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INTEGRATED ENVIRONMENTAL RISK ASSESSMENT FOR PETROLEUM-CONTAMINATED SITES – A NORTH AMERICAN CASE STUDY

Z. Chen, G. H. Huang and A. Chakma

Environmental Systems Engineering, Faculty of Engineering, University of Regina, Regina, SK S4S 0A2, Canada

ABSTRACT

Development of petroleum industries is associated with a number of environmental concerns. Among them, soil and groundwater contamination by petroleum products is of major concern. In this study, an integrated risk assessment approach is proposed for evaluating environmental risks derived from petroleum-contaminated sites. The proposed approach is composed of (i) a hydrocarbon spill screening model (HSSM) which is used for simulating immisicible flow of released hydrocarbons in vadose zone, formation of lens in capillary fringe, dissolution of pollutants at water table, and transport of the pollutants to receptors, and (ii) a fuzzy relation analysis (FRA) model which is developed for comprehensively evaluating risks caused by a number of pollutants with different impact characteristics, based on the HSSM results. This hybrid HSSM-FPA approach was applied to a case study for a petroleum-contaminated site in western Canada, where soil and groundwater was contaminated by industrial wastes containing benzene, toluene, ethylbenzene and xylenes (BTEXs). The results suggest that the HSSM-FRA can provide insight into the potential risk to the receptor of concern downward the acquifer and can serve as a basis for further remediation-related decision analysis. © 1998 Published by Elsevier Science Ltd. All rights reserved

KEYWORDS

Groundwater, hydrocarbon, petroleum, risk analysis, simulation, site contamination, soil.

INTRODUCTION

Industrial activities are often associated with various environmental concerns. Among them, threats from hydrocarbon spill and leakage have been widely anecdotal at almost every petroleum industry site. A number of studies for environmental risk assessment of petroleum contamination have been conducted. Rosenblatt (1994) proposed a method for evaluating health risks from a buried mass of diesel fuel before and after bioremediation. Liptak (1996) exploited a set of chemical-specific, risk-basd soil cleanup guidelines, which resulted in timely and cost-effective remediation. Koblis (1993) studied the impact of surrogate selection on risk assessment for total petroleum hydrocarbons. Hallenbeck and Flowers (1992) undertook a study of risk assessment for worker exposure to benzene.

Generally, most of the previous risk analysts argued that risk should be measured through probability (relative likelihood) of possible contamination and magnitude (seriousness) of consequences from the contamination. Thus, risk could be expressed as a probability distribution over a number of adverse consequences. However, when applied to diverse problems, probability theory often retains a fundamental assumption about the subject area involved. Specifically, it assumes that there exists a historical run for observation of events. In fact, when attempting to model behaviors of environmental processes, analysts often suffer from a lack of data or imperfect knowledge about the processes. This may frustrate rigorous probabilistic studies (Lein, 1992). Another problem with the probability theory is its law of excluded middle

[$p(A \cup A^c) = 1$] and contradiction [$p(A \cap A^c) = 0$]. For instance, rotating a dice, the results will be 6, 5, 4, 3, 2 or 1, but never 4.5 or 2.1. However, intuitively and commonsensically, this is not true in other problems (e.g. a color can be red, not red, or reddish) (Lai and Hwang, 1992).

Another major approach for risk assessment is based on fuzzy set theory, which is suitable for situations when probabilistic information is not available (uncertainties present as fuzzy membership functions) (Bardossy et al., 1991). There has been a lack of previous studies using fuzzy risk assessment for petroleum waste management. In comparison, many applications to other areas have been reported. For example, Ganoulis et al. (1995) proposed a fuzzy arithmetic for ecological risk management under uncertainty. Donald and Ross (1996) used fuzzy logic and similarity measures for risk management of hazardous wastes.

Generally, the fuzzy risk analysis methods have advantages in their effectiveness in reflecting uncertainties and their applicability to practical problems. It is typically more difficult for planners/engineers to specify probability distributions than to define membership functions. Thus, extension of the methods to petroleum waste management area would be desirable for generating effective evaluations and decisions.

