Ranking of the Remedial Priority of Contaminated Sites Using a Fuzzy Rule Based System

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Introduction

Numerous contaminated sites around the world are in need of remediation. Although the principle of "polluter pays" is adapted in many countries, orphan sites still require allocation of national financial resources. It not feasible to cleanup all contaminated sites at once given financial and other constraints. Thus, ranking may be required to allocate limited resources efficiently.

High quality data may be required for comparison and ranking of the severity of pollution at different sites. Yet, in most cases, parameters relevant to contaminant fate, transport, and exposure pathways are vague or imprecise. In this study, an alternative remedial priority ranking system (RPRS) is developed considering the vagueness in parameter values. RPRS is based on fuzzy theory. Potential human health risks due to contamination are assessed using sufficiently comprehensive and readily available parameters in describing the fate and transport of contaminants in air, soil and groundwater. RPRS is incorporated into software (ConSiteRPRS) for application. Rankings were employed for different real contamination cases.

Methodology

The decision tree employed in evaluating the priority ranking of contaminated sites is given in Figure 1. Final ranking score is obtained from the source category and the combined pathway-receptor category (Figure 1). RPRS considers inhalation and ingestion as potential means of exposure. Differentiation is applied for contaminations occurring on ground level (soil medium contamination only), underground directly in the aquifer (groundwater medium contamination only), or subsurface (both soil and groundwater media contamination).

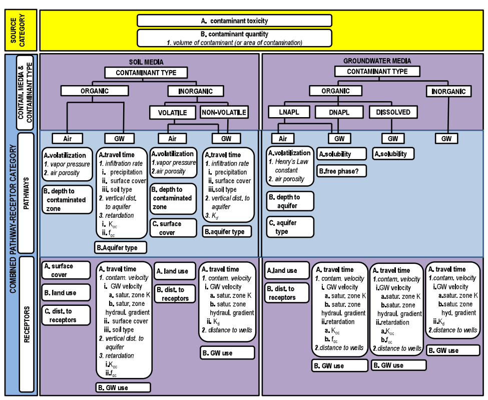

Figure 1. The decision tree for RPRS in ranking of contaminated sites

Parameters used in evaluation are grouped under four significance levels (first, second, third, and fourth) (Figure 1) designating relative weights in evaluation. Remedial priority was scored using a fuzzy expert system in which a collection of fuzzy membership functions and rules (rule base) are used. The general membership function used in fuzzification of the input parameters is depicted in Figure 2. Value ranges used in establishing the degree of membership to fuzzy subsets are given for example parameters in Table 2. Example fuzzy rules in inferring an outcome are provided in Table 3. An example rule is "If toxicity of contaminant is low and contaminant quantity is low then source score is very low".

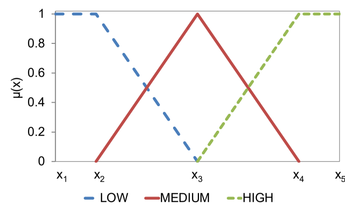

Figure 2. The general membership function used in fuzzification of input parameters (μ(x)=degree of membership)

Table 1. Membership function construction for fuzzification (x_1, x_2, x_3, x_4, and x_5 in Figure 2) for selected parameters

Parameters	x_1	x_2	x_3	x_4	x_5
Area (m^2)	0	2000	7000	12,000	14,000
Contaminant quantity (UL)*	0	10	50	90	100
Vapor Pressure (mm Hg)	10^{-6}	10^{-5}	10^{-2}	10	10^{2}
Depth to aquifer (m)	0	1.5	5.75	10	12
Distance to receptors (m)	0	50	175	300	350
Precipitation (mm/yr)	400	500	750	1000	1100
Hydraulic conduct. (m/s)	$10^{-5.5}$	10^{-5}	10^{-4}	10^{-3}	$10^{-2.5}$
Contaminant velocity (UL)	0	0.6	1.2	1.8	2
K_d (L/g)	0	1	3	5	6
Air pathway score (UL)	0	10	50	90	100

*UL=upper level parameter derived from lower level parameters (see Figure 1)

Table 2. Example fuzzy rule sets (VL=very low, L=low, LM=low-medium, M=medium, MH=medium-high, H=high, VH=very high)

Input	output	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
groundwater velocity		L	L	L	M	M	M	H	H	H
retardation		L	M	H	L	M	H	L	M	H
	contam. velocity	VL	VL	L	LM	M	MH	M	H	VH

At most 3 parameters are considered to produce an output using fuzzy rules. Inference is applied within a given parameter level to provide the fuzzy subset designation for the upper level parameters. Based on this approach and the framework given in Figure 1, final remedial priority ranking score is obtained in a chain like structure provided in Figure 3 (size of a ring is proportional to the weight of a parameter in the final priority ranking score).

