

How Far Will It Go? Predicting the Extent of Groundwater Plumes

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OVERVIEW

This module will explore the use of a solute transport model to assess the fate of organic contaminants in groundwater. An analytical solution to the advection-dispersion equation with retardation and transformation will be implemented in EXCEL. The module can be used in a lower-division undergraduate computer science class. The module serves as an introduction to more complex software and modeling scenarios using the Environmental Protection Agency (EPA)'s models, BIOSCREEN and BIOCHLOR. Knowledge of basic algebra and the ability to use EXCEL is required. Upon completion of the module, students will have gained an understanding possible natural bioremediation or natural attenuation of groundwater contaminants.

INTRODUCTION

Human activities have resulted in numerous groundwater contaminant plumes. Implementation of groundwater remediation (such as pumping and treatment of groundwater) is expensive and can fail to attain the low cleanup levels stipulated by a regulatory agency. In the past decade, the use of natural bioremediation or natural attenuation has gained interest as a technique for contaminant plume cleanup. Natural processes such as biotransformation, dispersion, volatilization, and dilution can attenuate or decrease the contaminant plume size and concentration levels. A remediation scenario in which this natural attenuation is monitored can be a low cost and effective cleanup technique.

A model and extensive monitoring data will be required to convince regulators of the viability of natural attenuation remediation. In this module, we will describe and use an analytical solution to the solute transport model to assess the natural attenuation potential of some common contaminants.

PROBLEM

Tools are needed for the evaluation of natural attenuation of groundwater contaminants. Simple screening models (such as analytical solutions) can be utilized to assess the potential for natural attenuation. Simulations predict the extent and concentration of contaminants in a groundwater plume at a given time and distance from the contaminant source.

BACKGROUND

Groundwater Contamination

Two predominant groups of groundwater contaminants are petroleum products and chlorinated solvents. Some important differences are found in these two types of pollutants (Table 1). Petroleum products have a lower density than water. When spilled in sufficient quantities, these light nonaqueous phase liquids (LNAPLs) will move from the ground surface to the shallow areas of the saturated zone (groundwater). Conversely, chlorinated solvents are dense nonaqueous phase liquids (DNAPLs) and, when spilled in sufficient quantities, will extend beyond the shallow groundwaters into deep regions of the subsurface.

While these nonaqueous phase liquids can be limited in their mobility from the source or spill zone, water-soluble chemicals within these liquids will dissolve into the surrounding mobile groundwaters. The resulting contaminated waters emanate from the spill zone outward in the direction of groundwater flow producing a groundwater plume. The primary water-soluble components in gasoline (which is a mixture of over 100 chemicals) are benzene, toluene, ethylbenzene, xylenes (BTEX) and a gasoline-additive, MTBE. As BTEX and MTBE dissolve into water from a NAPL mixture, the effective solubilities of these components from gasoline are lower than their single-component aqueous solubilities (Table 2). The most commonly used chlorinated solvents are tetrachloroethene (PCE) and trichloroethene (TCE). All these chemicals will dissolve in water at levels capable of causing health risks and above the regulatory limits or maximum contaminant levels (Table 2).

Assessment of these plumes in the 1980s and 1990s showed another important difference between these contaminant groups. In an article titled “Where’s the benzene?”, the authors pointed out while spills of both chemicals are equally prevalent, only the chlorinated solvents have produced large and persistent groundwater plumes (Hadley and Armstrong, 1991). Subsequent studies have confirmed the prevalence of smaller stable BTEX plumes emanating from gasoline spill sites. Biotransformation of BTEX in the oxygenated shallow groundwaters stops the transport of the contaminants past a certain distance from the spill. The plume extent is stabilized and controlled by a balance between the solute transport processes advancing the plume away from the spill (groundwater advection and dispersion) and the biotransformation process. Lower rates of biotransformation of MTBE, PCE and TCE result in larger and more persistent groundwater plumes.