The objective of this research is to develop an integrated environmental risk assessment approach and apply it to a case study for a petroleum-contaminated site in Saskatchewan, Canada. A hydrocarbon spill screening model (HSSM) is employed for simulating the process of contaminant transport in soil and groundwater. Based on the HSSM outputs, a fuzzy risk assessment model is then developed for comprehensively evaluating risks associated with the site contamination.

METHODS

Hydrocarbon Spill Screening Model (HSSM)

Contamination from petroleum products is usually characterized by contaminant concentrations in groundwater and soil. The petroleum-related contaminants under consideration include benzene, toluene, ethylbenzene, xylenes (BTEXs), and total petroleum hydrocarbons (TPH). In the HSSM, concentrations of contaminants at different temporal and spatial units can be obtained through the following transport equation (Weaver, 1996):

$$\eta R\,(\partial c/\partial t) = \nabla \cdot D\nabla c - q\cdot\nabla c - \lambda\eta R c + J(t) \qquad (1)$$

where η denotes porosity, R is retardation factor, c is contaminant concentration in groundwater (mg/m^3), q is darcy velocity (m/sec), D is dispersion constant (m), λ is the first order decay constant (sec^{-1}), J(t) is the amount of mass per unit volume of aquifer added per unit time (mg/m^3 sec).

The HSSM was recommended by the USEPA for simulating subsurface releases of light nonaqueous phase liquid (LNAPL) and its subsequences. Especially, it is useful for evaluating impacts of hydrocarbon releases on the subsurface acquifer (Weaver et al., 1994; Charbeneau et al., 1995). The model contains three modules for simulating LNAPL flow through vadose zone, LNAPL spreading in capillary fringe, and LNAPL transport along with groundwater flow. Generally, hydrocarbons are released near the surface and transported downward the vadose zone to water table. At the water table, a hydrocarbon lens forms and spreads laterally. Constituents from the hydrocarbon lens dissolve into groundwater flowing beneath the lens, creating a plume which may contaminate downgradient or other exposure points. Thus, the HSSM may be used for estimating effects of LNAPL loading, partition coefficients, and groundwater flow velocities on pollutant transport, and obtaining approximate concentrations of hydrocarbon constituents at receptors of concern.

The main modeling inputs include (i) parameters specifying the type, extent and magnitude of the LNAPL release, (ii) residual oil contents for the unsaturated and saturated zones, (iii) residual water content of the oil lens, (iv) transport properties of water and LNAPL (density, viscosity, and surface tension), (v) aquifer and soil/water retention characteristics (vertical and horizontal hydraulic conductivity, porosity, irreducible water content, pore size distribution index, and air entry head), (vi) dissolved constituent characteristics (initial concentrations within the LNAPL, aqueous solubility, and soil-water and oil-water partition coefficients), and (vi) aquifer transport characteristics (vertical, longitudinal and transverse dispersivities, hydraulic gradient, and half-lives of different constituents within the aquifer).

Fuzzy Relation Analysis (FRA)

Based on the HSSM simulation results, a fuzzy relation analysis (FRA) model is developed for comprehensively evaluating environmental risks due to multiple pollutants with uncertain impact characteristics. The concept of fuzzy relation was firstly applied to medical diagnosis by Zadeh (1969). It illustrates the link between the malfunctioning of a system and the possible symptom. In a very general setting, the process of fuzzy relation analysis can be conveniently described by pointing out relationships between a collection of pattern features and their class membership vectors. It is useful for multifactorial evaluation and risk assessment under imprecision and uncertainty (Asse, 1987; Pedrycz,1990). The axiomatic framework of fuzzy set operation provides a natural setting for constructing multiattribute value functions in order to sort a set of potential actions and make an effective assessment. The method has been applied to a number of practical problems, such as assessment of environmental quality, evaluation of industrial products, and classification of acute toxicity from poisons (Jennings,1988; Ivanov and Ryvkin, 1991). This study will provide an additional extension of its application.

