Environmental Informatics Archives, Volume 2 (2004), 151-167
EIA04-017
ISEIS Publication #002
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Fuzzy Health Risk Assessment for the Management of Petroleum-Contaminated Sites: a Western Canadian Case Study

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Abstract. A fuzzy health risk assessment (FHRA) approach is developed in this study to quantify uncertainties associated with health impact evaluation criteria. This development is based on (a) simulation for the fate of contaminant (e.g. benzene) in subsurface through a 3-D multiphase multi-component numerical model, (b) quantification of excess lifetime cancer risk evaluation criteria using fuzzy membership functions, and (c) assessment of health risk levels based on contaminant concentration and fuzzy evaluation criteria. The related cancer risk levels are categorized into low, low-to-medium, medium, medium-to-high, and high. The developed FHRA is applied to a petroleum-contaminated groundwater system in western Canada. Three remediation scenarios with different efficiency (0, 60%, and 90%) and planning periods (10, 20, 40, and 60 years later) are examined for the study site, and the temporal variations of membership values for different risk levels at locations of interest are then identified. The obtained results are useful for assessing potential human health impacts when the on-site groundwater is used for drinking water supply. The developed risk assessment approach in this study offers an improved tool for quantifying uncertainties associated with risk evaluation criteria in contaminated site management, and it provides realistic support for remediation-related decisions.

Keywords: contamination, evaluation criteria, groundwater, fuzzy, risk assessment, simulation, uncertainty

1. Introduction

Leakage and spill of petroleum products from underground storage tanks and pipelines may result in many environmental concerns to governments, communities, and polluters themselves, by posing significant threats to groundwater resources across many petroleum-related sites in North America. Therefore, it is important to implement effective management and cleanup at such contaminated sites.

Risk assessment is a crucial element of site management process, with the capability of offering a significant potential in cost savings through carefully assessing and ranking the severity of site contamination (Bogardi et al., 1987; CCME, 1996; Carrington and Bolger, 1998). However, the insight about risks is usually limited by various complexities related to the chances of their occurrence and the potential consequences. Therefore, risk is inherently linked with uncertainty (Johnson and Slovic, 1998; Hoffman et al., 1999). The major approaches to account for uncertainties in environmental applications include stochastic analysis and fuzzy set theory (Isukapalli, 1999). For example, Lee et al. (1994, 1995) estimated the human-health risk from groundwater contamination and evaluate

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possible regulatory actions, by using fuzzy-set approach to represent the uncertainties associated with interspecies extrapolation, dose-response modeling and data inaccuracy. Labieniec et al. (1997) evaluated carcinogenic risk due to contaminated sites, by using probability distribution functions to account for uncertainties in input parameters associated with contaminant transport model. Bennett et al. (1998) developed an integrated modeling system to evaluate health risk, by passing results from the three-dimensional contaminant transport simulation and the related Monte-Carlo-based uncertainty analysis as inputs to a calculation of human exposure and health risk, with consideration of combined uncertainties attributable to both transport and exposure parameters. Mohamed and Cote (1999) developed a decision analysis system to evaluate risks that polluted sites might pose to human health by using a series of transport models (e.g. groundwater transport, run-off-erosion, soil-air diffusion and sediment diffusion-resuspension), and the fuzzy set theory was adopted to account for uncertainties in the modeling input parameters, while an inference model using fuzzy logic was constructed for reasoning of decision analysis. More recently, Lee et al. (2002) applied the USEPA guidelines and the empirically measured contaminant levels and exposure parameters to estimate residents' chronic hazard and carcinogenic risk in a groundwater-contaminated community after on-site remediation, by using Monte Carlo simulation approach. Chen et al. (2003) applied Monte Carlo simulation and fuzzy set theory to conduct site risk assessment, and the uncertainties in environmental quality criteria were taken into account through fuzzy membership functions. More related studies can be found in Heida et al. (1995), Pelmulder et al. (1996), Chen and Soulsby (1997), Carrington and Bolger (1998), Duke and Taggart (2000), Harter (2000), Blair et al. (2001), and Cho et al. (2002).

It is found from literature review that most of the previous works were dealing with parameter uncertainties associated with contaminant transport model in a risk assessment process, and very few studies have been reported to address the uncertainties in health risk evaluation criteria. This kind of uncertainties may come from data scarcity and the difficulty of extrapolating clinical exposure study results with animals to human health. In fact, neglecting uncertainties in such risk evaluation criteria may result in missed information and thus impractical decision support with regard to site management. In addition, there is a lack of studies on integrating advanced numerical subsurface models, such as multi-phase multi-component analysis, within a risk assessment framework (Chen, 2000). This kind of integration, however, can effectively facilitate the assessment of long-term risks at hydrocarbon-contaminated sites. Such a long-term risk assessment will then be crucial for providing support for decisions related to pollution mitigation strategies in terms of effective site management. Since risk assessment results have significant influences on the site management decisions, it is imperative that efforts be made in implementing improved contaminant transport simulation in the assessment process, as well as effectively handling uncertainties in evaluation criteria.

As an extension of the previous efforts, the objective of this study is to develop a simulation-based fuzzy health risk assessment (FHRA) approach that can quantify uncertainties associated with health impact evaluation criteria, and apply it to a petroleum-contaminated groundwater system in western Canada. This development is based on (a) simulation for the fate of contaminant (e.g. benzene) in subsurface through a 3-D multiphase multi-component numerical model, (b) quantification of excess lifetime cancer risk evaluation criteria using fuzzy membership functions, and (c) assessment of health risk levels based on contaminant concentration and fuzzy evaluation criteria. The related cancer risk levels are categorized into low, low-to-medium, medium, medium-to-high, and high. The membership values for different risk levels at identified location of interest will then be identified under different remediation scenarios and planning periods. The proposed risk assessment approach will offer an improved tool for quantifying uncertainties associated with risk evaluation criteria, and it would provide more realistic support for remediation-related decisions.

2. Methodology

2.1. Modeling Petroleum Contaminant Transport in Subsurface

Modeling for subsurface petroleum pollutant transport requires comprehensive description of various physical, chemical and biological processes in the complicated subsurface environment. Some fundamental mechanisms should be incorporated with the modeling system, including flow of relevant fluid phases (e.g. water, gas, non-aqueous phase liquid), mass transfer of components between fluid phases, and component transport in each phase. As a result, a multiphase compositional simulation approach has been recognized as effective tool in investigating subsurface transport of petroleum contaminant (Miller et al., 1998). In this study, a three-dimensional multiphase compositional modeling system named UTCHEM is proposed for facilitating the forecasting of subsurface contaminant fate under different pollution remediation scenarios (UTA, 2000). The system incorporates a variety of physical, chemical and biological process models within a general framework to characterize various contaminant transport processes in the subsurface environment. The basic conservation equation for mass components in the subsurface can be written as (Delshad et al., 1996; UTA, 2000):

$$\frac{\partial}{\partial t}(\phi \tilde{C}_k \rho_k) + \vec{\nabla} \cdot [\sum_{l=1}^{n_p} \rho_k (C_{kl} \vec{u}_l - \phi S_l \vec{\vec{D}}_{kl} \cdot \vec{\nabla} C_{kl})] = R_k \tag{1}$$

where k is component index, l is phase index, ϕ is soil porosity, $\tilde{C}_k$ is overall concentration of component k (volume fraction), ρ_k is density of component k [ML^{-3}], n_p is number of phases, C_{kl} is concentration of component k in phase l (volume fraction), $\vec{u}_l$ is Darcy velocity of phase l [LT^{-1}], S_l is the saturation of phase l, R_k is total source/sink term for component k (volume of component k per unit volume of porous media per unit time), and $\vec{\vec{D}}_{kl}$ is the dispersion tensor. The dispersion tensor is a function of phase dispersivities, Darcy velocities, and phase saturations (Delshad et al., 1996).

