Streamlined remediation decisions for brownfield redevelopment

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Abstract

Brownfield cleanup and reuse is often a costly proposition. The evaluation and design process and the associated legal hurdles are expensive and time consuming. The general phases of the characterization/cleanup of potentially contaminated sites include site assessment, site investigation, assessment of cleanup options, and design and implementation of the remedy. There are many models that assist in tracking the movement of contaminants within the unsaturated zone and through the groundwater. These models vary in complexity and in the amount of input parameters required. Input parameters can be furnished either from field/laboratory tests or from published tables. In some cases expensive field testing is required to identify parameters utilized in a contaminant fate and transport model. In other cases, published values for such input parameters may suffice. Results of a contaminant fate and transport simulation are highly dependent on the input parameter set, as well as on the selected model. Therefore, the use of different models and/or different input parameters has a great impact on the ultimate decision regarding remediation at a Brownfield site. This paper focuses on an on-going research of the engineering analysis associated with Brownfield redevelopment in Michigan. It investigates the tasks associated with characterization of subsurface contamination and predictive modeling of contaminant transport. The objective of the research is to isolate factors that will assist in streamlining the technical aspects associated with Brownfield redevelopment. The results of this research will not only have local effects, but will also benefit the environmental regulations and the decision-making process wherever Brownfield redevelopment is desired.

Keywords: brownfield, redevelopment, vadose zone, contaminant, transport, unsaturated zone, soil, modeling, SESOIL.
1 Introduction

Brownfields are defined as abandoned, idled or underused industrial and commercial facilities where expansion or redevelopment is complicated by real or perceived environmental contamination. With an increasing trend towards urbanizing open space, potential redevelopment of brownfield properties has been considered. However, brownfields are considered both a benefit and a liability. They are beneficial because they usually encompass a good location and may possess some existing infrastructure, but they are also a liability because they have pre-existing environmental problems.

This paper presents obstacles associated with brownfield redevelopment, with particular focus on the engineering analysis associated with redevelopment of contaminated properties. This analysis can play a critical role in the decision making process associated with Brownfield redevelopment. In particular, this paper investigates the tasks associated with characterization of subsurface contamination and predictive modeling of contaminant transport at sites of Brownfield redevelopment. In addition, this paper presents an application of the SESOIL contaminant transport model to a site of known contamination in an effort to better identify the critical factors essential to the pre-remediation engineering analysis. Elimination of superfluous factors streamlines the technical aspects associated with redevelopment of brownfields.

2 Obstacles in brownfield redevelopment

Brownfield redevelopment has been slow to proceed, mainly due to environmental constraints and litigation complications. Brownfield properties have not been a preferred target for redevelopment due to site evaluation processes, testing, and uncertainty in environmental liability. The evaluation and design process and the associated legal hurdles are expensive and time consuming. The uncertainty associated with legal liabilities and other factors often deterred developer’s efforts to bring old industrial sites back to productive use. Therefore, development of green-space has been preferred over brownfield redevelopment. Contaminated sites were left idle while increased pressure was imposed on the development of open spaces.

Owners of brownfield properties who have considered the remediation option have frequently been stymied by a lack of flexibility in the regulatory process. Recently, however, with the advent of the United States Environmental Protection Agency (USEPA) Brownfield and Voluntary Remediation Programs (VRP), it has been found that redevelopment of contaminated sites can be cost effective, enhancing the value of the site and allowing re-development to proceed. Such changes in environmental regulation and public perceptions have lead to renewed interest in brownfield redevelopment.

Changes in policies and environmental regulations adopted in the US to promote brownfield redevelopment include Public Acts 381 (Brownfields Redevelopment Financing Act) and 382 (Single Business Tax Credit), and Part
Public Act 451 of 1994 (Michigan Natural Resources and Environmental Protection Act). Public Act 381 established a method to finance environmental response activities at contaminated properties. It allowed municipalities to develop and implement brownfield redevelopment financing plans to capture state and local property taxes from a contaminated property to cover the costs associated with conducting environmental response activities on that property. Public Act 382 provides a credit of 10% of both the real and personal property investment by an owner or tenant of contaminated property being cleaned up under a brownfield plan. The credit is not available to owners or tenants who are liable for the contamination under the state Superfund law.

3 Modeling the unsaturated zone

The vadose zone represents the unsaturated soil compartment between the ground surface and the groundwater table (Figure 1). Since the major concern associated with redeveloping a brownfield site is to evaluate whether the contaminants identified on site are capable of migrating off-site, adversely affecting adjacent properties, or are expected to remain on site, this paper focused on pollutant fate and transport of contaminants in the vadose zone.

