stochastic analysis. The authors also account for DAPS 1.0 as a unique model because it uses certain concepts of fuzzy set theory, in which uncertain input parameters are presented by fuzzy numbers to model uncertainty in the risk analysis. The decisions in this model are supported by the idea that there is not a precise line drawn between the results because the fuzzy set theory assigns a degree of membership (0≤ μ_x ≤ 1) to each element of a set (Mohammed and Coté, 1999). In conclusion, this study explains that the use of fuzzy logic in DAPS 1.0. is useful in terms of saving time and effort. Moreover, by the help of fuzzy logic, using more realistic and various linguistic risk variables (very high, high, medium-high, medium, low-medium, low) instead of giving the results only two values such as permeable or impermeable make the study valuable (Mohammed and Coté, 1999).

One of the most important studies reported recently is by Garcia et al (2006). The article deals with the classification of contaminated soils. When the contaminated soil classification is done improperly, the possible results can be high cost, restricted choice in landfill disposal sites, and future environmental impact. It is highlighted that the current systems of classification need a large quantity of data that is difficult to obtain and manage. In this study, to reduce the amount of information, a statistical analysis of data is performed to find the most relevant variables and 26 attributes were selected to build the knowledge base of a fuzzy expert system (Garcia et al, 2006).

Another detail making the study important is that the information used in the system has been obtained from an expert commission. The experts involved in the study helped to determine which attributes should use linguistic values rather than numerical ones, and also to design the membership functions associated with the linguistic values (Garcia et al, 2006).

In the article, evaluation of the results shows the efficiency of the use of fuzzy expert system. The result of some methods and techniques were assessed. For example, the experts tested two case studies of soil provided by the Risk Evaluation Guide. According to them, the results obtained with the fuzzy expert system were more adequate than the ones given by the guide, which means that good predictions could be made with less information (Garcia et al, 2006).

Consequently, the use of a hierarchic fuzzy expert system is proposed, in this article, to characterize the risk of contamination of soils. The tests and studies carried out indicate that the performance of the fuzzy expert system is effective when compared to manual evaluations and the results given by some other techniques (Garcia et al, 2006).

The paper by Hu et.al. (2002) is another study on rule-based expert system. This paper is based on two systems: remedial selection expert system (RSES), which is used for the selection of remediation techniques for petroleum contaminated sites, and a site characterization subsystem (SCSS), which is a fuzzy logic based subsystem. SCSS is an enhancement of RSES. SCSS has been developed as a subsystem because RSES requires much input on the site hydraulic characteristics to give potential remediation techniques as an output, (Hu et al., 2002).

It is mentioned in the article that the objective of SCSS is to deal with uncertainties inherent in the procedure of the analysis of the available data using fuzzy set theory. In this system, users can input basic soil sampling data and the SCSS will analyze the limited data with inherent uncertainties and define the site hydraulic properties for RSES. In the developed system, all these processes can be achieved by means of fuzzy set theory, which is a mathematically intuitive method of quantifying imprecision and uncertainty. Fuzzy sets are seen useful for describing ambiguity and vagueness in conceptual or mathematical models of empirical phenomena, and fuzzy set theory provides an improved extension of Boolean Logic for supporting definition of uncertainty in the SCSS. Methods of fuzzy knowledge representation and fuzzy reasoning were employed to convert uncertain system inputs to fuzzy linguistic information (Hu et al., 2002).

In order to validate the SCSS, two cases were examined and according to their results, it is indicated that the developed system in accordance with the fuzzy set theory, the SCSS, can effectively process the input data and clarify the hydraulic characteristics needed for RSES (Hu et al., 2002).

All of the conducted studies related with fuzzy set theory show that fuzzy set theory could easily handle the assessments, which may have uncertain parameter values or information, increasing the sensitivity of the ranking system.

The primary benefit of fuzzy systems theory is to approximate system behavior where analytic functions or numerical relations do not exist. Hence, fuzzy systems have high potential to understand the complex systems that are devoid of analytic formulations. Moreover, fuzzy systems theory can have utility in assessing some more conventional (less complex) systems. For example, for some problems exact solutions are not always necessary. An approximate, but fast, solution can be useful in making preliminary design decisions or as an initial estimate in a more accurate numerical technique to save computational costs or in the myriad of situations where the inputs to a problem are vague, ambiguous, or not known at all. Hence, fuzzy systems are very useful in two general contexts: (1) in situations involving highly complex systems whose behaviors are not well understood, and (2) in situations where an approximate, but fast, solution is warranted (Ross, 2004).

To sum up, as above studies revealed that a fuzzy system can be thought as an aggregation of “models of system” and “models of uncertainty” because it attempts to understand a system for which no model exists, and it does so with information that can be uncertain in a sense of being vague, or fuzzy, or imprecise, or altogether lacking. Systems whose behaviors are both understood and controllable are of the kind, which exhibit certain robustness to spurious changes. In this sense, robust systems are ones whose output (such as a decision system) does not change significantly under the influence of changes in the inputs, because the system has been designed to operate within some window of uncertain conditions. It is maintained that fuzzy systems too are robust because the uncertainties contained in both the inputs and outputs of the system are used in formulating the system structure itself, unlike conventional systems analysis which first poses a model, based on a collective set of assumptions needed to formulate a mathematical form, then uncertainties in each of the parameters of that mathematical abstraction are considered (Ross, 2004).

CHAPTER 3

DEVELOPMENT OF THE METHODOLOGY

A new system, Remedial Priority Ranking System, is developed as an alternative to existing priority ranking system for contaminated sites. Remedial Priority Ranking System (RPRS) evaluates the contaminated sites by taking vagueness in parameter values into account. Vagueness in parameter values is accounted for by means of fuzzy set theory. Therefore, in this part of the thesis, first general background information about the fuzzy set theory is given. Then, general framework applied for this study is introduced. Finally, an example for methodology implementation is presented to understand the evaluation principles of the developed new system.

3.1 Background for Application of Fuzzy Set Theory

The fundamental concepts of fuzzy set theory; fuzzy sets, fuzzy logic operations, membership functions, fuzzy rules and fuzzy expert system, are presented in the following subsection.

3.1.1 Crisps and Fuzzy Sets

In classical mathematics, crisp sets assign 1 or 0 according to one of the subsets in its value range. For example, in Figure 3.1 a set of f(x) is composed of all real numbers between 0 and 4, and a subset A is composed of all real numbers between 2 and 3. The elements, which are assigned to 1, can be interpreted as the elements that are in the set A and the elements, which are assigned to 0 as the elements that are not in the set A (Hellmann, 2001).

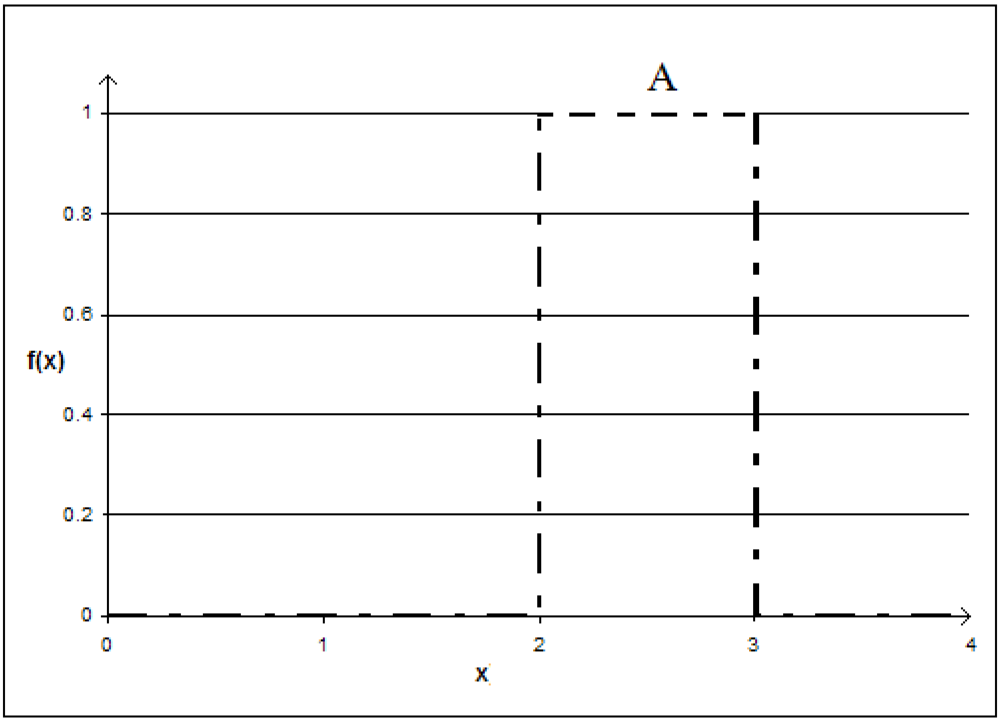


Figure 3.1 Crisp function of A in set f(x) (adapted from Hellman, 2001)

Crisp set concept is sufficient for many applications, but it can easily be seen that it lacks in flexibility for some applications (Hellmann, 2001). One of the applications that crisp set concept is insufficient is the contaminated site scoring system for risk analysis as in the example given in Section 3.1.3.

In fuzzy set, the interpretation of the numbers assigned to all elements is difficult when compared with crisp set but graphical functions enable to interpret the numbers. Again, the number 1 assigned to an element means that the element is in the set A and 0 means that the element is definitely not in the set A. All other values mean a gradual membership to the set A (Hellmann, 2001). Figure 3.2 illustrates the graphical representation of the set A. Here, subset A is composed of all real numbers between 1.5 and 3.5 but fully between 2 and 3, and partially in the rest. For example, when the subset value is 1.5, the corresponding membership value is 0 and it is 1 when the subset value is 2. However, when the subset value is 1.75, the corresponding membership value is 0.5.

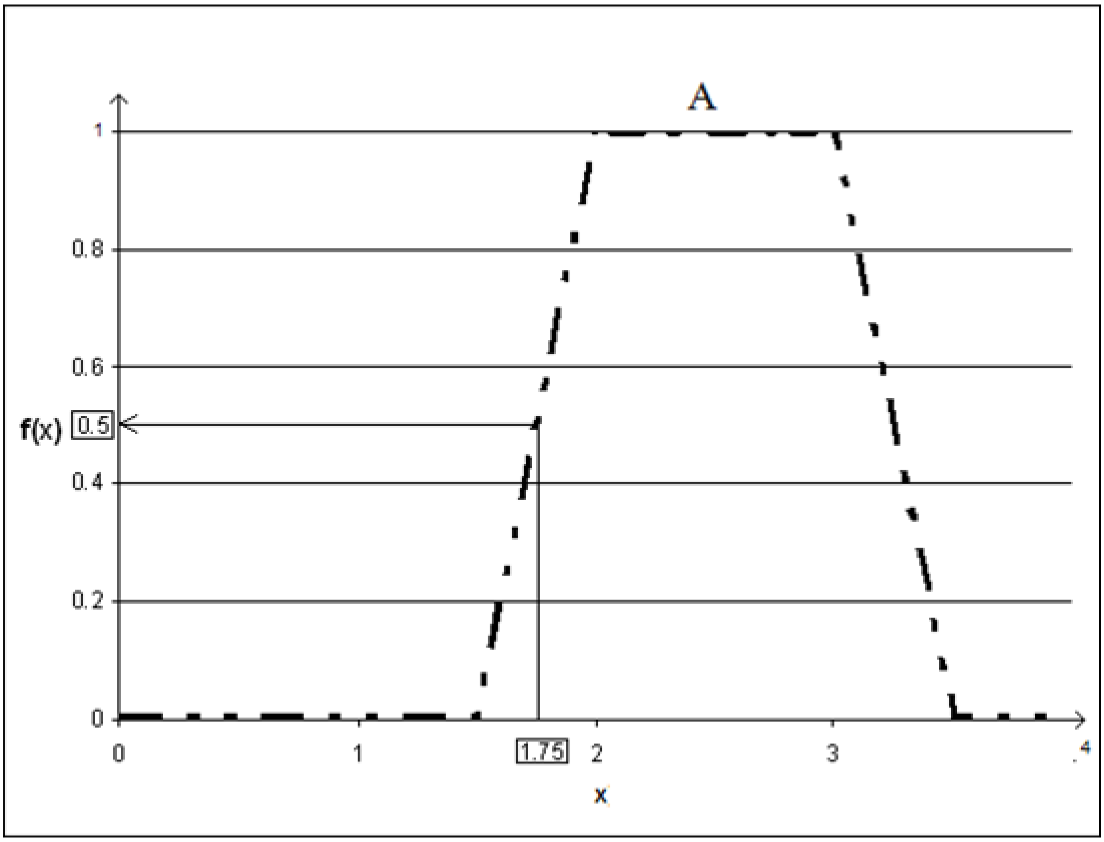


Figure 3.2 Membership function of A in set f(x)

3.1.2 Fuzzy Logic Operations

The basic operations on fuzzy sets are intersection, unification, averaging and negation of fuzzy sets. Zadeh (1965) suggested the minimum operator for the intersection (AND) and the maximum operator for the Union (OR) of two fuzzy sets (Parthiban, 1996).

3.1.2.1 Union Operator

The membership function of the union of two fuzzy sets A and B with membership functions μ_A and μ_B, respectively, is defined as the maximum of the two individual membership functions as seen in Figure 3.3. This is called the maximum criterion;

$$\mu_{A\cup B} = max(\mu_A, \mu_B) \tag{3.1}$$

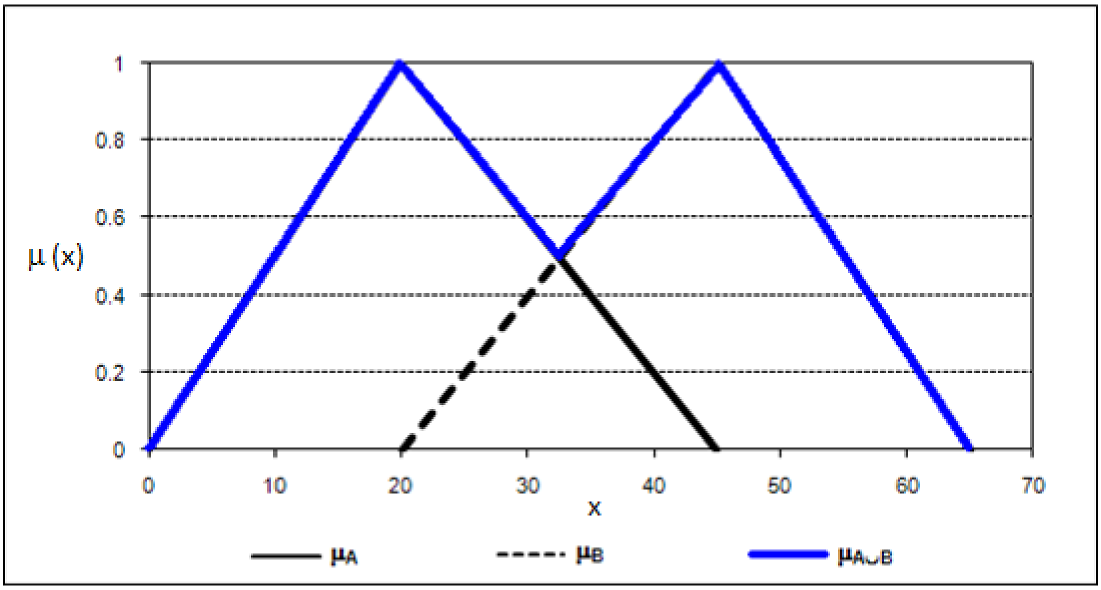


Figure 3.3 Union operation on membership functions of fuzzy sets A and B

The union operation in Fuzzy set theory is the equivalent of the OR operation in Boolean algebra.

3.1.2.2 Intersection Operator

The membership function of the Intersection of two fuzzy sets A and B with membership functions μ_A and μ_B, respectively, is defined as the minimum of the two individual membership functions as seen in Figure 3.4. This is called the minimum criterion;

$$\mu_{A\cap B} = min(\mu_A, \mu_B) \tag{3.2}$$

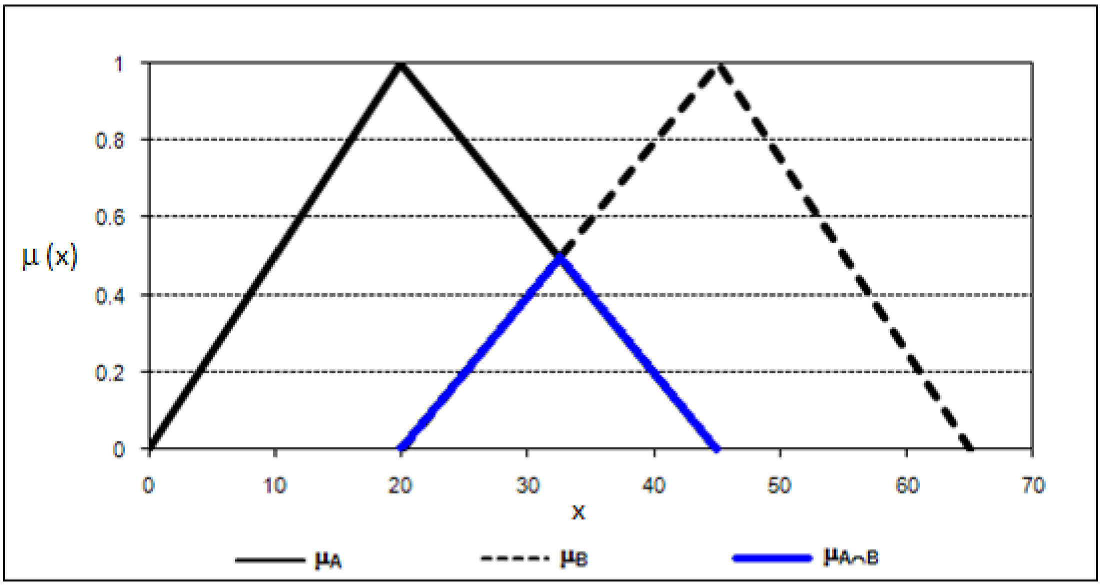


Figure 3.4 Intersection operation on membership functions of fuzzy sets A and B

The Intersection operation in Fuzzy set theory is the equivalent of the AND operation in Boolean algebra.

3.1.2.3 Averaging Operator

Averaging operators are aggregation operators that fall in the region between intersections and unions. Arithmetic mean, geometric mean and harmonic mean are the types of the averaging operation (Wolfram Research, 2009).

3.1.2.4 Negation Operator

The membership function of the Complement of a Fuzzy set A ($\mu_{\bar{A}}$) with membership function μ_A is defined as the negation of the specified membership function (Figure 3.5). This is called the negation criterion;

$$\mu_{\bar{A}} = 1 - \mu_A \qquad (3.3)$$

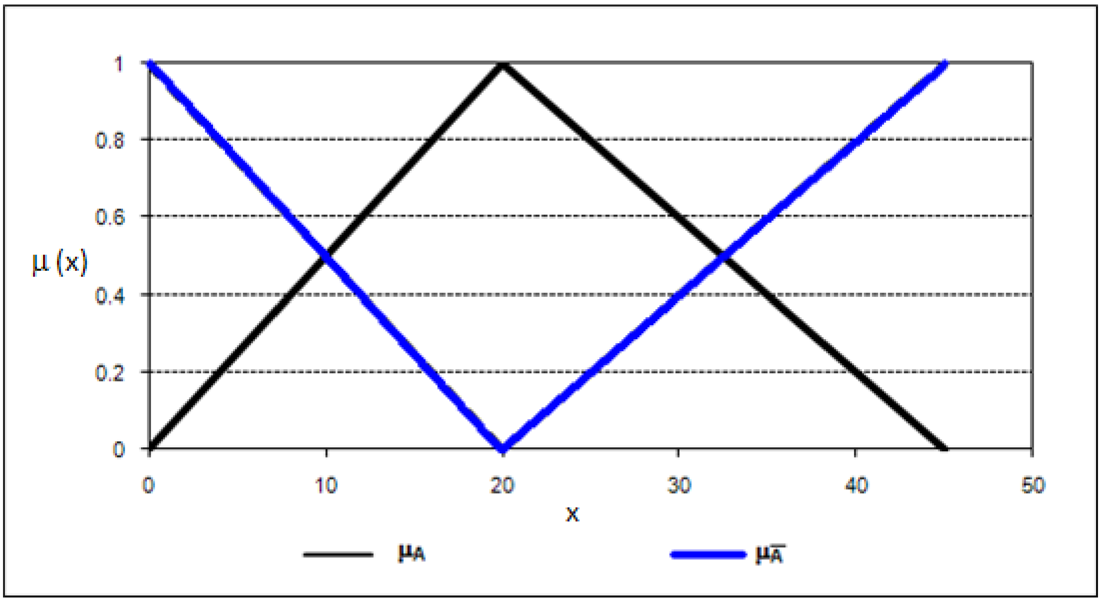


Figure 3.5 Complement operation on membership function of fuzzy sets A

The negation operation in fuzzy set theory is the equivalent of the NOT operation in Boolean algebra (Parthiban, 1996).

3.1.3 Membership Functions

The value of classical characteristic mapping of a classical set (i.e., crisp set) can be either 1, when an element belongs to the set; or 0, when it does not. However, in fuzzy set theory, an element can belong to a fuzzy set with its membership degree ranging from 0 to 1. Fuzzy sets are usually identified with the membership functions (Kildisas and Levisauskas, 2005). The membership function is a graphical representation of the magnitude of participation of each input. It associates a weighting with each of the inputs that are processed, defines functional overlap between inputs, and ultimately determines an output response (Kaehler, 1998).

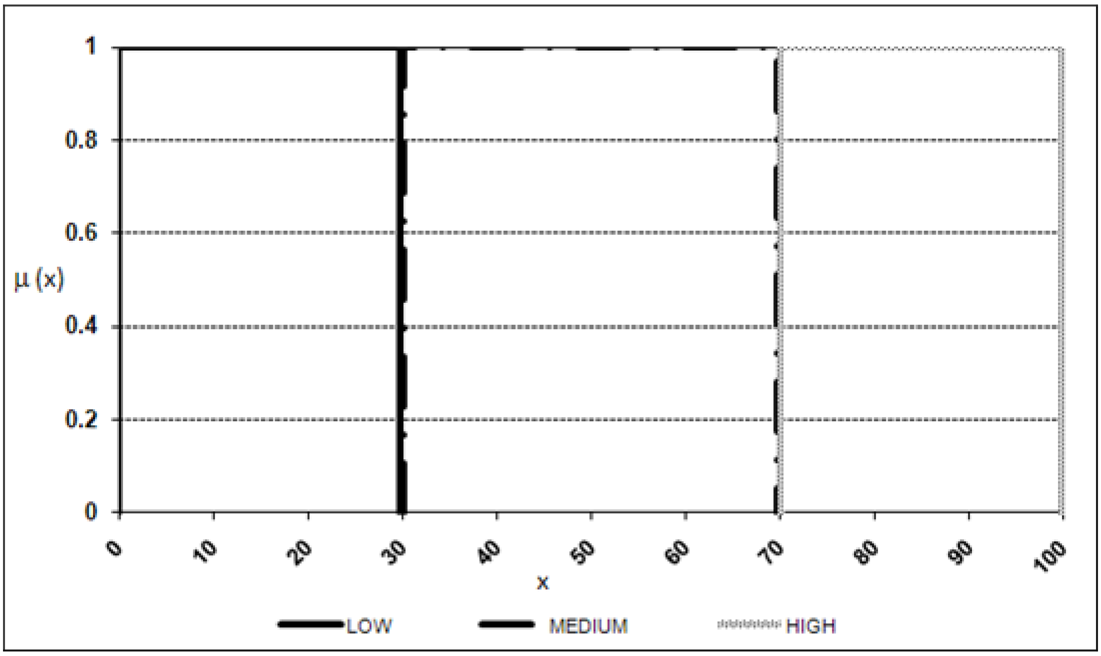


Figure 3.6 The crisp set of characteristic function of contamination risk

Let us consider the characteristic function in Figure 3.6 showing low, medium or high risk value intervals for a contaminated site. When the score of the contaminated site is between 0-29 out of 100, it can be assumed as a low risky contaminated site (the value is 1 for low part of crisp set and 0 for medium and high parts of crisp set). If the score is between 30-69, it can be assumed as a contaminated site with medium risk (the value is 1 for medium part of crisp set and 0 for low and high parts of crisp set). Moreover, if the score is between 70-100, it can be assumed as a contaminated site with high risk (the value is 1 for high part of crisp set and 0 for low and medium parts of crisp set).

According to these assessments, a risk decreasing action will not be taken for the site having score in between 0 and 29. However, an action will be taken for the site having a score higher than 29. On the contrary, a fuzzy set in fuzzy logic does not have such a sharp distinction between linguistic variables like low, medium and high as in this example.

Fuzzy set is a class of objects with a continuum of grades of membership. By the help of a membership function, fuzzy set is characterized, in which each object gets a grade of membership ranging between 0 and 1 (Zadeh, 1965). Thus, when the same example is considered according to fuzzy set theory, a contaminated site score of 29 has membership degrees for low and medium risk if its membership function is assumed as in Figure 3.7 (the degree of membership for low risk is 0.55 and the degree of membership for medium risk is 0.45).

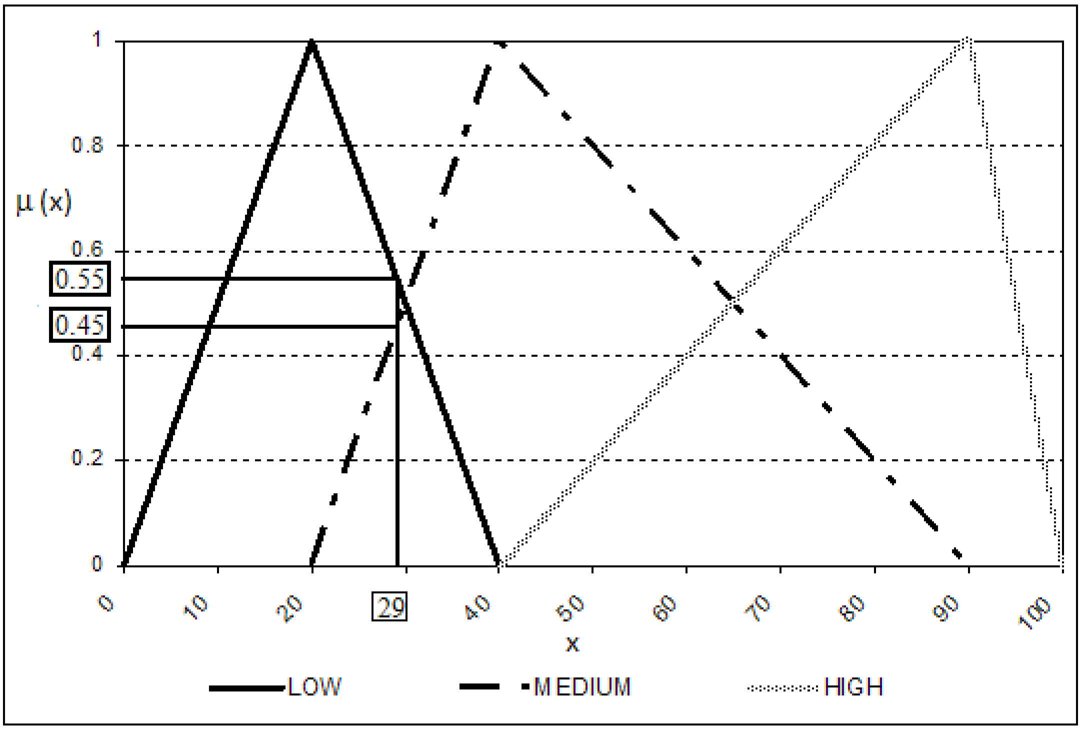


Figure 3.7 Membership degrees for the score of 29

While a contaminated site score is 30, its membership degrees becomes 0.5 for both low and medium risks as seen in Figure 3.8, now there is not a sharp difference between the scores owing to membership functions of fuzzy set theory.

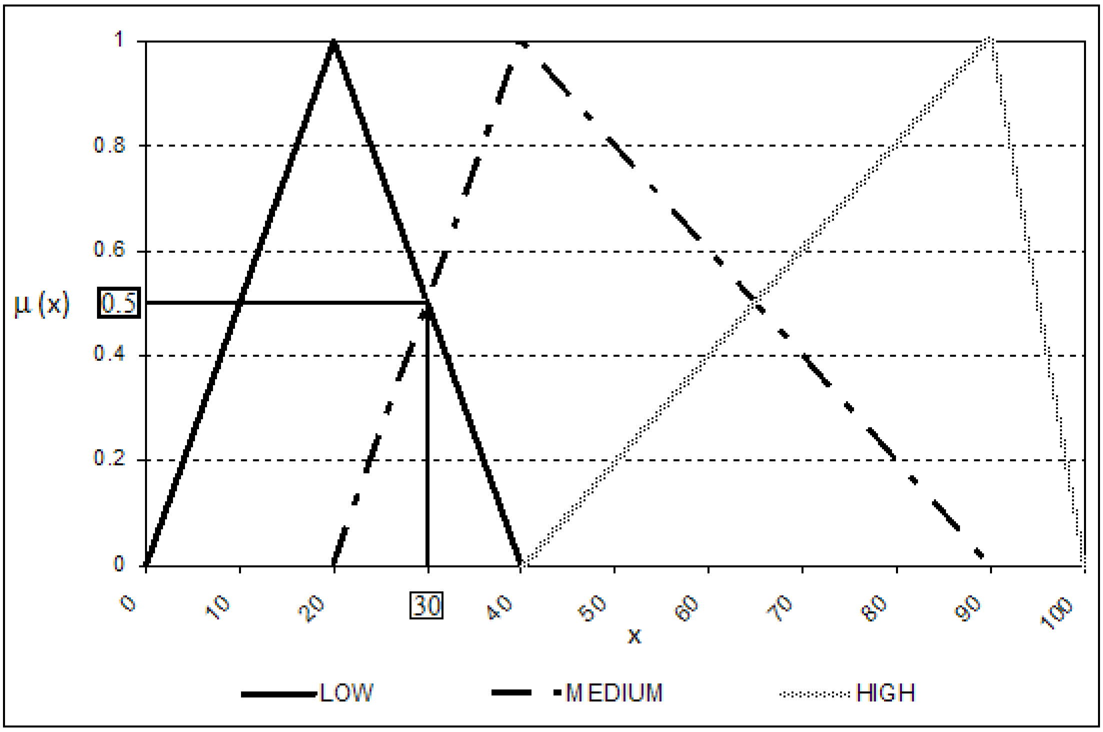


Figure 3.8 Membership degrees for the score of 30

There are different shapes of membership functions. Triangular is common, but bell, trapezoidal, haversine and exponential have been used (Kaehler, 1998). Functions that are more complex are possible but require greater computing overhead to implement.

The components of a membership function are height or magnitude (usually normalized to 1), width (of the base of function), shouldering (shouldered functions evaluate as 1.0 past their center), center points (center of the member function shape) and overlap (negative-zero, zero-positive, typically about 50 % of width but can be less) as seen in Figure 3.9 (Kaehler, 1998).