By substituting the multiphase-form Darcy's law in the above mass balance equation and summing over all components (n_{cv}), a pressure equation can be developed in terms of water phase pressure as follows (Delshad et al., 1996; de Blanc, 1998; UTA, 2000):

$$\phi C_t \frac{\partial P_w}{\partial t} + \vec{\nabla} \cdot \vec{\vec{K}} \cdot \lambda_{rT_c} \vec{\nabla} P_w = -\vec{\nabla} \cdot \sum_{l=1}^{n_p} \vec{\vec{K}} \cdot \lambda_{rlc} \vec{\nabla} z + \vec{\nabla} \cdot \sum_{l=1}^{n_p} \vec{\vec{K}} \cdot \lambda_{rlc} \vec{\nabla} P_{clw} + \sum_{k=1}^{n_{cv}} Q_k \tag{2}$$

where C_t is total compressibility, P_w is water phase pressure, λ_{rlc} is relative mobility, λ_{rTc} is total relative mobility, P_{clw} is capillary pressure difference between phase l and the water phase, and Q_k is injection/production rate for component k per bulk volume. Terms λ_{rlc} and λ_{rTc} are functions of component concentration and soil permeability (UTA, 2000), and the capillary pressure can be related to phase saturation and permeability based on pressure-saturation-permeability models such as the Lenhard and Parker model (Delshad et al., 1996).

The relevant equations can be solved numerically using the block-centered finite difference approach with the following solution procedures (Delshad et al., 1996; UTA, 2000): (a) solve the pressure equation implicitly to yield water phase pressure in all grid blocks; (b) capillary pressures from previous time step are used to determine the pressure of other phases in each grid block; (c) Darcy's law is used to determine phase velocities; (e) mass conservation equations are solved explicitly to yield concentration of each component in each grid block; (f) phase concentrations and saturations are determined through flash calculations; (g) new capillary pressures are determined from the new saturations, and (h) repeat the procedures for each time step until simulation ends.

2.2. Fuzzy Sets Theory

The foundation of fuzzy set theory is the membership function (MF) (or possibility distribution) that can be used to represent linguistic concepts. The MF indicates the degree to which an element of a set fits the linguistic concept, and the general notation of fuzzy sets can be as follows (Lai and Hwang, 1992):

$$A(x) = \{(x, \mu_A(x)), x \in X, \mu_A(x) \in [0,1]\} \tag{3}$$

where X={x} is a universe set of elements, $A(x)$ is a fuzzy set of X, and $\mu_A(x)$ is the grade or degree of membership for x in A. Usually $\mu_A(x)$ is a number in the range 0 to 1, with 1 representing full membership and 0 representing non-membership. Therefore, this theory has the power of handling the concept of "partial truth" (i.e. truth values between "completely true" and "completely false") in terms of uncertainty analysis. Accordingly, the linguistic variables are a critical aspect of many fuzzy set applications, where general terms such a "low", "medium" and "high" are each used to capture a range of numerical values. For example, the membership function of a fuzzy set of "approximately 10" may be described as follows (Figure 1):

$$\mu_A(x) = \begin{cases} x/2-4 & 8 \le x \le 10 \\ 6-x/2 & 10 < x \le 12 \\ 0 & otherwise \end{cases} \tag{4}$$

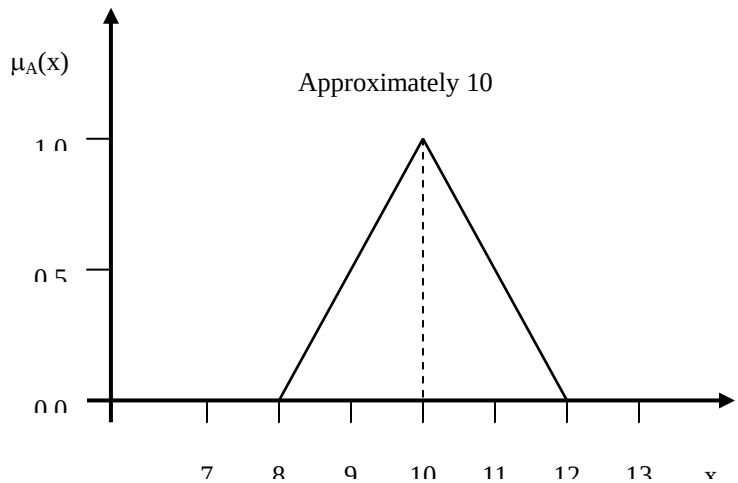

Figure 1 Membership function of "approximately 10"

Some other examples may include "less porous", "porous" and "more porous". Let $\mu_{A1}(\phi)$, $\mu_{A2}(\phi)$ and $\mu_{A3}(\phi)$ be the membership functions of the fuzzy sets "less porous", "porous" and "more porous", respectively, it can then be assumed that $\mu_{A1}(\phi)$, $\mu_{A2}(\phi)$ and $\mu_{A3}(\phi)$ are defined as follows in order to characterize such linguistic variables:

$$\mu_{A1}(\phi) = \begin{cases} 1 & if \quad \phi < 0.25 \\ (0.35-\phi)/0.1 & if \quad 0.25 \le \phi \le 0.35 \\ 0 & if \quad \phi > 0.35 \end{cases} \tag{5a}$$

$$\mu_{A2}(\phi) = \begin{cases} (\phi-0.25)/0.15 & if \quad 0.25 \le \phi \le 0.4 \\ (0.55-\phi)/0.15 & if \quad 0.4 \le \phi \le 0.55 \\ 0 & otherwise \end{cases} \tag{5b}$$

$$\mu_{A3}(\phi = \begin{cases} 0 & if \quad \phi < 0.45 \\ (\phi - 0.45)/0.1 & if \quad 0.45 \le \phi \le 0.55 \\ 1 & if \quad \phi > 0.55 \end{cases} \tag{5c}$$

where ϕ is the soil porosity. The membership functions of these three fuzzy sets can be shown in Figure 2. It can be found that the fuzzy set theory can allow these stratified sets to overlap (e.g., a porosity of 0.30 may be classified

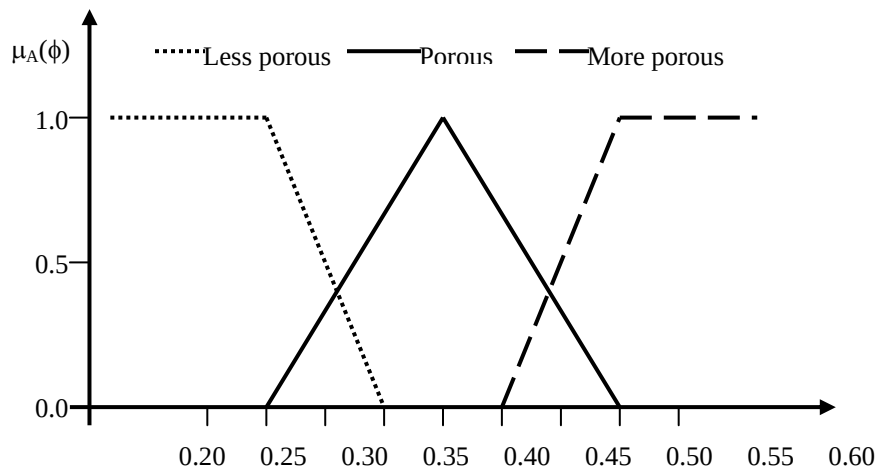

Figure 2 Membership functions of “less porous”, “porous”, and “more porous”

in both the “less porous” and “porous” categories, with varying degrees of belonging or membership to each group).