Fuzzy relations are fuzzy subsets of $\mathbf{X} \times \mathbf{Y}$ which present mappings for $\mathbf{X} \Rightarrow \mathbf{Y}$ (Zadeh 1965 and 1971; Kaufmann 1975). Definitions of fuzzy relations and their compositions for risk assessment are described as follows. Let $\mathbf{X}, \mathbf{Y} \subseteq \underset{\sim}{\mathbf{R}}$ be universal sets. Then $\underset{\sim}{\mathbf{R}} = \{ (x, y), \mu_{\underset{\sim}{R}}(x, y)) \mid (x, y) \subseteq \mathbf{X} \times \mathbf{Y} \}$ is a fuzzy relation on $\mathbf{X} \times \mathbf{Y}$. Let $\underset{\sim}{\mathbf{A}} = \{a_i \mid i = 1, 2, \dots, m\}$ be a n-dimension fuzzy vector, and $\underset{\sim}{\mathbf{R}} = \{r_{ij} \mid i = 1, 2, \dots, m; j = 1, 2, \dots, n\}$ be a m×n fuzzy relation matrix. Then, a m-dimension fuzzy vector $\underset{\sim}{\mathbf{B}}$ can be obtained as follows:

$$\underset{\sim}{\mathbf{B}} = \underset{\sim}{\mathbf{A}} \circ \underset{\sim}{\mathbf{R}} = \{b_1, b_2, \dots, b_n\}. \qquad (2)$$

The above process is named fuzzy transformation. According to the principle of fuzzy set operation, $\underset{\sim}{\mathbf{B}}$ can be determined by a max-min or max-∗ composition (Zadeh, 1971). For the max-min composition, we have:

$$b_j = \bigvee_{i=1}^{m} (a_i \wedge r_{ij}) = \max \{ \min(a_1, r_{1j}), \min(a_2, r_{2j}), \dots, \min(a_m, r_{mj}) \}, \quad j = 1, 2, \dots, n. \qquad (3)$$

For the max-∗ composition, we have:

$$b_j = \bigvee_{i=1}^{m} (a_i \times r_{ij}) = \max \{ (a_1 \times r_{1j}), (a_2 \times r_{2j}), \dots, (a_m \times r_{mj}) \}, \quad j = 1, 2, \dots, n. \qquad (4)$$

Thus, for a system containing several pollutants with high concentrations, we can analyze their integrated risks by using the above modeling approach. Assume that a_i is the degree of significance for pollutant i, and r_{ij} is the grade of membership for fuzzy relation between pollutant i and risk level j. Thus, b_j, which represents the membership grade for integrated risk level j to occur, can be obtained through model (2).

CASE STUDY

Overview of the Study System

The study site is located in western Canada (Figure 1). It has been operated as an oil refinery industry for more than 50 years. Petroleum derived contamination has been found since the 1960s due to underground piping, storage tank leakage, and hydrocarbon spills. Two preliminary studies (Fletcher and Munneke, 1994) indicated that soil and groundwater at the site were contaminated with petroleum derived pollutants.