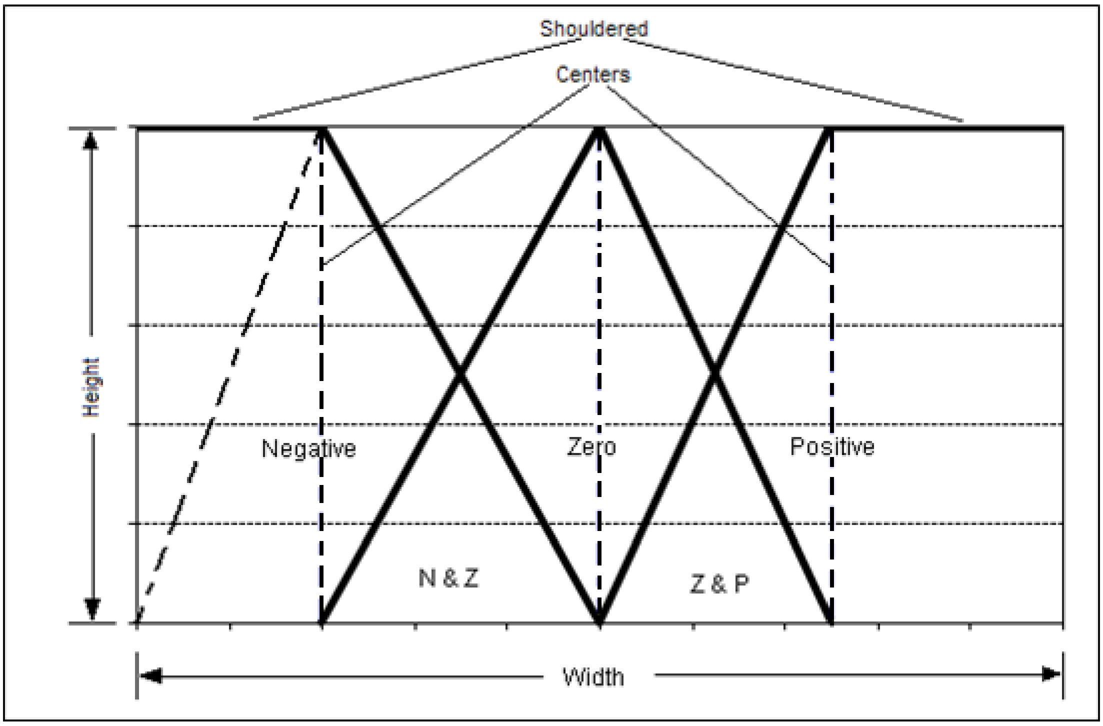


Figure 3.9 The features of a membership function

3.1.4 Fuzzy Rules

Human beings make decisions based on rules. The decisions people make are all like if-then statements. If the weather is fine, then it is decided to go out. If the forecast says the weather will be bad today, but fine tomorrow, then the decision become not to go today, and postpone it until tomorrow. Rules associate ideas and relate one event to another (Dhiman et al., 2008).

Systems using fuzzy set theory, which always tend to mimic the behavior of man, work the same way. However, the decision and the means of choosing that decision are replaced by fuzzy sets and the rules are replaced by fuzzy rules. Fuzzy rules in a fuzzy expert system also operate using a series of if-then statements. For instance, if "x" is low and "y" is high, then "z" becomes medium. Here, x and y are input variables (i.e., names for known data values), z is an output variable (i.e., a name for a data value to be computed), low is a membership function (i.e., fuzzy subset) defined on x, high is a membership function defined on y, and medium is a membership function defined on z. The antecedent (the rule's premise) describes to what degree the rule applies, while the conclusion (the rule's consequent) assigns a membership function to each of one or more output variables. Most tools for working with fuzzy expert systems allow more than one conclusion per rule. The set of rules in a fuzzy expert system is known as the rule base or knowledge base (CMU, 1993).

3.1.5 Fuzzy Expert System

A fuzzy expert system is an expert system that uses a collection of fuzzy membership functions and rules, instead of Boolean logic, to reason about data. A general scheme of a fuzzy expert system is given in Figure 3.10.

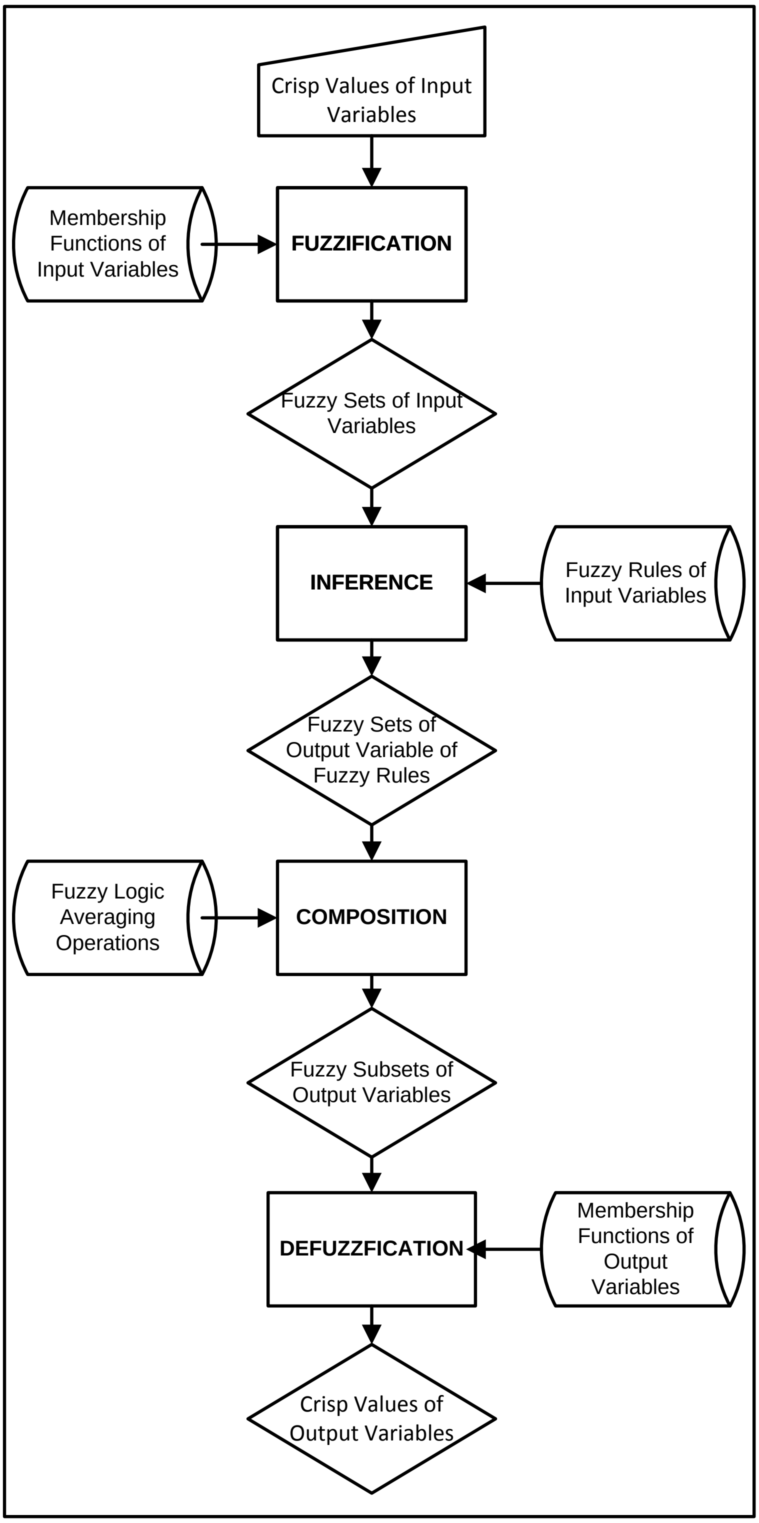


Figure 3.10 The scheme of a fuzzy expert system (Adopted from Letichevsky et al., 2007)

The fuzzy expert system uses the crisp inputs and membership functions of the parameters to progress fuzzy inference system, which proceeds in four steps: Fuzzification, Inference, Composition and Defuzzification (CMU, 1993). The *fuzzification* comprises the process of transforming crisp values of input variables into grades of membership for linguistic terms of fuzzy sets. Under inference, the output variable of each rule is computed. As for composition, output variables of fuzzy rules are combined together to form a single fuzzy subset, which corresponds to the composition of input variables. Finally, defuzzification converts the single fuzzy subset, obtained by composition step, into a unique number and makes a fuzzy number a crisp number (Ross, 2004).

There are several defuzzification methods (Hellendoorn, 2009):

- *Center of Area / Gravity Defuzzification*
- *Center of Largest Area Defuzzification*
- *First (Minimum) of Maxima Defuzzification*
- *Maximum (Last) of Maxima Defuzzification*
- *Middle of Maxima Defuzzification*
- *Height Defuzzification*

The center of area method (in the literature also called as "center of gravity" method) is the most well-known defuzzification method. This method determines the center of the area below the combined membership function. Figure 3.11 shows this operation in a graphical way.

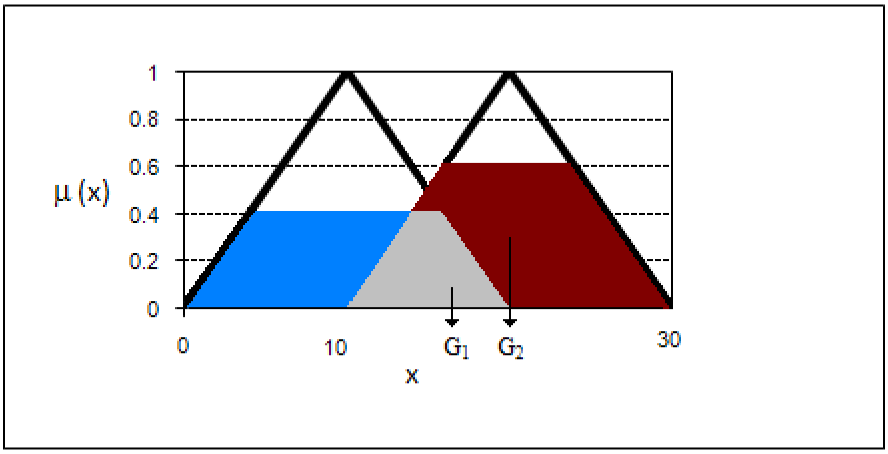


Figure 3.11 Defuzzification results of center of gravity and center of largest area approaches (Hellendoorn, 2009)

In center of area (G_1) defuzzification method, the area is considered as a whole. Moreover, if the areas of two clipped fuzzy sets overlap, then the overlapping area is not reflected in the calculation twice. In the figure, the intersection area (grey area) is not included in the calculation twice since the blue and brown areas overlap at the grey area. This operation is computationally more complex due to the complex geometry included.

The method of Center of Largest Area defuzzification selects the area having largest area and defuzzification result (G_2) becomes the center of that largest area as seen in Figure 3.11.

The methods of First (Minimum) of Maxima Defuzzification, Maximum (Last) of Maxima Defuzzification and Middle of Maxima Defuzzification select the area having highest height. First of maxima method uses the first point among the maximum points in the area. The corresponding value of that point becomes the result of defuzzification (G_1) as seen in Figure 3.12.

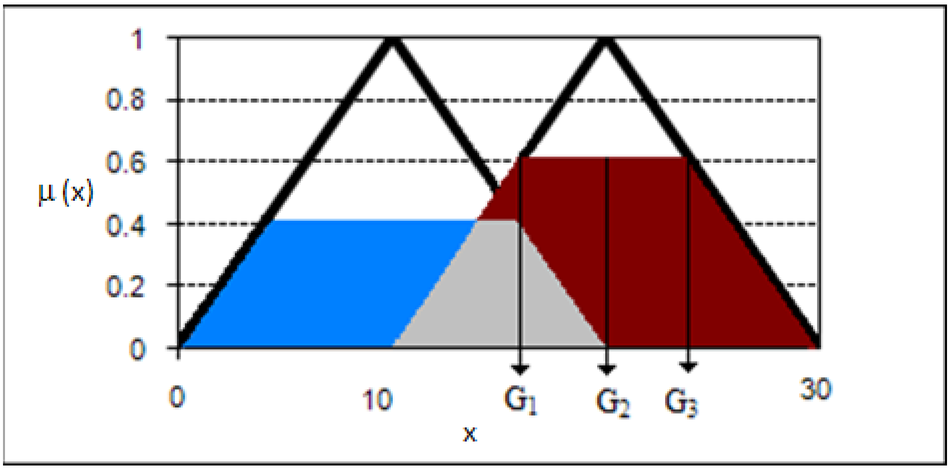


Figure 3.12 Results of first, last and middle defuzzification approaches (Hellendoorn, 2009)

Last of maxima method uses the last point among the maximum points in the area. The corresponding value of that point becomes the defuzzification result (G_3) as seen in Figure 3.12.

Middle of Maxima method uses the middle point among the maximum points in the area. The corresponding value of that point becomes the defuzzification result (G_2) as seen in Figure 3.12 (Hellendoorn, 2009).

Method of Height Defuzzification directly uses the membership values that are actually the height of the areas. The middle points among the points being on top of the each area designate the defuzzification result as seen in Figure 3.13.

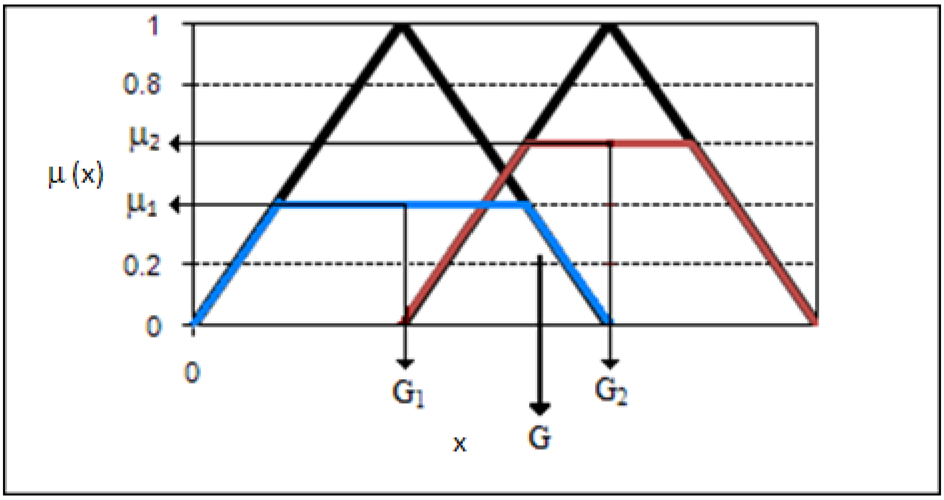


Figure 3.13 Defuzzification results of height defuzzification approach (Hellendoorn, 2009)

The maxima in each area (G_1 and G_2) are multiplied with the corresponding value of membership degree (μ_1 and μ_2) and the designation of "G" shown in Figure 3.13 is done by the formula in 3.4.

$$\frac{(\mu_1 \times G_1 + \mu_1 \times G_1)}{\mu_1 + \mu_2} \qquad (3.4)$$

3.2 General Framework Applied for the Study

The details of steps followed to develop Remedial Priority Ranking System (RPRS) based on the forging discussions are given in this section of the study. Main components of the system, parameters used and their values, and developed fuzzy expert system in RPRS are introduced.

3.2.1 Development of Remedial Priority Ranking System

RPRS is a system that assigns ranking score for contaminated sites using the fuzzy set theory. Developing procedure was started to search the comprehensive parameters that affects the fate and transport of contaminants during the movement of contamination towards the receptors through exposure routes like air, groundwater, surface water, etc. After the results of the investigations of parameters, the schematic description in Figure 3.14 is built up. In the meantime, researches on fuzzy expert systems were started and the results of the researches show that the higher the number of parameter used in fuzzy rules, the more difficult to progressing the data (Afshar et. al., 2007 and Garcia et al, 2006). Because, when three linguistic variables (like low, medium and high) are used for the fuzzy rules and there exists 10 parameters in the rules, the possible number of fuzzy rules becomes 1000 (10^3). Therefore, the fuzzy rules used in fuzzy expert system of RPRS are grouped at most 3 parameters. This enable at most 27 fuzzy rules for a-three-grouped parameters and 8 fuzzy rules for a-two-grouped parameters. Based on this limitation, the flowchart of the RPRS is built as in Figure 3.15.

By doing so, the parameters in RPRS becomes as if each of them is a ring of a chain. The main chain, which is composed of upper level parameters, also has smaller chains that are composed of lower level parameters. The size of a ring, or a parameter, can be considered as if it is the weight of that parameter, which means the larger the size, the higher the weight. Parameters in each chain form the bigger chains and this goes on until the final result is obtained. The parameter chains are schematically illustrated by a drawing given in Figure 3.16.

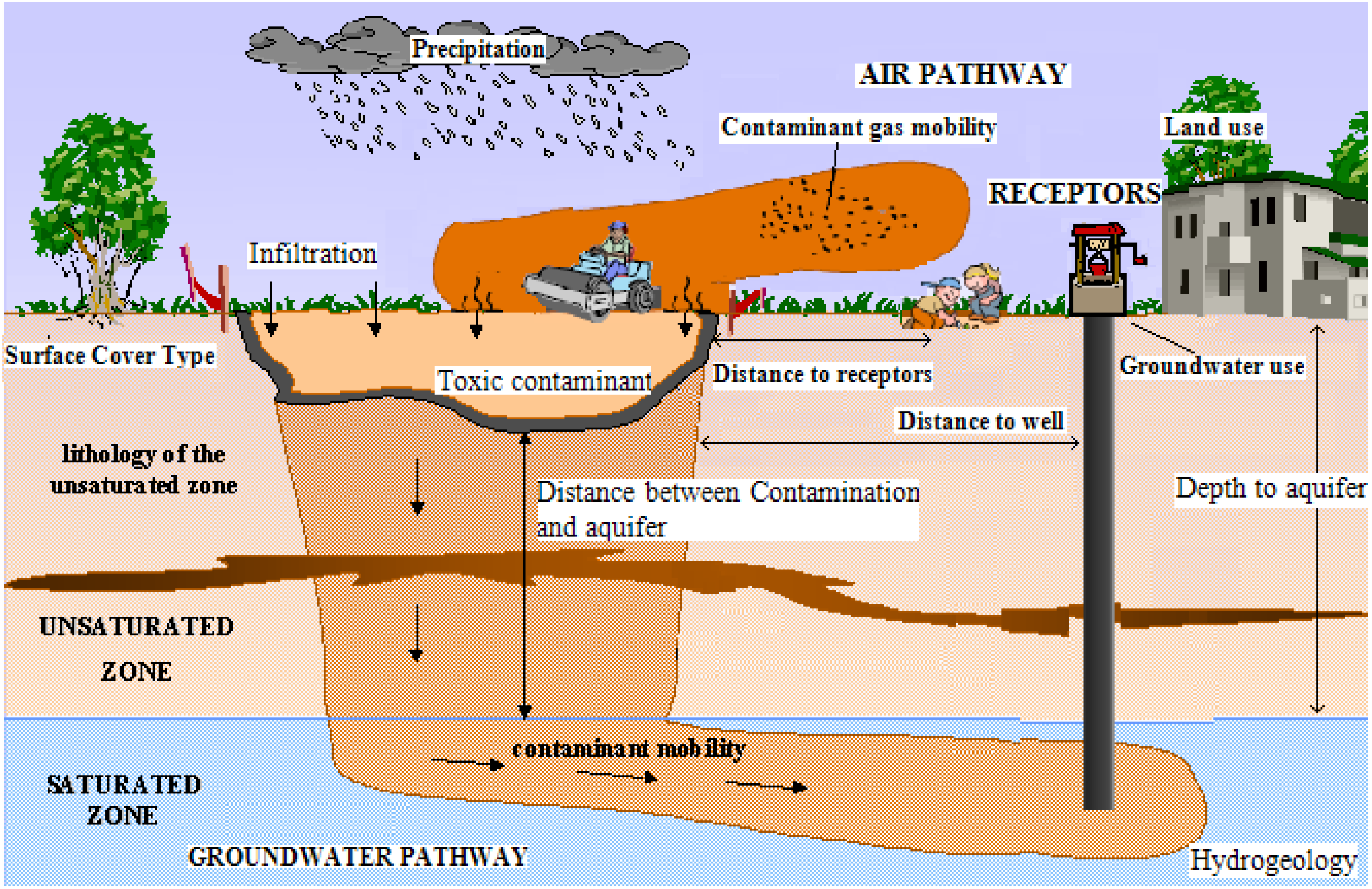
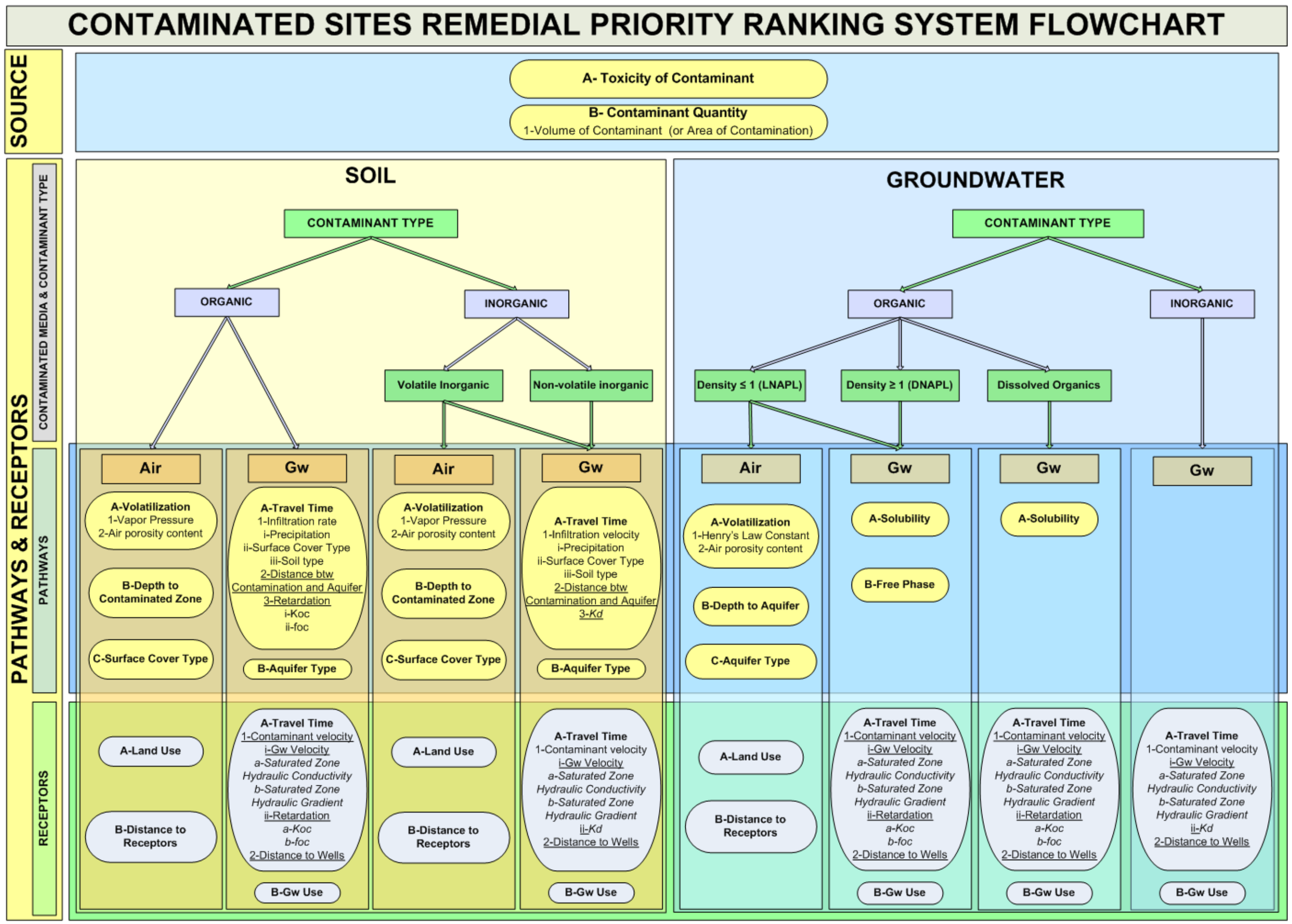


Figure 3.14 Schematic description of Source-Pathway-Receptor triplet (adopted from EEA, 2005)



Parameters having capital letters (A, B or C) are the **first level** parameters.
Parameters having numbers (1, 2 or 3) are the **second level** parameters used to obtain upper level parameters.
Parameters having roman number (i, ii and iii) are the **third level** parameters used to obtain second level parameters.
Parameters having small letter (a, b or c) are the **forth level** parameters used to obtain third level parameters.

Figure 3.15 Flowchart for Remedial Priority Ranking System for Contaminated Sites

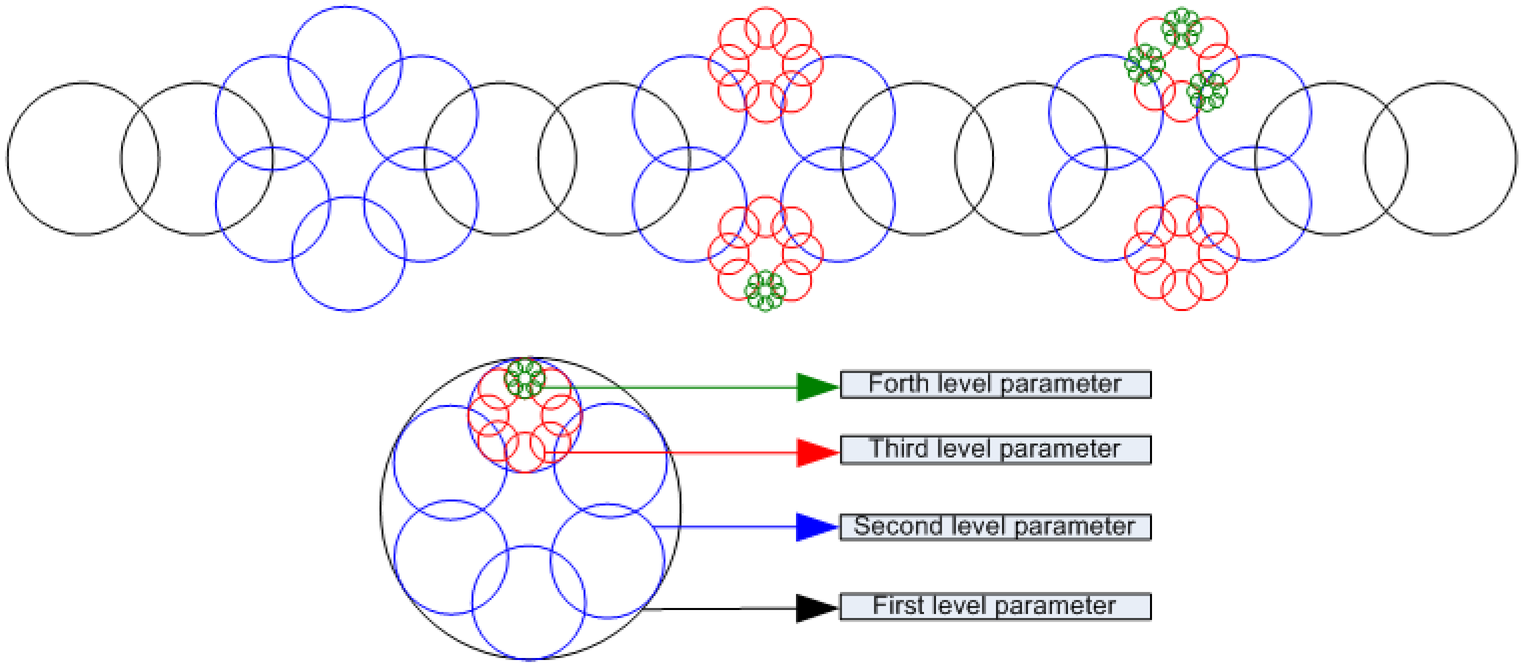


Figure 3.16 Distribution of the parameters in RPRS as a ring (weight) in a chain

Since a fuzzy expert system will be used, a software tool assigning ranking scores for contaminated sites is needed to be developed. It is also aimed to make all calculations in fuzzy expert system automatically; therefore, a tool called ConSiteRPRS is developed The Microsoft Office Excel 2007 platform was sufficient to have such a tool so the system was developed on it. The development of ConSiteRPRS is given in Section 4.

In order to decrease the users' workload during contaminated sites evaluation process, a user-friendly interface was built up and fuzzy set theory and fuzzy expert system component needed for the evaluations were embedded in Microsoft Office Excel 2007 to make the evaluations automatically.

ConSiteRPRS evaluates the contaminated sites via linguistic variables; LOW, MEDIUM and HIGH, which are the commonly used variables in fuzzy set theory. Parameter inputs can be either numerical values or linguistic expressions. When the user enters the numerical values of the parameters (or literal expressions for linguistic parameter), the system uses the linguistic variables that corresponds to the numerical inputs (i.e., fuzzification). For the final result, obtained linguistic values are converted back to a numerical value (i.e., defuzzification). Figure 3.17 illustrates an evaluation process of contaminated sites.

When the users enter a contaminant to the system, in order to obtain physical-chemical properties of the chemical (vapor pressure, Henry's constant, solubility, soil organic partition coefficient and soil-water partition coefficient), a chemical database was built up in ConSiteRPRS. This prevents loosing time for finding the related properties of the selected chemical. In the other systems, the user has to obtain properties of contaminant of concern and enter them into the systems because they do not have such a database to ease the workload of the user.