2.3. Fuzzy Health Risk Assessment

Health risk assessment (HRA) is specifically focused on the aspect of human health impacts, and it determines the risks that contaminated sites pose and/or may pose in the future to human health. The approach for HRA is to compare the contaminant concentration with the corresponding health risk limit (HRL). The HRL is the concentration of a groundwater contaminant, or a mixture of contaminants, that can be safely consumed daily for a lifetime. The critical variable in the calculation of a health risk limit is the potency of the substance or chemical. To quantify human health risks, pollutants are characterized as carcinogens and non-carcinogens. The measure of potency for non-carcinogens is called the “reference dose” (RfD) and the measure of potency for carcinogens is called the “slope factor” (SF). In practical situation, the HRA is usually conducted through the models recommended by USEPA (1992). They include the excess lifetime cancer risk (ELCR) method for carcinogenic risk, and hazard index (HI) method for non-carcinogenic risk (USEPA 1992):

$$\text{ELCR} = \text{CDI} \times \text{SF} \tag{6}$$

$$\text{HI} = \text{CDI} / \text{RfD} \tag{7}$$

where CDI is the chronic daily intake (mg/kg·d); SF is a carcinogen slope factor (kg.d/mg); ELCR is the probability of excess lifetime cancer from exposure to a specific pollutant, and RfD is a reference dose (mg/kg·day). The CDI can be obtained based on pollutant concentrations in groundwater, which is expressed as follows (USEPA, 1989):

$$\text{CDI} = \text{CW} \times \text{IR} \times \text{EF} \times \text{ED} / (\text{AT} \times \text{BW}) \tag{8}$$

where CW is pollutant concentration in groundwater (mg/L); IR is human ingestion rate (L/day); EF is exposure frequency (days/year); ED is average exposure duration (year); BW is average body weight (kg), and AT is

averaging time (AT = 365 × ED days).

Eq. (8) provides the relationship between chronic daily exposure level (i.e., CDI value) and many impact factors. Excess lifetime cancer risk (ELCR) can then be calculated by multiplying the CDI with the cancer slope factor based on Eq. (6). Carcinogen risk value means how many people will get the cancer per million of population because of exposure to contaminants. On the other hand, non-carcinogen risk is denoted by hazard index (HI), which is calculated from the chemical intake (mg/kg/day) divided by non-carcinogenic reference dose (RfD) (mg/kg/day). For example, the carcinogenic health risk of an adult for drinking groundwater containing 0.3 mg/L of benzene for 30 years can be calculated as follows. According to USEPA (1989), the values of parameters for calculating CDI using Equation (8) are IR = 2 L/day, EF = 350 days/year, ED = 30 years, AT = (365 days/year) × (30 years), and BW = 70 kg. Then $CDI_{benzene}$ is 0.00823 mg/kg.d based on Equation (8). The carcinogenic risk (ELCR) is thus 2.4E-4 based on Eq. (6) by applying the SF value of 0.029 $(mg/kg.d)^{-1}$ as recommended by USEPA (1989), meaning that if 10,000 people were exposed to a carcinogen (e.g., benzene), 2.4 persons would be expected to develop cancer over their lifetime as a result of such exposure.

The toxicologic data used to calculate reference doses (RfD) and slope factors (SF) usually come from laboratory studies on animals. The health risk assessment usually adopts reference doses and slope factors published by the USEPA. The USEPA can provide updating of the health risk limits to keep them current. As more toxicologic studies are completed and evaluated, updated data on reference doses and cancer potency slope factors may be added to the USEPA databases. The USEPA may change an RfD or slope factor due to new scientific data. This may result in great differences in the calculated risks, and there will be a number of uncertainties existing when such toxicological parameters were applied to calculate human health risks, leading to uncertainties in health risk evaluation criteria (e.g. ELCR). For example, the USEPA defines acceptable risk for carcinogens as within a wide range of 10^{-4} to 10^{-6}, leading to unsuitability of evaluation criteria and thus uncertainties in the assessment of health risks. Therefore the evaluation criteria uncertainties should be incorporated into the process of quantifying risks. However, it is hard to apply probabilistic distribution to describe the applicability or suitability of such criteria, resulting difficulties in quantifying the associated health risks. These uncertainties usually show subjective features, as a result, the fuzzy set theory is proposed in this study to account for the uncertainties.

In this study, the carcinogenic health risk introduced by benzene will be investigated. The health risk levels will be categorized into “low”, “low-to-medium”, “medium”, “medium-to-high”, and “high” by associating with different magnitudes of ELCR. The investigated ELCR is set to change from 1E-6 to 1E-2 by increasing to around 5 times for each interval. The eight conversion scale figures developed by Chen et al. (1992) will be used to systematically transform linguistic terms to their corresponding fuzzy sets. These scale figures cover the universe of expressing the terms “HIGH” vs “LOW”. The corresponding linguistic-term conversion procedure involves selecting a figure that contains all the verbal terms given by the decision-maker, and then using the membership function set for that figure to represent the meaning of these verbal terms. As a result, the membership functions of these five fuzzy sets can be constructed as shown in Figure 3.

For example, if the calculated ELCR is 5E-5, then the associated risk level can be categorized as partly “low-to-medium” (with a membership grade of 0.50) and partly “medium” (with a membership grade of 0.50). Therefore, the possibility of different risk levels at location of interest can then be obtained by considering the uncertainties in risk evaluation criteria. The membership functions of the five fuzzy sets can then be expressed as follows, where “L”, “L-M”, “M”, “M-H”, and “H” represent risk levels of “low”, “low-to-medium”, “medium”, “medium-to-high”, and “high”, respectively.

$$\mu_L(ELCR) = \begin{cases} 1 & if \quad ELCR < 1E-6 \\ -5 - Log(ELCR) & if \quad 1E-6 \le ELCR < 1E-5 \\ 0 & if \quad ELCR \ge 1E-5 \end{cases} \tag{9}$$

$$\mu_{L-M}(ELCR) = \begin{cases} 0 & if \quad ELCR < 1E-6 \\ 6 + Log(ELCR) & if \quad 1E-6 \le ELCR < 1E-5 \\ 4 - Log(ELCR) & if \quad 1E-5 \le ELCR < 1E-4 \\ 0 & if \quad ELCR \ge 1E-4 \end{cases} \tag{10}$$

$$\mu_M(ELCR) = \begin{cases} 0 & if \quad ELCR < 1E-5 \\ 5 + Log(ELCR) & if \quad 1E-5 \le ELCR < 1E-4 \\ 3 - Log(ELCR) & if \quad 1E-4 \le ELCR < 1E-3 \\ 0 & if \quad ELCR \ge 1E-3 \end{cases} \tag{11}$$

$$\mu_{M-H}(ELCR) = \begin{cases} 0 & if \quad ELCR < 1E-4 \\ 4 + Log(ELCR) & if \quad 1E-4 \le ELCR < 1E-3 \\ 2 - Log(ELCR) & if \quad 1E-3 \le ELCR < 1E-2 \\ 0 & if \quad ELCR \ge 1E-2 \end{cases} \tag{12}$$