Table 1: Major Groundwater Contaminants and Their Properties

	Petroleum Products	Chlorinated Solvents
Type of chemical liquid	Light Nonaqueous Phase Liquid (LNAPL) – density is less than water, can extend from ground surface to shallow groundwaters	Dense Nonaqueous Phase Liquid (DNAPL) – density is higher than water, can extend from ground surface to bottom of groundwater aquifers
Most common examples	Gasoline Diesel Jet fuel	Tetrachloroethene (PCE) Trichloroethene (TCE)
Use(s)	Fuel	Metal degreasers, dry cleaning
Potential Releases	Fuel transfer spills, leaking storage tanks	Leaking storage tanks
Primary dissolved chemicals which will form groundwater plumes	Benzene (B) Toluene (T) Ethylbenzene (E) Xylenes (X) Methyl tert butyl ether (MTBE)	PCE TCE Transformation byproducts: cis dichloroethene (DCE) vinyl chloride (VC)
Historic Findings	BTEX groundwater plumes tend to be limited to relatively short distances from the spill source	Very large and persistent groundwater plumes

Table 2. Contaminant Health Risks, Regulatory Limits and Solubilities

Contaminant	Health Concern	Maximum Contaminant Level (ppm)	Aqueous Solubility (ppm)	Example Effective Solubility in Gasoline (ppm)
Benzene	Anemia, cancer	0.005	1730	16.8
Toluene	Nervous system, kidney or liver problems	1.0	535	21
Ethylbenzene	Liver or kidney problems	0.7	161	1.3
Xylenes	Nervous system damage	10.0	175	3.0
MTBE	Potential carcinogen, taste&odor problem	0.035 (cancer)* or 0.005 (taste)*	50,000	5,840
PCE	Liver problems, cancer	0.005	150	Not applicable
TCE	Liver problems, cancer	0.005	1100	Not applicable
cisDCE	Liver problems	0.07	800	Not applicable
Vinyl chloride	Cancer	0.002	6800	Not applicable

* potential advisory levels, state of California

Solute Transport

A solute transport model must simulate all the processes controlling the fate of an organic chemical dissolved in water. All chemicals dissolved in moving groundwater will be subjected to advection or movement of the groundwater and dispersion or spreading out of the groundwater. The advection and dispersion processes are primarily controlled by the aquifer properties (hydraulic conductivity and its distribution, hydraulic gradient). In simple models of uniform flow, advection is simulated by an average pore-water velocity calculated from Darcy's Law:

$$v = K i / \theta$$

where, v = average pore-water velocity
 K = hydraulic conductivity of aquifer (L/T)
 i = hydraulic gradient in aquifer (L/L)
 θ = effective porosity of aquifer

The dispersion or spreading out of contaminated water results in an increase in groundwater plume size and a decrease in the contaminant concentrations. Dispersion is caused by the mechanical mixing of water, tortuous pathways through groundwater pores, heterogeneities in hydraulic conductivities and chemical diffusion. The chemical diffusion component of hydrodynamic dispersion tends to be negligible compared to the mechanical dispersion component. In a uniform flow field, dispersion will occur in the direction of flow (longitudinal dispersion coefficient, D_L), horizontally and perpendicular to the direction of flow (transverse dispersion coefficient, D_T) and vertically and perpendicular to the direction of flow (vertical dispersion coefficient, D_V). These dispersion coefficients are estimated with the following empirical equations:

$$D_L = \alpha_L v$$

$$D_T = \alpha_T v$$

$$D_V = \alpha_V v$$

where, v = average pore-water velocity (L/T)
 α_L = longitudinal dispersivity of aquifer (L)
 α_T = transverse dispersivity of aquifer (L)
 α_V = vertical dispersivity of aquifer (L)

The relationship between dispersivity and dispersion coefficient and velocity was found in laboratory solute transport experiments. Field estimates of dispersivity have shown a scale effect with larger dispersivities for larger transport distances. For this module, we will assume constant dispersivity values but obey the following rule-of-thumb:

$$\alpha_L = 10 \alpha_T$$

$$\alpha_T = 10 \alpha_V$$

Many organic compounds have limited water solubility and will tend to adsorb onto aquifer solid surfaces. These hydrophobic compounds will have a particular affinity to adsorb onto organic carbon coatings on the sediments. The most common model for the sorption process is an instantaneous, reversible process at equilibrium. As the compounds adsorb onto sediments and desorb off of sediments, there is no permanent loss of contaminant mass through the sorption process. However, there is a slowing or retarding of the apparent advection of the sorbed contaminant plume. The parameter used to simulate equilibrium sorption is the retardation factor, R , which will be a function of the organic compound and the aquifer sediment:

$$R = 1 + \frac{\rho_b}{\theta} K_d$$

where, ρ_b = aquifer bulk density (g/cm^3) = $(1-\theta) \rho_s$
 ρ_s = sediment solid density (g/cm^3)
 θ = aquifer porosity
 K_d = sorption partition coefficient (cm^3/g)

The sorption partition coefficient is a function of the chemical's affinity for organic carbon and the amount of organic carbon present in the sediment. The following equation is used to estimate K_d in sediments with more than % organic carbon:

$$K_d = f_{oc} K_{oc}$$

where, f_{oc} = fraction of organic carbon in sediment
 K_{oc} = organic carbon partition coefficient (cm^3/g)

In this module, we will be setting our advective, dispersive and sorption parameters to constant values and examine the effect of differing biotransformation rates. For exercises in evaluating the effect of advection, dispersion and sorption, see Thorbjarnarson et al. (2002).

