Mass separation and risk assessment of commingled contamination in soil and ground water

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ABSTRACT
This study focuses on risk assessment and management of contamination in soil and ground water caused by petroleum hydrocarbon releases from multiple sources. These multiple release sources lead to commingling of subsurface contaminant plumes, which require identification, assessment and control in a proper manner. Based on Alberta's regulatory framework for risk management of contaminated sites, a commingled ground water plume can be divided into several protection zones corresponding to different exposure pathways (inhalation, ingestion and freshwater aquatic life) from which risk management decisions can be made. Effective assessment and management of commingled plumes require the cooperation among responsible parties through sharing information and knowledge on contaminated sites and developing joint programs for investigation, monitoring, remediation and risk management. The study proposes methodologies for determining mass contribution to a commingled plume from multiple contaminant sources. Reliable mass separation depends on adequate site characterization and application of mathematical models to simulate subsurface flow and transport processes.

RÉSUMÉ
Notre étude se concentre sur l'évaluation de risques et le contrôle de contaminants dans les sols et dans les eaux souterraines, provoqués par les fuites d'hydrocarbures de sources multiples. Ces fuites multiples mènent à un mélange d'aigrettes de contaminants souterrains qui exigent une identification, une évaluation et un contrôle efficace. Dans le cadre de la règlementation du gouvernement de l'Alberta pour le contrôle de risques de sites contaminés, une aigrette de contaminants souterrains pourrait être divisée en plusieurs zones de protection qui correspondent aux divers sentiers, tels inhalation, ingestion et vie aquatique, desquels on pourrait prendre les décisions qui s'imposent. Une évaluation efficace et le contrôle des aigrettes mélangées demandent la coopération des parties responsables via le partage des informations et des connaissances concernant les sites contaminés, en plus d'évaluer les programmes conjoints d'investigation, de surveillance, mesures de correction et le contrôle de risques. L'investigation propose des méthodes pour évaluer la contribution globale de plusieurs sources de contaminants à une aigrette. Une séparation fiable dépend d'une étude adéquate des sites et l'application de modèles mathématiques pour réaliser une simulation du mouvement souterrain et des processus de transport.

1 INTRODUCTION

In urban areas, many petroleum service stations with underground petroleum storage tanks (PST) are located along roads with major traffic. Some PST sites were contaminated with petroleum hydrocarbons (PHC) released through leakage from tanks, pipes or pipe joints. Depending on site-specific hydrogeologic conditions, the PHC could retain in soil, float on top of the ground water table, dissolve in ground water, and partition into soil vapor (Fig. 1).

Following the release of PHC into soil, it is initially absorbed onto the soil particles until the soil adsorption capacity is reached; then it starts to move vertically and laterally within the unsaturated zone. On reaching the ground water table, certain components of PHC, known as free products or Light Non-Aqueous Phase Liquids (LNAPL), can float and move on top of the water table in the general ground water flow direction. Some PHC components are soluble in ground water; their movements are controlled by the flow and transport processes within the saturated zone that can pose risks to human health through ground water ingestion and Freshwater Aquatic Life (FAL) through ground water-surface water interaction. Subsurface PHC can partition into soil vapor that has the potential to migrate into residential or commercial buildings through foundation slabs or basements, hence can pose inhalation risk to human health (CCME 2006).

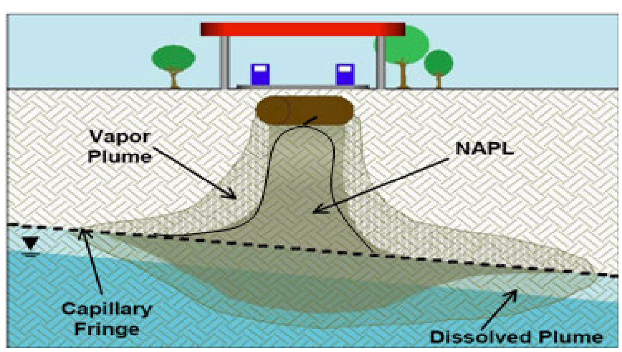

Figure 1. Petroleum hydrocarbon release to the subsurface (modified from API, 2003)

Multiple PHC releases from several service stations close to each other can further complicate contamination issues involving commingling of contaminant plumes in soil and ground water. Once commingled, it is difficult to determine the proportional contribution to subsurface contamination from each site, thus making it difficult to resolve disputes associated with liabilities among responsible parties. If a service station uses unique fuel that is different from those used by other parties, it may be able to fingerprint the contaminant source (e.g. lead and MTBE additions). In most cases, fuels used by service stations are similar or upgraded around similar period, hence making it difficult to trace the contaminant sources.

The two objectives of this study are to examine the assessment and management of commingled plumes based on Alberta's risk-based regulatory framework on contaminated sites and to provide methodologies for mass separation of commingled plumes in soil and ground water.