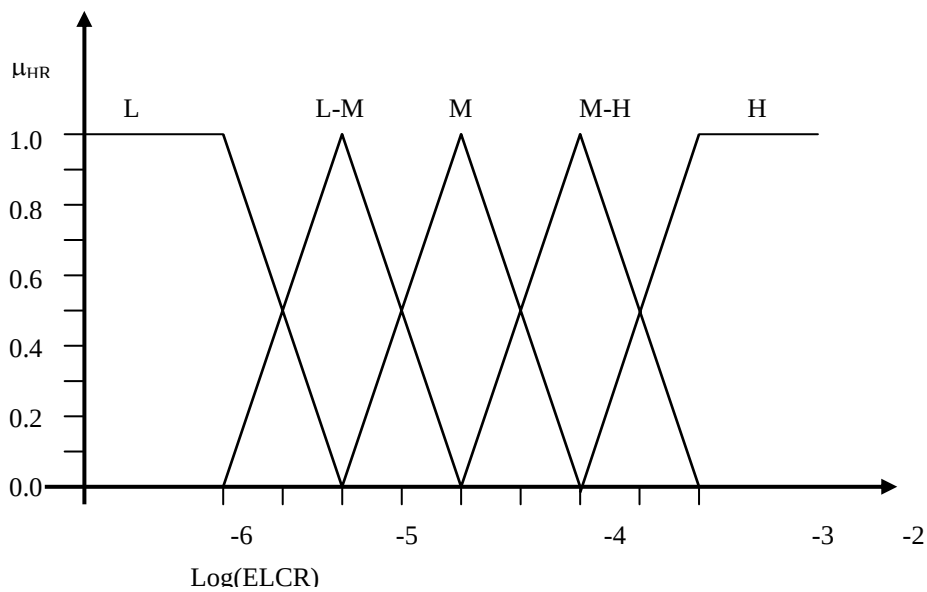

Figure 3 Membership function of excess lifetime cancer risk (ELCR)

$$\mu_H(ELCR) = \begin{cases} 0 & if \quad ELCR < 1E-3 \\ 3 + Log(ELCR) & if \quad 1E-3 \le ELCR < 1E-2 \\ 1 & if \quad ELCR \ge 1E-2 \end{cases} \tag{13}$$

3. CASE STUDY

A petroleum-contaminated site in western Canada was selected as a case to illustrate the proposed risk assessment

approach. The site has been operated as a natural gas processing plant to remove naphtha condensate from the natural gas stream prior to transport to a regional transmission line. Figure 4 shows an overview of the study site. Throughout the history of the site, naphtha condensate, a waste liquid removed from the gas by a series of scrubbers, was disposed of in a previous underground storage tank (UST). Due to leakage of this UST in the past years, the site has been contaminated. During the past several years, a number of field investigations have been conducted to examine the site hydro-geologic conditions and related pollution problems. The groundwater flow is towards the northwest direction at the site, which was obtained through multiple site investigation results. The previous UST that was at the upgradient location of the site has leaked around 55 m^3 of petroleum products before it was removed. Various forms of the pollutants were found at the downgradient directions, and they include free product, vapor phase hydrocarbon, dissolved hydrocarbon in groundwater, and trapped hydrocarbon in the soil. In this study, the benzene from petroleum contaminants is selected as the constituent of interest. Figure 5 shows the observed benzene concentrations in groundwater at the site. The highest benzene concentration of 0.345 mg/L was observed at a monitoring well located in the west of the previous UST, and this concentration is much higher than the regulated local environmental quality guideline (e.g. 0.005 mg/L). As a result, the soil and groundwater contamination at this site may pose serious health risk to the surrounding communities, and conducting effective risk assessment is desired.

4. Results Analysis

4.1 Spatial and temporal distribution of excess lifetime cancer risk

The proposed multiphase compositional modeling system facilitates dynamic modeling on pollutant fate and transport under a number of remediation scenarios, and the related results provide sound bases for clarifying contamination conditions at the site in the future. Based on the modeling results, a number of critical questions can be answered, such as “if no remediation is taken for the site, what will happen underground?”, “if a remediation action with an efficiency of 60% is taken, what will happen underground?”, and “if a remediation action with an efficiency of 90% is taken, what will happen underground?”. The simulated benzene concentrations in groundwater and the relevant plume extents at 10, 20, 40, and 60 years later under 0%, 60%, and 90% remediation actions, are therefore used as crucial information for assessing risks at the site due to groundwater contamination when the on-site groundwater is used for drinking water supply. The relevant parameters for health risk assessment model as described by Eqs. (6) and (8) include the following values: IR = 2 L/day, EF = 350 days/year, ED = 30 years, BW = 70 kg, and SF = 0.029 $(mg/kg.d)^{-1}$.