Biotransformation

The biologically mediated transformation (biotransformation) of organic compounds generally involves reduction-oxidation (redox) reactions. Redox reactions involve the transfer and acceptance of electrons between two compounds. The rate of transformation will be controlled by the chemical type, redox conditions of the aquifer, type and population of bacteria, etc. In our module, this complex process will be simulated by a simple first-order rate model:

$$C = C_o e^{-\lambda t}$$

where, C_0 = initial chemical concentration
 λ = first-order transformation rate (1/T)

The transformation process is sometimes described by a chemical's half-life, $t_{1/2}$. In a first-order model, the relationship between the first-order transformation rate and half-life is:

$$\lambda = \frac{\ln 2}{t_{1/2}}$$

A chemical's transformation rate will vary with differing aquifer redox conditions. Aerobic redox conditions will tend to occur in oxygenated (high levels of oxygen) shallow groundwaters. Deeper groundwaters which are farther from the atmospheric oxygen source can tend to be low in oxygen or anaerobic.

MODEL DETAILS

We will be solving the following advection-dispersion equation:

$$R \frac{\partial C}{\partial t} = -v \frac{\partial C}{\partial x} + D_L \frac{\partial^2 C}{\partial x^2} + D_T \frac{\partial^2 C}{\partial y^2} + D_V \frac{\partial^2 C}{\partial z^2} - \lambda C$$

where,

C = contaminant concentration as a function of x, y, z, t
 R = retardation factor representing equilibrium sorption
 v = uniform pore-water velocity (L/T)
 D_L = longitudinal dispersion coefficient (in the direction of flow) = $\alpha_L v$
 D_T = transverse dispersion coefficient (\perp to flow horizontally) = $\alpha_T v$
 D_V = vertical dispersion coefficient (\perp to flow vertically) = $\alpha_V v$
 α_L = longitudinal dispersivity (L)
 α_T = transverse dispersivity (L)
 α_V = vertical dispersivity (L)
 λ = first-order transformation rate coefficient (1/T) = $\ln 2 / t_{1/2}$
 $t_{1/2}$ = half-life of transformation rate (T)

This model includes:

- one-dimensional advection or uniform groundwater flow
- three-dimensional dispersion
- equilibrium sorption or retardation
- first-order transformation

SOLUTION METHODOLOGY

A solution to the above advection-dispersion equation was found by Domenico (1987). The solution includes initial conditions of zero concentration and a constant source concentration of C_0 at $x=0$ along a vertical rectangular plane perpendicular to the direction of flow (Figure 1).

Rectangular Contaminant Source

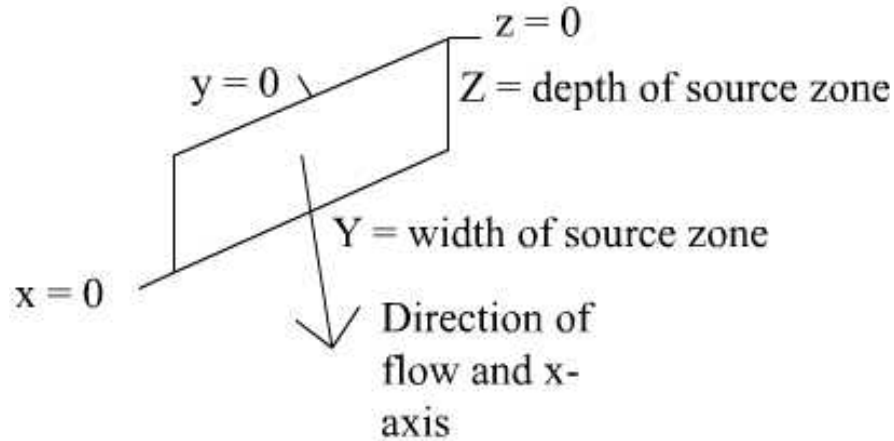


Figure 1. Orientation of rectangular contaminant source with respect to the x, y and z axes and groundwater flow.