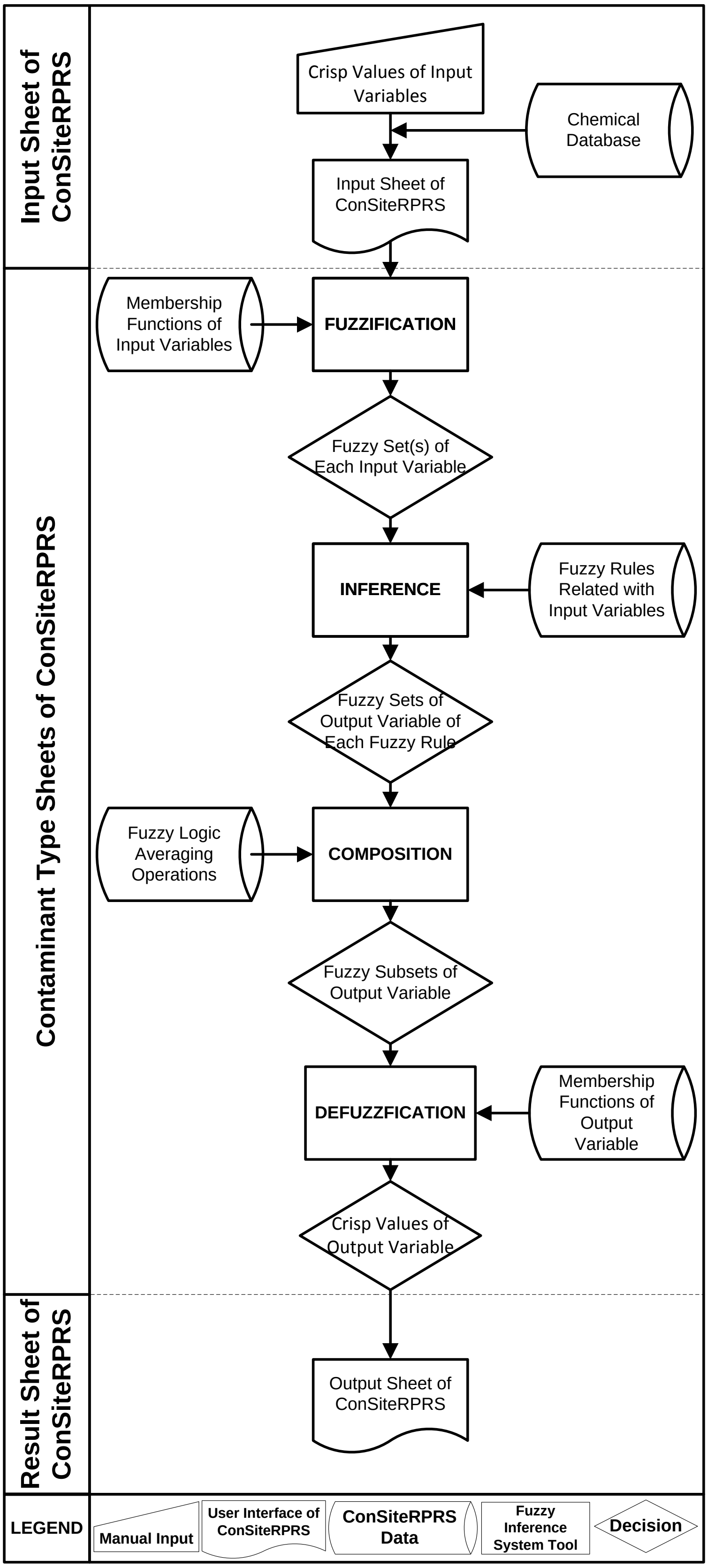


Figure 3.17 Schematic illustration of evaluation process in ConSiteRPRS

The developed ConSiteRPRS needs just inputs of necessary parameters (not all parameters' values). When the user inputs the numerical or literal values of parameters into the user interface of ConSiteRPRS, the system first select the related contaminant type group (described in Section 3.2.1.1) and the values of chemical properties present in the contaminant type group are taken from the chemical database as seen in Figure 3.17. Simultaneously, the input values (crisp values) are started to be fuzzified in fuzzification process. Therefore, the fuzzy expert system is to be started. ConSiteRPRS has membership functions of the fuzzified and defuzzified parameters and fuzzy rules, which are embedded into the Excel. All items of fuzzy set theory are used by the system automatically when the turn of each component of fuzzy expert system comes. An example methodological implementation showing the each step in Figure 3.17 in detail will be given in Section 3.3

The shape of a membership function used in RPRS is presented in Figure 3.18. First and last areas have right trapezoidal shapes and middle one has a triangular shape. The borders of the trapezoidal and triangular areas show the membership degree of the low, medium and high parts at a specific point in the domain. The membership functions of fuzzified parameters are given in Appendix A.

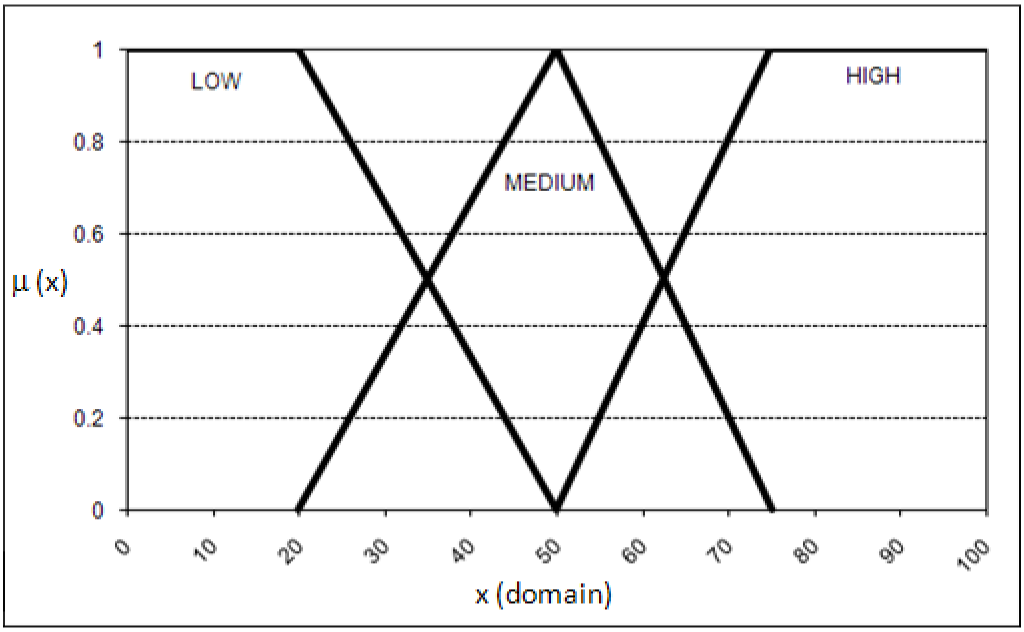


Figure 3.18 Shape of the membership functions

When the fuzzy sets of the parameters are obtained, the fuzzy rules related the parameters group is activated. In RPRS, a fuzzy rule can have two input parameters three input parameters. As mentioned earlier, the linguistic variables of fuzzified parameters are low, medium and high in RPRS. Therefore, there are 9 fuzzy rules (3^2) for two-input-parameter fuzzy rules and 27 rules (3^3) for three-input-parameter fuzzy rules.

Fuzzy rules have been constituted by the help of six experts from Turkey and the Netherlands. The input parameters of the rules have been sent to 3 experts from Turkey and 3 experts from the Netherlands. The experts have made their decisions on output parameters of the fuzzy rules. Some of experts have had difficulty to answer their decisions for each fuzzy rule, so for some fuzzy rules, there are less than six answers. Finally, the fuzzy rules have been completed by considering the decisions of the experts. The sent documents, an explanation sheet for giving fuzzy rule decisions and fuzzy rules tables, to the experts are given in Appendix B and all groups and fuzzy rules are given in Appendix C.

Fuzzy rules are used to make inference and composition of the fuzzy sets of input variables. The average fuzzy logic operator is used for the composition to increase the diversity in the ranking score. The result of composition process is a fuzzy subset for each fuzzy rule of output variables. When the system obtain a final fuzzy subset for the related fuzzy rules for a group parameters, there is left a last step, defuzzification, converting the obtained fuzzy value to a crisp set. This is done by the help of membership functions of defuzzified parameters. There are seven linguistic variables in the membership functions of defuzzified parameters to have diversity in the ranking score for the contaminated sites. The linguistic variables are very low (VL), low (L), low-medium (LM), medium (M), medium-high (MH), high (H) and very high (VH). For the defuzzification process, the height method is used in RPRS because its implementation is easier and it gives more diverse results when compared to the other methods.

Thus, the evaluation done in RPRS is finished after defuzzification process. The result of the evaluation is shown in the Output Sheet of the ConSiteRPRS with the all parameters' values used in the evaluation.

In the following sections, the components of RPRS shown in Figure 3.15, parameters of the system and values of the parameters are given.

3.2.1.1 Components of RPRS

RPRS adopts a scoring system based on S-P-R conceptualization of contaminated sites, as in most of the methodologies currently used. However, while the existing methodologies consider and assess source, pathway and receptor one by one to get to the final score, RPRS considers all pathways and receptors together due to the direct relationship between them, and the outcome of pathways and receptors is evaluated together with the outcome of source to obtain the final ranking score. Therefore, RPRS is divided two, Source and Pathways&Receptors, as seen in Figure 3.15.

The source of a contamination is one of the most important factors for the evaluation of environmental risk. As in all methodologies, RPRS assesses the source of contamination. Source component of RPRS is composed of two parameters: *Toxicity of Chemicals* and *Contaminant Quantity* as seen in Figure 3.15.

A hazardous contaminant follows exposure pathways to reach the receptors when it spills on soil or in groundwater. The pathway becomes important if the receptors are affected by the contamination. If the contaminant moves through a pathway and the receptors are not affected by the contamination, the importance of pathway decreases. Therefore, the concepts of pathways and receptors are taken into account together.

Pathways&Receptors component considers two contaminated media: “Soil” and “Groundwater” as seen in Figure 3.15. Therefore, a contaminated site can be evaluated on the basis of soil medium if the contamination is only in vadose zone (i.e., unsaturated zone) or on the basis of groundwater medium if the contamination is only in groundwater (i.e., saturated zone) or on the basis of both soil and groundwater if both media are contaminated.

Each contaminated medium is further divided according to the contaminant type, being as organic, inorganic, volatile, non-volatile, Light Non-Aqueous Phase Liquids (LNAPL) or Dense Non-Aqueous Phase Liquids (DNAPL). Inorganics are handled in two groups as volatile inorganics and non-volatile inorganics. Thus, there are three contaminant groups considered under soil medium: Soil-Organic Contaminants (SOC), Soil-Volatile-Inorganic Contaminants (SVIC) and Soil-Non-volatile-Inorganic Contaminant (SNVIC). If the contaminated medium is soil and the contaminant is an organic, the contaminant is classified as SOC for the evaluation. If the contaminant is an inorganic and it is not volatile, then it is classified SNVIC. If the contaminant is one of the volatile inorganics, Mercury and Chlorine, it is classified as SVIC.

If contaminated medium is groundwater, four contaminant groups are considered for organics and one for inorganics. These are DNAPL, LNAPL, Groundwater-Dissolved Organic Contaminants (GDOC) and Groundwater-Inorganic Contaminants (GIC). If the contaminated medium is groundwater and contaminant is an organic with a LNAPL free phase, the contaminant is classified as LNAPL. If the free phase is DNAPL, then it is classified as DNAPL. If there is no free phase, i.e., only dissolved phase present, it is classified as GDOC. If the contaminant is an inorganic, then it is classified as GIC.

The receptor can be affected by contamination through several exposure pathways. RPRS considers inhalation of air and soil particles, and ingestion of soil and groundwater. Therefore, each contaminant group is divided into two: air and groundwater (see Figure 3.15). As can be seen from Figure 3.15, the contaminant groups of SNVIC, GDOC and GIC do not have any exposure routes through air since volatilization of the contaminant is negligible.

The contaminated sites are evaluated by considering possible contact of contamination with the receptors and the possibility of the contamination movement towards the receptors. If the contaminant is an organic and in the soil media, the evaluation of air is made to designate whether the contamination reach to the receptors through volatilization and how the receptors are close to the contamination. If the volatilization is at an important level and the receptors are close to the contamination, then the risk due to that contamination becomes high. Moreover, evaluation of groundwater is made to designate whether the contamination reach to the receptors through groundwater. Therefore, the possibility of the contamination to reach to the groundwater, and the potential usage of the groundwater by the receptors is evaluated. This logic is used for the other possible groups of contaminant types in RPRS. For the GIC group, the possibility of contamination movement through the receptors by groundwater is accepted as at the maximum level since the inorganics can move in groundwater freely.

3.2.1.2 Parameters of Remedial Priority Ranking System

RPRS uses 31 different parameters, which includes toxicological, hydrogeologic, lithologic, climatic and land use characteristics of site, and parameters related to nature of contamination and physical-chemical properties of contaminants as seen in Table 3.1. The parameters are selected by considering possible contaminant movements in air, soil and groundwater media. Parameters that affect the fate of the contaminant during its movement towards the receptors are considered in RPRS.

The parameters are grouped under four levels: first level, second level, third level and forth level. The levels designate the weight of the parameters in the evaluation as mentioned in the Section 3.2.1. When the level of parameters decreases from first level to forth level, the relative weight of the parameters group decreases, as well. To clarify the weights of the parameters, a specific notation is used in a systematic manner for categorization of parameters. In this notation, first level parameters are always indicated with capital letters: A, B and C. The numbers are used as 1, 2 and 3 for the second level parameters; roman numerals (i, ii and iii) are used for the third level parameters and finally lower case letters (a, b and c) are used for fourth level parameters (see Figure 3.15). Moreover, some parameters may belong to two different levels. For example, the parameter of "Surface Cover Type" is used as a first level parameter in air pathway, and a third level parameter in groundwater pathway. Similarly, the parameter soil/water partition coefficient (K_d) is used as a third level parameter in groundwater pathway, but a forth level parameter in groundwater receptor.

Table 3.1 Parameters used in the Remedial Priority Ranking System

Parameters	Units	Parameters	Units
Toxicology		**Nature of Contamination**	
Toxicity of contaminant	-	Contaminant name	-
Hydrogeology		Contaminant media	-
Depth to aquifer	m	Contaminant type	-
Aquifer type	-	Existence of free phase	-
Distance to well	m	Density of contaminant	kg/L
Groundwater use	-	Contaminant volume	m^3
Hydraulic conductivity	m/s	Area of contamination	m^2
Hydraulic gradient	%	Depth to contamination	m
Soil Characteristics		Distance between contamination and aquifer	m
Organic carbon fraction in soil, $f_{oc\ soil}$	-	**Physical-Chemical of Contaminant**	
Organic carbon fraction in saturated zone, $f_{oc\ aquifer}$	-	Vapor pressure	mm Hg
Vadose zone porosity	-	Henry's constant	dimensionless
Soil water content	-	Partition coefficient soil/water, K_d	L/kg
Soil air content	-	Soil/organic water partitioning coefficient, K_{oc}	L/kg
Surface cover type	-	Solubility	mg/L
Soil type	-	**Land Use**	
Climate		Land use of the site	-
Precipitation	mm/yr	Distance to receptors	m

The parameters of RPRS are given in Table 3.2 with their meanings according to pathways. The Source component is composed of 2 parameters: *Toxicity of Contaminant* and *Contaminant Quantity*. *Toxicity* shows the degree of toxicological effects of hazardous substances. The toxicity values of the chemicals are obtained from several methodologies: NRS, MIFO, ISM, RSS and AHMR. The value of toxicity of a contaminant can be one of the three literal expressions: low concern, medium concern or high concern of contaminant.

Contaminant Quantity shows the amount of the contamination. There are two ways to obtain a value for *Contaminant Quantity*; if the volume of the contaminant is known, it defines the *Contaminant Quantity*. If the volume of contaminant is not known, the *Area of the Contamination* is used to define the *Contaminant Quantity*.

The volume information of contaminant gives more comprehensive information about the contamination; therefore, such kind of hierarchical evaluation is used in *Contaminant Quantity*. *Volume of the Contaminant* and *Area of Contamination* are numerical parameters. The value ranges of volume and area information for fuzzy variables are composed considering the values used in reviewed methodologies and the help of professional experts judgments.

Here, *Toxicity of Contaminant* and *Contaminant Quantity* are the first level parameters. Since one of the parameters: *Volume of Contaminant* or *Area of Contamination* is used to designate the *Contaminant Quantity*, these two parameters are also considered as first level parameters.

Table 3.2 Parameters of the Remedial Priority Ranking System

SOURCE	**A) Toxicity** Toxicity of contaminants **B) Contaminant quantity** <u>1) Volume of contaminants:</u> The volume of hazardous substance that has been spilled or leaked at the sites <u>2) Area of contamination:</u> The area of contamination in contaminated site.
PATHWAYS & RECEPTORS	**CONTAMINATED MEDIA: SOIL MEDIA** **AIR PATHWAY** **A) Volatilization** <u>1) Vapor Pressure:</u> Vapor pressure of related contaminant (mm Hg) <u>2) Soil Air content:</u> Percentage of air-filled pores in the vadose zone (%). Soil Air Content is obtained from; <u>Vadose Zone Porosity:</u> Porosity in the vadose zone of contaminated site. <u>Water Content:</u> Volumetric Soil water content in the vadose zone of contaminated site. **B) Depth to Contaminated Zone:** Distance between the land surface and the location of contamination at the contaminated site. **C) Surface Cover Type:** Cover type of the surface on the contaminated site. (bare, grass or pavement)
	AIR RECEPTOR **A) Land Use:** Type of Land use near the contaminated site (industrial, commercial, sylvan, agricultural, orchard, schools, parks or residential) **B) Distance to Receptors:** Distance between the source of contamination at the site and the receptor that could be affected by volatile contaminant(s).

Table 3.2 (continued) Parameters of the Remedial Priority Ranking System

PATHWAYS & RECEPTORS	**GROUNDWATER PATHWAY** **A) Travel Time in Unsaturated Zone** 1) Infiltration Rate *i) Precipitation:* Precipitation amount around the contaminated site. *ii) Surface Cover Type (bare, grass or pavement):* Cover type of the surface on the contaminated site. *iii) Soil Type:* Predominant soil type according to drainage availability (poorly, moderately and well drained soil) 2) Distance between Contamination and Aquifer: Distance between the contaminated zone and aquifer that could be affected by the contamination. 3) Retardation of Contaminant (for organics) *i)* K_{oc}*:* K_{oc} of the contaminant in the contaminated site *ii)* f_{oc}*:* f_{oc} of soil in the vadose zone of contaminated site. **OR** 3) K_d (for inorganics): K_d of the contaminant in the contaminated site **B) Aquifer Type:** Aquifer type that could be affected by the contamination. (unconfined or confined)
	GROUNDWATER RECEPTOR **A) Travel Time in Saturated Zone** 1 Contaminant Velocity *i) Groundwater Velocity* a) Hydraulic Conductivity: Saturated zone hydraulic conductivity at the contaminated site. b) Hydraulic Gradient: Saturated zone hydraulic gradient at the contaminated site. *ii) Retardation of Contaminant (for organics)* a) K_{oc}: K_{oc} of the contaminant in the contaminated site b) f_{oc}: f_{oc} of soil in the saturated zone of contaminated site. **OR** *ii)* K_d *(for inorganics):* K_d of the contaminant in the contaminated site 2) Distance to Well: The distance between the source of contamination at the site and the most frequently used downstream groundwater well. **B) Groundwater Use:** Type of groundwater use at the most frequently used well (low, irrigation, industrial or drinking quality)
	CONTAMINATED MEDIA: GROUNDWATER MEDIA **AIR PATHWAY** **A) Volatilization** 1) Henry's Law Constant: Henry's Law Constant of the contaminant of concern 2) Vadose Zone Porosity: Soil porosity in the vadose zone of contaminated site. 3) Water Content: Volumetric soil water content in the vadose zone of contaminated site. **B) Depth to Aquifer:** Distance between the land surface and the top of the aquifer at the contaminated site. **C) Aquifer Type:** Aquifer type that could be affected by the contamination. (unconfined or confined)

Table 3.2 (continued) Parameters of the Remedial Priority Ranking System

PATHWAYS & RECEPTORS	**AIR RECEPTOR** **A) Land Use:** Land use type near the contaminated site (industrial, commercial, sylvan, agricultural, orchard, schools, parks or residential) **B) Distance to Receptors:** The distance between the source of contamination at the site and the receptor that could be affected by volatile contaminant.
	GROUNDWATER PATHWAY **A) Solubility:** Solubility of the contaminant of concern
	GROUNDWATER RECEPTOR **A) Travel Time in Saturated Zone** 1 Contaminant Velocity: *i) Groundwater Velocity* a) Hydraulic Conductivity: Saturated zone hydraulic conductivity at the contaminated site. b) Hydraulic Gradient: Saturated zone hydraulic gradient at the contaminated site. *ii) Retardation of Contaminant (for organics)* a) K_{oc}: K_{oc} of the contaminant in the contaminated site b) f_{oc}: f_{oc} of soil in the saturated zone of contaminated site. **OR** *ii) K_d (for inorganics):* K_d of the contaminant in the contaminated site 2) Distance to Well: The distance between the source of contamination at the site and the most frequently used downstream groundwater well. **B) Groundwater Use:** Type of groundwater use at the most frequently used well (low, irrigation, industrial or drinking quality)

In Pathways&Receptors component, the number of parameters changes according to contamination type as seen in Table 3.3. Although the total number of parameters used for the evaluation of contaminated sites is 31, the user should not gather 31 input data for each evaluation. Data requirement differs according to considered path. For instance, if the contaminated medium is soil and the contaminant is an organic, then only the parameters under the SOC are required.

Table 3.3 Parameters required in Remedial Priority Ranking System

	Parameters	SOC	SNVIC	SVIC	LNAPL	DNAPL	GDOC	GIC
	Total# of parameters in the System	25	16	23	23	15	14	11
	# of parameters asked by the System	19	12	17	15	9	9	7
1	Contaminated Media	√	√	√	√	√	√	√
2	Contaminant Name	√	√	√	√	√	√	√
3	Existence of Free Phase				√	√	√	
4	Density of Contaminant*				-	-	-	
5	Contaminant Type*	-	-	-	-	-	-	-
6	Toxicity of contaminant*	-	-	-	-	-	-	-
7	Volume of contaminant	√	√	√	√	√	√	√
8	Area of contamination**	-	-	-	-	-	-	-
9	Vapor pressure*	-		-				
10	Henry's constant*				-			
11	Vadose zone porosity	√		√	√			
12	Water content	√		√	√			
13	Air porosity content***	-		-	-			
14	Depth to contamination	√		√				
15	Depth to aquifer				√			
16	Surface cover type	√	√	√				
17	Aquifer type	√	√	√	√			
18	Precipitation	√	√	√				
19	Soil type	√	√	√				
20	Distance between contamination and aquifer	√	√	√				
21	K_{oc}*	-			-	-	-	
22	$f_{oc\ soil}$	√						
23	$f_{oc\ aquifer}$	√			√	√	√	
24	K_d*		-	-				-
25	Solubility*				-	-		
26	Land use	√		√	√			
27	Distance to receptors	√		√	√			
28	Hydraulic conductivity	√	√	√	√	√	√	√
29	Hydraulic gradient	√	√	√	√	√	√	√
30	Distance to well	√	√	√	√	√	√	√
31	Groundwater use	√	√	√	√	√	√	√

* Value of the parameter is assigned by the system automatically when the contaminant is selected by the user.

** Value of area of Contamination is asked by the system if the user enters "unknown" for the Contaminant Volume parameter.

*** Value of Soil Air Content is assigned by the system when the user enters the value of Vadose Zone Porosity and Water Content.

The first level parameters in Air Pathway of the Soil Media are Volatilization, Depth to Contaminated Zone and Surface Cover Type as seen in Figure 3.15 and Table 3.2. Vapor Pressure and Soil Air Content are the second level parameters, combination of which forms Volatilization. Land Use and Distance to Receptors are first level parameters of Air Receptor part.

Groundwater Pathway of Soil Medium contains two first level parameters: *Travel Time in Unsaturated Zone* and *Aquifer Type*. *Infiltration Rate*, *Distance between Contamination and Aquifer*, and *Retardation of Contaminant in Unsaturated Zone* for organic and *Soil-Water Partition Coefficient (K_d)* for inorganic as second level parameters for *Travel Time in Unsaturated Zone* parameter. In addition, *Precipitation, Surface Cover Type* and *Soil Type* are the third level parameters in *Infiltration Rate* and *Soil-Organic Partition Coefficient (K_{oc})* and *Fraction of Organic Carbon (f_{oc})* are the third level parameters for organic in *Retardation of Contaminant in Unsaturated Zone*.

Groundwater Receptor of Soil Medium also contains two first level parameters, Travel Time in Saturated Zone and Groundwater Use. There are two second level parameters in Travel Time in Saturated Zone: Contaminant Velocity and Distance to Well. Moreover, Contaminant Velocity contains two third level parameters including Groundwater Velocity and Retardation of Contaminant in Saturated Zone for organics and K_d for inorganics (metals). Retardation of Contaminant in Saturated Zone is composed of two forth level parameters: Hydraulic Conductivity in Saturated Zone and Hydraulic Gradient of the Aquifer beneath the contamination zone. Furthermore, Retardation of Contaminant in Saturated Zone has two forth level parameters, K_{oc} and f_{oc} if the contaminant is an organic.

The first level parameters, Volatilization, Depth to Aquifer and Aquifer Type, are the parameters in Air Pathways of Groundwater Media. Henry's Law Constant and Soil Air Content are the second level parameters, which form Volatilization. Land Use and Distance to Receptors are first level parameters of Air Receptor part the same as in Air Receptor part of Soil Media.

Groundwater Pathway of Groundwater Medium contains two first level parameters: Solubility of Contaminant and the existence of free phase. Groundwater Receptor of Groundwater Medium contains two first level parameters: Travel Time in Saturated Zone and Groundwater Use. There are two second level parameters in Travel Time in Saturated Zone: Contaminant Velocity and Distance to Well. Moreover, Contaminant Velocity contains two third level parameters including Groundwater Velocity and Retardation of Contaminant in Saturated Zone for organics and K_d for inorganics. As in the Groundwater Pathway part in Soil Media, Retardation of Contaminant in Saturated Zone is defined by two forth level parameters, Hydraulic Conductivity in Saturated Zone and Hydraulic Gradient of the Aquifer beneath contaminated zone. Furthermore, Retardation of Contaminant in Saturated Zone has two forth level parameters, K_{oc} and f_{oc} if the contaminant is an organic.

3.2.1.3 Designation of Parameter Value Intervals

Some of the parameters in RPRS have numerical value ranges while some of them have literal expressions. In order to obtain ranking score, each numerically described parameter needs its own special membership function. Since the membership functions are composed of linguistic variables like low, medium and high, the value range of each linguistic variable should be specified.

In RPRS, the main linguistic variables for fuzzification are Low, Medium and High. In order for a better understanding of the ranges of parameter values, currently used methodologies have been reviewed; and the value ranges corresponding to medium linguistic variable are used to define the medium value ranges of common parameters in RPRS. The ranges of medium linguistic variable obtained from currently used methodologies are given in Table 3.4.

The value ranges show great differences from one methodology to other as seen in Table 3.4. The main reason for these differences is because of that their aims in using any given parameter can be different. For instance, volume information is used to define three different volumes: volume of waste (in dumpsites), volume of the contaminant or volume of contaminated soil. Moreover, the evaluation criterion for Depth to Aquifer changes from one methodology to another. For instance, 7.5 m is used for the minimum value to yield the maximum score in the NRS method, but it is the maximum value used to yield the minimum score in the SAPS and WARM methods. The same condition exists for some literal parameters. For instance, if the contaminated site is on a school site, it indicates a medium risk in RRSM method while it indicates a high risk in RASCL method.

Table 3.4 Value interval for Linguistic variable "medium"

Parameters	Methodologies or Reference	Value Range	Explanation
Volume (m^3)	AHMR	75-1500	Contaminated soil volume is concerned
	NCSCS	100-1000	
	RSS	100-1000	
	PRAMS	5000-1500000	
	SRA	10000-100000	
	SAPS	4-480	
	SRA	10-100	Volume of the contaminant is concerned
	TÜBİTAK-KAMAG. (2009)	10-100	
	ISM	8-1900	
	Bulgaria Ministry of Environment and Water (2001)	10000-500000	Volume of Waste (in dump sites) is concerned
	SAM	50-2500	
Area (m^2)	AHMR	10-4050	Area of contamination is concerned.
	Bulgaria Ministry of Environment and Water (2001)	100-5000	
	PRAMS	1000-300000	
	SRA	10000-100000	
	SAM	2000-250000	
	SAPS	450-40000	
Toxicity	ISM	0	No toxicity
		1	Slight Toxicity
		2	Moderate Toxicity
		3	Severe Toxicity

Table 3.4 (continued) Value interval for Linguistic variable "medium"

	RSS	0.2	Low concern contaminants
		0.6	Medium concern contaminants
		1.0	High concern contaminants
Vapor Pressure (mm Hg)	NRS	0.01-1	
	WARM	0.00001-10	
	PRAMS	0.00001-10	
Henry's Law Constant	WARM	1.0E-07-1.0E-03	
	PRAMS	1.0E-07-1.0E-03	
Solubility (mg/L)	NRS	1-1000	
	SRA	0.01-1000	
	SAPS	1-1000	
	PRAMS	0.01-1000	
Vadose Zone Porosity	Freeze and Cherry (1979).	0.25-0.70	
Depth to Contaminated Zone (m)	SPPS	0.5-2	
	RSS	1-3	
Depth to Aquifer (m)	DRASTIC	1.5-30	
	ISM	6-45	
	HRS	7-75	
	NCSCS	3-10	
	NRS	1.5-7.5	
	RASCL	3-10	
	SRA	4-10	
	SAPS	7.5-90	
	PRAMS	5-50	
	WARM	7.5-90	
Surface Cover Type	RSS	0.3	no access, or paved
		0.8	limited access or paving
		1	no restraint to access
Land Use	RRSM	Low risk	industrial and commercial
		Medium risk	playing fields, public open space
		High risk	informal play areas, schools housing
	RASCL	0.2	Commercial /industrial
		0.7	Schools-recreation-agricultural
		1	Residential
Distance to Receptors (m)	ISM	15-3200	
	RRSM	50-250	
	RSS	50-300	
Precipitation (mm/yr)	NCSCS	200-1000	
	-	200-500	
K_{oc} (L/kg)	RIVM Document	10-100000	
Distance between Contaminant and aquifer (m)	Bulgaria Ministry of Environment and Water (2001)	2-10	
	ISM	6-45	
	WARM	7.5-90	
	Garcia et al, 2006	40-240	

Table 3.4 (continued) Value interval for Linguistic variable "medium"

Aquifer Type	HRS	Karst and other aquifers	
Hydraulic Conductivity (m/s)	Bulgaria Ministry of Environment and Water (2001)	1.00E-06-1.00E-04	
	NCSCS	1.00E-06-1.00E-04	
	SRA	1.00E-07-1.00E-04	
Hydraulic Gradient	SDSU, 2002	0.0001-0.001	
K_d (L/kg)	Sheppard et. al.	10-1000	
Distance to Well (m)	ISM	600-5000	Distance to downstream well that could be affected by contamination
	NCSCS	100-5000	
	SAPS	800-3200	
	WARM	200-3000	
	PRAMS	150-3000	
	TÜBİTAK-KAMAG. (2009)	300-5000	
Groundwater Use	RRSM	Low risk	industrial or agricultural use
		Medium risk	private supply
		High risk	public supply
	PRAMS	65	Potable
		60	Private well
		55	Irrigation
		35	Other use not specified (ex. Golf, parks)
		20	Industrial
		5	Non used
		0	No groundwater body present

Ranges of the parameters and literal values used in RPRS have been specified according to expert judgment and the current available methodologies. The intervals of *medium* linguistic variable designated for the numerical parameters of RPRS are given in Table 3.5.