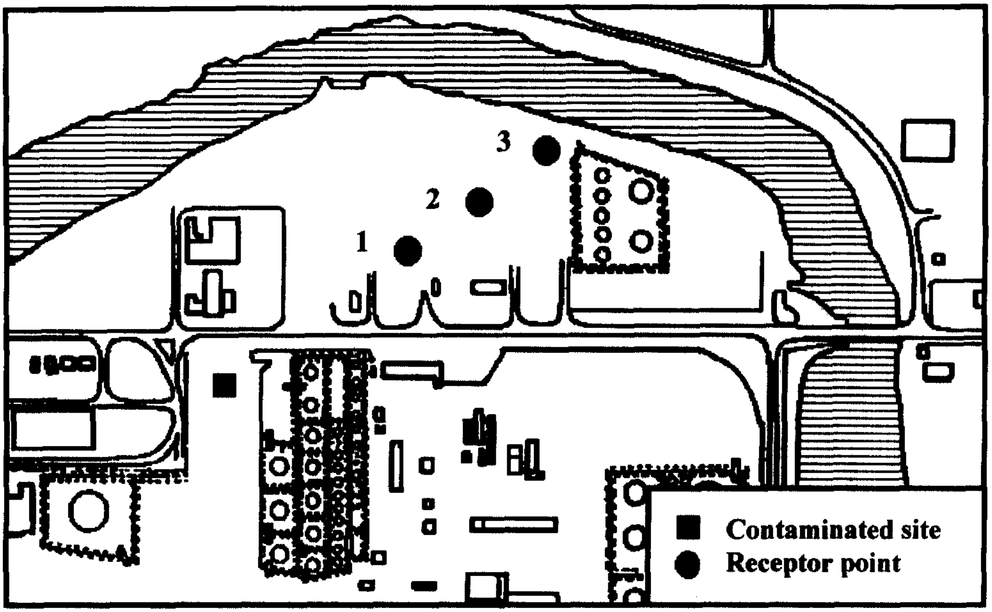

Figure 1. The study site

Data Investigation

The study area has approximately 23,000 m^3 of contaminated soil. The release of hydrocarbon was continuous from the early 1960s to the 1990s. In the recent years, bioremediation and other control activities were undertaken to recover the contaminated soil and groundwater (Fletcher and Munneke, 1994). Table 1 presents the results of laboratory analyses for hydrocarbon concentrations in the soil. The depth of groundwater table is 1.1 to 1.5 m. Therefore, the groundwater can be easily affected by the contaminated soil. The groundwater plume flows from the site towards a creek which is an important recreational water body for the nearby city. The distance from the contaminated site to the receptor point which is closest to the creek is about 450 m (Figure 1). Thus, contaminants within the soil can be carried through the groundwater into the creek. Historical monitoring data indicated that the creek water has indeed been contaminated by hydrocarbon constituents. Consequently, it is desired that effective evaluation of the associated risks to public water use be undertaken.

Results

Figure 2 presents the result of HSSM simulation modeling at the three receptor points with distances to the contaminated site being 250, 350 and 450 m, respectively. It is indicated that, before the remediation activities are undertaken, high concentrations of BTEXs exist at the three points with little variation. This is mainly due to the fact that release of LNAPL from the industry was continuous in most of the time during the 1960s - 1990s. Since the 1990s, some remediation activities, such as bioremediation, soil regeneration, biobarrier and biofilter, have been undertaken. These activities lead to significant decline of BTEXs concentrations in soil and groundwater (Fletcher and Munneke, 1994).

Table 2 shows the result of integrated risk assessment through the HSSM-FRA approach (for receptor point 3), with the details for year 2001 provided in Figure 3. The related guidelines for hydrocarbon concentrations in groundwater are given in Table 3. Generally, because remediation activities have been undertaken since early 1990s, the risk levels for the receptor points have been significantly reduced after 1995. After 2002, the threat from this site may become insignificant.

Table 1. Hydrocarbon concentrations in the soil (ppm)

Contaminated Site	Composite 1	Composite 2	Composite 3	Average
Landfarm Area	5330	1100	3500	3310
Loading Facility	4300	1600	1700	2533

Table 2. Result of integrated risk assessment through HSSM-FRA approach

	Unit	1985	1995	2001	2002
Benzene	(mg/L)	11.7	10.3	0.25	0.01
Toluene	(mg/L)	36.0	29.2	0	0
Ethylbenzene	(mg/L)	62.0	57.3	0.375	0.009
Xylenes	(mg/L)	48.6	14.8	0	0
Risk level		Highly risky	Highly risky	Slightly risky	Clean