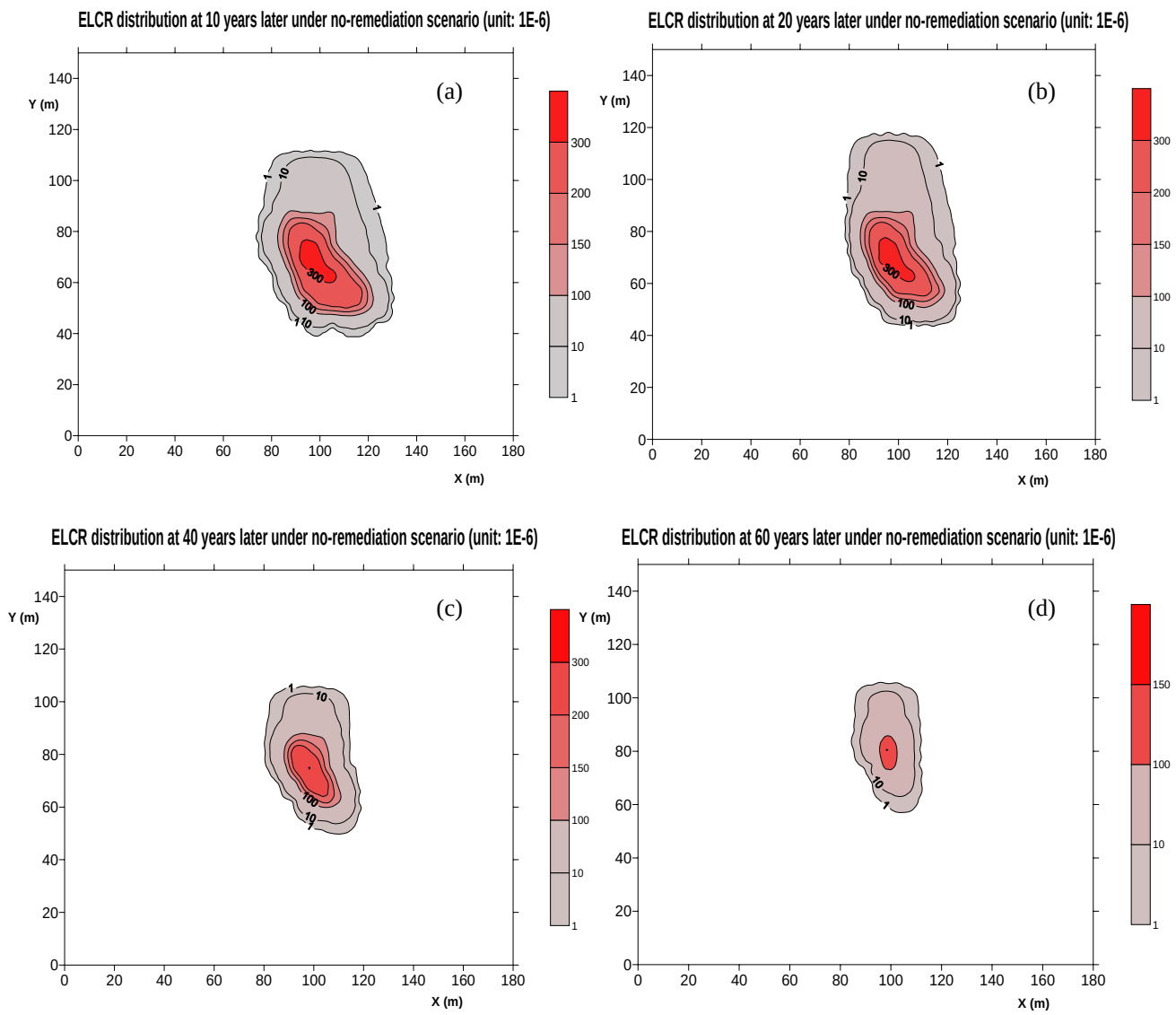

Figure 6 ELCR distributions under no-remediation scenario

Figure 6(a) shows spatial distribution of the predicted ELCR 10 years later under the no-remediation scenario. The results illustrate that the 1E-6-ELCR (corresponding to the upper bound for low risk with membership value of 1) violated zone will extend almost 46 m northwest of the site's previous UST with an area of about 3,340 m^2; the 1E-5-ELCR (corresponding to low-to-medium risk with membership value of 1) violated zone will extend over 42 m northwest of the former UST, and the total area of this zone is about 2,500 m^2; the 1E-4-ELCR (corresponding to medium risk with membership value of 1) violated zone extends over 35 m northwest of the former UST with a total area of 1,100 m^2. Quantitatively, the probability of getting cancer will be more than one out of 10,000 people who use the groundwater under this zone as the drinking water source. There is no 1E-3-ELCR (corresponding to medium-to-high risk with membership value of 1) violated zone. Similarly, Figure 6(b) shows spatial ELCR distribution 20 years later under the no-remediation scenario. It is indicated that the shapes and distributions of the above zones are similar to those 10 years later. However, the plume of the 1E-6-ELCR violated zone will move

backward to the southwest and become smaller. The reasons for this small variation primarily lie in that slow groundwater flow and low soil permeability lead to slow migration of contaminants and the rate of biodegradation for contaminants is very slow. Likewise, Figures 6(c) and 6(d) present spatial distribution of these zones under the no-remediation scenario 40 and 60 years later, respectively. It is indicated that these zones will shrink and become smaller as time goes on.

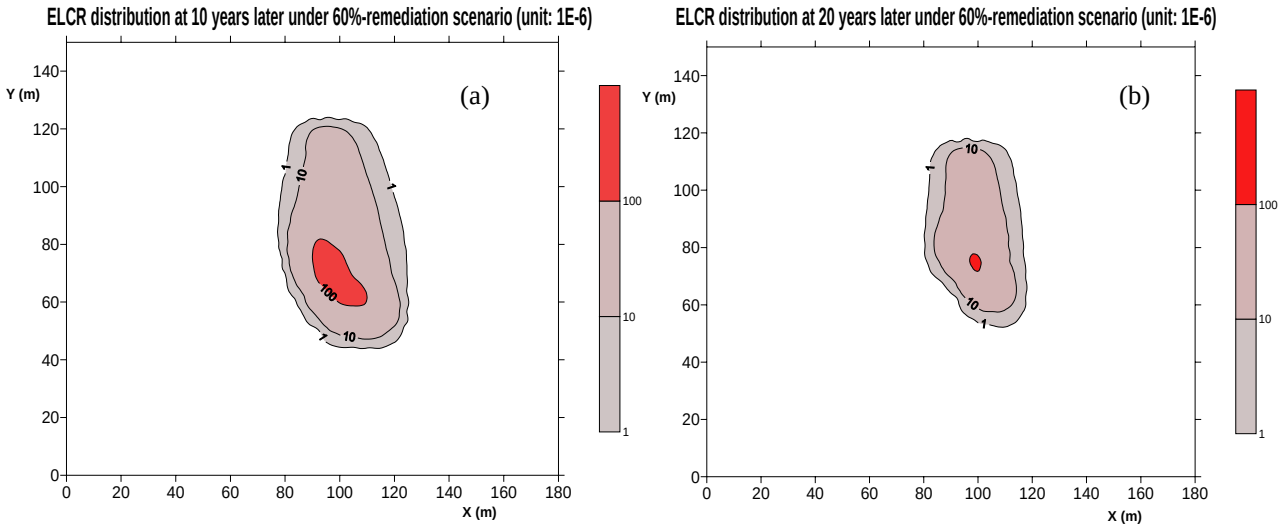

Figure 7 ELCR distributions under 60%-remediation scenario

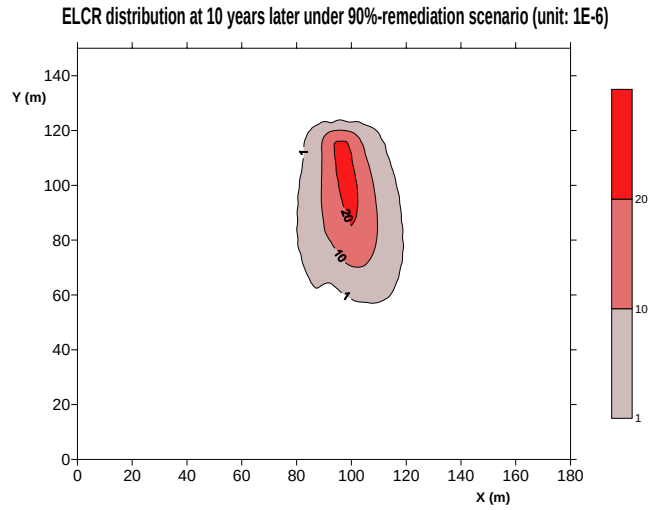

Figure 8 ELCR distribution under 90%-remediation scenario

Figures 7(a) and 7(b) illustrate the spatial distribution of ELCR under the 60%-remediation scenario at 10 and 20 years later, respectively. The results indicate that the 1E-6-ELCR violated zone will extend over 42 m northwest of the former UST with a total area of 3,160 m^2 at 10 years later, and 39 m northwest of the former UST with an area of 2,142 m^2 at 20 years later; the 1E-5-ELCR violated zone will have areas of 2,176 and 1,267 m^2 at 10 and 20 years later, respectively. The 1E-4-ELCR violated zone will become much smaller at 10 years later and almost diminish at 20 years later under this scenario. Figure 8 presents the spatial ELCR distribution under the 90%-remediation scenario at 10 years later. It is found that the 1E-6-ELCR violated zone will decrease to 2,278 m^2, while the

1E-5-ELCR violated zone decreases to 822 m^2. There will be 1E-4-ELCR violated zone under this scenario at 10 years later. In addition, it is found that the 1E-6-ELCR violated zone significantly decreases to an area of about 30 m^2 at 20 years later under the 90%-remediation scenario while the 1E-5-ELCR violated zone will diminish.

4.2 Possibility variations of different risk levels at locations of interest

Two locations of interest are selected for examining the possibility (i.e. membership value) of different levels of risk under the three remediation scenarios at various planning periods. They include grid 318 at (105, 87) and grid 380 at (117, 75) that are close to the former UST as shown in Figure 9. Figures 10(a) to 10(d) and Figures 11(a) to 11(c) present the possibility variations of different risk levels with planning periods under different remediation