Table 3.5 The value intervals for *medium* linguistic variable of numerical parameters

Parameters	**Range of Medium Linguistic Variable and Literal Expressions**
Volume (m^3)	1-10
Area (m^2)	2000-12000
Vapor Pressure (mm Hg)	0.00001-10
Henry's Law Constant (dimensionless)	0.0000001-0.001
Solubility (mg/L)	0.01-1000
Soil Air Content (dimensionless)	0.2-0.4
Depth to Contamination (m)	0.5-2
Depth to Aquifer (m)	1.5-10
Distance to Receptors (m)	50-300
Precipitation (mm/yr)	500-1000
K_{oc} (L/kg)	10-100000
$f_{oc\ soil}$ (dimensionless)	0.01-0.03
Distance between Contaminant and aquifer (m)	1.5-10
Hydraulic Conductivity (m/s)	0.00001-0.001
Hydraulic Gradient (dimensionless)	0.0001-0.01
$f_{oc\ aquifer}$(dimensionless)	0.001-0.003
K_d (L/kg)	10-100000
Distance to Well (m)	300-3000

In order to compose the membership function of the parameters, the value where the membership degree is 1 for range of *medium linguistic variable* for a variable has to be designated. This requires very detailed investigations. The value of the *medium* linguistic variable, corresponding to a membership degree of 1, for a variable can be close to the left boundary of the range or close to the right boundary. Those values are determined from the average of the value ranges boundaries of *medium* linguistic variables to be conservative. Therefore, the range of *medium linguistic variable* in membership functions becomes Isosceles triangles for fuzzified parameters as seen in Appendix A. After determining those values, the value ranges of three linguistic variables for fuzzified parameters are given in Table 3.6.

Table 3.6 The accepted value ranges for the fuzzified parameters of RPRS

Parameters	Low	Medium	High
Volume (m^3)	0-1-5.5	1-5.5-10	5.5-10-11
Area (m^2)	0-2000-7000	2000-7000-12000	7000-12000-14000
Toxicity of Contaminant	Low Concern Contaminant	Medium Concern Contaminant	High Concern Contaminant
Contaminant quantity	0 – 10 - 50	10 –50 - 90	50 – 90 - 100
Vapor Pressure (mm Hg)	10^{-6} - 10^{-5} - 10^{-2}	10^{-5} - 10^{-2} - 10	10^{-2} – 10 - 10^{2}
Henry's Law Constant	10^{-6} - 10^{-5} - 10^{-2}	10^{-5} - 10^{-2} - 10	10^{-2} – 10 - 10^{2}
Solubility (mg/L)	10^{-3} - 10^{-2} - 10	10^{-2} – 10 - 10^{3}	10 - 10^{3} - 10^{4}
Free Phase	No		Yes
Soil Air Content	0.01-0.05-0.175	0.05-0.175-0.3	0.175-0.3-0.5
Volatilization	0 - 10 - 50	10 - 50 - 90	50 - 90 - 100
Depth to Contamination (m)	0 - 0.5 - 1.25	0.5 - 1.25 - 2	1.25 - 2 - 2.5
Depth to Aquifer (m)	0 - 1.5 - 5.75	1.5 - 5.75 - 10	5.75 - 10 - 12
Surface Cover Type	Pavement	Grass	Bare
Land Use	Industrial	Agriculture	Residential
Distance to Receptors (m)	0 - 50 - 175	50 - 175 - 300	175 - 300 - 350
Precipitation (mm/yr)	400-500-750	500-750-1000	750-1000-1100
Soil Type	Poorly Drained	Moderately Drained	Well Drained
Infiltration Rate	0 - 0.6 – 1.2	0.6 – 1.2 - 1.8	1.2 - 1.8 – 2
Travel Time in Unsaturated Zone	0 – 1.2 – 2.4	1.2 – 2.4 – 3.6	2.4 – 3.6 – 4
K_{oc} (L/kg)	0 – 10 – 10^{3}	10 – 10^{3} – 10^{5}	10^{3} – 10^{5} – 10^{6}
$f_{oc\ soil}$	0-0.01-0.02	0.01-0.02-0.03	0.02-0.03-0.04
Retardation	0 – 1 – 2	1 – 2 – 3	2 – 3 – 4
Distance between Contaminant and aquifer (m)	0 – 1.5 – 5.75	1.5 – 5.75 – 10	5.75 – 10 – 12
Aquifer Type	Confined	-	Unconfined
Hydraulic Conductivity (m/s)	$10^{-5.5}$-10^{-5}-10^{-4}	10^{-5}-10^{-4}-10^{-3}	10^{-4}-10^{-3}-$10^{-2.5}$
Hydraulic Gradient	$10^{-4.5}$-10^{-4}-10^{-3}	10^{-4}-10^{-3}-10^{-2}	10^{-3}-10^{-2}-$10^{-1.5}$
Groundwater Velocity	0 – 0.6 – 1.2	0.6 – 1.2 – 1.8	1.2 – 1.8 – 2
Contaminant Velocity	0 – 0.6 – 1.2	0.6 – 1.2 – 1.8	1.2 – 1.8 – 2
$f_{oc\ aquifer}$	0-0.001-0.002	0.001-0.002-0.003	0.002-0.003-0.004
K_d (L/kg)	0 – 1 – 3	1 – 3 – 5	3 – 5 – 6
Distance to Well (m)	0-300-1650	300-1650-3000	1650-3000-3300
Travel Time in Saturated Zone	0 – 1.6 – 3.2	1.6 – 3.2 – 4.8	3.2 – 4.8 – 6
Groundwater Use	Low Quality	Irrigation and Industrial	Drinking Quality
Air Pathway	0 - 10 - 50	10 - 50 - 90	50 - 90 - 100
Air Receptor	0 - 10 - 50	10 - 50 - 90	50 - 90 - 100
Groundwater Pathway	0 - 10 - 50	10 - 50 - 90	50 - 90 - 100
Groundwater Receptor	0 - 10 - 50	10 - 50 - 90	50 - 90 - 100
Air Pathway&Receptor	0 - 10 - 50	10 - 50 - 90	50 - 90 - 100
Groundwater Pathway&Receptor	0 - 10 - 50	10 - 50 - 90	50 - 90 - 100
Pathways&Receptors	0 - 10 - 50	10 - 50 - 90	50 - 90 - 100

In Table 3.6, for example, the value of Low linguistic variable of volume parameter is read as that the value of membership function is 1 if the value of parameter is between 0 and 1, and the value of membership function decreases gradually to 0 if the value of volume parameter is increases towards 5.5. For the medium linguistic variable, the value of membership function is 0 if the value of volume parameter is 1 or 10. The value of membership function increases to 1 if the value of the parameter increases towards 5.5 and it becomes 1 when the parameter value becomes 5.5. While the value of volume parameter increases from 5.5 to 10, the value of membership function decreases gradually to 0 for the medium linguistic variable. For the high linguistic variable, the value of the membership function is 0 when the value of volume parameter is 5.5. The membership function value becomes 1 if the value of volume parameter is higher than 10.

The membership functions used for defuzzification process are chosen to have 7 linguistic variables. This enables RPRS to be able to differentiate and rank the contamination sites even if there are small changes in parameters. The defuzzification process designates the diversity of the results; therefore, the value ranges for 7 linguistic variables are not arranged evenly. Making them uneven enables to have different results for different values of parameters. Therefore, the value ranges for linguistic variables are designated not to creating isosceles triangles. The determined ranges for 7 linguistic variables for defuzzified parameters are given in Table 3.7 and all membership functions of parameters applied defuzzification are given in Appendix A.

Table 3.7 The accepted value ranges for bulk parameters defined as a function of one or more of the 31 individual parameter of RPRS

	Parameters	Formed by	Very Low	Low	Low-Medium	Medium	Medium-High	High	Very High
1	Contaminant quantity (%)	Volume of Source or Area of Contamination	-	0-10-40	-	10-40-90	-	40-90-100	-
2	Source (%)	Toxicity of Contaminant / Contaminant quantity	0 - 8 - 20	8 - 20 - 33	20 - 33 - 50	33 - 50 - 65	50 - 65 - 82	65 - 82 - 95	82 - 95 - 100
3	Volatilization[a] (%)	Vapor Pressure or Henry's Law Constant / Soil Air Content	0 - 8 - 20	8 - 20 - 33	20 - 33 - 50	33 - 50 - 65	50 - 65 - 82	65 - 82 - 95	82 - 95 - 100
4	Air Pathway[b] (%)	Volatilization / Depth to Contamination or Depth to Aquifer / Surface Cover Type or Aquifer Type	0 - 8 - 20	8 - 20 - 33	20 - 33 - 50	33 - 50 - 65	50 - 65 - 82	65 - 82 - 95	82 - 95 - 100
5	Air Receptor (%)	Land Use / Distance to Receptors	0 - 8 - 20	8 - 20 - 33	20 - 33 - 50	33 - 50 - 65	50 - 65 - 82	65 - 82 - 95	82 - 95 - 100
6	Infiltration Rate	Precipitation / Surface Cover Type / Soil Type	0 - 0.2 - 0.4	0.2 - 0.4 - 0.6	0.4 - 0.6 - 0.9	0.6 - 0.9 - 1.2	0.9 - 1.2 - 1.5	1.2 - 1.5 - 1.8	1.5 - 1.8 - 2
7	Retardation	K_{oc} / $f_{oc\ soil}$	0 - 0.4 - 0.8	0.4 - 0.8 - 1.2	0.8 - 1.2 - 1.8	1.2 - 1.8 - 2.4	1.8 - 2.4 - 3.0	2.4 - 3.0 - 3.6	3.0 - 3.6 - 4.0

Table 3.7 (continued) The accepted value ranges for bulk parameters defined as a function of one or more of the 31 individual parameter of RPRS

	Parameters	Formed by	Very Low	Low	Low-Medium	Medium	Medium-High	High
8	Travel Time in Unsaturated Zone[c]	Retardation or K_d Distance btw Contamination & Aquifer Infiltration Rate	0 - 0.4 - 0.8	0.4 - 0.8 - 1.2	0.8 - 1.2 - 1.8	1.2 - 1.8 - 2.4	1.8 - 2.4 - 3.0	2.4 - 3.0 - 3.6
9	Groundwater Pathway[d] (%)	Travel Time in Unsaturated Zone Aquifer Type	0 - 8 - 20	8 - 20 - 33	20 - 33 - 50	33 - 50 - 65	50 - 65 - 82	65 - 82 - 95
10	Groundwater Pathway[d] (%)	Solubility	-	0 - 10 - 40	-	10 - 40 - 90	-	40 - 90 - 100
11	Groundwater Velocity	Hydraulic Conductivity Hydraulic Gradient	0 - 0.2 - 0.4	0.2 - 0.4 - 0.6	0.4 - 0.6 - 0.9	0.6 - 0.9 - 1.2	0.9 - 1.2 - 1.5	1.2 - 1.5 - 1.8
12	Retardation	K_{oc} $f_{oc\ aquifer}$	0 - 0.4 - 0.8	0.4 - 0.8 - 1.2	0.8 - 1.2 - 1.8	1.2 - 1.8 - 2.4	1.8 - 2.4 - 3.0	2.4 - 3.0 - 3.6
13	Contaminant Velocity[e]	Retardation or K_d[*] Groundwater Velocity	0 - 0.2 - 0.4	0.2 - 0.4 - 0.6	0.4 - 0.6 - 0.9	0.6 - 0.9 - 1.2	0.9 - 1.2 - 1.5	1.2 - 1.5 - 1.8
14	Travel Time in Saturated Zone	Contaminant Velocity Distance to Well	0 - 0.5 - 1.0	0.5 - 1.0 - 1.6	1.0 - 1.6 - 2.2	1.6 - 2.2 - 3.0	2.2 - 3.0 - 4.0	3.0 - 4.0 - 4.8
15	Groundwater Receptor (%)	Travel Time in Saturated Zone Groundwater Use	0 - 8 - 20	8 - 20 - 33	20 - 33 - 50	33 - 50 - 65	50 - 65 - 82	65 - 82 - 95
16	Air Pathway &Receptor (%)	Air Pathway Air Receptor	0 - 8 - 20	8 - 20 - 33	20 - 33 - 50	33 - 50 - 65	50 - 65 - 82	65 - 82 - 95

Table 3.7 (continued) The accepted value ranges for bulk parameters defined as a function of one or more of the 31 individual parameter of RPRS

	Parameters	Formed by	Very Low	Low	Low-Medium	Medium	Medium-High	High	Very High
17	Groundwater Pathway&Receptor (%)	Groundwater Pathway / Groundwater Receptor	0 - 8 - 20	8 - 20 - 33	20 - 33 - 50	33 - 50 - 65	50 - 65 - 82	65 - 82 - 95	82 - 95 - 100
18	Pathways&Receptors (%)	Air Pathway&Receptor / Groundwater Pathways&Receptors	0 - 8 - 20	8 - 20 - 33	20 - 33 - 50	33 - 50 - 65	50 - 65 - 82	65 - 82 - 95	82 - 95 - 100
19	Final Score (%)	Source / Pathways&Receptors	0 - 8 - 20	8 - 20 - 33	20 - 33 - 50	33 - 50 - 65	50 - 65 - 82	65 - 82 - 95	82 - 95 - 100

[a] If the contaminant type is LNAPL, the system uses Henry's Law Constant, if it is SO or SVI, the system uses Vapor Pressure.

[b] If the contaminant type is LNAPL, the system uses Depth to Aquifer, if it is SO or SVI, the system uses Depth to Contaminated Zone.

[c] If the contaminant is an organic, the system uses Retardation, if contaminant is an inorganic, the system uses K_d.

[d] If the contaminated medium is Soil, the system uses Travel Time in Unsaturated Zone and Aquifer Type for the evaluation of Groundwater Pathway, If the contaminated medium is Groundwater, the system uses Solubility.

[e] If the contaminant is an organic, the system uses Retardation, if contaminant is an inorganic, the system uses K_d.

3.3 Example Methodology Implementation

The parameters used for the ranking procedure in RPRS are grouped in twain or triad as seen in Figure 3.15. The evaluation in ConSiteRPRS is seen in Figure 3.17 proceeds for each group, simultaneously. There are a total of 40 parameters (Table 3.6) that can be fuzzified and 19 (Table 3.7) parameters that can be defuzzified. In this section of the study, the steps for a two-grouped-parameter are shown to better understanding procedures shown in Figure 3.17.

The parameters are *Source* and *Pathways&Receptors.* These parameters are used to obtain *Final Score* of an evaluation. The input values of *Source* and *Pathways&Receptors* come from the parameters at lower levels. For example, the defuzzification of *Toxicity of Contaminant* and *Contaminant Quantity* form *Source*, and *Groundwater Pathway&Receptor* and *Air Pathway&Receptor* form *Pathways&Receptors.* Let us assume the defuzzification results of those parameter groups are 42 and 66, respectively. Therefore, the fuzzy expert system is started by fuzzification process.

3.3.1 Fuzzification

For the fuzzification, the membership functions in Figure 3.19 and 3.20 are used for the parameters *Source* and *Pathways&Receptors,* respectively. ConSiteRPRS apply fuzzification to those parameters. The corresponding membership degrees of fuzzy value of *Source* parameters is obtained as is Figure 3.21 and the corresponding membership degrees of fuzzy value of *Pathways&Receptors* parameters is obtained as is Figure 3.22. The results of fuzzifications and corresponding fuzzy sets are given in Table 3.8 in a tabulated form.

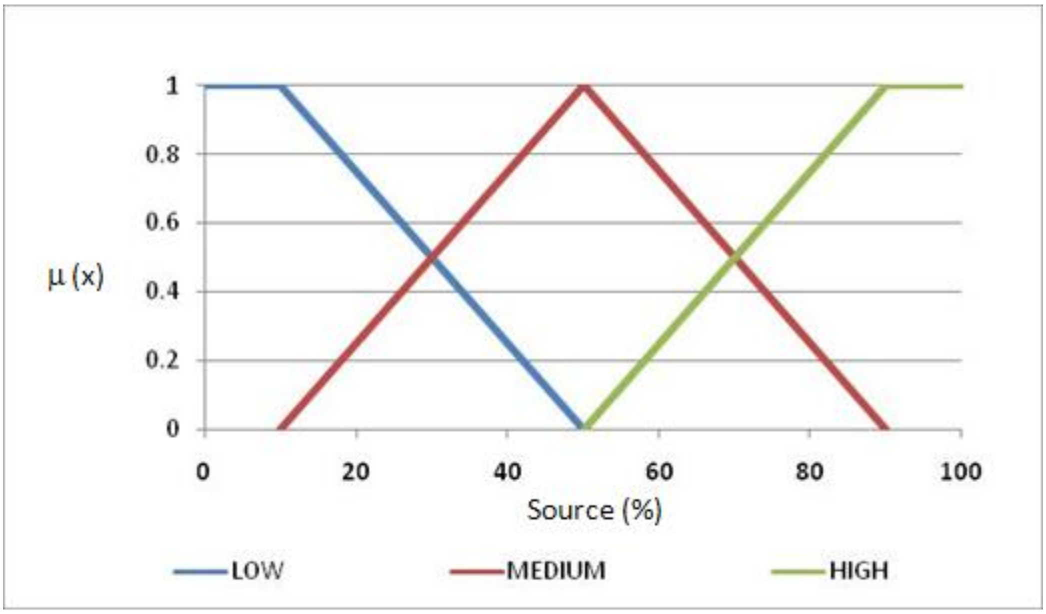


Figure 3.19 Membership function of *Source* parameter, (%)

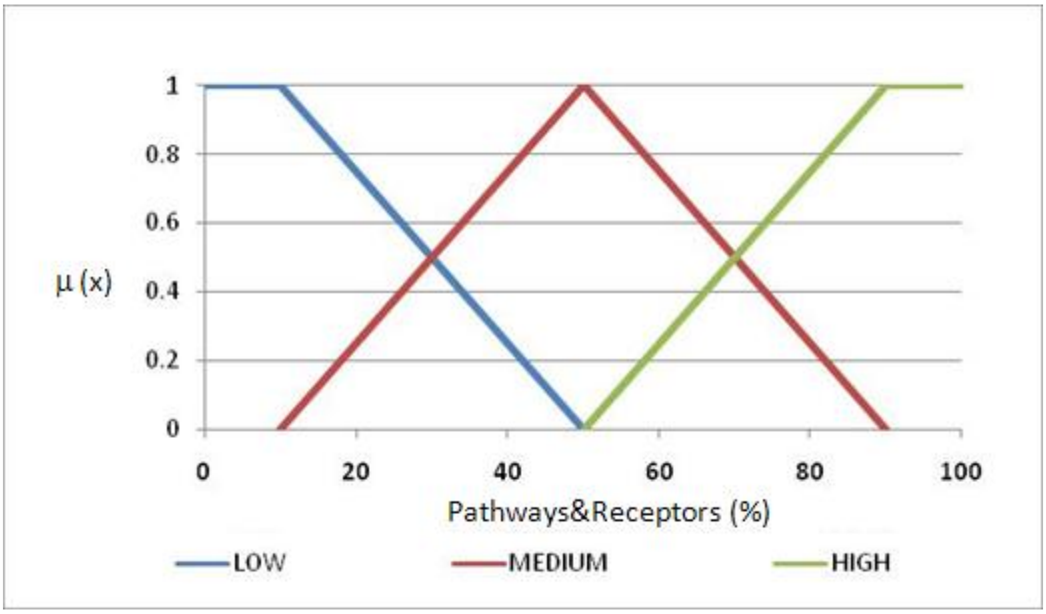


Figure 3.20 Membership function of *Pathways&Receptors* parameter, (%)

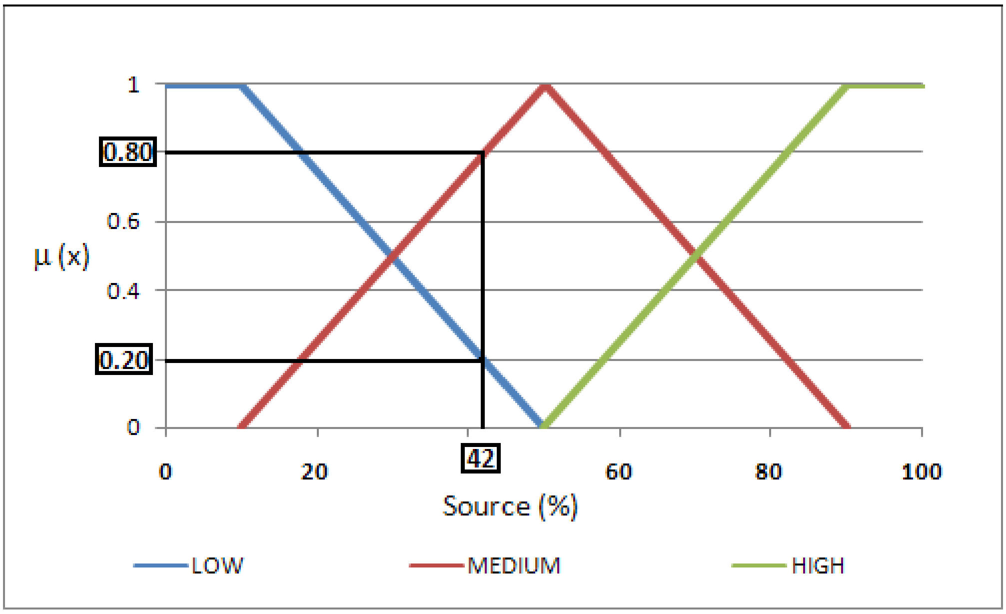


Figure 3.21 Membership degrees of Source parameter at the value of 42

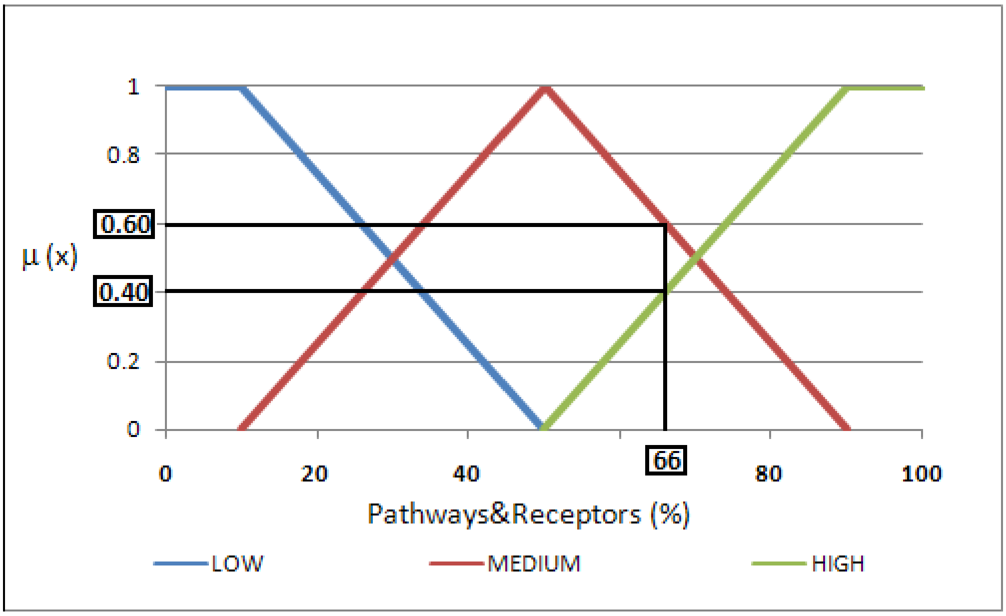


Figure 3.22 Membership degrees *Pathways&Receptors* parameter at the value of 66

Table 3.8 Fuzzification results of *Source* and *Pathways&Receptors*

Parameter	Value	Fuzzification Results		
Source	42	0.2 Low	0.80 Medium	0 High
Pathways&Receptors	66	0 Low	0.60 Medium	0.40 High

3.3.2 Inference

The inference process needs fuzzy rules of parameter group to make inference of each fuzzy rule. There are 9 (3^2) possible fuzzy rules related with the parameter and they are shown in Table 3.9. The results of inference in the example are given in Table 3.10 that shows the results of the fuzzy rules according to fuzzification process.

Table 3.9 Fuzzy rules of parameters *Source* and *Pathways&Receptors*

		Source		
		Low	Medium	High
Pathways & Receptors	Low	VL	L	MH
	Medium	L	M	H
	High	MH	H	VH

Table 3.10 Inferences of fuzzy rules

		Source		
		0.20 Low	0.80 Medium	0 High
Pathways & Receptors	0 Low	VL	L	MH
	0.60 Medium	**L**	**M**	H
	0.40 High	**MH**	**H**	VH

Therefore, the emerged rules of the example are:

If the *Source* is *low* and the *Pathways&Receptors* is *medium*, the *Score* becomes *low,*

If the *Source* is *low* and the *Pathways&Receptors* is *high*, the *Score* becomes *medium-high,*

If the *Source* is *medium* and the *Pathways&Receptors* is *medium*, the *Score* becomes *medium,* and

If the *Source* is *medium* and the *Pathways&Receptors* is *high*, the *Score* becomes *high.*

3.3.3 Composition

The results of the inference process show that there are four fuzzy rules related with *Source* and *Pathways&Receptors* parameters. Now, the system evaluates the fuzzy subset of each fuzzy rule of output variable by composition process. The results are shown in Table 3.11.

Table 3.11 Results of the single fuzzy subset for each output variable according to average (AVG) operator

Rules	***Source***	**Operator**	***Pathways&***	**Final Score**
1	0.20 Low	AVG	0.60 Medium	0.40 Low
2	0.20 Low	AVG	0.40 High	0.30 Medium-High
3	0.80 Medium	AVG	0.60 Medium	0.70 Medium
4	0.80 Medium	AVG	0.40 High	0.60 High

3.3.3 Defuzzification

After the fuzzy subsets are obtained in composition process, the system activates the defuzzification process. The membership function of the output variable, *Final Score*, is used for the defuzzification. Each fuzzy subset of the output variable is inserted in its membership function as shown in Figure 3.23.

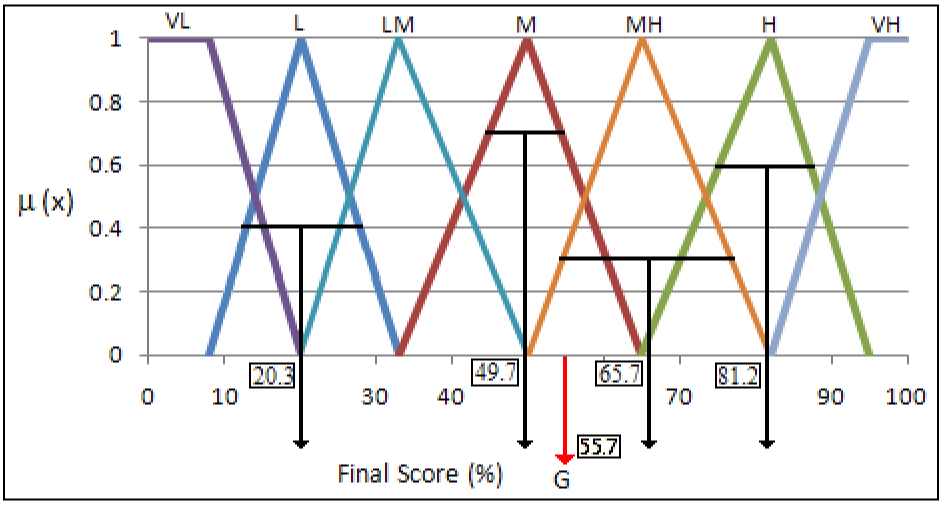


Figure 3.23 Defuzzification result of the example

Finally, the result of the defuzzification, which is the overall result of the contaminated site ranking score is calculated as 55.7 as seen in Figure 3.23. The calculation of G in defuzzification method needs calculations of the parameters (μ, a, x, c and z) shown in Figure 3.24. μ is the average of the membership degrees of the parameters in each fuzzy rule (the μ values for the rules used in the example are 0.40, 0.30, 0.60 and 0.70). In order to calculate the defuzzification result, the distances, assigned as *z* in Figure 3.24, between the origin (0,0) and the points corresponding to each height defuzzification operations (20.3, 49.7, 65.7and 81.2 respectively in Figure 3.23) are needed. As seen in Figure 3.24, a, x and c values are used to calculate the *z* values (Eqn. 3.5).

$$z = x + c + \frac{a}{2} \quad (3.5)$$

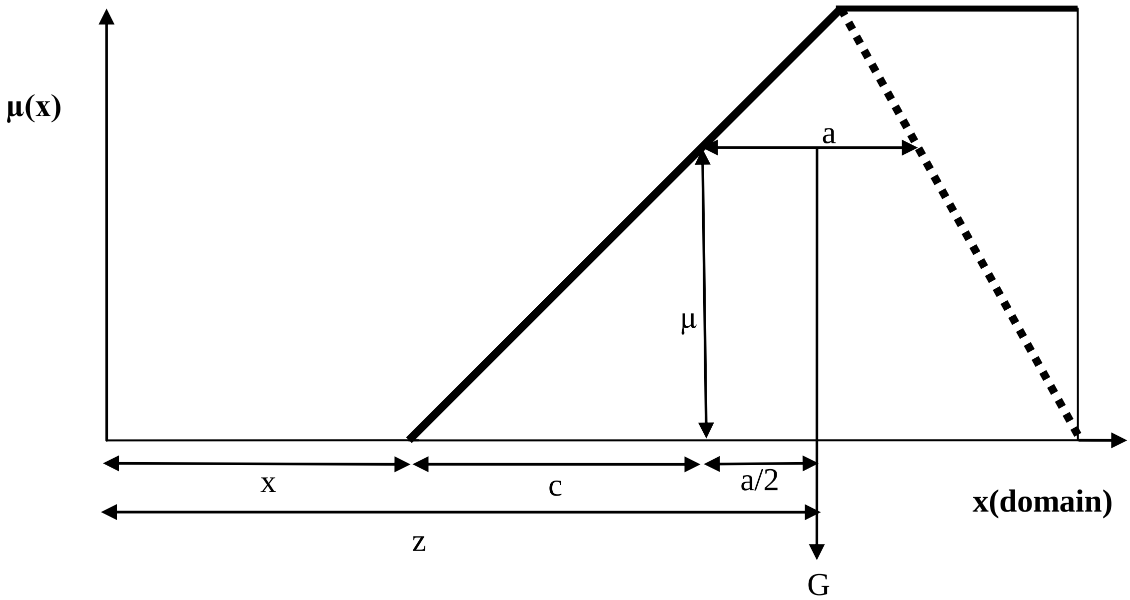


Figure 3.24 Schematic demonstration of notations used in defuzzification process

Each *z* in low, medium, medium-high and high area in Figure 3.23 is calculated and the defuzzification result is obtained by using equation 3.6.

$$\frac{(0.40 \times 20.3 + 0.70 \times 49.7 + 0.30 \times 65.7 + 0.60 \times 81.2)}{0.40 + 0.70 + 0.30 + 0.60} = 55.7 \quad (3.6)$$

For each contaminated site, this procedure is applied for different groups of parameters changing according to contaminant type groups. If there is more than one contaminant in the contaminated site, the user should run the system separately and get the site score for each contaminant. Highest score should be considered as the ranking score.

CHAPTER 4

SOFTWARE DEVELOPMENT

The currently used methodologies for the contaminated site usually lack a user-friendly interface needed for easy implementation of the ranking process. The users generally need to do calculations during the data entry, which is considered a major inconvenience from the users' standpoint. This can lead to additional misevaluation of the contaminated sites.