2 RISK ASSESSMENT AND MANAGEMENT

The regulatory framework for risk assessment and management of contaminated sites in Alberta is designed to achieve three policy outcomes: pollution prevention, health protection and productive use (AENV 2007a, b). Under this framework, the three management options are Tier 1, Tier 2 and Exposure Control. Tier 1 generic soil and ground water remediation guidelines are developed to protect sites at the more sensitive end of the range; hence can be used at most sites without modification. Tier 2 guidelines allow consideration of site-specific conditions through modification of Tier 1 guidelines and/or removal of exposure pathways not applicable to the site. Exposure Control involves risk management through the use of exposure barriers or administrative controls based on site-specific risk assessment.

To detect and assess the extent of PHC contamination in soil and ground water, Tier 1 guidelines use a basic set of chemical parameters as indicators of the contamination, including Benzene, Toluene, Ethylbenzene and Xylenes (BTEX), PHC Fraction 1 (F1) and PHC Fraction 2 (F2). In a commingled plume, the measured concentration distributions of these chemical parameters are the results of single/multiple releases from different sources.

Tier 1 criteria are developed based on the consideration of site-specific land uses, receptors and pathways that are important for determining risks to human and environmental health. In general, ingestion and FAL are considered as the more stringent pathways than the vapor inhalation pathway for the protection of human health from PST contamination. Based on the criteria established for different exposure pathways, a commingled ground water plume can be divided into several types of protection zones (Fig. 2).

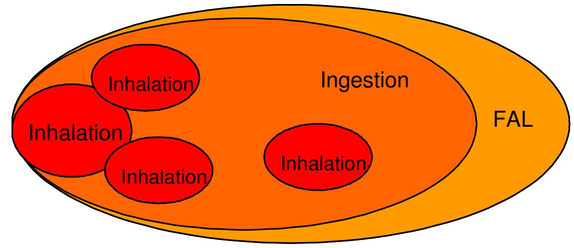

Figure 2. Protection zones identified for different pathways within a commingled ground water plume

The relative importance of these pathways and their associated risks depend on many factors such as type of contaminants, site-specific hydrogeologic conditions, receptor locations and environmental regulations. As an example, some service stations are located more than 300 meters away from surface water bodies that have weak hydraulic connection with the contaminated aquifer and many city by-laws prohibit residents from drilling wells within the city limit for drinking water supplied by the municipal water distribution system. Under such circumstances, ground water ingestion and FAL pathways are not considered risk management priorities; management of inhalation risk to occupants of residential and commercial areas becomes a higher priority.

To assess and manage a commingled contaminant plume, it is essential for the responsible parties to adopt a cooperative approach. The amount of cooperative effort depends on the identified levels of risk. As illustrated in Fig. 2, cooperation can include all parties when ingestion pathway/FAL is considered or some of the parties when inhalation pathway is considered only. All parties can demonstrate their willingness to cooperate in the following manner:

1. Share data, information and knowledge in support of contaminated sites assessment and management.
2. Apply and/or develop consistent risk assessment criteria.
3. Participate in cooperative investigation for effective delineation of contaminant plumes.
4. Develop and implement joint monitoring programs (e.g., optimization of monitoring network design and ensuring consistency in sampling, analysis and interpretation).
5. Work together toward contaminated sites remediation.
6. Develop and implement joint risk management programs.

3 MASS SEPARATION OF A COMMINGLED CONTAMINANT PLUME

A commingled plume gives rise to the need of identifying contaminant sources and their respective contributions. Methodologies are provided below for estimating the respective mass contributions from multiple contaminant sources.

3.1 Soil Contamination

The PHC released into soil initially migrates vertically downward under the influence of gravity. With sufficient amount of release, it eventually moves through the unsaturated zone to the capillary fringe and the water table; additional releases result in mounding of the hydrocarbon plume and its radial outflow (API, 2003).

After the full extent of soil contamination is delineated, the total contaminant mass loading can be calculated using the following equation:

$$T_m = \int_0^v c_v \, dv \tag{1}$$

where T_m is the total mass of contaminant, v is the total volume of contaminated soil, and c_v is the contaminant concentration.

Separate release from two PST sites near each other can lead to commingling of two hydrocarbon plumes in the unsaturated zone. Fig. 3 provides a cross section across two sites showing individual and combined concentration distributions at a particular depth for a given time. Evidence of releases from two separate sources is shown in this figure by the bimodal curve representing the combined distribution. The extent of commingling is shown by the overlap of two individual concentration distributions, with each distribution produced by a separate source.

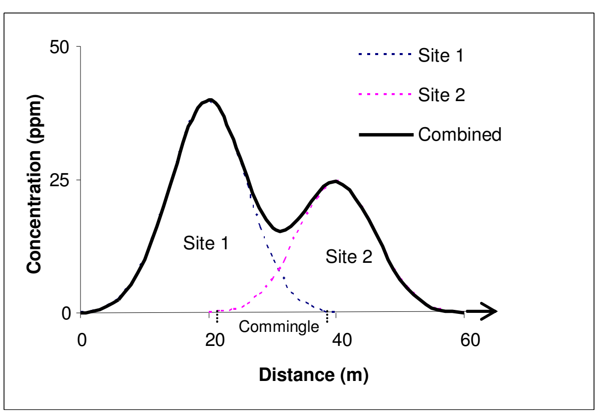

Figure 3. Commingled concentration distribution in soil

If site characterization is adequate and the combined concentration distribution is sufficiently delineated, a mathematical model incorporating unsaturated flow and transport processes can be used to simulate the observed combined distribution. After adequate matching of observed and simulated distributions, the model can be used to generate individual concentration distribution representing each source for evaluating the commingling extent. Once calibrated, the model can also be used for the prediction of contaminant migration.