Table 3. Guidelines for hydrocarbon concentrations in groundwater

Area	Media	Chemicals	Guideline Limit (ug/L)
Petroleum Industry Area	Water	Benzene	300
		Ethylbenzene	700
		Toluene	300
		Xylenes	5,000

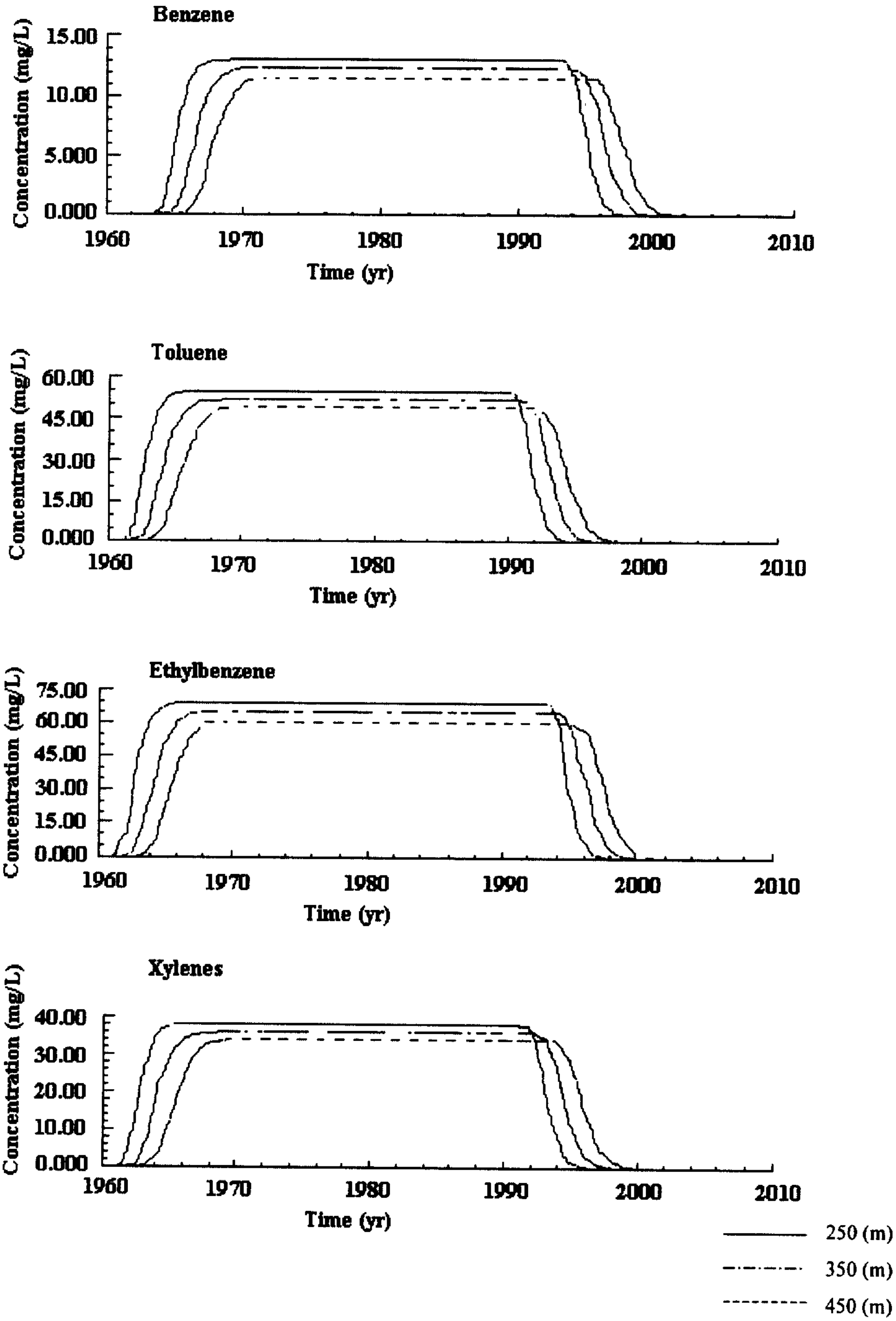

Figure 2. Result of HSSM simulation modeling for BTEXs at the three receptor points (with distances to the contaminated site being 250, 350, and 450 m, respectively)