Fuzzy set theory used in the developed RPRS requires many calculations and takes considerable time to obtain a result, especially for system like RPRS, which have relatively large number of parameters. Therefore, a fuzzy expert system used in RPRS has been developed using the Microsoft Office Excel 2007 to decrease the workload of the users during data processing and data entry. Moreover, by the help of developed tool, it is aimed to make all calculations and assessments error free. The software developed in Excel is called Contaminated Sites Remedial Priority Ranking System, for short ConSiteRPRS.

Moreover, in RPRS, there are some bulk parameters defined as a function of (i.e., depend on) one or more of the 31 parameters. To illustrate, physical-chemical-parameters of the contaminant are contaminant specific. However, not all of them are used for every contaminated site evaluation. Therefore, to ease the user work, ConSiteRPRS does not ask the irrelevant parameter values. For example, when the user selects the contaminant, relevant physical-chemical contaminant parameters are automatically assigned from the database and this allows the user to enter less input data. 354 chemicals are listed in the database with their physical-chemical properties in ConSiteRPRS. Furthermore, the contamination area parameter is required only if the contaminant volume is unknown. The system does not require area parameter, if the user enters a contaminant volume. By this way, the number of parameters that the user should enter is minimized.

The ConSiteRPRS is composed of 10 workbooks. The fist one is the input sheet. Seven of them are for the possible contamination groups varying according to the contaminant type as mentioned in Section 3.2.1.2. Another sheet is used as the database of RPRS including chemicals and numerical values of their properties, and the literal expressions used for *combo boxes* used in input sheet. The final sheet is the result sheet showing all values of parameters used in evaluations and the ranking result between 8 and 100.

4.1 Input Sheet

The Inputs sheet of the RPRS has been designed for the users to enter the crisp values or literal expressions of the parameters. There are 22 entries in the input sheet, 8 of which are for the parameters having literal expressions and 14 of which are for the parameters having numerical values. The form of the input sheet is shown in Table 4.1.

Table 4.1 Input parameters form of the RPRS.

Parameter	Value		
Contaminated Media	◊ Soil	◊ Groundwater	◊ Soil & groundwater
Contaminant Name	crisp value		
Free Phase	◊ Yes		◊ No
Volume of Source (m^3)	crisp value		
Area of Contamination (m^2)	crisp value		
Soil Drainage Type	◊ Poorly	◊ Moderately	◊ Well
Vadose zone porosity	crisp value		
Water Content	crisp value		
Depth to Contamination (m)	crisp value		
Surface Cover Type	◊ Bare	◊ Grass	◊ Pavement
Aquifer Type		◊ Unconfined	◊ Confined
Land Use	◊ Industrial, Commercial or Nature	◊ Agricultural, Sylvan or Orchard	◊ Residential, Schools or Parks
Distance to Receptors (m)	crisp value		
Precipitation (mm/year)	crisp value		
Soil organic-carbon fraction	crisp value		
Distance between	crisp value		
Saturated Zone Hydraulic	crisp value		
Hydraulic Gradient	crisp value		
Aquifer organic-carbon fraction	crisp value		
Distance to Well (m)	crisp value		
Groundwater Use (Quality)	◊ Low	◊ Irrigation or Industrial Quality	◊ Drinking Quality

The users select the inputs having literal expressions via combo boxes. These combo boxes have been generated by using the Form Control feature of Excel. Seven combo boxes contain 3 choices, however, combo box containing contaminant name includes 354 choices.

The ConSiteRPRS does not display the cells of the parameters that are irrelevant for the contamination. That is, the user does not need to enter the values of all parameters; the user enters only the values of relevant parameters. According to the answer given for the contaminated media, contaminant type or the existence of free phase, the values of parameters not relevant for the evaluation are not asked to the user, which is implemented by means of conditional formatting feature of the Excel. In the cells of those parameters, the conditions have been written and when the conditions are met, the relevant parameter cell is colored in black in order not to be seen by the user.

The system completes the evaluation simultaneously with the work of entering the inputs. A macro has been recorded and assigned to a button named “RUN” in the input sheet. When this button is pressed, the result sheet is shown to the user.

4.2 Contaminant Type Sheets

As discussed earlier there are seven possible contaminant types in soil or groundwater media: SOC, SNVIC, SVIC, DNAPL, LNAPL, GDOC and GIC. The fuzzy expert system has been embedded in each contamination type sheet.

The input values of the parameters are fuzzified in the related contamination sheet by the membership functions of the parameters that are readily formulated in the sheets. Table 4.2 shows the view in ConSiteRPRS for the parameters *Toxicity of Contaminant* and *Contaminant Quantity*. The membership functions of the parameters having literal expression like *toxicity of contaminant* in Table 4.2 are considered as if they are crisp function since they have just three possible answers. Therefore, the result of membership function of *toxicity of contaminant* parameter can be either 1 or 0 for linguistic variables.

Table 4.2 A view of fuzzified parameters in ConSiteRPRS

Toxicity of Contaminant						**Value**			LOW	0
						Medium-concern contaminant			MEDIUM	1
									HIGH	0
Contaminant quantity										
						Value			LOW	0.52
LOW		**MEDIUM**		**HIGH**		**24.5**			MEDIUM	0.48
0	1	10	0	40	0				HIGH	0
10	1	40	1	90	1					
40	0	40	1	100	1					
		90	0							
A	-0.025	**A1**	0.025	**A**	0.025					
B	1.25	**B1**	-0.25	**B**	-1.25					
		A2	-0.025							
		B2	2.25							

The shape of the membership functions, as mentioned earlier, has been selected as triangular so that the evaluation becomes easier. Let us consider the parameter of *Toxicity of Contaminant* and *Contaminant Quantity* in Table 4.2 and membership function of *Contaminant Quantity* in Figure 4.1.

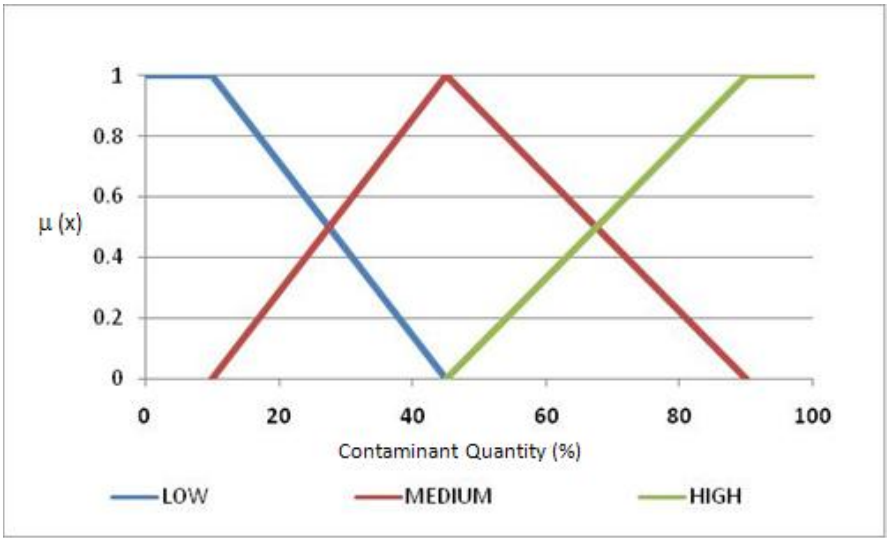


Figure 4.1 Membership function of Contaminant quantity

There are three linguistic variables (Low, Medium and High) in the membership function of *Contaminant Quantity*. Table 4.2 shows the parameter values and corresponding membership degrees at the boundaries and corner points of each subset of *Low*, *Medium* and *High*. Moreover, the letters (A, B, A1, B1, A2 and B2) in Table 4.2 are the coefficients in the sloping functions (y = Ax + B) of subset *Low*, *Medium* and *High* in the membership function of *Contaminant Quantity* parameter. These coefficients are used to make fuzzification of the crisp values of the parameters. The results of the fuzzifications are shown at the right hand side of Table 4.2. Moreover, the *Toxicity of Contaminant* is one of the parameters described by literal expressions. The value of *Toxicity of Contaminant* is shown as a "Medium concern contaminant" in Table 4.2, therefore, the linguistic variable is *Medium* and the fuzzy value of the parameter is assigned 1. The crisp value of *Contaminant Quantity* is 24.5 and the corresponding fuzzy values are 0.52 for *Low* set, 0.48 for *Medium* set and 0 for *High* set.

Figure 4.1 shows the subsets *Low*, *Medium* and *High* in the membership function of the *Contaminant Quantity* parameter. If the value of *Contaminant Quantity* is between 0 and 10, the corresponding membership degree is 1 for the *Low* set. If the value increases from 10 to 40, then the membership degree gradually decreases to 0. The membership degree of *Medium* set increases from 0 to 1 when the value changes from 10 to 40, and decreases from 1 to 0, when the value changes from 40 to 90. The membership degree becomes 1 only when the parameter value is 40 as seen in Figure 4.1. For the *High* set, membership degree increases from 0 to 1 when the value changes from 40 to 90, and it becomes 1 no matter what the value is in between 90 and 100.

The obtained fuzzified values of *Toxicity of Contaminant* and *Contaminant Quantity* parameters are inferred according to fuzzy rules. All possible fuzzy rules for two or three parameter groups have been listed on the contaminant type sheets in ConSiteRPRS. For example, there are 9 possible fuzzy rules for parameters of *Toxicity of Contaminant* and *Contaminant Quantity* as seen in Table 4.3. Again with the help of Excel functions, the related rules are operated. The capital letters in Table 4.3 refer to the linguistic variables: Very Low (VL), Low (L), Low Medium (LM), Medium (M), Medium High (MH), High (H) and Very High (VH). The first row of Table 4.3 shows the number of the rules. The second row is for the first parameter (*Toxicity of Contaminant* for this case) and third row for the second parameter (*Contaminant Quantity* for this case). The fourth row is for the outputs variables of the fuzzy rules. The membership degrees of *Toxicity of Contaminant* is written in the fifth row by the system in the related cells (for this case the fourth, fifth and sixth columns of the fifth row are filled with 1 due to medium-concern contaminant and the others are filled with 0.). The membership degree of *Contaminant Quantity* is written in the sixth row by the system in the related cells (for this case the all cell other than ones having H in third column are filled with the membership degrees, 0.52 for L and 0.48 for M). Therefore, two rules, shown in Table 4.3, among the nine are valid for this case and the calculations related to these two rules are calculated as seen in Table 4.3. As described in Section 3.1.5.4, μ is the membership degree, *z* is the distance between the origin and center of maxima in the related linguistic variable, *a* and *c* is the necessary length used for the calculation of *z*, and finally *r* is the defuzzification result.

Table 4.3 An evaluation part of ConSiteRPRS

1		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
2		L	L	L	M	M	M	H	H	H
3		L	M	H	L	M	H	L	M	H
4		**VL**	**L**	**LM**	**LM**	**M**	**MH**	**M**	**H**	**VH**
5	Toxicity of Contaminant	0	0	0	1	1	1	0	0	0
6	Contaminant quantity	0.52	0.48	0	0.52	0.48	0	0.52	0.48	0
7	μ	0	0	0	0.76	0.74	0	0	0	0
8	a	0	0	0	7.26	8.25	0	0	0	0
9	c	**0**	**0**	**0**	**9.85**	**12.62**	**0**	**0**	**0**	**0**
10	z	0	0	0	33.48	49.74	0	0	0	0
11	μ*z	0	0	0	25.38	36.91	0	0	0	0
12	r	41.5								

After this step, the progress continues to obtain the parameter that is at one of the upper levels (third, second or first level described in Section 3.2.2). The parameter of *Source*, an upper level parameter for this case, is obtained by *Toxicity of Contaminant* and *Contaminant Quantity*. The sheets also contain the value range of those parameters as seen in Table 4.4. To have a more reliable result and be able to distinguish between all different sites, seven levels of risk class are used in RPRS. These are Very Low (VL), Low (L), Low Medium (LM), Medium (M), Medium High (MH), High (H) and Very High (VH).

Table 4.4 A view for defuzzified parameters in ConSiteRPRS

	VERY LOW			**LOW**			**LOW-MEDIUM**			
	0	0		8	0		20	0		
	8	1		20	1		33	1		
	8	1		20	1		33	1		
	20	0		33	0		50	0		
MEDIUM			**MEDIUM-HIGH**			**HIGH**			**VERY HIGH**	
33	0		50	0		65	0		82	0
50	1		65	1		82	1		95	1
50	1		65	1		82	1		95	1
65	0		82	0		95	0		100	0

The related cells have been written necessary formulations, described in Section 3.1.5.4, to obtain the values of z. For the eighth, ninth and tenth rows in Table 4.3, the values in Table 4.4 are used to find the results of fuzzy expert system. When the values of z are found by the system, the defuzzification progress is applied. The last two rows in Table 4.3 are for the defuzzification process. Finally, the value of r is the result of the fuzzy expert system. That is, for the example case, the value of *Source* parameter evaluated from the input values of *Toxicity of Contaminant* and *Contaminant Quantity* is obtained as 41.5 out of 100.

For each contaminated site, this procedure is applied for 39 different groups of parameters, last of which is to obtain the final result.

To decrease the workload of the system, not all similar calculations are formulized in each contamination type. The SOC sheet contains all formulas, and fuzzification results of the same groups of parameter are taken from SOC sheet for the others.

4.3 Database Sheet

As mentioned in Section 3.2, properties of chemicals are stored in this database sheet. There are 354 chemicals with their physical-chemical properties and the references of the information are included in the sheet. Moreover, the literal expressions used in combo boxes in the input sheet are stored in this sheet.

The properties of the chemicals have been obtained from different sources. The Risk Assessment Information System (RAIS, 2009) has been used for the parameters of organic carbon partition coefficient, solubility and soil water partition coefficient. Moreover, Pennsylvania Department of Environmental Protection (PDEP, 2009) has been used for the parameters of vapor pressure, Henry's Law Constant and density. Furthermore, some currently used methodologies namely NRS (MDEP, 2007), MIFO (SEPA, 2002), ISM (IDEM, 1987), RSS (PDP, 2001) and AHMR (ADEC, 2003) have been used for the toxicity parameters of the chemicals.

4.4 Result Sheet

The result sheet shows the final score of the evaluation, all parameters and their values used for the evaluation. The values are taken from input and database sheets. When the user enters a value for a parameter in input sheet, it is directly seen in result sheet in related cell by the feature of Excel.

The result sheet also shows the final score of the evaluation. There are 12 possible contamination situations for the results. A formula has been generated by using contaminated media (soil, groundwater and soil&groundwater), contaminant type (organic and inorganic) and type of free phase (LNAPL and DNAPL) to show the result related with the contamination situation. If both contamination medias are considered as contaminated for a contaminated site, the *Final Score* is obtained by summing the scores coming from both media and multiplying a coefficient to normalize the maximum *Final Score* to 100. The formula is given in equation 4.1.

$$\left[(SS + GwS) \times \frac{5}{190}\right] + max(SS, GwS) \tag{4.1}$$

where SS = Soil Pathway Score
GwS = Groundwater Pathway Score

CHAPTER 5

CASE STUDY APPLICATIONS

A variety of contaminated site cases was investigated using the Remedial Priority Ranking System. Before the implementation of the case study applications, a sensitive analysis is made for a better understanding of the result of the case study applications.

5.1 Analysis of Sensitive Parameters

RPRS has 4 level of parameters (first, second, third and forth) as discussed in Section 3.2.2. Forth level parameters compose third level parameters, third level parameters compose second level parameters, second level parameters compose first level parameters and first level parameters are used to obtain final ranking score after the application of fuzzy expert system for each. Some parameters are directly assigned as the third, second or first level parameters. For example, there are 9 parameters that are directly assigned as the first level parameters; *Depth to Contaminated Zone, Surface Cover Type, Land Use, Distance to Receptors, Aquifer Type, Groundwater Use, Depth to Aquifer, Solubility* and *Free Phase* as seen in Figure 3.15. Moreover, the parameters of *Toxicity of Contaminant, Volume of Contaminant* and *Area of the Contaminated Site* have an exception. These compose *Source* parameter and the changes in their values make a big effect in the ranking result, that is, these parameters are most sensitive parameters in RPRS. Actually, the sensitivity of a parameter increases from forth level to first level and *Toxicity of*

Contaminant, Volume of Contaminant and *Area of the Contaminated Site* are more sensitive than the first level parameters in overall ranking score.

In order to have a more reliable ranking, the user should know the most sensitive parameters other than *Toxicity of Contaminant, Volume of Contaminant* and *Area of the Contaminated Site* in each contamination type in RPRS.

For SOC and SVIC, *Land Use*, *Distance to Receptors*, *Travel Time in Unsaturated* and *Saturated Zones*, *Aquifer Type* and *Groundwater Use* have similar sensitivities on the ranking result. If the ratio of change in their values is the same, the score becomes also the same. This is because those parameters are applied to fuzzy inference process with one parameter, that is, they are all in two-group parameters. Although the parameters of *Volatilization, Depth to Contaminated Zone* and *Surface Cover Type* in SOC are the first level parameters, they are less sensitive since they are in three-group parameter.

The parameters of *Travel Time in Unsaturated* and *Saturated Zones, Aquifer Type* and *Groundwater Use* are the more sensitive parameters in SNVIC. *Land Use, Distance to Receptors, Travel Time in Saturated Zone, Groundwater Use, Solubility* and *Free Phase* are in LNAPL*, Solubility, Free Phase, Travel Time in Saturated Zone* and *Groundwater Use* are in DNAPL, *Solubility* in GDOC, and *Travel Time in Saturated Zone* and *Groundwater Use* in GIC are the more sensitive parameters.

For example, tables below show two cases having the same values for parameters except one of the most sensitive parameter, *Contaminant Volume*. As seen from Table 5.1 and 5.2 the *Volume of Contaminant* is 9 m^3 for one case and 3 m^3 for the other one.

Table 5.1 Sensitive analysis case with 9 m^3 contaminant volume

Parameter	Value
Contaminated Media	Soil
Contaminant	Heptachlor
Volume of Contaminant (m^3)	9
Soil Type	Moderately Drained
Vadose Zone Porosity (%)	0.245
Water Content (%)	0.15
Depth to Contamination (m)	3.4
Surface Cover Type	Pavement
Aquifer Type	Unconfined
Land Use	Residential
Distance to Receptors (m)	150
Precipitation (mm/yr)	830
Organic Carbon Content (soil)	0.02
Distance between Contamination and Aquifer	20
Saturated Zone Hydraulic Conductivity (m/s)	0.0025
Hydraulic Gradient (%)	0.00035
Organic Carbon Content (groundwater)	0.002
Nearest Distance to Wells (m)	1250
Groundwater Use	Drinking Quality

Table 5.2 Sensitive analysis case with 3 m^3 contaminant volume

Parameter	Value
Contaminated Media	Soil
Contaminant	Heptachlor
Volume of Contaminant (m^3)	3
Soil Type	Moderately Drained
Vadose Zone Porosity (%)	0.245
Water Content (%)	0.15
Depth to Contamination (m)	3.4
Surface Cover Type	Pavement
Aquifer Type	Unconfined
Land Use	Residential
Distance to Receptors (m)	150
Precipitation (mm/yr)	830
Organic Carbon Content (soil)	0.02
Distance between Contamination and Aquifer	20
Saturated Zone Hydraulic Conductivity (m/s)	0.0025
Hydraulic Gradient (%)	0.00035
Organic Carbon Content (groundwater)	0.002
Nearest Distance to Wells (m)	1250
Groundwater Use	Drinking Quality

In the first case, the ranking result is obtained as 76.7 and in the second case, the result is 70.0. However, when the value of another parameter, at the lower level, is changed, the difference is not as much as in the contaminant volume case. The value of the parameter of *Distance to Receptor* is chosen as 150 m and 270 m. The change in the value of parameter is done according to the change in the value of *Contaminant Volume*. The corresponding values are 76.7 and 76.3. Consequently, it is seen easily from the results that the *Contaminant Volume* is more sensitive than the *Distance to Receptors* as expected.

5.2 Hypothetical Cases Study Application of ConSiteRPRS

ConSiteRPRS can assign scores to contaminated sites between 8 and 100. It is expected from the ConSiteRPRS that it should differentiate the cases, as it should be. Two hypothetical cases are generated and they are evaluated in the ConSiteRPRS to test that. Table 5.3 shows the values of the parameters of the hypothetical cases. These cases are designed so that the severities of contamination cases are significantly different although the toxicities of contaminants are similar. Yet, the parameter values that define the fate and transport characteristics create the difference in the severity of contamination. In this sense, it is expected that the ranking scores obtained by ConSiteRPRS would be significantly different.

Table 5.3 Parameter values of two hypothetical cases

Parameter	Values of Case 1	Values of Case 2
Contaminated Media	Soil&Groundwater	Soil
Contaminant	Acrylonitrile	Benzo(a)pyrene
Free Phase	Yes	-
Volume of Contaminant (m^3)	7.5	2
Soil Type	Moderately Drained	Poorly Drained
Vadose Zone Porosity (%)	0.5	0.5
Water Content (%)	0.1	0.2
Depth to Contamination (m)	0.5	2
Surface Cover Type	Grass	Bare
Aquifer Type	Unconfined	Confined
Land Use	Residential	Agriculture
Distance to Receptors (m)	50	250
Precipitation (mm/yr)	750	500
$f_{oc\ soil}$	0.01	0.03
Distance between Contamination and Aquifer (m)	4	8
Saturated Zone Hydraulic Conductivity (m/s)	0.0005	0.00001
Hydraulic Gradient (%)	0.0008	0.0001
$f_{oc\ aquifer}$	0.001	0.003
Nearest Distance to Wells (m)	950	2150
Groundwater Use	Drinking Quality	Low Quality

The ranking scores are 94.5 and 48.3 for case 1 and case 2, respectively. When the parameter values of the cases are compared, it is seen that case 1 is more severe than case 2. Almost all values of the parameters in case 1 are at the higher risk level. While the contamination in case 1 can easily reach to receptors through air and groundwater with a high amount, it takes a long time to reach to receptors in case 2 since there is, for example, one possible exposure route to follow. Another case is applied such that the highly toxic contaminant benzo(a)pyrine in case 2 is replaced by a less toxic Biphenyl. In this case the ranking score decrease to 21.7, which shows that ConSiteRPRS can differentiate clearly between different cases of varying severity.

5.3 Real Case Study Applications

A real case study application could be better to accept the ConSiteRPRS one of methodologies for evaluation of contaminated sites. Seven contaminated site cases from Netherlands and Turkey have been tested with RPRS. Six cases, namely Katwijk Furniture Factory, Katwijk Municipal Dump Site, Oostflakkee Dump Site, Dry Cleaner, Lead Paint Factory and Electric Tram Company, are from the Netherlands and seventh one, namely Incirlik Air Base, is from Turkey. The authorities had decided to apply remedial actions when these cases have become a problem for the environment. The risk levels of the cases were not known but the importance order of the cases is designated by the help of the experts. Therefore, the obtained results from the ConSiteRPRS can be compared to each other. The names, countries and importance sequences, designated by experts, of the contaminated site cases are given in Table 5.3.

Table 5.3 Importance order of contaminated sites

Case	Country	Importance order
Incirlik Air Base	Turkey	1
Katwijk Municipal Dump Site	The Netherlands	2
Dry Cleaner	The Netherlands	2
Lead Paint Factory	The Netherlands	2
Electric Tram Company	The Netherlands	3
Oostflakkee Dump Site	The Netherlands	4
Katwijk Furniture Factory	The Netherlands	5

The Incirlik Air Base case from Turkey is detected as the most hazardous case and the Katwijk Furniture Factory case from the Netherlands is detected as the least hazardous. However, the experts had a difficulty to separate Katwijk Municipal Dump Site, Dry Cleaner, and Lead Paint Factory since they are so close cases that it is difficult to rank them without a model or tool. The summary of the contamination in each case and related parameters used in the ConSiteRPRS are given in the following sections.

5.3.1 Katwijk Furniture Factory

A Furniture Factory located in Katwijk had some tanks containing mineral oil used in the factory. The owner of the factory decided to remove one of the old tanks under the ground. However, there were problems of odor and color near the site where the tank was. Thinking that there could be some negative effects, the owner decided to apply a consultant to investigate the site and an investigation started. Result of the investigation was that the site did not have serious soil pollution problem. Therefore, there was no need to do further investigation. However, when the tank was removed, it was seen that the tank was leaking and the soil near the site was contaminated. Therefore, exploratory investigation stage of the Netherlands soil management system was applied at the site. At the end of the investigation, it was concluded that the site needed remediation and remediation works were started (Büyüker and Polat, 2009).

The parameters and their values are given in Table 5.4 for the case. Benzene is one of the contaminant in the contaminated area. It is used in the assessment of the case since it is the most dangerous contaminant in the contaminated area. The ConSiteRPRS ranking score for Katwijk Furniture Factory is calculated as 52.4 out of 100 when the values of parameters in Table 5.4 are entered into the input sheet of ConSiteRPRS. The result sheet of the case is given in Figure 5.1.

Table 5.4 Parameter values of Katwijk Furniture Case

Parameter	**Value**
Contaminated Media	Soil
Contaminant	Benzene
Area of Contamination (m^2)	3000
Soil Type	Well Drained
Vadose Zone Porosity (%)	0.3
Water Content (%)	0.275
Depth to Contamination (m)	0.1
Surface Cover Type	Grass
Aquifer Type	Confined
Land Use	Industrial
Distance to Receptors (m)	100
Precipitation (mm/yr)	750
Organic Carbon Content (soil)	0.02
Distance between Contamination and Aquifer (m)	20
Saturated Zone Hydraulic Conductivity (m/s)	0.001
Hydraulic Gradient (%)	0,00001
Organic Carbon Content (groundwater)	0,002
Nearest Distance to Well (m)	5000
Groundwater Use	Low Quality

CONTAMINATED SITES REMEDIAL PRIORITY RANKING SYSTEM RESULT SHEET

				INPUTS	UNIT	REFERENCES
CONTAMINATED MEDIA				Soil		
CONTAMINANT NAME				Benzene		
CONTAMINANT TYPE				Organic		
FREE PHASE						
DENSITY OF CONTAMINANT					kg/L	Pennsylvania
SOURCE	Contamination/Contaminant Quantity		Toxicity of Contaminant	High concern contaminant		NRS
			Area of Contamination	3000.00	m^2	
			Volume of Source	unknown	m^3	
AIR PATHWAYS	Volatilization		Vapor Pressure	9.480E+01	mm Hg	Pennsylvania
			Henry's Law Constant			Pennsylvania
			Vadose Zone Porosity	0.3		
			Water Content	0.275		
			Air Content	0.025		
			Depth to Contamination	0.1	m	
			Surface Cover Type	Grass		
			Depth to Aquifer		m	
			Aquifer Type	Confined		
AIR RECEPTORS			Land Use	Industrial		
			Distance to Receptors	100	m	
GROUNDWATER PATHWAYS	Travel time in Vadose Zone (year)	Infiltartion Rate (m/year)	Precipitation	750	mm	
			Surface Cover Type	Grass		
			Soil Type	Well Drained		
		Retardation	Koc	1.660E+02	L/kg	RAIS
			$f_{oc\ soil}$	0.02		
			Distance between Contamination and Aquifer	20	m	
			Aquifer Type	Confined		
			Solubility		mg/L	RAIS
GROUNDWATER RECEPTORS	Travel time in Saturated Zone (year)	Groundwater Velocity (m/year)	Saturated Zone Hydraulic Conductivity	1.000E-03	m/s	
			Hydraulic Gradient	1.000E-05		
		Retardation	Koc	1.660E+02	L/kg	RAIS
			$f_{oc\ groundwater}$	0.002		
			Nearest Distance to Wells	5000	m	
			Kd		L/kg	RAIS
			Groundwater Use	Low Quality		
			FINAL SCORE	**52.4**		

Figure 5.1 Evaluation result sheet of the Katwijk Furniture case

5.3.2 Katwijk Municipal Dump Site

Katwijk Municipal Dump Site was a huge dumping site with 4 hectares of surface area and 20 meters of depth. Any kind of municipal and chemical wastes are dumped in the site during 1960s and 70s. The site was investigated in 1982 within the context of general investigation procedure for old dump sites in the Netherlands. It was concluded that there was groundwater contamination both inside and outside the site boundaries. Most important contaminant was benzene besides xylene and naphthalene. However, although there was a serious contamination, the authorities decided to take action according to the development and land use. When Katwijk municipality decided to use the site for sport facilities, they decided to take action. Nowadays, discussions on the solution for remediation and use of the site are going on (Büyüker and Polat, 2009). Related parameter values of the site are given in Table 5.5.

Table 5.5 Parameter values of Katwijk Municipal Dump Site Case

Parameter	Value
Contaminated Media	Groundwater
Contaminant	Benzene
Free Phase	No
Area of Contamination (m^2)	40,000
Saturated Zone Hydraulic Conductivity (m/s)	0.001
Hydraulic Gradient (%)	0,0001
Organic Carbon Content (groundwater)	0,002
Nearest Distance to Wells (m)	3000
Groundwater Use	Low Quality

The ConSiteRPRS ranking score of Katwijk Municipal Dump Site is obtained as 71.2 out of 100. The parameters values used for the evaluation of the site are given in Table 5.5.

5.3.3 Oostflakkee Dump Site

While digging a backyard in a residential area, waste material and color change were discovered. After historic investigation, they found out that all kind of wastes from the old harbor close to the site was dumped there both before and after the demolition. Harbor mud, soil, sewage sludge and any kind of household wastes were present at the site. There were many houses and gardens on the contaminated site, which were investigated separately. After investigations, lead was determined to be the most important contaminant in addition to zinc and copper. The lead concentrations exceeded the Dutch intervention value, which is used to determine the seriousness of soil contamination, and after determination of urgency, the site was decided to be remediated immediately, because children were exposed to lead with soil ingestion and plant uptake. However, due to lack of money, the remediation was delayed. They ensured that there was no direct contact with contaminated soil and they started further investigation for plant uptake. According to further investigation, a site specific intervention value was calculated for lead. When this intervention value was considered, the contamination was not serious (risks were acceptable). The authorities decided not to remediate but they promised inhabitants to take all necessary measures and to remediate the site whenever it is possible (Büyüker and Polat, 2009). Information about the site is given in Table 5.6.

Table 5.6 Parameter values of Oostflakkee Dump Site Case

Parameter	Value
Contaminated Media	Soil
Contaminant	Lead
Area of Contamination (m^2)	8,000
Soil Type	Poorly Drained
Surface Cover Type	Grass
Aquifer Type	Confined
Precipitation (mm/yr)	850
Distance between Contamination and Aquifer (m)	20
Saturated Zone Hydraulic Conductivity (m/s)	0.00001
Hydraulic Gradient (%)	0,0001
Nearest Distance to Wells (m)	3000
Groundwater Use	Low Quality

The ConSiteRPRS ranking score of Oostflakkee Dump Site having values of parameters in Table 5.6 is evaluated as 56.6 out of 100.