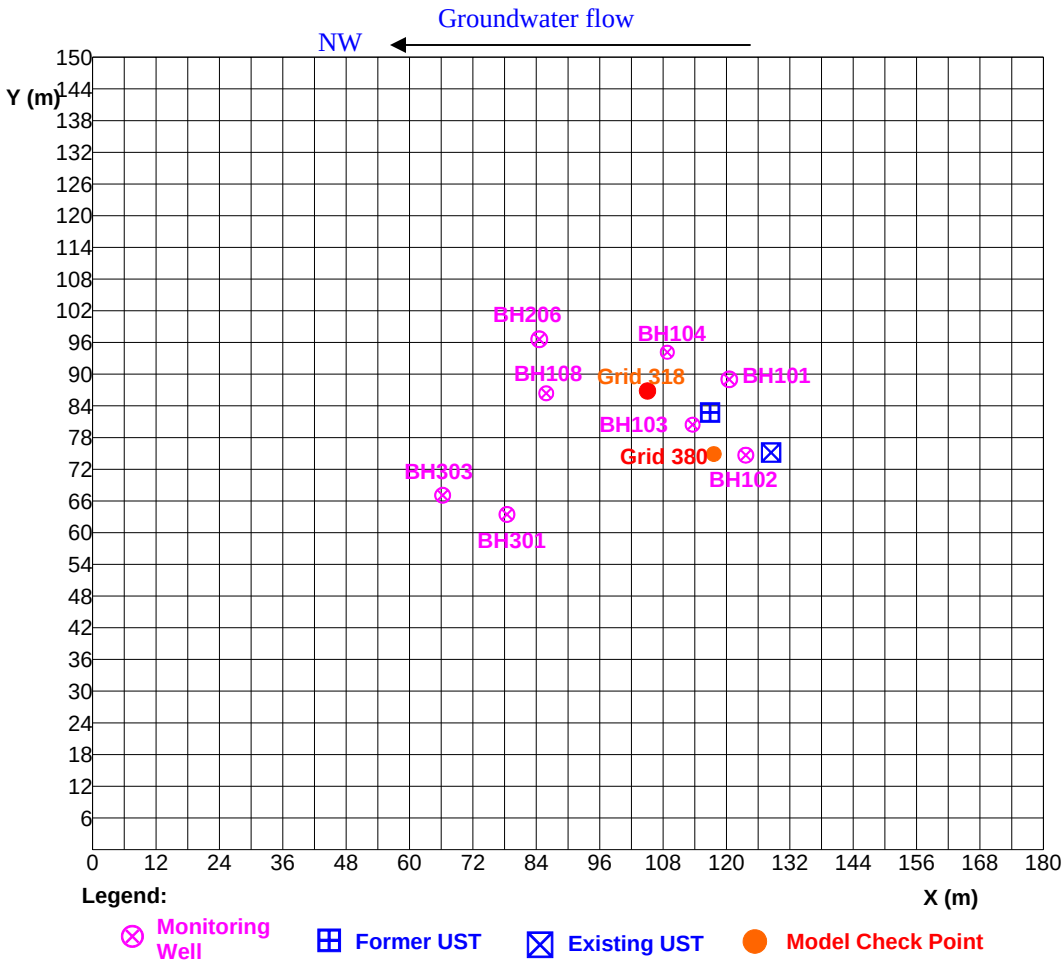

Figure 9 Simulation domain for the study site

scenarios at grids 318 and 380, respectively.

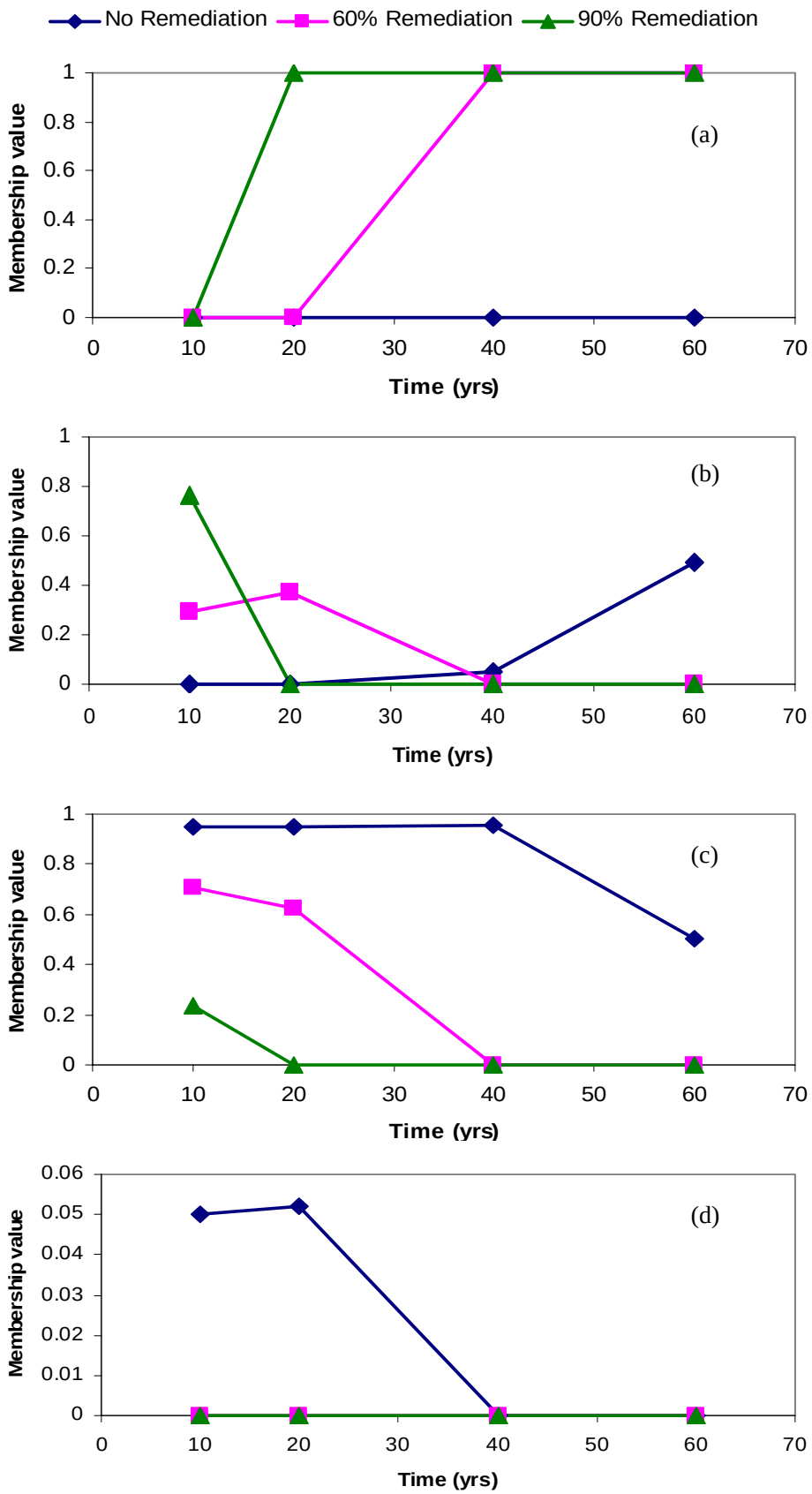

Figure 10 Membership value of various risk levels under different remediation scenarios at node (105,87), a: L, b: L-M, c: M, d: M-H