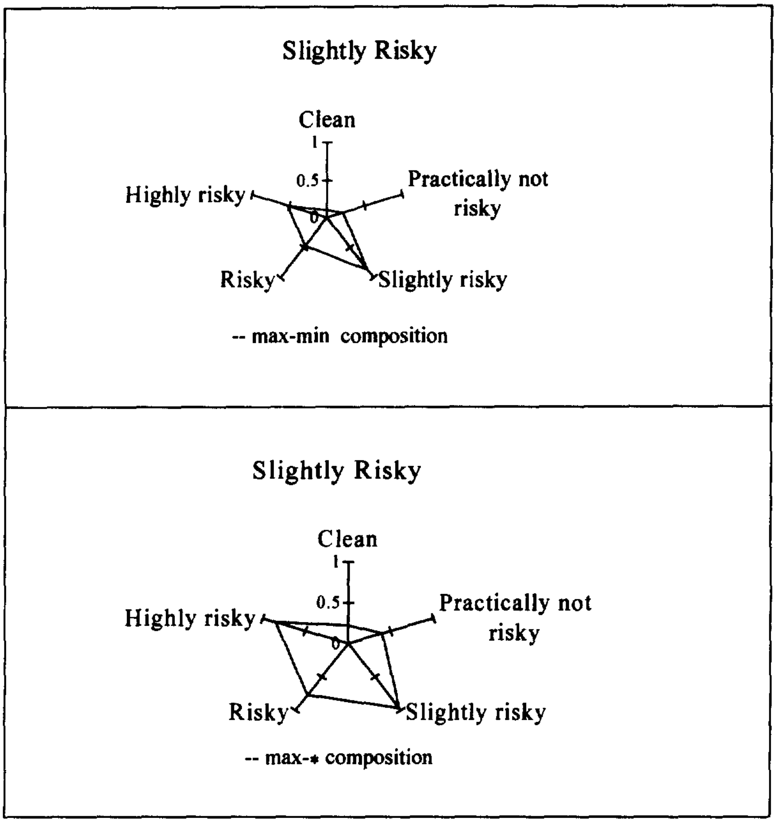

Figure 3. Result of integrated risk assessment through the HSSM-FRA approach

The HSSM-FRA approach is useful for comprehensively evaluating risks within a system containing many factors with complicated interrelationships. For the study problem under consideration, this method allows managers to have a systematic and consistent method for assessing environment risks associated with different source conditions. The results can thus provide useful bases for determining desirable site remediation strategies.

CONCLUSIONS

An integrated risk assessment approach, HSSM-FRA, is proposed for environmental risk assessment of petroleum-contaminated sites. The HSSM is used for conservatively simulating (i) LNAPL transport from near the surface to the capillary fringe, (ii) radial spreading of a LNAPL lens through the capillary fringe, (iii) dissolution of LNAPL constituents into a water table aquifer, and (iv) transport of LNAPL through the flowing groundwater to a potential exposure location. The FRA is used for integrated assessment of effects and risks caused by a number of contaminants. Thus, the HSSM-FRA can incorporate information of emission source, pollutant transport, pollution impacts, and remediation techniques within a general framework.

The HSSM-FRA approach is applied to the case study for a petroleum-contaminated site in western Canada. The results are useful for risk analysis of LNAPL spill and/or leakage as well as their impacts on soil, groundwater, and potential receptors.

Further explorations based on the proposed methodology would be beneficial. For example, the HSSM-FRA can also be used for analyzing other site contamination problems, such as leakage from underground storage tanks. Integration of the HSSM-FRA with other simulation tools for surface water quality will provide a more effective decision-support system for managing the site contamination problems.

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