5.3.4 Dry Cleaner

The Dry cleaner was in an urban area and the investigations started due to the complaints of odor from people living around. Waste chemical (trichloroethylene) was being dumped in the backyard of the dry cleaner for many years. Moreover, wastewater was being discharged to sewer and PVC pipes were destructed. During visual inspection, strong odor of TCE has realized and they have seen a thin layer of waste in the backyard. In preliminary investigation, soil and groundwater samples were taken. High concentrations of trichloroethylene and tetrachloroethylene were present, especially in groundwater. The next step was to carry out further investigation in order to determine the distribution of contamination. Due to impermeable peat layer and since the amount (weight) of NAPL was not heavy enough, contaminant could not reach to sandy aquifer; that is 29 meter down from ground surface. Moreover, due to natural characteristics, groundwater was not used in that region. Therefore, the most important exposure pathway to consider was 'inhalation indoors'. Indoor air quality was analyzed in the houses, which are located above the contaminant plume. The concentrations were so high that they decided to take action immediately. However, since the area was highly urbanized, it was impossible to apply pump and treat. The final solution was to enhance biological degradation, which was already fast due to high organic matter content of peaty soil (Büyüker and Polat, 2009). Information about the site is given in Table 5.7.

Table 5.7 Parameter values of Dry Cleaner Case

Parameter	Value
Contaminated Media	Soil
Contaminant	Trichloroethylene
Area of Contamination (m^2)	12,000
Soil Type	Poorly Drained
Vadose Zone Porosity (%)	0.225
Water Content (%)	0.2
Depth to Contamination (m)	0.3
Surface Cover Type	Bare
Aquifer Type	Confined
Land Use	Residential
Distance to Receptors (m)	50
Precipitation (mm/yr)	840
Organic Carbon Content (soil)	0.02
Distance between Contamination and Aquifer (m)	29
Saturated Zone Hydraulic Conductivity (m/s)	0.00001
Hydraulic Gradient (%)	0,0001
Organic Carbon Content (groundwater)	0,002
Nearest Distance to Wells (m)	5000
Groundwater Use	Low Quality

The ConSiteRPRS ranking score of Dry Cleaner is obtained as 69.7 out of 100. Related parameters and their values used for the evaluation are given in Table 5.7.

5.3.5 Lead Paint Factory

24 lead paint factories were present in Rotterdam and all of them were closed in 1930s. One of them, at Oudedijk, was active between 1829 and 1902. In Oudedijk, horse manure, which was used as a source of sulfate and highly contaminated with lead, was being sold to farmers around the factory as fertilizer. During a big construction project in 1987, high lead contamination was discovered within the borders of the area of Oudedijk (10.000 mg/kg). Since the concentrations were so high that they decided to take action immediately and investigations were started (Büyüker and Polat, 2009).

Table 5.8 Parameter values of Lead Paint Factory Case

Parameter	**Value**
Contaminated Media	Soil
Contaminant	Lead
Area of Contamination (m^2)	12,000
Soil Type	Poorly Drained
Surface Cover Type	Pavement
Aquifer Type	Confined
Precipitation (mm/yr)	830
Distance between Contamination and Aquifer (m)	20
Saturated Zone Hydraulic Conductivity (m/s)	0.00001
Hydraulic Gradient (%)	0,0001
Nearest Distance to Wells (m)	5000
Groundwater Use	Low Quality

The ConSiteRPRS ranking score of Lead Paint Factory is evaluated as 70.7 out of 100. Table 5.8 shows the values of the parameters used for the evaluation.

5.3.6 Electric Tram Company

An electric tram company led to a contamination including benzo(a)pyrene. Municipality of Rotterdam was aware of contamination and they decided to investigate the site. There was an obvious contamination in soil that can be seen and smelled because of the activities such as cleaning with chlorinated materials and burning (Büyüker and Polat, 2009). Information about the site is given in Table 5.9.

Table 5.9 Parameter values of Electric Tram Company Case

Parameter	Value
Contaminated Media	Soil
Contaminant	Benzo(a)pyrene
Area of Contamination (m^2)	8,000
Soil Type	Well Drained
Vadose Zone Porosity (%)	0.4
Water Content (%)	0.2
Depth to Contamination (m)	0.5
Surface Cover Type	Pavement
Aquifer Type	Confined
Land Use	Industrial
Distance to Receptors (m)	50
Precipitation (mm/yr)	750
Organic Carbon Content (soil)	0.02
Distance between Contamination and Aquifer (m)	20
Saturated Zone Hydraulic Conductivity (m/s)	0.00001
Hydraulic Gradient (%)	0,0001
Organic Carbon Content (groundwater)	0,002
Nearest Distance to Wells (m)	5000
Groundwater Use	Low Quality

The ConSiteRPRS ranking score of Electric Tram Company is acquired as 59.3 out of 100. Parameters and values of parameters are given in Table 5.9.

5.3.7 Incirlik Air Base

The Old Defense Reutilization and Marketing (DRMO) Yard was in use since the early 1970s, and storage of waste oil drums containing polychlorinated biphenyls (PCB) oil was practiced. Several of the drums leaked PCB into the topsoil during storage and pickup activities. Yard activities were terminated at the end of 1988. An excavation about 0.5 meters deep was made in October 1991, leaving the excavated soil stored in approximately 300 steel drums and in a pile of soil on the site. Several investigations have been performed at the site previous to and following the excavation activities, to determine the extent of PCB contamination. Highest concentrations were found in the central portion of the Old DRMO Yard, a north-south oriented rectangular area (Law Environmental, Inc., 1997). Information about the site is given in Table 5.10.

Table 5.10 Parameter values of Incirlik Air Base Case

Parameter	**Value**
Contaminated Media	Soil
Contaminant	Polychlorinated Biphenyls
Volume of Contaminant (m^3)	1,585
Soil Type	Moderately Drained
Vadose Zone Porosity (%)	0.2
Water Content (%)	0.05
Depth to Contamination (m)	0.5
Surface Cover Type	Bare
Aquifer Type	Confined
Land Use	Industrial
Distance to Receptors (m)	300
Precipitation (mm/yr)	600
Organic Carbon Content (soil)	0.02
Distance between Contamination and Aquifer (m)	20
Saturated Zone Hydraulic Conductivity (m/s)	0.00001
Hydraulic Gradient (%)	0,0001
Organic Carbon Content (groundwater)	0,002
Nearest Distance to Wells (m)	300
Groundwater Use	Drinking Quality

The ConSiteRPRS ranking score of Incirlik Air Base is evaluated as 75.5 out of 100 when the values of parameters in Table 5.10 are entered into the input sheet of ConSiteRPRS and this becomes the highest score in the case study application. The result sheet of the Incirlik Air Base case is given in Figure 5.2.

CONTAMINATED SITES REMEDIAL PRIORITY RANKING SYSTEM RESULT SHEET

				INPUTS	UNIT	REFERENCES
CONTAMINATED MEDIA				Soil		
CONTAMINANT NAME				Polychlorinated Biphenyls		
CONTAMINANT TYPE				Organic		
FREE PHASE						
DENSITY OF CONTAMINANT					kg/L	Pennsylvania
SOURCE			Toxicity of Contaminant	High concern contaminant		MIFO
	Contamination/Contaminant Quantity		Area of Contamination		m^2	
			Volume of Source	1585	m^3	
AIR PATHWAYS	Volatilization		Vapor Pressure	8.630E-05	mm Hg	Pennsylvania
			Henry's Law Constant			Pennsylvania
			Vadose Zone Porosity	0.2		
			Water Content	0.05		
			Air Content	0.15		
			Depth to Contamination	0.5	m	
			Surface Cover Type	Bare		
			Depth to Aquifer		m	
			Aquifer Type	Confined		
AIR RECEPTORS			Land Use	Industrial		
			Distance to Receptors	300	m	
GROUNDWATER PATHWAYS	Travel time in Vadose Zone (year)	Infiltartion Rate (m/year)	Precipitation	600	mm	
			Surface Cover Type	Bare		
			Soil Type	Moderately Drained		
		Retardation	Koc	4.480E+04	L/kg	RAIS
			$f_{oc\ soil}$	0.02		
			Distance between Contamination and Aquifer	20	m	
			Aquifer Type	Confined		
			Solubility		mg/L	RAIS
GROUNDWATER RECEPTORS	Travel time in Saturated Zone (year)	Groundwater Velocity (m/year)	Saturated Zone Hydraulic Conductivity	1.000E-05	m/s	
			Hydraulic Gradient	1.000E-04		
		Retardation	Koc	4.480E+04	L/kg	RAIS
			$f_{oc\ groundwater}$	0.002		
			Nearest Distance to Wells	300	m	
			Kd		L/kg	RAIS
			Groundwater Use	Drinking Quality		
			FINAL SCORE	**75.5**		

Figure 5.2 Evaluation result sheet of the Incirlik Air Base case

5.3.8 Comparisons of Case Studies

The scores of ConSiteRPRS and the ranking order of contaminated site cases are shown in Table 5.11.

Table 5.11 Comparison of the ranking scores of contaminated site cases

Case	Ranking Score (out of 100)	Ranking Result
Incirlik Air Base	75.5	1
Katwijk Municipal Dump Site	71.2	2
Lead Paint Factory	70.7	3
Dry Cleaner	69.7	4
Electric Tram Company	59.3	5
Oostflakkee Dump Site	56.6	6
Katwijk Furniture Factory	52.4	7

According to the ranking score results, Incirlik Air Base Case is the most severe case. When the parameter values of each case are compared to each other to see which case should have the highest score due to the contamination level, it is obvious that Incirlik Air Base case should have the highest score because the most severe parameter (e.g. *Distance to Well*, *Groundwater Use* and *Contaminant Name*). are in that case (see Table 5.12). Another factor that makes the Incirlik case the most severe one is that the receptors can be affected from the contamination through both air and groundwater since the contaminant type is SOC.

Moreover, the receptors can be affected by the contamination through both air and groundwater in Dry Cleaner, Katwijk Furniture and Electric Tram cases. However, groundwater use and the proximity of the receptors to the used well are at the low risk levels for these cases.

Table 5.12 Comparison of the ranking scores of contaminated site cases

Parameters	Incirlik Air Base	Katwijk Dump site	Lead Paint	Dry Cleaner	Electric Tram	Oostflakkee Dump site	Katwijk Furniture
Contaminated Media	Soil	Gw	Soil	Soil	Soil	Soil	Soil
Contaminant Name	PCB	Benzene	Lead	TCE	Benzo(a)pyrene	Lead	Benzene
Area of Contamination	-	40000	12000	12000	8000	8000	3000
Volume of Source	1,585	Unknown	unknown	unknown	unknown	unknown	unknown
Soil Type	Moderately Drained	-	Poor Drained	Poor Drained	Well Drained	Poor Drained	Well Drained
Vadose Zone Porosity	0.2	-	-	0.225	0.4	-	0.3
Water Content	0.05	-	-	0.2	0.2	-	0.275
Depth to Contamination	0.5	-	-	0.3	0.5	-	0.1
Surface Cover Type	Bare	-	Pavement	Bare	Pavement	Grass	Grass
Depth to Aquifer	-	-	-	-	-	-	-
Aquifer Type	Confined	-	Confined	Confined	Confined	Confined	Confined
Land Use	Industrial	-	-	Residential	Industrial	-	Industrial
Distance to Receptors	300	-	-	50	50	-	100
Precipitation	600	-	830	840	750	850	750
$f_{oc\ soil}$	0.02	-	-	0.02	0.02	-	0.02
Distance between Contamination and Aquifer	20	-	20	29	20	20	20
Saturated Zone Hydraulic Conductivity	0.00001	0.001	0.00001	0.00001	0.00001	0.00001	0.001
Hydraulic Gradient	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.00001
$f_{oc\ aquifer}$	0.002	0.002		0.002	0.002		0.002
Distance to Wells	300	3000	5000	5000	5000	3000	5000
Groundwater Use	Drinking Quality	Low Quality	Low Quality	Low Quality	Low Quality	Low Quality	Low Quality
Final Score	**75.5**	**71.2**	**70.7**	**69.7**	**59.3**	**56.6**	**52.4**

Although, the Katwijk Municipal Dump Site case has only one way (groundwater) to affect the receptors, its score is higher than other five cases. The reason for high-ranking score is the contaminant, benzene, which is one of the high priority pollutants, and *Contaminant Quantity (Area of Contamination)*, which is at the very high level. Moreover, the *Groundwater Velocity* of the case moves faster than other cases. Therefore, these make the score higher for Katwijk Municipal Dump Site.

The third highest score is obtained for Lead Paint Factory case. The *Area of Contamination* is at a higher level for this case when compared to other three cases (except Dry Cleaner case). Dry Cleaner case also the same amount of area of contamination but TCE, contaminant of Dry Cleaner case, is less dangerous than Lead. Moreover, Oostflakke Dump site case also has the same contaminant with Lead Paint Factory case but the *Area of Contamination (having the higher weight in the evaluations)* of the Oostflakke case is less than Lead Paint Factory case.

The fourth highest score is obtained for Dry Cleaner case since *Surface Cover Type, Land Use, Distance to Receptors, Precipitation and Hydraulic Gradient* in the Dry Cleaner case are at the higher or at least similar risk level when compared to parameters in the left three cases. Although, there are some other parameters in the Dry Cleaner case whose values are at the lower risk level compared to those in other three cases (*Soil Type, Depth to Contamination and Hydraulic Conductivity*), these are not enough to make the score smaller since the weight of those parameter are smaller and the differences between the values in the evaluation are not so much.

The common parameters of the Electric Tram Company and Oostflakkee Dump Site cases are almost similar. However, there are two possible exposure pathway routes in the Electric Tram Company case with high risk level and Oostflakkee

Dump Site has one. Moreover, while the parameter of *Soil Type* of Electric Tram Company case is well drained and it is poorly drained for Oostflakkee Dump Site case. Therefore, these make score of Electric Tram Company case higher.

The Katwijk Furniture case is the least dangerous case since it has the smallest *Area of Contamination*. This parameter is enough to have such a low score since the parameter of *Area of Contamination* is one of the parameter having a high weight. In other words, as mentioned earlier, its parameter level is higher than the first level parameters. Therefore, Katwijk Furniture case becomes the least dangerous case.

When the results of the ConSiteRPRS and the experts' expectations are compared, the conformity of these results is seen. The most severe cases are the same for the evaluation results of the RPRS and decisions of the experts. Moreover, the least severe cases are designated in the same order, Oostflakkee Dump Site and Katwijk Furniture cases.

The experts were doubtful about the order of severity of three cases, Katwijk Municipal Dump Site, Dry Cleaner and Lead Paint Factory, and the results obtained from the ConSiteRPRS show that the scores of these cases are very close to each other as seen in Table 5.11. Therefore, it can be concluded from these case study applications that the RPRS gives results consistent with the experts' decisions.

CHAPTER 6

SUMMARY AND DISCUSSIONS

6.1. Summary and Conclusions

The number of the contaminated sites is high and it is almost impossible to clean all these sites due to remediation costs. Therefore, it is necessary to rank the contaminated sites and select the most risky ones. By this way, it may be possible to use the budget for cleaning process more effectively.

In this study, the Remedial Priority Ranking System has been developed as an alternative to existing priority ranking systems. The developed system takes vagueness in parameter values into account by means of fuzzy set theory. The uniqueness of this study is the conceptual model used to define the fate and transport of contaminants as well as the use of fuzzy set theory in ranking the remedial priority of contaminated sites.

The S-P-R linkage principle between the parameters is adopted in the developed system. In the RPRS, several comprehensive and readily available parameters are used for the evaluations, which enable the user to make the evaluation easily. The developed methodology is embedded into Microsoft Office Excel 2007 for easy implementation of the evaluation and providing an extensive database for chemical properties.

The developed system is applied to two hypothetical cases. One of the cases has a severe contamination with a very toxic contaminant and the other has not a severe contamination with a very toxic contaminant. The result shows that although the contaminants are very toxic, the site having severe contamination obtains very high ranking score (94.5) and the other one obtain a score considered not to be a high score (48.3). Therefore, ConSiteRPRS is able to differentiate the contaminated sites, as it should be.

Developed software, ConSiteRPRS, is also applied to several real contamination cases, the remedial priorities of which are already determined by the experts. The case study applications showed that remedial priority determined by the experts and obtained by ConSiteRPRS are in good agreement.

6.2 Recommendations for Future Studies

The developed system is a human health risk based system. However, ecological risk assessment can be included to the system since it is another important issue. Moreover, RPRS does not use some exposure pathways. It just considers exposure pathways transported through air and groundwater. Nevertheless, the exposure pathways transported through surface water or sediment can be included to the system.

Furthermore, developed system can be compared in systematic manner with the other currently used existing methodologies. By doing this, the performance of RPRS relative to other methods can be tested.

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APPENDIX A

MEMBERSHIP FUNCTIONS OF THE PARAMETERS IN RPRS

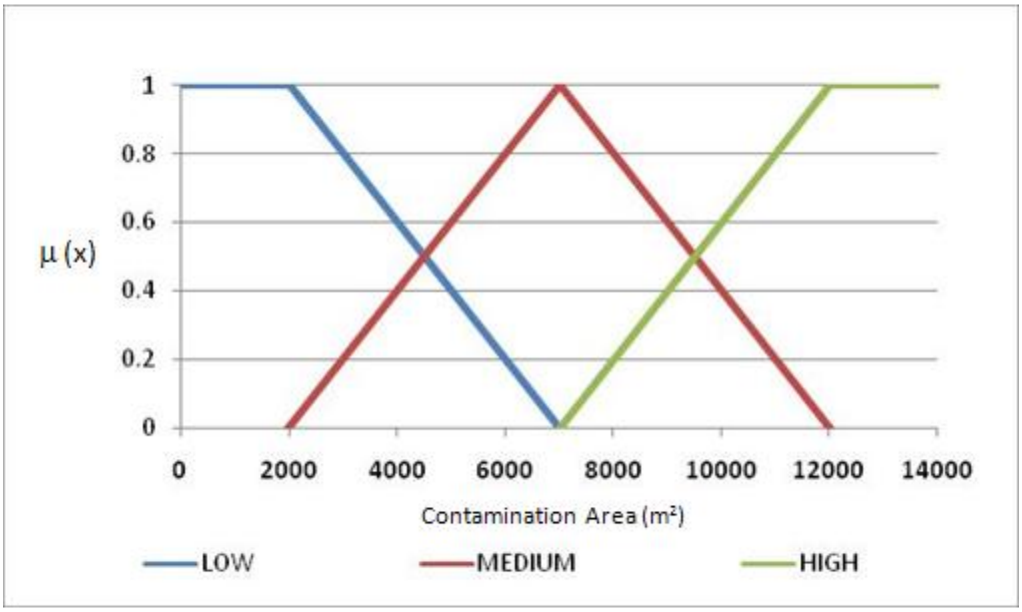

Figure A.1 Membership function of *Contamination Area* (m^2) for fuzzification

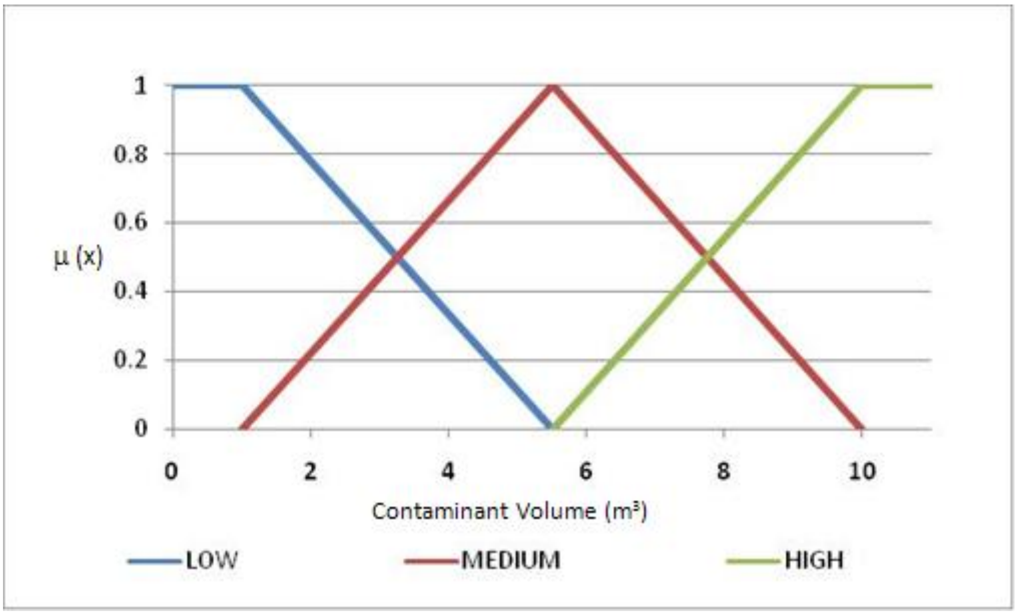

Figure A.2 Membership function of *Contaminant Volume* (m^3) for fuzzification

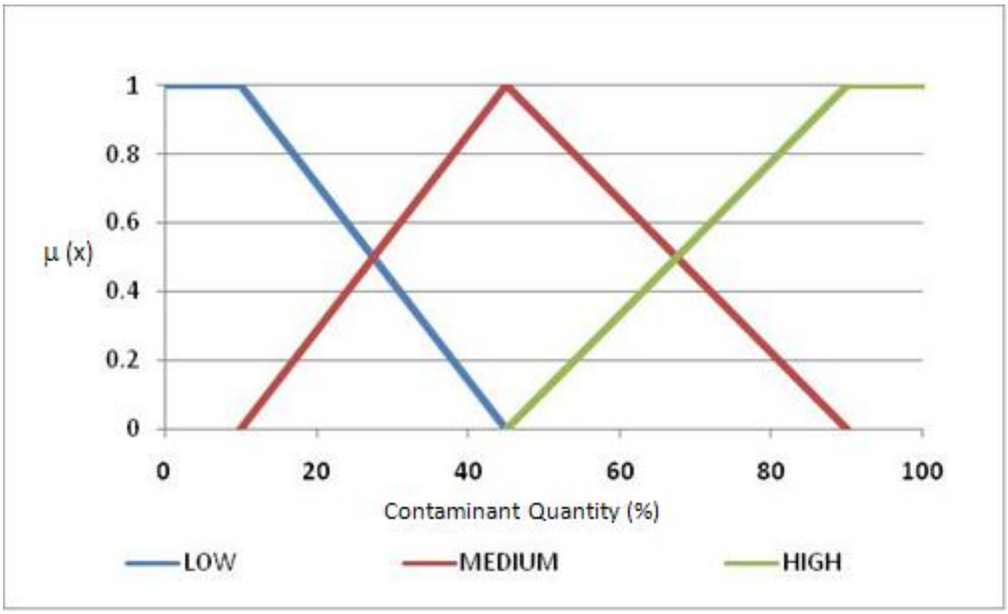

Figure A.3 Membership function of *Contaminant Quantity* for defuzzification

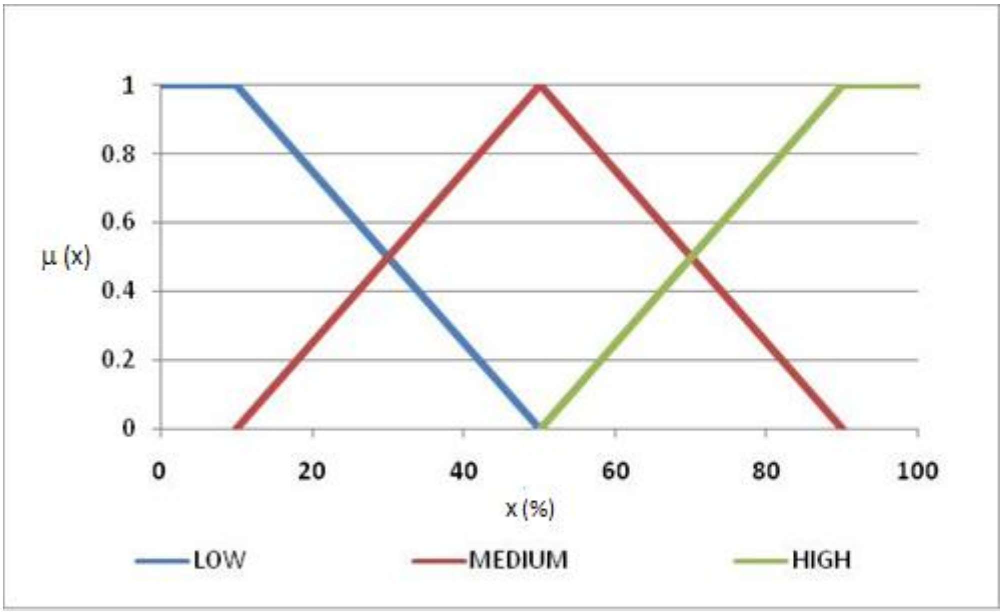

Figure A.4 Membership function of *Contaminant Quantity, Volatilization, Air Pathway, Air Receptor, Groundwater Pathway, Groundwater Receptor, Air Pathway&Receptor, Groundwater Pathway&Receptor, Source And Pathways&Receptors* for fuzzification

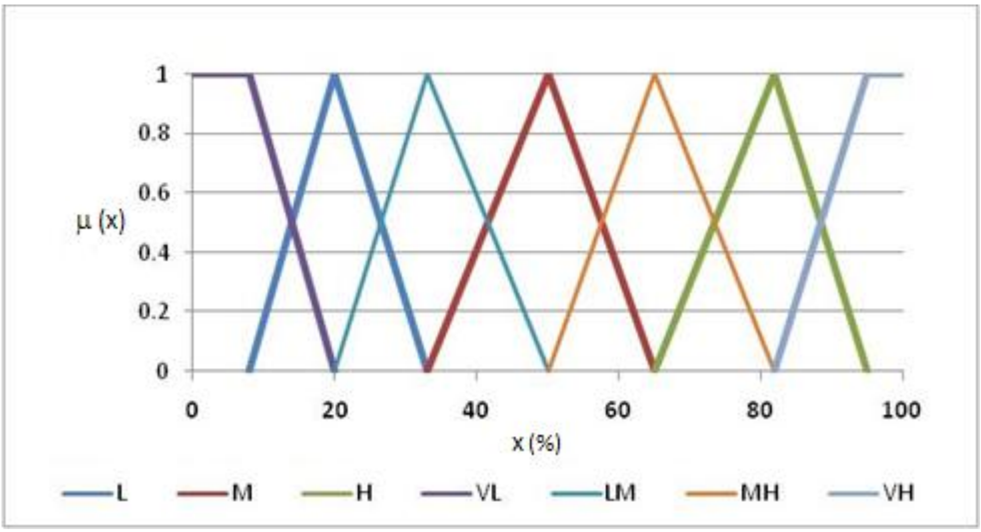

Figure A.5 Membership function of *Source, Volatilization, Air Pathway, Air Receptor, Groundwater Pathway, Groundwater Receptor, Air Pathway&Receptor, Groundwater Pathway&Receptor, Pathways&Receptors And Final Result* for defuzzification

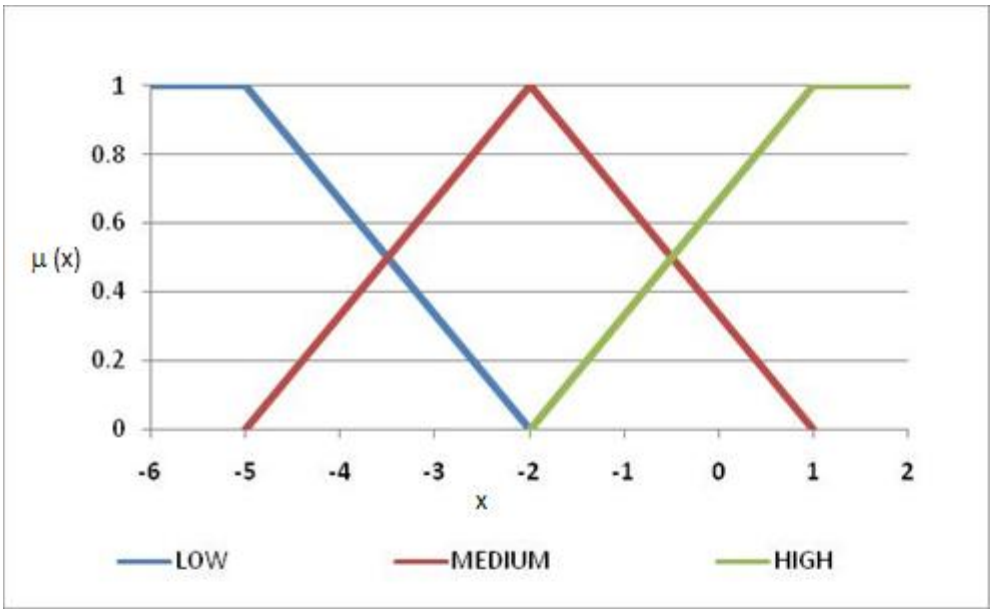

Figure A.6 Membership function of *Vapor Pressure* (log10) and *Henry's Law Constant* (log10) for fuzzification