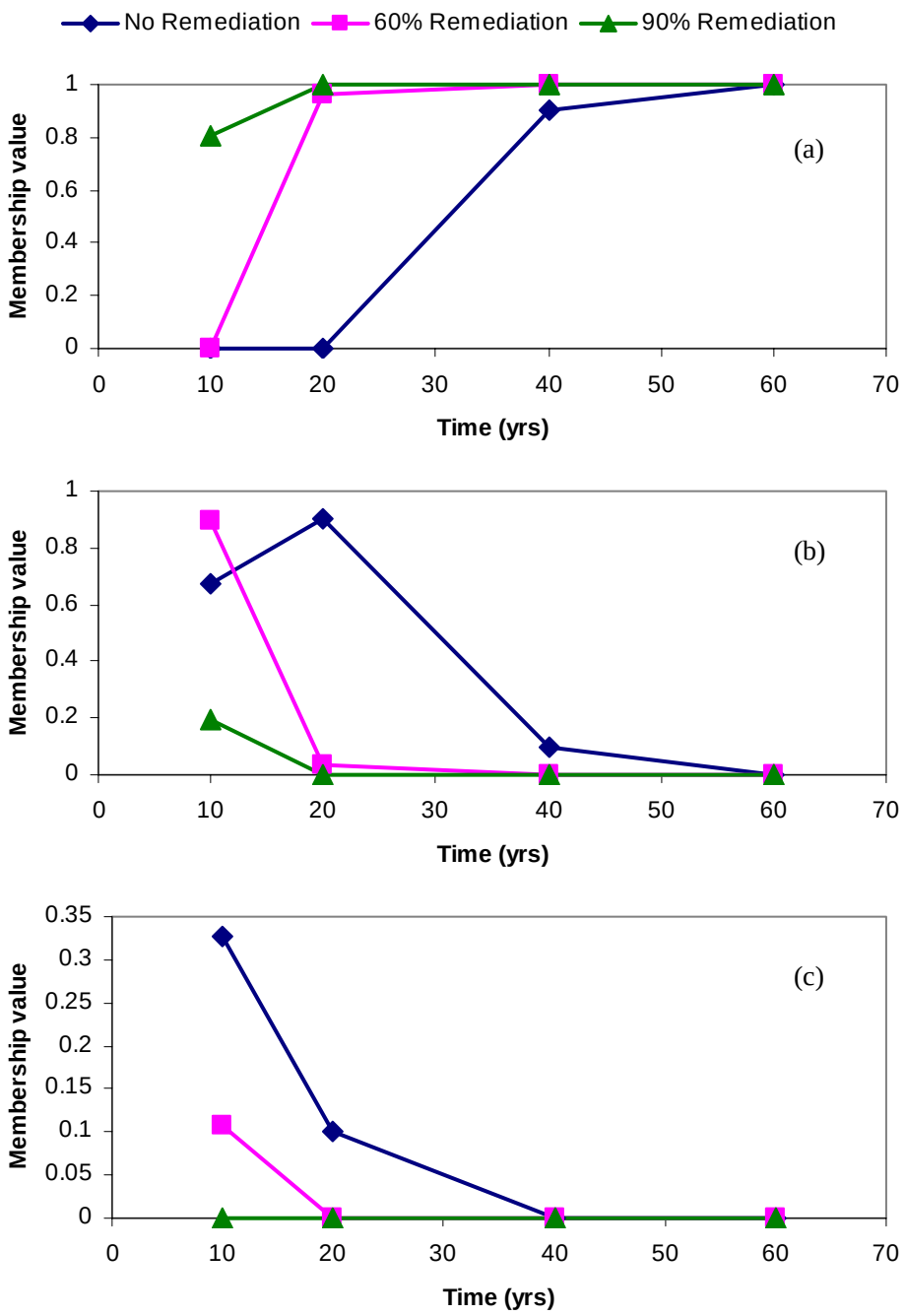

Figure 11 Membership value of various risk levels under different remediation scenarios at node (117,75), a: L, b: L-M, c: M

(1) No-remediation scenario

For grid 318, it is illustrated from Figure 10(a) that the possibility of low risk is zero under the no-remediation scenario at all the planning periods (e.g. 10, 20, 40 and 60 years later), indicating the existence of higher extents of risks; the membership value of low-to-medium risk [Figure 10(b)] is zero at 10 and 20 years later, and increases to 0.047 and 0.495 at 40 and 60 years later, respectively, indicating the reduction of risk extents as time goes on; the

membership values of medium risk [Figure 10(c)] are 0.95, 0.948, 0.953 and 0.505 at 10, 20, 40 and 60 years later, respectively, indicating the highest possibility of medium risk at grid 318 at most of the planning periods and the reduction of risk extents at 60 years later under no-remediation scenario; the possibility of medium-to-high risk is very low, with membership values of 0.05, 0.052, 0, and 0 at 10, 20, 40 and 60 years later, respectively [Figure 10(d); the possibility of high risk level is zero for all the planning periods, indicating that the ELCR is always less than 1E-3. As a result, there will be high possibility of medium risk level at grid 318 under this scenario.

For grid 380, it is found from Figure 11(a) that the membership values of low risk are 0, 0, 0.9 and 1.0 at 10, 20, 40 and 60 years later under the no-remediation scenario, indicating the existence of higher extents of risks at 10 and 20 years later, and the reduction of risk extents starting from 40 years later; the membership values of the low-to-medium risk [Figure 11(b)] are 0.674, 0.9, 0.1, and 0 at 10, 20, 40 and 60 years later, respectively; the membership values of medium risk are 0.326 and 0.1 at 10 and 20 years later, respectively, and then decrease to zero at 40 years later; there is no possibility of medium-to-high risk at grid 380 at all the planning periods.

(2) 60%-remediation scenario

For grid 318, it is illustrated from Figure 10(a) that the possibility of low risk is zero under the 60%-remediation scenario at 10 and 20 years later, and increases to 1.0 starting from 40 years later, indicating the existence of higher extents of risks in the beginning, and then significant reduction of such risks after 40 years later; the membership values of low-to-medium risk [Figure 10(b)] are 0.296, 0.374, 0, and 0 at 10, 20, 40 and 60 years later, respectively, indicating the reduction of risk extents as time goes on; the membership values of medium risk [Figure 10(c)] are 0.704, 0.626, and 0 at 10, 20, and 40 years later, respectively, indicating the highest possibility of medium risk at grid 318 at the beginning of the planning periods; there is no possibility of medium-to-high risk at any planning periods under the 60%-remediation scenario, indicating that this scenario considerably decreases risk levels as compared to the no-remediation scenario.

For grid 380, it is found from Figure 11(a) that the membership values of low risk are 0, 0.963, and 1.0 at 10, 20, and 40 years later under the 60%-remediation scenario, indicating the existence of higher extents of risks only at 10 years later, and the significant reduction of risk extents starting from 20 years later; the membership values of the low-to-medium risk [Figure 11(b)] are 0.893, 0.037, and 0 at 10, 20, and 40 years later, respectively; the membership values of medium risk are 0.107 at 10 years later, and then decrease to zero at 20 years later, indicating the lower extents of risks as compared to the no-remediation scenario.

(3) 90%-remediation scenario

For grid 318, it is illustrated from Figure 10(a) that the possibility of low risk is zero under the 90%-remediation scenario at 10 years later, and increases to 1.0 starting from 20 years later, indicating the significant reduction of risk extents after 20 years later; the membership values of low-to-medium risk [Figure 10(b)] are 0.763 and 0 at 10 and 20 years later, respectively, indicating the high possibility of low-to-medium risk only at the beginning of the planning periods; the membership values of medium risk [Figure 10(c)] are 0.237 and 0 at 10 and 20 years later, respectively, indicating that this scenario can significantly reduce risks even at the earlier stages of the planning periods; there is no possibility of medium-to-high risk under this scenario.

For grid 380, it is found from Figure 11(a) that the membership values of low risk are 0.805 and 1.0 at 10 and 20 years later under the 90%-remediation scenario, indicating very high possibility of low risk at all the planning

periods; the membership values of the low-to-medium risk [Figure 11(b)] are 0.195 and 0 at 10 and 20 years later, respectively; there is no possibility of medium risk at grid 380 under the 90%-remediation scenario.