In some cases, it is not feasible to perform mathematical modeling due to the lack of site information to provide reliable values for many model input parameters or subsurface hydrocarbon migration is mainly controlled by uncertain preferential pathways such as utilities corridors, sand/gravel lenses, soil fissures or bedrock fractures. If the combined concentration distribution is sufficiently delineated, it may be feasible to fit either parametric or non-parametric distributions to the observed data representing the non-commingled portions of the combined distribution. The best matching distributions obtained in this manner can be used for separating the commingled plume.

The general concept discussed previously for two sources can be extended to a commingled plume generated by releases from multiple sources.

3.2 Ground Water Contamination

In many cases, the commingling of contaminant plumes does not occur within the unsaturated zone, but occurs in the saturated zone only. The migration of dissolved PHC is mainly controlled by the flow and transport processes in ground water.

After the full extent of ground water contamination is delineated, Equation 1 can similarly be used to calculate the total contaminant mass in a ground water plume; c_v is contaminant concentration in ground water and v is the total volume of contaminated ground water.

There are many governing factors affecting contaminant transport in ground water such as boundary conditions, source loading distribution, hydraulic conductivity, hydraulic gradient, adsorption, dispersion, and biodegradation. BIOSCREEN, a mathematical model developed by United States Environmental Protection Agency (EPA 1996), incorporates many of these governing factors into contaminant transport modeling. Through the use of Monte Carlo simulation, the model provides sensitivity analysis of hydrogeologic system responses to a wide range of model input parameter values.

Consider a commingled plume caused by releases from two PST sites, the observed concentration distribution over distance is shown in Fig. 4. To separate the contaminant contribution at the upgradient site (identified as site 1 in Fig. 4) from the downgradient site (site 2), BIOSCREEN can be used to simulate the non-commingled portion of the observed concentration distribution representing site 1 in order to generate a most likely decay curve for this site (represented by the dotted line in Fig. 4). By comparing the simulated concentration distribution for site 1 with the observed concentration curve, the respective contributions from two sites can be separated.

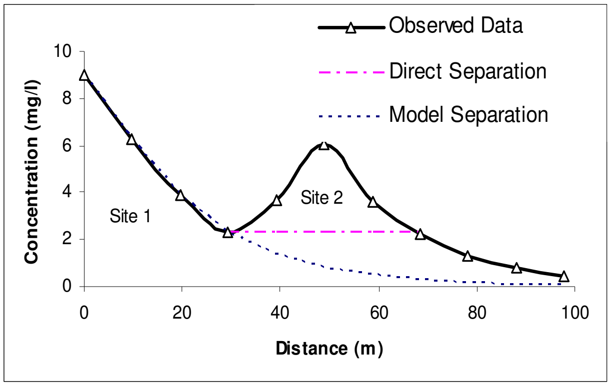

Figure 4. Separation of commingled ground water plumes based on direct separation and BIOSCREEN model separation

Due to complicated hydrogeology (e.g., PHC migration through fracture bedrock) or insufficient information to prepare model input parameters, it is sometimes not feasible to perform mathematical modeling. For such case, the mass separation line is assumed to be a horizontal line (refer to Fig. 4) drawn from the point where the slope of the non-commingled portion of the observed data curve changes in sign (i.e., from negative to positive slope); this direct separation method serves as a crude estimate of the respective mass contribution from each source.

4 CONCLUSIONS

This study considers the commingling of petroleum hydrocarbon plumes in soil and ground water caused by multiple sources of releases. The following conclusions can be drawn:

- Alberta's regulatory framework for contaminated sites management provides a viable approach for risk assessment and management of commingled plumes. By considering contaminant sources, migration pathways and potential receptors, the levels of risk to human and environmental health can be assessed based on established guideline criteria and/or modified criteria determined through site-specific risk assessment.

- As part of risk assessment, mass separation of commingled plumes in the subsurface can provide guidance to responsible parties on their likelihood of contribution to subsurface contamination. Petroleum hydrocarbon migration in the subsurface is influenced by many inherent uncertainties such as contaminant release and remediation histories, preferential pathways and hydrogeologic boundary conditions. Reliable mass separation requires proper site characterization to provide adequate delineation of contaminant plumes and improved understanding of governing flow and transport processes of contaminants.

- In addition to the removal of contaminant sources, it is an effective risk management approach for the responsible parties to cooperative in the development of joint programs for investigation, monitoring, remediation and risk management of commingled plumes.

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