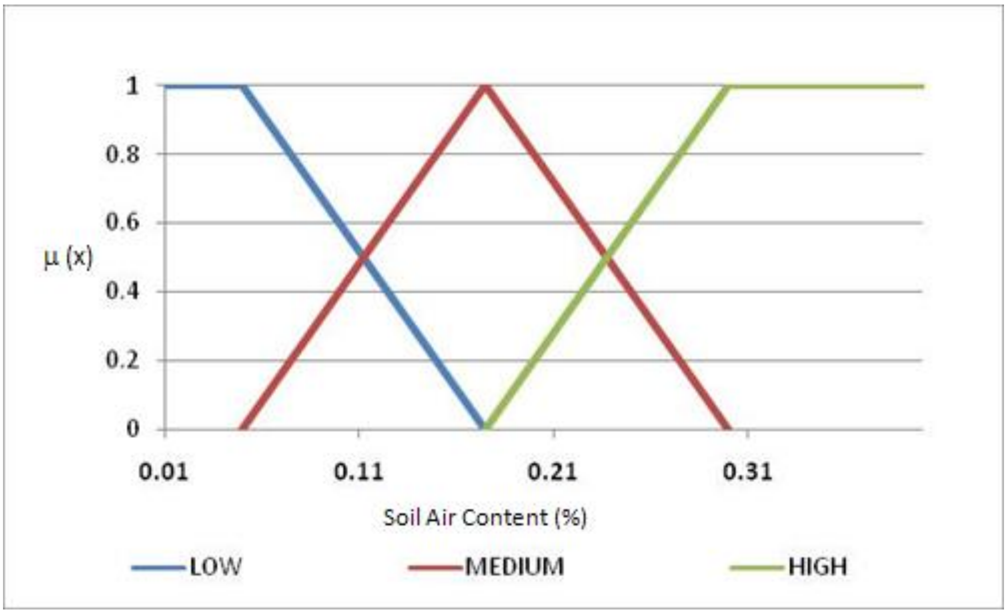

Figure A.7 Membership function of *Soil Air Content* (%) for fuzzification

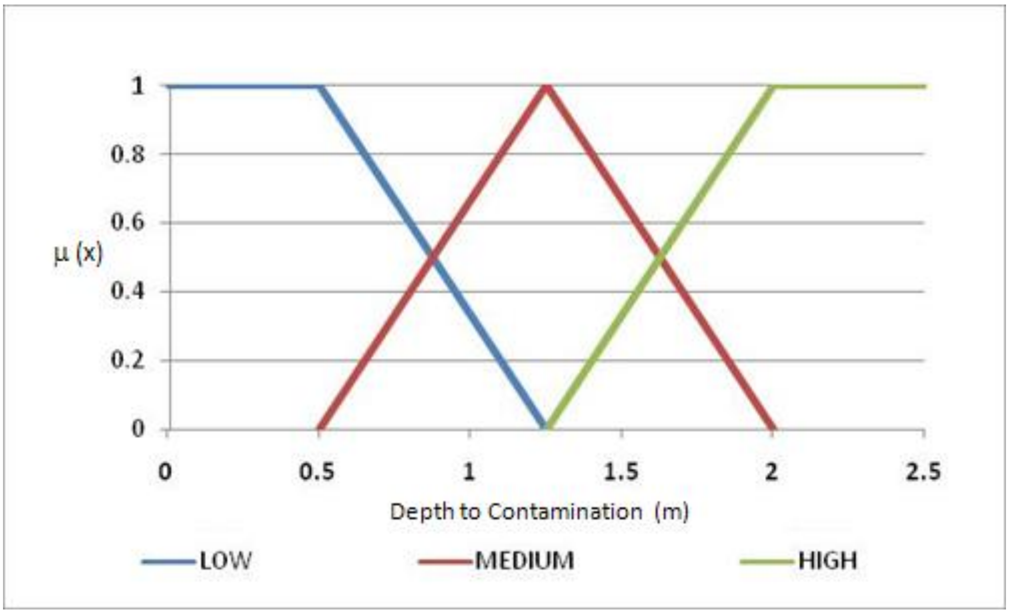

Figure A.8 Membership function of *Depth to Contamination* (m) for fuzzification

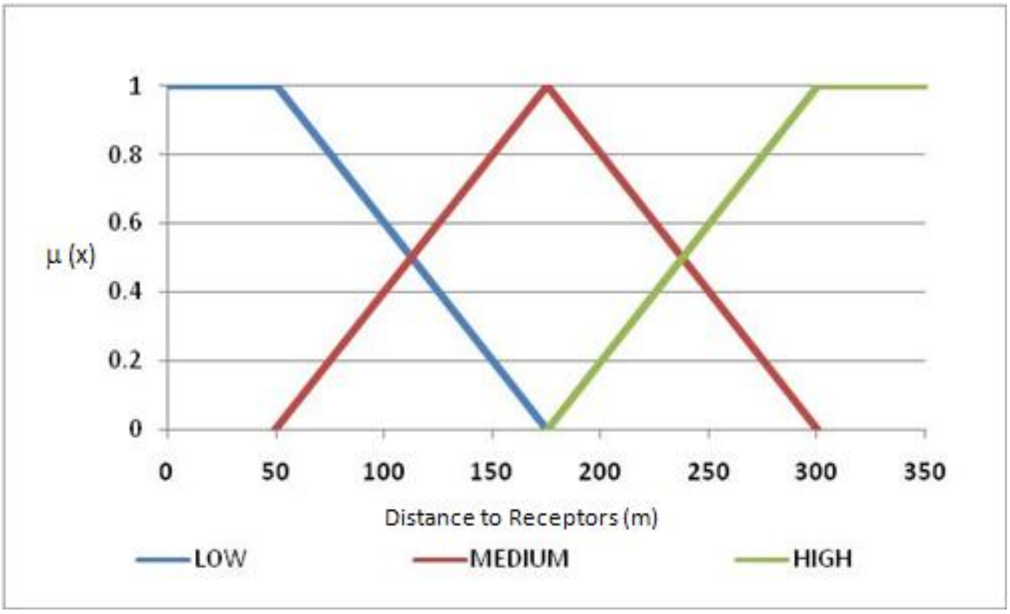

Figure A.9 Membership function of *Distance to Receptors* (m) for fuzzification

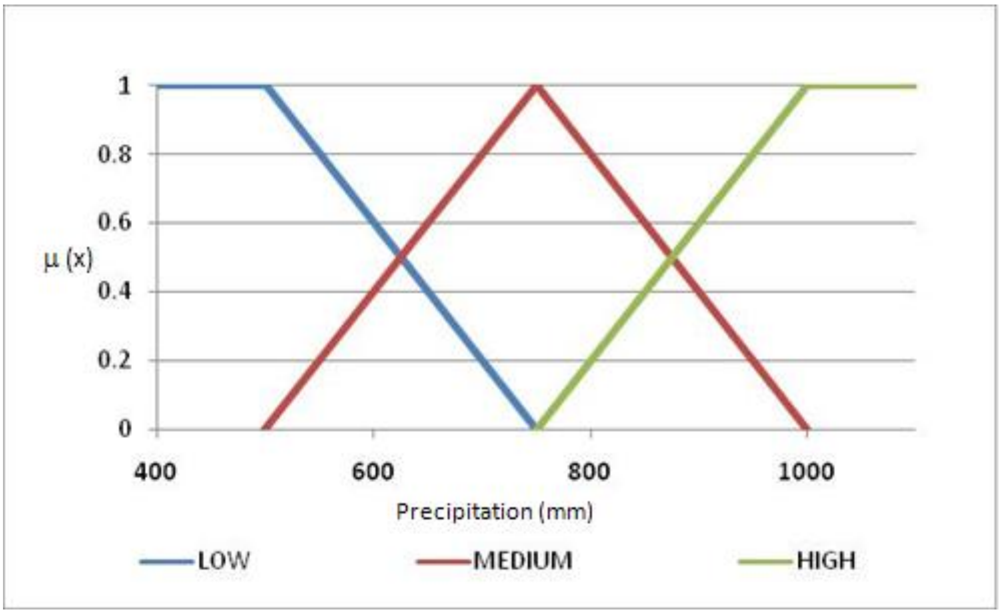

Figure A.10 Membership function of *Precipitation* (mm) for fuzzification

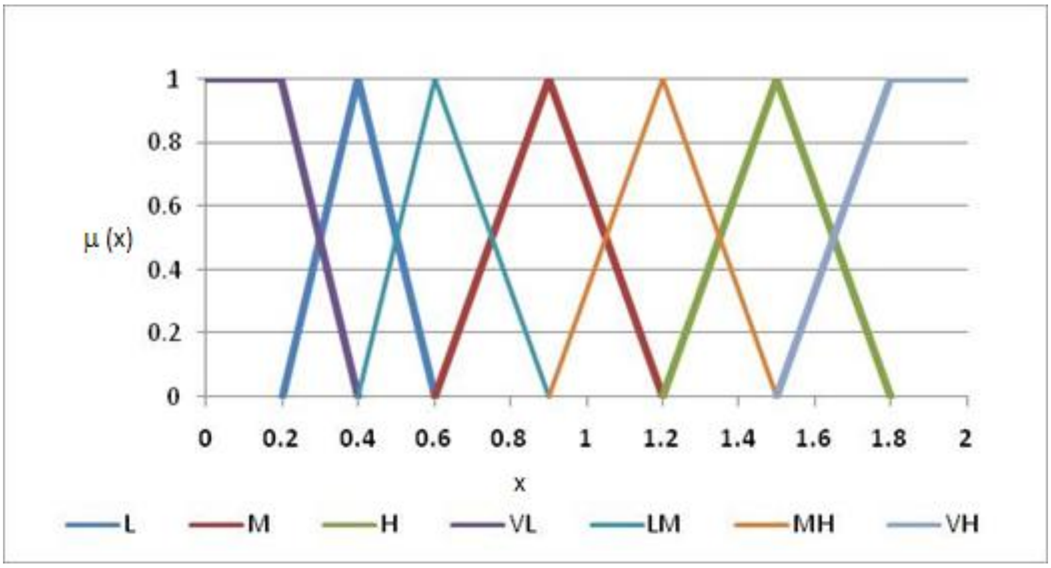

Figure A.11 Membership function of *Infiltration* (m/year) and *Groundwater Velocity* (m/year) for defuzzification

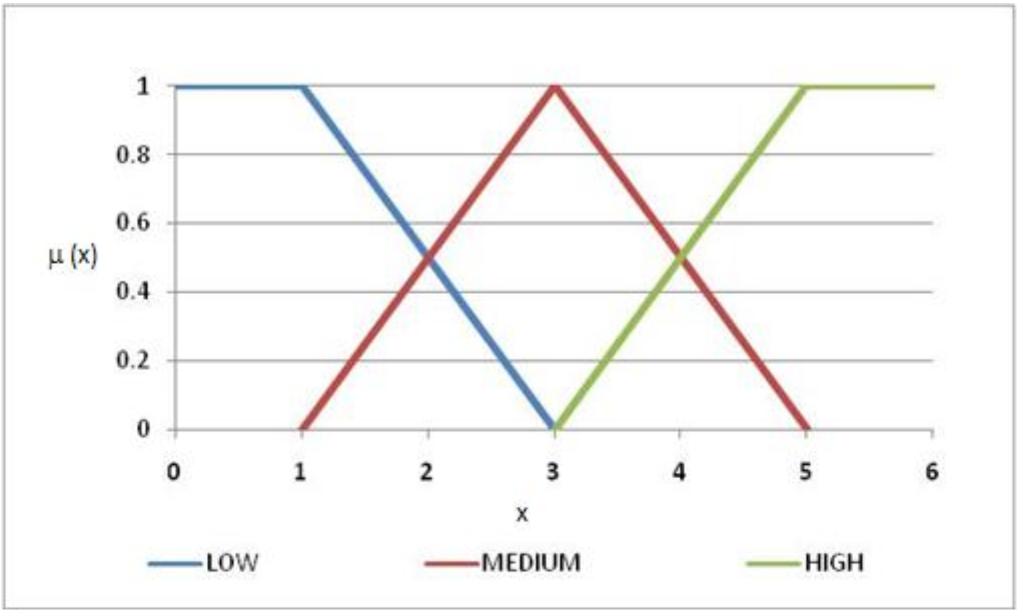

Figure A.12 Membership function of K_{oc} (log10) and K_d (log10) for fuzzification

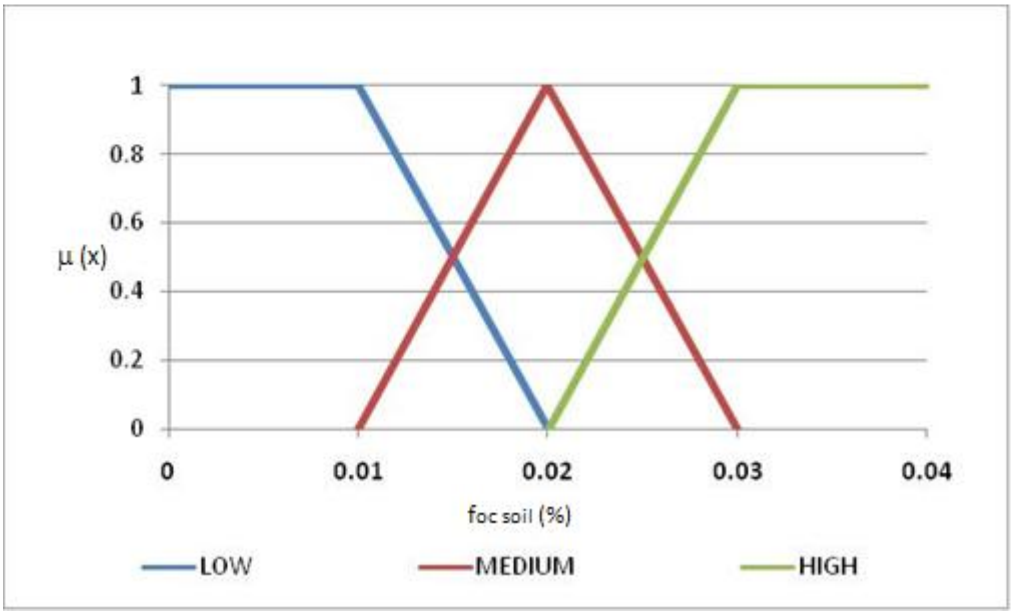

Figure A.13 Membership function of $f_{oc\ soil}$ (%) for fuzzification

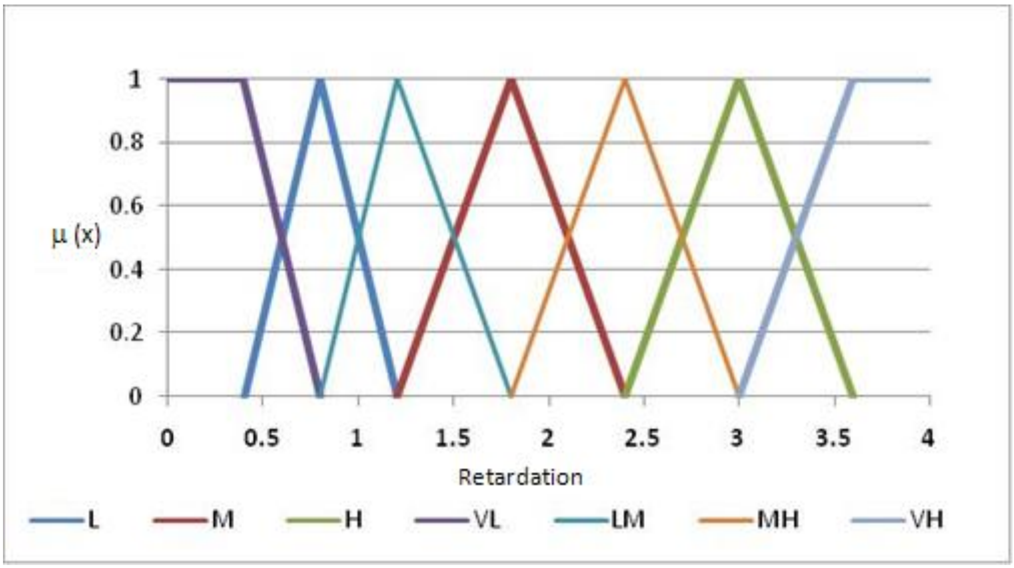

Figure A.14 Membership function of *Retardation* for defuzzification

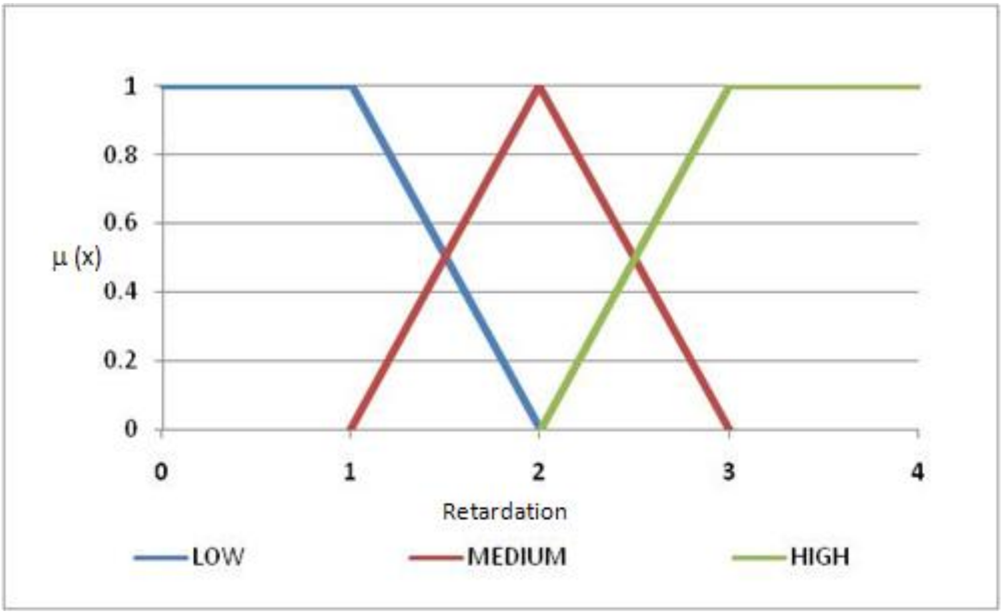

Figure A.15 Membership function of *Retardation* for fuzzification

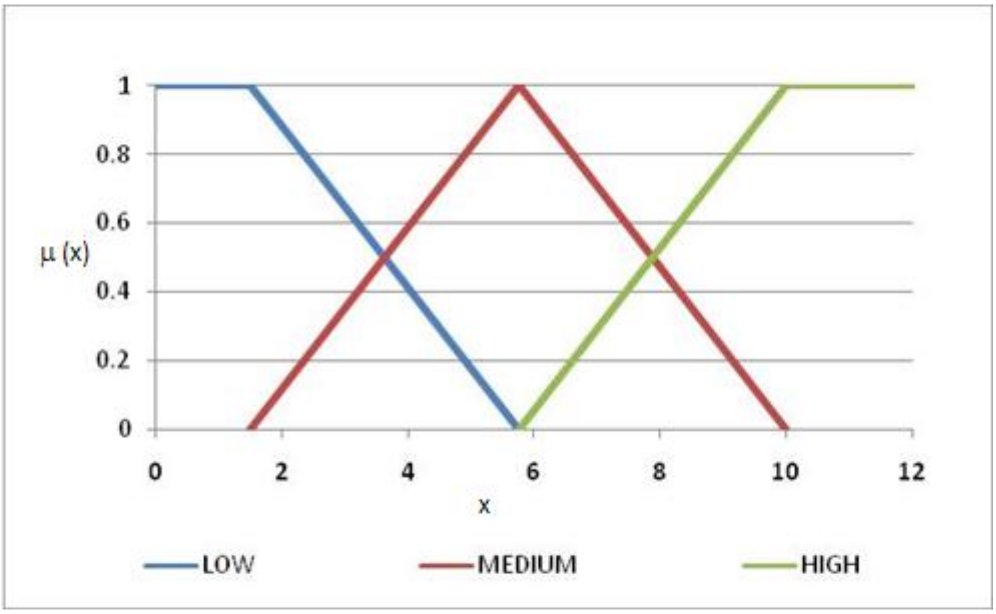

Figure A.16 Membership function of *Distance between Contamination and Aquifer* (m), and *Depth to Water* (m) for fuzzification

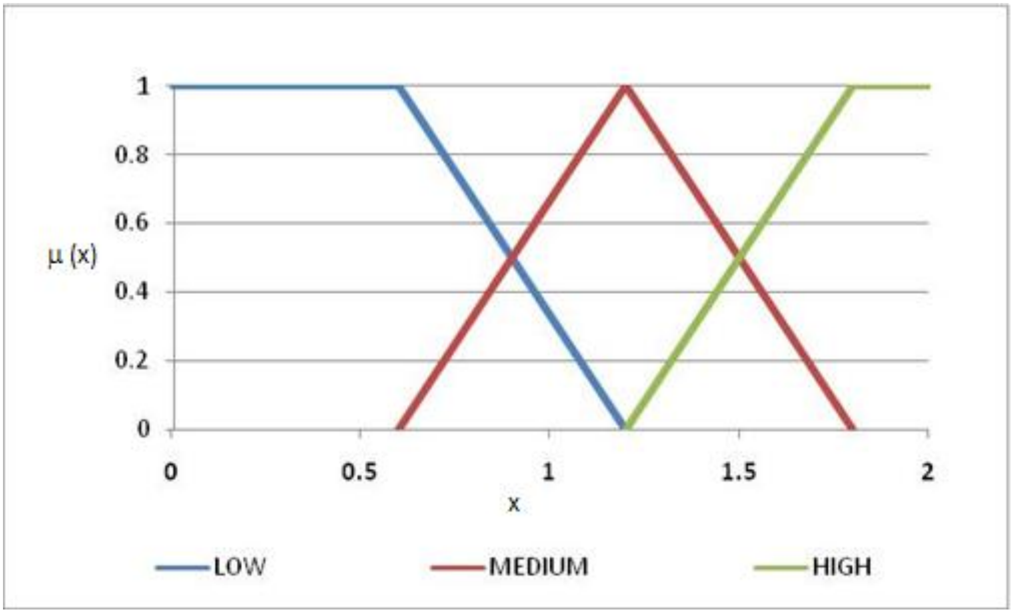

Figure A.17 Membership function of *Infiltration, Groundwater and Contaminant Velocity* (m/year) for fuzzification

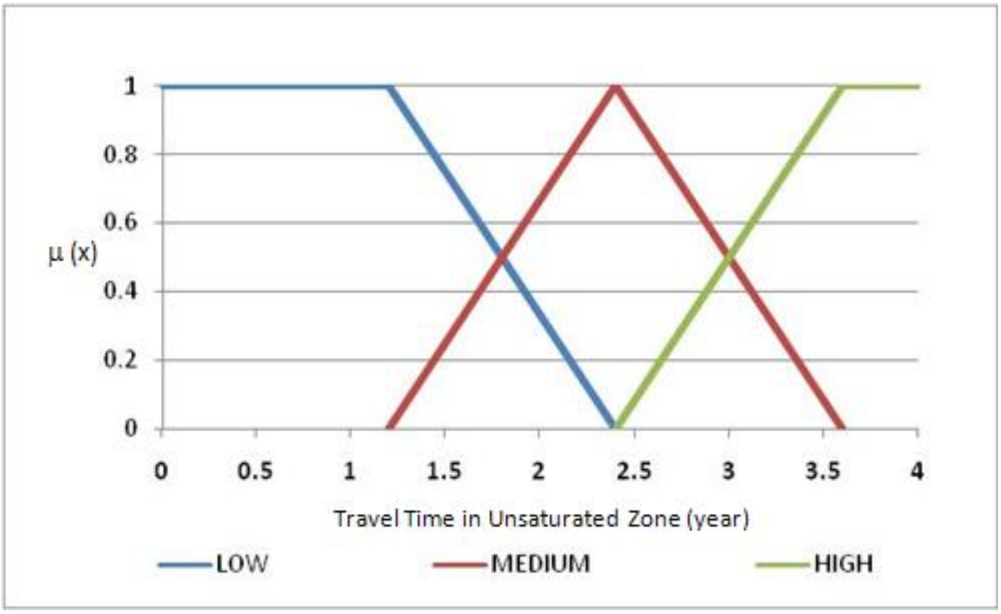

Figure A.18 Membership function of *Travel Time in Unsaturated Zone* (year) for fuzzification

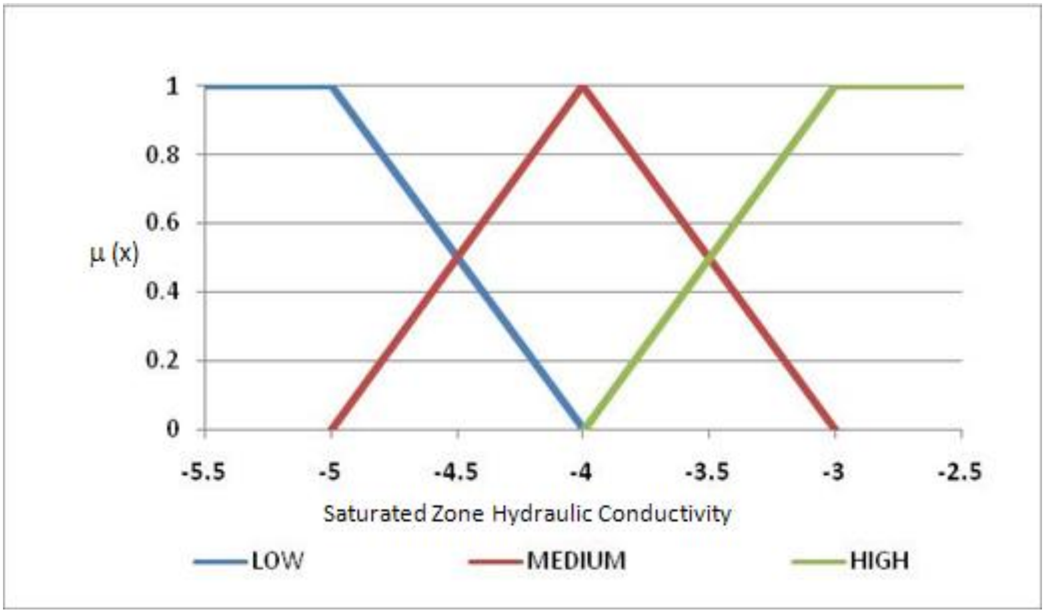

Figure A.19 Membership function of *Saturated Zone Hydraulic Conductivity* (m/s) (log10) for fuzzification

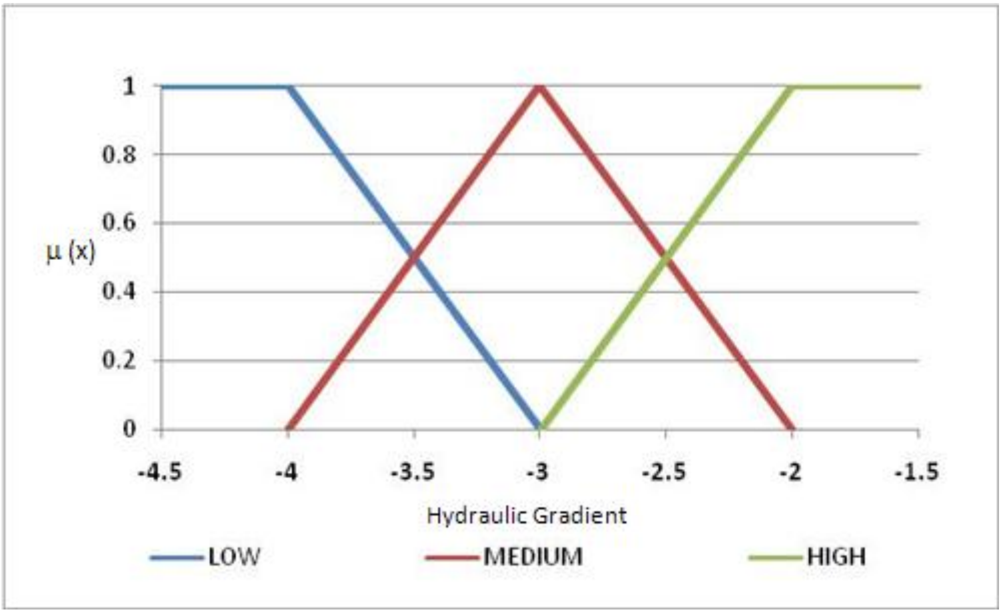

Figure A.20 Membership function of *Hydraulic Gradient* (log10) for fuzzification

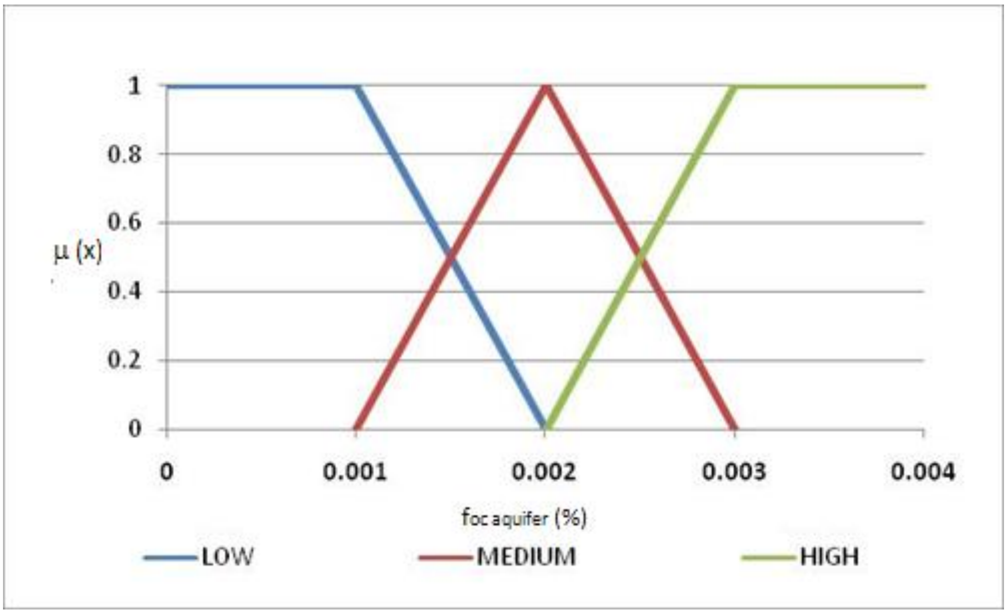

Figure A.21 Membership function of $f_{oc\ aquifer}$ (%) for fuzzification

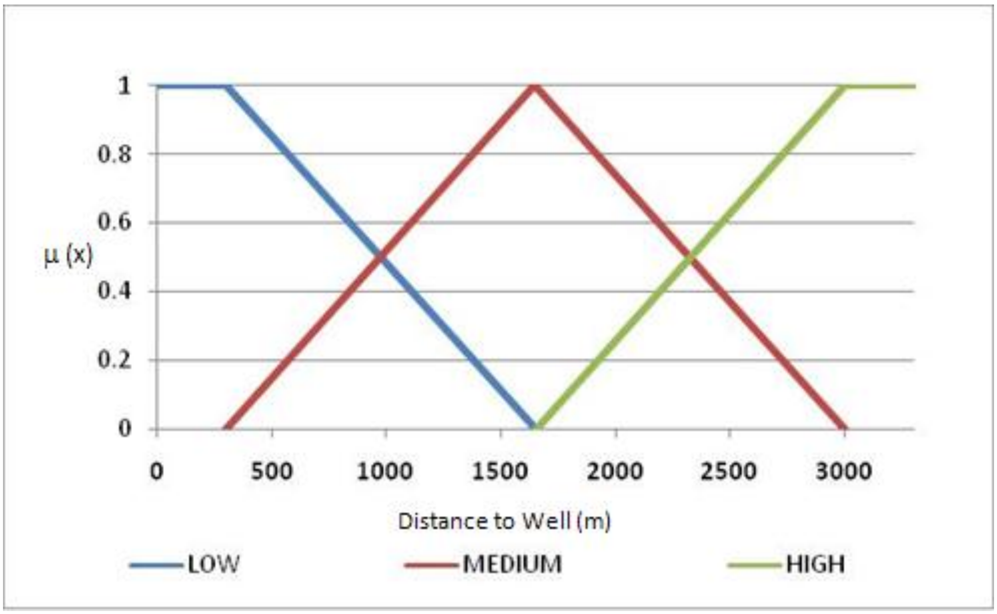

Figure A.22 Membership function of *Distance to Well* (m) for fuzzification

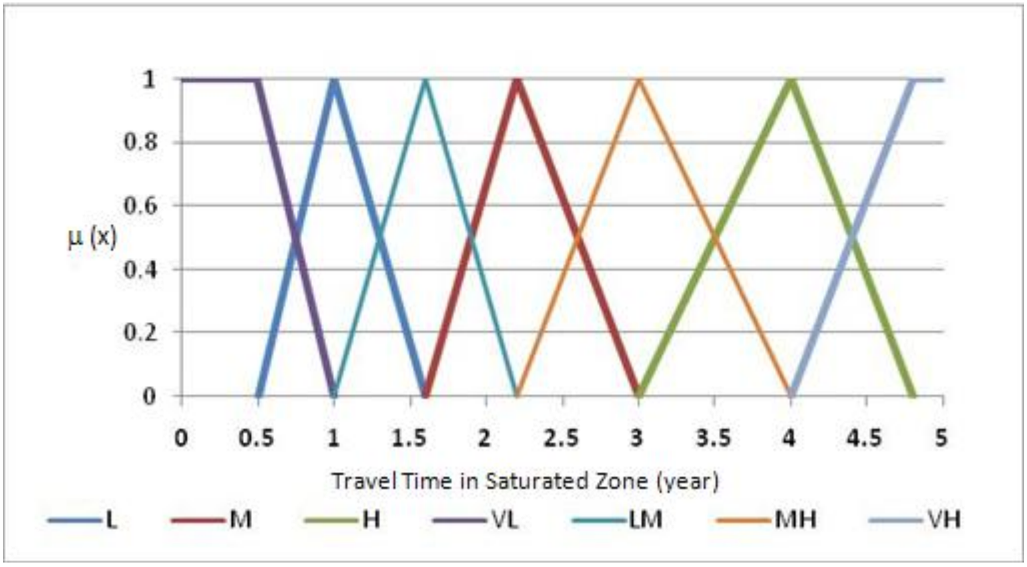

Figure A.23 Membership function of *Travel Time in Saturated Zone* (year) for defuzzification