5. Conclusions

In this study, an integrated approach for risk assessment of the subsurface contamination was developed through incorporation of multi-phase compositional subsurface modeling within a general health risk assessment framework using the concept of excess lifetime cancer risk (ELCR). The uncertainties in health impact evaluation criteria (e.g. ELCR) were effectively incorporated within the assessment process. This development was based on (a) simulation for the fate of contaminant (e.g. benzene) in subsurface through the proposed 3-D multiphase multi-component numerical model under different remediation scenarios (e.g. 0%, 60% and 90% remediation efficiencies) for different planning periods (e.g. 10, 20, 40 and 60 years later), (b) quantification of excess lifetime cancer risk evaluation criteria using fuzzy membership functions while the risk levels were categorized into five fuzzy sets including low, low-to-medium, medium, medium-to-high and high risks, and (c) assessment of health risk levels based on ELCR distributions and fuzzy evaluation criteria. The developed fuzzy health risk assessment (FHRA) approach was applied to a petroleum-contaminated groundwater system in western Canada. The zones with different ELCR distributions were calculated, and the membership values for different risk levels at identified location of interest were effectively identified under the three remediation scenarios and four planning periods. The proposed risk assessment approach will offer an improved tool for quantifying uncertainties associated with risk evaluation criteria, and it would provide more realistic support for remediation-related decisions. This study examined the carcinogenic risk from one contaminant, and considered uncertainties in health impact evaluation criteria. However, the comprehensive consideration of carcinogenic and non-carcinogenic risks from a number of contaminants may be needed for site management decisions, and the methodology developed in this study can be expanded to accommodate this kind of comprehensive consideration. In addition, many other uncertainties related to soil properties and human exposure, such as daily ingestion rate, body weight and exposure time, may also affect the risk levels, and should be examined in further studies.

References

Bennett, D. H., A. L. James, T. E. McKone, and C. M. Oldenburg, 1998. On uncertainty in remediation analysis: variance propagation from subsurface transport to exposure modeling, *Reliability Engineering and System Safety*, 62 (1/2): 117-129.

Blair, A. N., B. M. Ayyub, and W. J. Bender, 2001. Fuzzy stochastic risk-based decision analysis with the mobile offshore base as a case study, *Marine Structures*, 14 (1): 69-88.

Bogardi, I., L. Duckstein, and A. Bardossy, 1987. Uncertainty in environmental risk analysis, In: Y.Y. Haimes and E.Z. Stakhiv (Editors), *Risk Analysis and Management of Natural and Man-made Hazards*, ASCE, New York, 154-170.

Carrington, C. D., and P. M. Bolger, 1998. Uncertainty and risk assessment, *Human and Ecological Risk Assessment*, 4 (2): 253-257.

CCME (Canadian Council of Ministers of the Environment), 1996. *A Framework for Ecological Risk Assessment: General Guidance*. Canadian Council of Ministers of the Environment, National Contaminated Sites Remediation

Program, Ottawa, ON.

Chen, M., and C. Soulsby, 1997. Risk assessment for a proposed groundwater abstraction scheme in Strathmore, North-East Scotland: a modelling approach, *Journal of the Institution of Water and Environmental Management*, 11 (1): 47-55.

Chen, S. J., C. L. Hwang, M. J. Beckmann, and W. Krelle, *Fuzzy Multiple Attribute Decision Making: Methods and Applications*, Springer-Verlag, New York, 1992.

Chen, Z., 2000. *Integrated Environmental Modeling and Risk Assessment under Uncertainty*, Ph.D. dissertation, University of Regina, Regina, SK, Canada.

Chen, Z., G. H. Huang, and A. Chakma, 2003. Hybrid fuzzy-stochastic modeling approach for assessing environmental risks at contaminated groundwater systems, *Journal of Environmental Engineering*, 129 (1): 79-88.

Cho, H. N., H. H. Choi, and Y. B. Kim, 2002. A risk assessment methodology for incorporating uncertainties using fuzzy concepts, *Reliability Engineering & System Safety*, 78 (2): 173-183.

de Blanc, P. C., 1998. *Development and Demonstration of a Biodegradation Model for Non-aqueous Phase Liquids in Groundwater*, PhD Dissertation, The University of Texas at Austin, Austin, TX.

Delshad, M., G. A. Pope, and K. Sepehrnoori, 1996. A compositional simulator for modeling surfactant enhanced aquifer remediation, 1. formulation, *Journal of Contaminant Hydrology*, 23 (4): 303-327.

Duke, L. D., and M. Taggart, 2000. Uncertainty factors in screening ecological risk assessments, *Environmental Toxicology and Chemistry*, 19 (6): 1668-1680.

Harter, T., 2000. Application of stochastic theory in groundwater contamination risk analysis: suggestions for the consulting geologist and/or engineer, *Special Papers (Geological Society of America)*, 348: 43-52.

Heida, H., M. V. D. Berg, and K. Olie, 1995. Risk assessment approach to evaluate potential remedial actions at the Diemerzeedijk hazardous waste site, *Hazardous Waste & Hazardous Materials*, 12 (1): 1-14.

Hoffman, F. O., D. B. Chambers, and R. H. Stager, 1999. Uncertainty is part of making decisions, *Human and Ecological Risk Assessment*, 5 (2): 255-261.

Isukapalli, S. S. 1999. *Uncertainty Analysis of Transport-Transformation Models*, PhD Dissertation, The State University of New Jersey, New Brunswick, NJ.

Johnson, B. B., and P. Slovic, 1998. Lay views on uncertainty in environmental health risk assessment, *Journal of Risk Research*, 1 (4): 261-279.

Labieniec, P. A., D. A. Dzombak, and R. L. Siegrist, 1997. Evaluation of uncertainty in a site-specific risk assessment, *Journal of Environmental Engineering*, 123 (3): 234-243.

Lai, Y. –J., and C.-L. Hwang, 1992. *Fuzzy Mathematical Programming Methods and Applications*, Springer-Verlag, Berlin.

Lee, L. J. H., C. C. Chan, C. W. Chung, Y. C. Ma, G. S. Wang, and J. D. Wang, 2002. Health risk assessment on residents exposed to chlorinated hydrocarbons contaminated in groundwater of a hazardous waste site, *Journal of Toxicology and Environmental Health, Part A*, 65 (3/4): 219-235.

Lee, Y. W., M. F. Dahab, and I. Borgardi, 1994. Fuzzy decision making in ground water nitrate risk management, *Water Resources Research*, 30(1): 135-148.

Lee, Y. W., M. F. Dahab, and I. Bogardi, 1995. Nitrate-risk assessment using fuzzy-set approach, *Journal of Environmental Engineering*, 121 (3): 245-256.

Miller, C. T., G. Christakos, P. T. Imhoff, J. F. McBride, and J. A. Pedit, 1998. Multiphase flow and transport modeling in heterogeneous porous media: challenges and approaches, *Advances in Water Resources*, 21 (2): 77-120.

Mohamed, A. M. O., and K. Cote, 1999. Decision analysis of polluted sites –a fuzzy set approach, *Waste Management*, 19 (7): 519-533.

Pelmulder, S. D., W. W. G. Yeh, and W. E. Kastenberg, 1996. Regional scale framework for modeling water resources and health risk problems, *Water Resources Research*, 32 (6): 1851-1861.

USEPA (U.S. Environmental Protection Agency), 1989. *Risk Assessment Guidance for Superfund, Volume I: Human Health Evaluation Manual (Part A)*, U.S. Environmental Protection Agency, Office of Emergency and Remedial Response, EPA 540/1-89/002, Washington, D.C.

USEPA (U.S. Environmental Protection Agency), 1992. *Guidelines for Exposure Assessment*, USEPA 600Z-92/001, 29 May 1992, U.S. Environmental Protection Agency, Risk Assessment Forum, Washington, DC, 170 pp.

UTA (University of Texas at Austin), 2000. *Technical Documentation for UTCHEM-9.0: A Three-Dimensional Chemical Flood Simulator*, Reservoir Engineering Research Program, Center for Petroleum and Geosystems Engineering, University of Texas at Austin, TX. July 2000.