![Figure 1: Contaminant transport through the vadose zone.](image)

3.1 Contaminant transport

Contaminants migrate through the environment in a gaseous, liquid, and/or solid form. The contaminant may exist in several phases such as free, dissolved, vapor, and sorbed. Many processes including advection, dispersion, diffusion, sorption, and biodegradation dictate the behavior of a contaminant in air, soil, and water.
3.1.1 Advection
Advection is the transport of dissolved constituents caused by the bulk movement of liquids and/or gasses. Mathematically, one-dimensional advective flux for the $i^{th}$ constituent is represented by the following equation [1]:

$$ J_i = V_x * C * n $$

Where:
- $J_i$ = The mass flux of I (M/L$^2$T)
- $V_x$ = The linear groundwater velocity in the x direction (L/T)
- $C$ = Dissolved concentration (M/L$^3$)
- $n$ = Porosity

The velocity of the advective transport can be characterized by Darcy’s Law, as follows:

$$ V = - \frac{K}{n_e} \frac{\partial h}{\partial l} $$

Where:
- $K$ = Hydraulic conductivity (L/T)
- $n_e$ = Effective porosity
- $\frac{\partial h}{\partial l}$ = Hydraulic gradient

3.1.2 Diffusion
Diffusion is the spreading of contaminants due to concentration gradients. Molecular diffusion originates from the random molecular motion due to thermal kinetic energy of a solute. The diffusion coefficient, which describes this scattering, is smaller in a porous medium than in pure liquids because collision with the solids of the medium hinders diffusion [1]. Diffusion in the liquid phase is generally much smaller than the other elements of the transport process.

3.1.3 Dispersion
Dispersion represents the three-dimensional spreading of dissolved constituents in the soil and/or groundwater due to the tortuous path of fluid movement through the soil pores. Dispersion results in spreading constituent mass beyond the region that would be occupied due solely to advection. Unlike diffusion, dispersion is dependent on the presence of an advective flux. The dispersion coefficients are related to the linear groundwater velocity through the dispersivity coefficients:

$$ D_L = \alpha_L * V $$

$$ D_T = \alpha_T * V $$

Where:
- $D_L$ = Longitudinal dispersion coefficient (L$^2$/T)
$D_T$ = Transverse dispersion coefficient \( (L^2/T) \)

$\alpha_L$ = Longitudinal dispersivity \( (L) \)

$\alpha_T$ = Transverse dispersivity \( (L) \)

$V$ = velocity in the direction of flow \( (L/T) \)

### 3.1.4 Sorption

Sorption is the equilibrium partitioning process that occurs between dissolved constituents and soil particles. Sorption can be modeled using several experimentally derived relationships (isotherms), such as the Freundlich Isotherm:

$$C_s = K_F \cdot C^n \quad \text{(Freundlich Isotherm)} \quad (5)$$

Where:

- $C_s$ = concentration in adsorbed phase \( (M/L^3) \)
- $C$ = concentration in dissolved phase \( (M/L^3) \)
- $K_F$ = Freundlich adsorption constant
- $n$ = Freundlich exponent (0.7 to 1.2)

### 3.1.5 Biodegradation

Biodegradation is the process of transformation of a chemical by biological agents [10]. This process reduces the chemical concentration by changing the form in which the individual chemical component exists. The most significant rates of biodegradation occur by means of aerobic reactions, and therefore the availability of oxygen significantly affects this process. In chemical transport modeling, biodegradation is usually treated as a first-order degradation process:

$$\frac{\partial C}{\partial t} = -K_{DE} \cdot C^n \quad (6)$$

Where:

- $C$ = Dissolved concentration of pollutant soil moisture \( (M/L^3) \)
- $K_{DE}$ = Rate of degradation \( (\text{day}^{-1}) \)
- $n$ = Order of reaction

### 3.2 Analytical models

There are many models that assist in tracking the movement and behavior of contaminants within the unsaturated zone and through the groundwater. These models vary in complexity and in the amount of input parameters required. Input parameters are furnished either from field/laboratory tests or from published tables. In some cases, expensive field testing is required to identify the input parameters utilized in a contaminant fate and transport model. In other cases, published values for such input parameters may suffice. Results of a contaminant fate and transport simulation are highly dependent on the input...
parameter set and can have a great impact on the ultimate decision regarding redevelopment and remediation at a Brownfield site.

Selection of an appropriate contaminant transport model is dependent on many factors, such as level of detail required (screening versus detailed evaluation), transport pathways, and model’s complexity.

3.2.1 Uncertainty in modelling the unsaturated zone
Careful identification of soil characteristics in vadose zone modeling provides insights critical to decision making by assisting in determination the extent of soil contamination, required soil clean-up levels, and remediation alternatives. Site-specific information about the soil characteristics in which contamination occurs, is required as input to any vadose zone transport model and the accuracy of a model’s output is highly dependent on the accuracy of input information.

Historically, the application of vadose zone transport models has been stalled by the uncertainty associated with input parameters. This includes uncertainties associated with model assumptions, time of release, and quantity of release, soil sampling, sample transport, and analytical procedures.

3.2.2 SESOIL Contaminant Transport Model
SESOIL is a contaminant transport model that simulates long-term pollutant fate and migration from the ground surface to the groundwater table. It describes pollutant concentrations and masses in water, soil, and air phases. It also accounts for pollutant volatilization at the ground surface and migration to groundwater. Pollutant transport in washload due to surface runoff and erosion at the ground surface can also be addressed using this model.