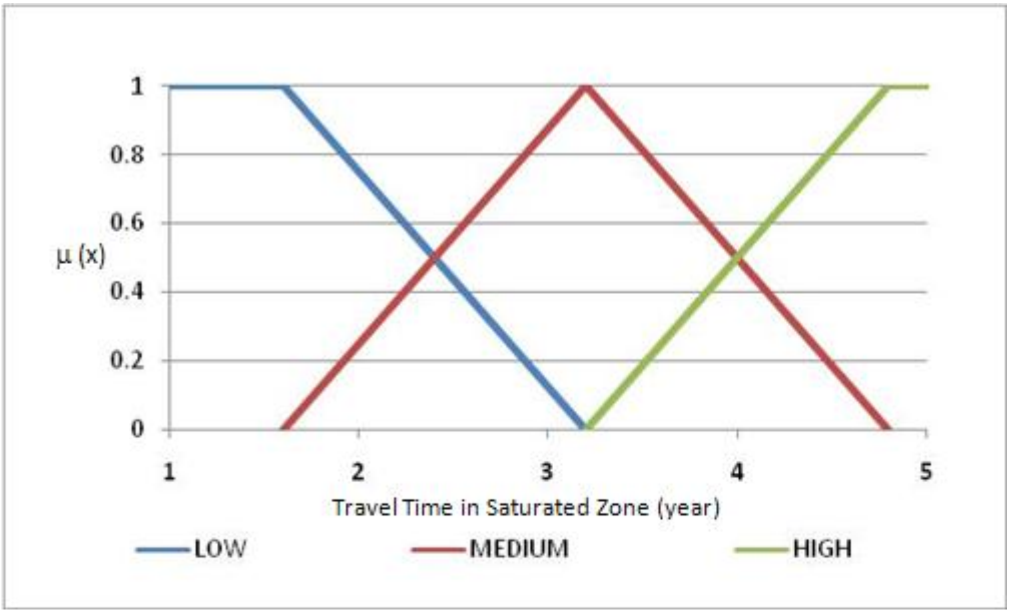

Figure A.24 Membership function of *Travel Time in Saturated Zone (year)* for fuzzification

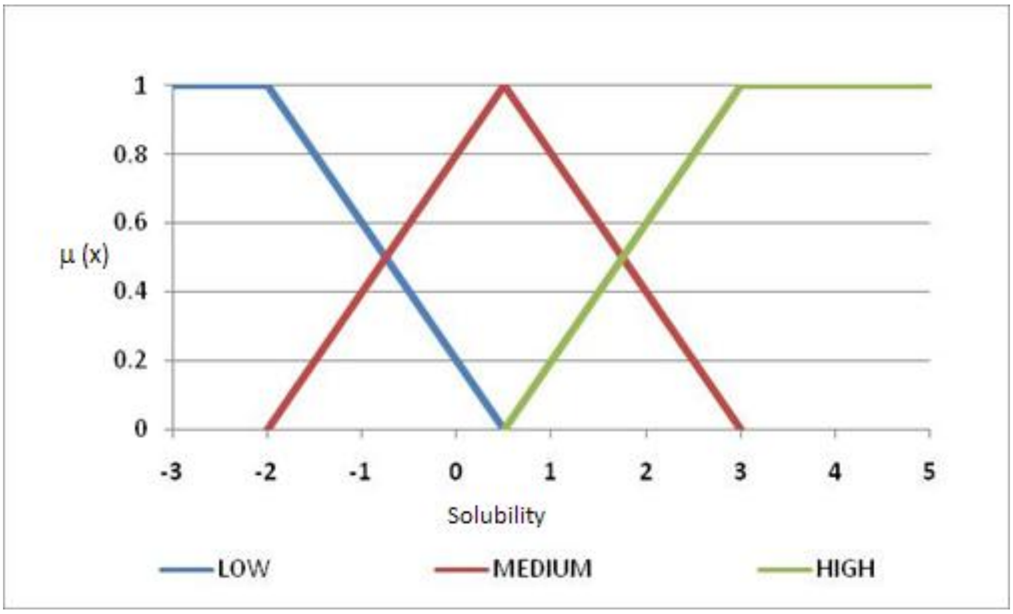

Figure A.25 Membership function of *Solubility* (mg/L) (log10) for fuzzification

APPENDIX B

EXPLANATION DOCUMENT FOR THE DEVELOPMENT OF FUZZY RULES STUDY

Fuzzy Expert System Questionnaire

The system, Remedial Priority Ranking System for Contaminated Sites, is used for the designation of contaminated sites' remediation priority. In the system, fuzzy logic and fuzzy inference system will be used for vagueness in parameter values. The parameters used in the system will have fuzzy value (Low, Medium or High) and fuzzy experts system will be used for the evaluation of the sites. Therefore, this questionnaire has been prepared for the expert decisions on Fuzzy rules. For this purpose, this questionnaire is delivered to various experts studying in the field of soil and groundwater contamination.

In order to develop the fuzzy expert system, it is decided to apply a simple Delphi Method. However, unlike the Delphi Method, experts will not be together in the same room to discuss the answers. The answers will be collected from the experts and corresponding results for each fuzzy rule will be designated according to experts' decisions.

During the evaluation of a contaminated site, two or three parameter groups are considered together. For the groups having two parameters, there are 9 possibilities (Table B.1) and for the groups having three parameters, there are 27 possibilities (Table B.2) for fuzzy rules. Each possibility has a-value-groups of linguistic variables like Low, Medium or High indicating the risk level.

There are three different meanings of linguistic variables. The first one is that if the numerical value of parameter increases, the linguistic variable for that parameter changes accordingly, from Low to Medium or from Medium to High because of the increase in the risk (e.g. Vapor Pressure, Precipitation, Hydraulic Conductivity, Solubility, etc.). The second one is vice versa of the first one, that is; the linguistic variable changes from Medium to Low or from High to Medium if the numerical value of parameter increases because of the decrease in the risk (e.g. Depth to Contamination and Aquifer, Distance to Receptors and Wells, Retardation of contaminants, etc.). The third one is that the value of parameter can be a literary expression and risk changes according to meaning of the literary expressions (e.g. Surface Cover Types: Pavement, Grass, Bare. Land use: Industrial, Agriculture, Residential. Aquifer Type: Confined, Unconfined, Leaky, etc.).

Let us think one of the groups may have parameters a, b and c. These parameters will have a value obtained from membership functions formed for each. Let us say, one of the possibility among 27 possibilities is like this; value of parameter a is “LOW”, value of parameter b is “MEDIUM” and value of parameter c is “MEDIUM”. To be able to continue the evaluation, the overall result of these three parameters should be decided. At this point fuzzy rules will be used.

Fuzzy Rules Tables were formed for experts to provide their decisions on the results of every possible parameter combinations. For example, for the first group, *Area of Contamination* and *Volume of Contaminant* are the parameters whose values are known. The parameter Contaminant quantity is the parameter for which value is searched.

If the value of the parameter Area of Source/Contamination is HIGH (H) and the value of the parameter Volume of Source/Contamination is LOW (L), the value of parameter Contaminant quantity, let say MEDIUM (M), should be written by the experts into the box of last row and the seventh column as it‘s seen in Table B.1.

Table B.1 Example for stating the experts’ answer for fuzzy rule study

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Area of Source/Contamination	L	L	L	M	M	M	H	H	H
Volume of Source/Contamination	L	M	H	L	M	H	L	M	H
Contaminant quantity-Fuzzy Rules							M		

If you are not certain about some of your decisions on fuzzy rules, please give your answer using the following alternative way; For example, for the one of the three-parameter group, let us say Vapor Pressure is LOW, Porosity is MEDIUM and Water Content is HIGH. If the experts doubt to give the answer for the parameter Volatilization is MEDIUM or HIGH, the experts should write M-H into the box of last row and the sixth column as it‘s seen in Table B.2.

Table B.2 Example for stating the experts’ uncertain answer for fuzzy rule study

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Vapor Pressure	L	L	L	L	L	L	L	L	L	M	M	M
Porosity	L	L	L	M	M	M	H	H	H	L	L	L
Water Content	L	M	H	L	M	H	L	M	H	L	M	H
Volatilization-Fuzzy Rules						M-H						

Name of the expert : ---

Department/Organization : ---

Table B.3 Fuzzy rules decision table for groups having two parameters

Parameters	**Risk Level**								
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
1 Toxicity of Contaminant	L	L	L	M	M	M	H	H	H
2 Contaminant quantity	L	M	H	L	M	H	L	M	H
Frank Swartjes	L	M	M	M	M	H	M	H	H
Piet Otte	L	M	M	M	M	H	M	H	H
Kees Versluijs	L	LM	M	M	M	MH	MH	H	H
Prof. Dr. Kahraman Ünlü	L	LM	M	M	M	H	M	H	H
Asst. Prof. Dr. Elçin Kentel	L	L	M	M	M	H	H	H	H
Assoc. Prof. Dr. Ayşegül Aksoy	L	L	M	M	M	H	M	H	H

3 Vapor Pressure/Henry's Law Constant	L	L	L	M	M	M	H	H	H
4 Soil Air Content	L	M	H	L	M	H	L	M	H
Frank Swartjes	L	M	M	M	M	M	H	H	H
Piet Otte	L	M	M	M	M	M	H	H	H
Kees Versluijs	L	L	M	L	M	MH	L	MH	H
Prof. Dr. Kahraman Ünlü	L	L	M	M	M	M	L	H	H
Assoc. Prof. Dr. Ayşegül Aksoy	L	L	M	M	M	M	L	H	H

Land Use: If a contaminated site is in or near a(n);
-residential, park or school area; the risk is *HIGH*,
-agricultural or sylvan area, the risk is *MEDIUM,*
-industrial or commercial area, the risk is *LOW.*

Distance to Receptors is **indirectly** related with the risk.
- if distance to receptors is long, risk is *LOW*,
- if distance to receptors is medium, risk is *MEDIUM*,
- if distance to receptors is short, risk is *HIGH*.

5 Land Use	L	L	L	M	M	M	H	H	H
6 Distance to Receptors	L	M	H	L	M	H	L	M	H
Frank Swartjes	L	L	M	M	M	M	M	H	H
Piet Otte	L	L	M	M	M	M	M	H	H
Kees Versluijs	L	L	LM	L	M	M	MH	H	H
Prof. Dr. Kahraman Ünlü	L	M	MH	L	M	H	M	H	H
Asst. Prof. Dr. Elçin Kentel	L	M	H	M	M	H	H	H	H
Assoc. Prof. Dr. Ayşegül Aksoy	L	M	M	L	M	H	M	H	H

Table B.3 (Continued) Fuzzy rules decision table for groups having two

7 K_{oc} of Contaminant	L	L	L	M	M	M	H	H	H
8 f_{oc} soil or aquifer	L	M	H	L	M	H	L	M	H
Frank Swartjes	L	M	M	L	M	H	M	H	H
Piet Otte	L	M	M	L	M	H	M	H	H
Kees Versluijs	L	LM	M	M	M	M	M	H	H
Prof. Dr. Kahraman Ünlü	L	L	M	L	M	M	M	H	H
Asst. Prof. Dr. Elçin Kentel	L	LM	M	LM	M	MH	M	MH	H
Assoc. Prof. Dr. Ayşegül Aksoy	L	M	M	M	M	H	M	H	H

Travel time of contamination to aquifer is **indirectly** related with the risk. if travel time is long, risk is LOW, if travel time is medium, risk is MEDIUM, if travel time is short, risk is HIGH.	**Aquifer Type:** If aquifer type is; confined, risk is LOW, confined and leaky, risk is MEDIUM, unconfined or unconfined & leaky, risk is HIGH.

9 Travel Time in Unsaturated Zone	L	L	M	M	H	H
10 Aquifer Type	L	H	L	H	L	H
Frank Swartjes	L	M	M	M	M	H
Piet Otte	L	M	M	M	M	H
Kees Versluijs	L	M	LM	MH	M	H
Prof. Dr. Kahraman Ünlü	L	M	M	M	M	H
Asst. Prof. Dr. Elçin Kentel	L	M	M	H	H	H
Assoc. Prof. Dr. Ayşegül Aksoy	L	M	L	H	LM	H

11 **Hydraulic Conductivity**	L	L	L	M	M	M	H	H	H
12 **Hydraulic Gradient**	L	M	H	L	M	H	L	M	H
Prof. Dr. Kahraman Ünlü	L	M	M	L	M	H	M	H	H

Groundwater Velocity is directly related with risk	**Retardation or K_d** is **indirectly** related with risk; - if retardation is high, risk is LOW, - if distance is medium, risk is MEDIUM, - if distance is low, risk is HIGH.

13 **Groundwater Velocity**	L	L	L	M	M	M	H	H	H
14 **Retardation or K_d**	L	M	H	L	M	H	L	M	H
Prof. Dr. Kahraman Ünlü	L	L	L	M	M	M	H	H	M

	Distance Wells is **indirectly** related with risk if distance is long, risk is LOW, if distance is medium, risk is MEDIUM, if distance is short, risk is HIGH.

15 **Contaminant Velocity**	L	L	L	M	M	M	H	H	H
16 **Distance to Well**	L	M	H	L	M	H	L	M	H
Prof. Dr. Kahraman Ünlü	L	L	L	M	M	M	H	H	H

Table B.3 (Continued) Fuzzy rules decision table for groups having two

Travel time of contamination to wells is **indirectly** related with the risk. if travel time is long, risk is LOW, if travel time is medium, risk is MEDIUM, if travel time is short, risk is HIGH.	**Groundwater Use:** If groundwater is used for; industrial purpose or not used, risk is LOW, irrigation purpose or not used but usable, risk is MEDIUM, drinking purpose, risk is HIGH.								
17 Time in Saturated Zone	L	L	L	M	M	M	H	H	H
18 Groundwater Use	L	M	H	L	M	H	L	M	H
Frank Swartjes	L	M	H	M	H	H	M	H	H
Piet Otte	L	M	H	M	H	H	M	H	H
Kees Versluijs	L	LM	H	LM	M	H	M	H	H
Prof. Dr. Kahraman Ünlü	L	L	M	L	M	H	M	MH	H
Asst. Prof. Dr. Elçin Kentel	L	M	H	M	M	H	M	H	H
Assoc. Prof. Dr. Ayşegül Aksoy	L	M	H	L	M	H	M	H	H

19 Air Pathway	L	L	L	M	M	M	H	H	H
20 Air Receptors	L	M	H	L	M	H	L	M	H
Frank Swartjes	L	M	H	M	H	H	H	H	H
Piet Otte	L	M	H	M	H	H	H	H	H
Kees Versluijs	L	L	M	L	M	MH	M	MH	H
Prof. Dr. Kahraman Ünlü	L	L	M	L	M	MH	M	M	H

21 Groundwater Pathway	L	L	L	M	M	M	H	H	H
22 Groundwater Receptors	L	M	H	L	M	H	L	M	H
Frank Swartjes	L	M	M	M	M	H	M	H	H
Piet Otte	L	M	M	M	M	H	M	H	H
Kees Versluijs	L	L	M	L	M	MH	M	MH	H
Prof. Dr. Kahraman Ünlü	L	L	M	L	M	MH	M	M	H

23 Air Pathway&Receptor	L	L	L	M	M	M	H	H	H
24 Groundwater Pathway&Receptor	L	M	H	L	M	H	L	M	H
Frank Swartjes	L	M	M	L	M	H	M	M	H
Piet Otte	L	M	M	L	M	H	M	M	H
Kees Versluijs	L	M	H	M	MH	H	H	H	H
Prof. Dr. Kahraman Ünlü	L	M	H	M	M	H	M	H	H
Asst. Prof. Dr. Elçin Kentel	L	M	H	M	M	H	H	H	H
25 Source	L	L	L	M	M	M	H	H	H
26 Pathways&Receptors	L	M	H	L	M	H	L	M	H
Frank Swartjes	L	M	M	L	M	H	M	M	H
Piet Otte	L	M	M	L	M	H	M	M	H
Kees Versluijs	L	LM	M	LM	M	H	M	H	H
Prof. Dr. Kahraman Ünlü	L	L	M	M	M	H	M	H	H

Table B.4 (continued) Fuzzy rules decision table for groups having three parameters

Parameters	Risk Level																										
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**
Volatilization is drictly related with risk.	Depth to Contamination Zone is **indirectly** related with the risk. If depth is - high, risk level is LOW. - medium, risk level is MEDIUM, - low, risk level is HIGH.													Surface Cover Type: If surface cocer type is; - pavement, risk level is LOW, - vegetation, risk level is MEDIUM, - bare, risk level is HIGH.													
Volatilization of contaminant	L	L	L	L	L	L	L	L	L	M	M	M	M	M	M	M	M	M	H	H	H	H	H	H	H	H	H
Depth to contamination zone	L	L	L	M	M	M	H	H	H	L	L	L	M	M	M	H	H	H	L	L	L	M	M	M	H	H	H
Surface cover type	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
Frank Swartjes	L	L	L	M	M	M	M	M	M	M	M	M	M	M	M	H	H	H	M	M	M	H	H	H	H	H	H
Piet Otte	L	L	L	M	M	M	M	M	M	M	M	M	M	M	M	H	H	H	M	M	M	H	H	H	H	H	H
Kees Versluijs	L	L	L	L	LM	LM	L	LM	M	L	LM	L	LM	M	M	LM	M	MH	LM	L	M	M	MH	MH	MH	H	H
Prof. Dr. Kahraman Ünlü	L	L	L	L	L	L	L	L	M	M	M	M	M	M	M	M	M	H	M	M	H	M	H	H	M	H	H

Precipitation is drictly related with risk.	Surface Cover Type: If surface cover type is; - pavement, risk level is LOW, - vegetation, risk level is MEDIUM, - bare, risk level is HIGH.											Soil Type: If soil type is; - poorly drained, risk level is LOW, - moderately drained, risk level is MEDIUM, - well drained, risk level is HIGH.															
Precipitation	L	L	L	L	L	L	L	L	L	M	M	M	M	M	M	M	M	M	H	H	H	H	H	H	H	H	H
Surface Cover Type	L	L	L	M	M	M	H	H	H	L	L	L	M	M	M	H	H	H	L	L	L	M	M	M	H	H	H
Soil Type	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
Frank Swartjes	L	L	M	L	M	M	M	M	H	L	M	M	M	M	M	M	M	H	L	M	H	M	M	H	H	H	H
Piet Otte	L	L	M	L	M	M	M	M	H	L	M	M	M	M	M	M	M	H	L	M	H	M	M	H	H	H	H
Kees Versluijs	L	L	L	L	L	LM	L	ML	MH	L	L	L	ML	M	MH	M	M	MH	LM	LM	LH	M	M	MH	MH	H	H
Prof. Dr. Kahraman Ünlü	L	L	L	L	L	M	L	M	M	L	LM	M	M	M	M	LM	M	H	LM	M	M	M	M	H	MH	H	H

Table B.4 (continued) Fuzzy rules decision table for groups having three parameters

Infiltration rate is directly related with risk.

Distance between contamination and aquifer is indirectly related with the risk. If distance is
- long, risk level is LOW.
- medium, risk level is MEDIUM,
- short, risk level is HIGH.

Retardation or Kd is indirectly related with risk;
- if retardation is high, risk is LOW,
- if distance is medium, risk is MEDIUM,
- if distance is low, risk is HIGH.

Parameters	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
Infiltration Rate	L	L	L	L	L	L	L	L	L	M	M	M	M	M	M	M	M	M	H	H	H	H	H	H	H	H	H
Distance between contamination and	L	L	L	M	M	M	H	H	H	L	L	L	M	M	M	H	H	H	L	L	L	M	M	M	H	H	H
Retardation or K_d	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
Frank Swartjes	L	L	M	L	M	M	M	M	H	L	M	M	M	M	M	M	M	H	L	M	H	M	M	H	H	H	H
Piet Otte	L	L	M	L	M	M	M	M	H	L	M	M	M	M	M	M	M	H	L	M	H	M	M	H	H	H	H
Kees Versluijs	L	L	L	L	L	LM	L	LM	LM	L	LM	L	M	M	M	M	M	M	M	M	M	M	MH	H	MH	H	H
Prof. Dr. Kahraman Ünlü	L	L	L	L	M	M	M	MH	H	L	LM	M	M	M	M	H	H	H	M	M	H	H	H	H	H	H	H

Volatilization is directly related with risk.

Depth to Aquifer is indirectly related with risk; f depth is
- high, risk level is LOW,
- medium, risk level is MEDIUM,
- low, risk level is HIGH.

Aquifer Type: If aquifer type is;
- confined, risk is LOW,
- unconfined or unconfined & leaky, risk is HIGH.

Parameters	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Volatilization	L	L	L	L	L	L	M	M	M	M	M	M	H	H	H	H	H	H
Depth to Aquifer	L	L	M	M	H	H	L	L	M	M	H	H	L	L	M	M	H	H
Aquifer Type	L	H	L	H	L	H	L	H	L	H	L	H	L	H	L	H	L	H
Frank Swartjes	L	L	M	M	M	M	M	H	H	H	H	H	H	H	H	H	H	H
Piet Otte	L	M	L	M	M	H	L	M	M	M	M	H	L	H	H	H	H	H
Kees Versluijs	L	L	L	LM	L	MH	L	L	LM	M	M	MH	LM	MH	MH	H	MH	H
Prof. Dr. Kahraman Ünlü	L	L	L	M	L	M	L	M	M	M	LM	H	LM	MH	MH	H	H	H

APPENDIX C

FUZZY RULES

The notation in fuzzy rules tables;

VL = Very Low　　　L = Low
LM = Low-Medium　　　M = Medium
MH = Medium-High　　　H = High
VH = Very High

The tables should be read as the example given for Table 1. In Table 1, there are 2 parameters and there are 9 fuzzy rules for these parameters. The first rule is in the second column of the table and the second one is in the third column and so on. The rule in the first column is that "if *Toxicity of contaminant* is Low and *Contaminant quantity* is Low, then *Source* is Very Low".

Table C.1 Fuzzy rules source parameters

	Fuzzy Rules								
Rule Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Toxicity of Contaminant	L	L	L	M	M	M	H	H	H
Contaminant quantity	L	M	H	L	M	H	L	M	H
Source	**VL**	**L**	**LM**	**LM**	**M**	**MH**	**M**	**H**	**VH**

Table C.2 Fuzzy rules volatilization parameters

	Fuzzy Rules								
Rule Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Vapor Pressure/ Henry's Law Constant	L	L	L	M	M	M	H	H	L
Soil Air Content	L	M	H	L	M	H	L	M	L
Volatilization	**VL**	**L**	**LM**	**LM**	**MH**	**H**	**MH**	**VH**	**VL**

Table C.3 Fuzzy rules air pathway parameters

	Fuzzy Rules								
Rule Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Volatilization	L	L	L	L	L	L	L	L	L
Depth to Contamination	L	L	L	M	M	M	H	H	H
Surface Cover Type	L	M	H	L	M	H	L	M	H
Air Pathway	**VL**	**VL**	**L**	**VL**	**L**	**LM**	**L**	**LM**	**M**
Rule Number	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
Volatilization	M	M	M	M	M	M	M	M	M
Depth to Contamination	L	L	L	M	M	M	H	H	H
Surface Cover Type	L	M	H	L	M	H	L	M	H
Air Pathway	**LM**	**M**	**M**	**LM**	**M**	**MH**	**M**	**MH**	**H**
Rule Number	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**
Volatilization	H	H	H	H	H	H	H	H	H
Depth to Contamination	L	L	L	M	M	M	H	H	H
Surface Cover Type	L	M	H	L	M	H	L	M	H
Air Pathway	**LM**	**M**	**MH**	**M**	**MH**	**H**	**MH**	**H**	**VH**

Table C.4 Fuzzy rules air receptor parameters

	Fuzzy Rules								
Rule Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Land Use	L	L	L	M	M	M	H	H	H
Distance to Receptors	L	M	H	L	M	H	L	M	H
Air Receptor	**VL**	**LM**	**M**	**LM**	**M**	**H**	**MH**	**H**	**VH**

Table C.5 Fuzzy rules infiltration velocity parameters

	Fuzzy Rules								
Rule Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Precipitation	L	L	L	L	L	L	L	L	L
Surface Cover Type	L	L	L	M	M	M	H	H	H
Soil Type	L	M	H	L	M	H	L	M	H
Infiltration velocity	**VL**	**VL**	**VL**	**VL**	**L**	**M**	**VL**	**M**	**M**
Rule Number	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
Precipitation	M	M	M	M	M	M	M	M	M
Surface Cover Type	L	L	L	M	M	M	H	H	H
Soil Type	L	M	H	L	M	H	L	M	H
Infiltration velocity	**L**	**LM**	**M**	**LM**	**MH**	**H**	**M**	**MH**	**H**
Rule Number	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**
Precipitation	H	H	H	H	H	H	H	H	H
Surface Cover Type	L	L	L	M	M	M	H	H	H
Soil Type	L	M	H	L	M	H	L	M	H
Infiltration velocity	**LM**	**M**	**MH**	**M**	**MH**	**H**	**MH**	**H**	**VH**

Table C.6 Fuzzy rules retardation parameters

	Fuzzy Rules								
Rule Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
K_{oc}	L	L	L	M	M	M	H	H	H
f_{oc}	L	M	H	L	M	H	L	M	H
Retardation	VH	H	M	H	M	LM	MH	L	VL

Table C.7 Fuzzy rules travel time in unsaturated zone parameters

	Fuzzy Rules								
Rule Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Retardation/K_d	L	L	L	L	L	L	L	L	L
Distance btw Cont.&Aquifer	L	L	L	M	M	M	H	H	H
Infiltration Velocity	L	M	H	L	M	H	L	M	H
Travel Time in Unsat. Zone	**VL**	**L**	**L**	**LM**	**L**	**LM**	**LM**	**M**	**MH**
Rule Number	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
Retardation/K_d	M	M	M	M	M	M	M	M	M
Distance btw Cont.&Aquifer	L	L	L	M	M	M	H	H	H
Infiltration Velocity	L	M	H	L	M	H	L	M	H
Travel Time in Unsat. Zone	**L**	**LM**	**M**	**LM**	**M**	**MH**	**MH**	**H**	**H**
Rule Number	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**
Retardation/K_d	H	H	H	H	H	H	H	H	H
Distance btw Cont.&Aquifer	L	L	L	M	M	M	H	H	H
Infiltration Velocity	L	M	H	L	M	H	L	M	H
Travel Time in Unsat. Zone	**LM**	**M**	**M**	**M**	**MH**	**H**	**M**	**MH**	**VH**

Table C.8 Fuzzy rules groundwater pathway parameters

	Fuzzy Rules					
Rule Number	**1**	**2**	**3**	**4**	**5**	**6**
Travel Time in Unsaturated Zone	L	L	M	M	H	H
Aquifer Type	L	H	L	H	L	H
Groundwater Pathway	**VL**	**MH**	**LM**	**H**	**M**	**VH**

Table C.9 Fuzzy rules groundwater pathway parameters

	Fuzzy Rules		
Rule Number	**1**	**2**	**3**
Solubility	L	M	H
Free Phase	H	H	H
Groundwater Pathway	**L**	**M**	**H**

Table C.10 Fuzzy rules groundwater velocity parameters

	Fuzzy Rules								
Rule Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Saturated Z. Hydraulic K	L	L	L	M	M	M	H	H	H
Hydraulic Gradient	L	M	H	L	M	H	L	M	H
Groundwater Velocity	**VL**	**L**	**M**	**L**	**M**	**MH**	**M**	**H**	**VH**

Table C.11 Fuzzy rules contamination velocity parameters

	Fuzzy Rules								
Rule Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Groundwater Velocity	L	L	L	M	M	M	H	H	H
Retardation	L	M	H	L	M	H	L	M	H
Contaminant Velocity	**VL**	**VL**	**L**	**LM**	**M**	**MH**	**M**	**H**	**VH**

Table C.12 Fuzzy rules travel time in saturated zone parameters

	Fuzzy Rules								
Rule Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Contaminant Velocity	L	L	L	M	M	M	H	H	H
Distance to well	L	M	H	L	M	H	L	M	H
Travel Time in Sat. Zone	**VL**	**L**	**LM**	**L**	**M**	**MH**	**LM**	**H**	**VH**

Table C.13 Fuzzy rules groundwater receptors parameters

	Fuzzy Rules								
Rule Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Travel Time in Saturated	L	L	L	M	M	M	H	H	H
Groundwater Use	L	M	H	L	M	H	L	M	H
Groundwater Receptors	**VL**	**L**	**H**	**L**	**M**	**VH**	**LM**	**MH**	**VH**

Table C.14 Fuzzy rules air pathway and receptor parameters

	Fuzzy Rules								
Rule Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Air Pathway	L	L	L	M	M	M	H	H	H
Air Receptors	L	M	H	L	M	H	L	M	H
Air Pathway&Receptor	**VL**	**L**	**LM**	**L**	**M**	**H**	**MH**	**H**	**VH**

Table C.15 Fuzzy rules Travel Time in Unsaturated Zone parameters

	Fuzzy Rules								
Rule Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Groundwater Pathways	L	L	L	M	M	M	H	H	H
Groundwater Receptors	L	M	H	L	M	H	L	M	H
Groundwater Pathway&Receptor	**VL**	**L**	**LM**	**L**	**M**	**H**	**MH**	**H**	**VH**

Table C.16 Fuzzy rules pathway and receptor parameters

	Fuzzy Rules								
Rule Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Air Pathway&Receptor	L	L	L	M	M	M	H	H	H
Gw Pathway&Receptor	L	M	H	L	M	H	L	M	H
Pathways&Receptors	**VL**	**L**	**LM**	**L**	**M**	**MH**	**LM**	**H**	**VH**

Table C.17 Fuzzy rules final result parameters

	Fuzzy Rules								
Rule Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Source	L	L	L	M	M	M	H	H	H
Pathways&Receptors	L	M	H	L	M	H	L	M	H
Final Result	**VL**	**L**	**MH**	**L**	**M**	**H**	**MH**	**H**	**VH**