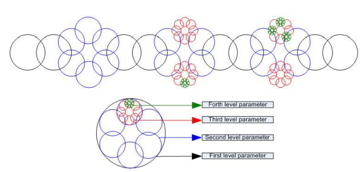

Figure 3. The ring like structure used in inferencing in RPRS

The average fuzzy logic operator is used at the composition stage where all fuzzy subsets assigned to each output variable are combined to form a single fuzzy subset. Then "height defuzzification" (Driankov et al. 1996) is applied to obtain crisp values for soil and groundwater media to determine the final ranking score. The centroid of a relevant output membership function (G_1 and G_2 in Figure 4) is evaluated. The final output ("G_A" in Figure 4) is then calculated as the average of the individual centroids weighted by their degree of memberships (μ_1 and μ_2 in Figure 4).

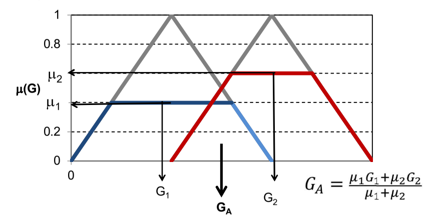

Figure 4. The height defuzzification approach

The RPRS system was incorporated into ConSiteRPRS which was developed in Microsoft Office Excel 2007 using Visual Basic (Figure 5). In ConSiteRPRS, a total of 354 chemicals are in database with their physical-chemical properties. The user enters only the values of pertinent parameters in relevance to contaminated media, contaminant type or existence of free phase.

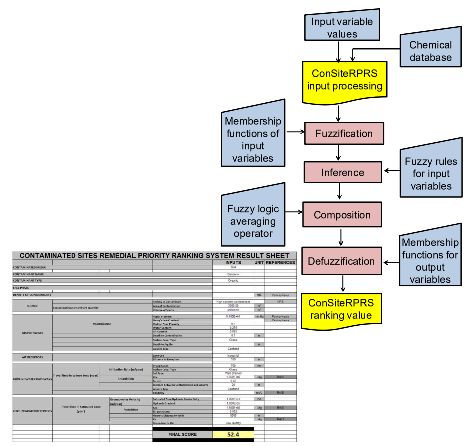

Figure 5. Process flowchart and result sheet in ConSiteRPRS

Application and Results

Actual contaminated sites from the Netherlands and one case from Turkey (Buyuker and Polat 2009) were considered for ranking by ConSiteRPRS. Brief information about the cases is provided in Table 3. These cases were also evaluated by a group of experts. In ranking through expert opinion, the experts agreed that the military base and the furniture factory cases were relatively the most and the least hazardous cases, respectively. However, they had difficulty in differentiating between the severities of other cases, but agreed priority rankings should be higher compared to furniture factory case.

There was conformity between the evaluations by ConSiteRPRS and experts (Table 3). Although ranking scores were close, ConSiteRPRS was able to differentiate between the cases where experts could not.

Table 3. Parameters and priority rankings of actual contaminated sites (MD=moderately drained, PD=poor drained, WD=well drained, DQ=drinking quality, LQ=low quality, - = unknown)

Parameters	Military Base	Municipal Dump Site	Lead Paint Factory	Dry Cleaner	Furniture Factory
Contaminated media	soil	GW	soil	soil	soil
Contaminant	PCB	benzene	lead	TCE	TCE
Area of contamination (m^2)	-	40.000	12,000	12,000	3000
Volume of source (m^3)	1585	-	-	-	-
Soil type	MD	-	PD	PD	WD
Vadose zone porosity	0.2	-	-	0.225	0.3
Water content	0.05	-	-	0.2	0.275
Depth to contamination (m)	0.5	-	-	0.3	0.1
Surface cover type	bare	-	pavement	bare	grass
Aquifer type	confined	-	confined	confined	confined
Land use	industrial	-	-	residential	industrial
Distance to receptors (m)	300	-	-	50	100
Precipitation (mm/yr)	600	-	830	840	750
f_{oc_soil}	0.02	-	-	0.02	0.02
Saturated zone K (m/s)	$1x10^{-5}$	$1x10^{-3}$	$1x10^{-5}$	$1x10^{-5}$	$1x10^{-3}$
Hydraulic gradient	$1x10^{-4}$	$1x10^{-4}$	$1x10^{-4}$	$1x10^{-4}$	$1x10^{-5}$
Distance to wells (m)	300	3000	5000	5000	5000
Groundwater use	DQ	LQ	LQ	LQ	LQ
RPRS score	76.5	71.2	70.7	69.7	52.4
Rankings by ConSiteRPRS	1	2	3	4	5
Rankings by expert opinion	1	2	2	2	5

Conclusions

RPRS can evaluate remedial priority based on readily available, easily measured and accessible technical data relevant to fate and transport of contaminants. It was successfully applied for real contamination cases. Remedial priority rankings were in agreement with expert opinion. ConSiteRPRS may be of value for categorization of sites posing risks to human health. Ecological risks can be integrated into RPRS in the future.

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