The fate and transport processes accounted for in SESOIL are volatilization, adsorption, cation exchange, biodegradation, hydrolysis and complexation. It estimates average monthly concentrations for up to 999 years of simulation time, accommodating different soil properties in the soil column.

Results from SESOIL include time varying pollutant concentrations at various soil depths, pollutant loss to unsaturated zone (surface runoff, percolation to groundwater, volatilization, and degradation).

4 Case study evaluation

4.1 Site description
The site is a five-acre parcel of land, located in Kent County, Michigan. The site was used as a bulk chemical transfer plant from 1952 to 1991. During its operation, a variety of chemicals were handled at this site including, but not limited to toluene, ethyl benzene, trichloroethylene (TCE), and tetrachloroethylene (PCE).

4.2 Modelling approach
SESOIL simulations for the site were developed to help predict the future migration of Toluene, one of the major contaminants identified on site. Two
simulations were identified for the studied site by examining soil sample results taken at different depths from up to 42 soil borings, creating cross sections of the soil profiles, and identifying the types of material encompassing the vadose zone at the site.

Table 1: SSESOL parameters.

<table>
<thead>
<tr>
<th>Parameter Description</th>
<th>Simulation 1</th>
<th>Simulation 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Climate Data</strong></td>
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<td></td>
</tr>
<tr>
<td>Climate Database</td>
<td>Grand Rapids WB</td>
<td></td>
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<tr>
<td>Number of years of climate Data</td>
<td>5</td>
<td></td>
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<tr>
<td>Number of years of simulation</td>
<td>6</td>
<td></td>
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<tr>
<td><strong>Soil Data</strong></td>
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<td>Bulk density (g/cm³)</td>
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<td></td>
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<td>Intrinsic permeability (cm²)</td>
<td>1E-6</td>
<td>1E-8</td>
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<tr>
<td>Effective porosity</td>
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<td></td>
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<tr>
<td>Organic carbon content (%)</td>
<td></td>
<td>0.581</td>
</tr>
<tr>
<td><strong>Chemical Properties</strong></td>
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<td></td>
</tr>
<tr>
<td>Solubility (mg/l)</td>
<td>526</td>
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<tr>
<td>Diffusion coefficient in air (cm²/sec)</td>
<td>0.087</td>
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<tr>
<td>Henry’s constant (cm²-atm/mole)</td>
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<tr>
<td>Koc (ug/l-OC)/(ug/ml)</td>
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</tr>
<tr>
<td>Molecular weight (g/mole)</td>
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<td><strong>Soil Column Properties</strong></td>
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<td>Layer (1)</td>
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<td>Thickness (cm)</td>
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<tr>
<td>Thickness (cm)</td>
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<td>91.44</td>
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<td>Number of Sub Layers</td>
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<td>3</td>
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<tr>
<td>Layer (3)</td>
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<td>Thickness (cm)</td>
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<td>Number of Sub Layers</td>
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<td>Layer (4)</td>
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<td>Thickness (cm)</td>
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<td>91.44</td>
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<tr>
<td>Number of Sub Layers</td>
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<td>3</td>
</tr>
</tbody>
</table>

4.3 SSESOL data requirement

Data is required by SSESOL in four categories: climate, soil, chemical, and application data. Relevant input data for the case study is presented in Table 1. The initial toluene concentrations for layers 1, 2, 3 and 4 for simulation 1 were 720, 130, 86, and 210 ug/g. The values for simulation 2 were 210, 170, 850, and 570 ug/g.
4.4 SESOIL results and sensitivity analysis

The results of both simulations were compared against observed toluene concentrations in close proximity to the simulated locations. The comparison indicated a large discrepancy between the SESOIL results and the site-specific collected data. A sensitivity analysis was conducted for the two simulations using revised values as shown in Table 2.

Table 2: Sensitivity analysis.

<table>
<thead>
<tr>
<th>Parameter Description</th>
<th>Simulation 1</th>
<th>Simulation 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Original Simulation</td>
<td>Sensitivity Analysis</td>
</tr>
<tr>
<td>Bulk density (g/cm³)</td>
<td>1.438</td>
<td>1.55</td>
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<tr>
<td>Intrinsic permeability (cm²)</td>
<td>1E-6</td>
<td>1E-5</td>
</tr>
<tr>
<td>Organic carbon content (%)</td>
<td>0.581</td>
<td>1.75</td>
</tr>
</tbody>
</table>

As can be seen from Figures 2 and 3, toluene’s behavior at the elevation S-1 at 360 cm and S-2 at 420 cm varied significantly in some cases from the original simulations. SESOIL was highly sensitive to changes in intrinsic permeability, with smaller values resulting in delayed pollutant travel time. Conversely, larger values resulted in relatively faster transport to deeper layers. The organic carbon
content directly affects the pollutant sorption. The larger the organic carbon content of the soil, the greater the amount of the pollutant adsorbed onto the soil particles. Hence, it takes longer for the pollutant mass to leach into deeper layers. Average bulk density values do not vary significantly, and small changes were simulated here – with no significant effect observed.

Figure 3: Sensitivity analysis (simulation 2).

References