Analytical Solution:

$$C(x, y, z, t) = C_0 \frac{1}{8} \exp \left[\frac{x}{\alpha_x} \left(1 - (1 + 4\lambda \alpha_x / v)^{\frac{1}{2}} \right) \right] \operatorname{erfc} \left[\frac{(x - vt(1 + 4\lambda \alpha_x / v)^{\frac{1}{2}})}{2(\alpha_x vt)^{\frac{1}{2}}} \right]$$

$$\left\{ \operatorname{erf} \left[\frac{y + Y/2}{2(\alpha_y x)^{\frac{1}{2}}} \right] - \operatorname{erf} \left[\frac{y - Y/2}{2(\alpha_y x)^{\frac{1}{2}}} \right] \right\} \left\{ \operatorname{erf} \left[\frac{Z}{2(\alpha_z x)^{\frac{1}{2}}} \right] - \operatorname{erf} \left[\frac{-Z}{2(\alpha_z x)^{\frac{1}{2}}} \right] \right\}$$

where,

C_0 = constant source concentration

α_x = longitudinal dispersivity in the direction of flow (L)

α_y = transverse dispersivity (perpendicular and horizontal to flow) (L)

α_z = vertical dispersivity (perpendicular and vertical to flow) (L)
 v = contaminant velocity = velocity corrected for retardation (L/T)
 $v = (K i) / (\theta R)$
 where, K = hydraulic conductivity of aquifer (L/T)
 i = hydraulic gradient of aquifer (L/L)
 θ = effective porosity of aquifer (unitless)
 R = retardation factor of equilibrium sorption (unitless)
 λ = first-order transformation coefficient (1/T)
 t = time since contaminant source started leaking (T)
 Y = width of contaminant source (L)
 Z = depth of contaminant source (L)
 x = horizontal distance from the rectangular contaminant source in the direction of groundwater flow (L)
 y = horizontal distance from the middle of the rectangular contaminant source in the direction perpendicular to groundwater flow (L)
 z = vertical distance from the top of the aquifer (L)

We will be solving for the contaminant concentrations along the centerline of the groundwater plume ($y=0$). The solution for the centerline $C(x,t)$ is:

$$C(x, y, z, t) = C_o \frac{1}{8} \exp \left[\frac{x}{\alpha_x} \left(1 - (1 + 4\lambda \alpha_x / v)^{\frac{1}{2}} \right) \right] \operatorname{erfc} \left[\frac{(x - vt(1 + 4\lambda \alpha_x / v)^{\frac{1}{2}})}{2(\alpha_x vt)^{\frac{1}{2}}} \right] \\
 \left\{ \operatorname{erf} \left[\frac{Y/2}{2(\alpha_y x)^{\frac{1}{2}}} \right] - \operatorname{erf} \left[\frac{Y/2}{2(\alpha_y x)^{\frac{1}{2}}} \right] \right\} \left\{ \operatorname{erf} \left[\frac{Z}{2(\alpha_z x)^{\frac{1}{2}}} \right] - \operatorname{erf} \left[\frac{-Z}{2(\alpha_z x)^{\frac{1}{2}}} \right] \right\}$$

The above solution can be calculated in EXCEL. The ERF and ERFC are available in the Analysis ToolPak. After you install the Analysis ToolPak in EXCEL, you must enable it by using the Add-Ins command on the Tools menu. Some general information on these functions and how they should be used in EXCEL follows.

ERF

Returns the error function integrated between lower_limit and upper_limit.

If for some reason, the Analysis ToolPack does not function. ERF(X) can be approximated by the analytical expression:

$$ERF(X) = \sqrt{1 - EXP\left(\frac{-4X^2}{\pi}\right)}$$

The EXCEL ERF(X) function will not accept negative X values. Use the relationship $ERF(-X) = -ERF(X)$.

The EXCEL ERF(X) function will exhibit an error if the X value is greater than 27. Use a logic statement to correct this. ERF is 1.0 for all X values greater than 3.

EXAMPLE:

IF(X<0,-ERF(-X), IF(X<27, ERF(X), 1))

ERFC

Returns the complementary ERF function integrated between x and infinity.

If for some reason, the Analysis ToolPack does not function. ERFC(X) can be calculated by $ERFC(X) = 1 - ERF(X)$

For negative values of X, use the logic function and $ERFC(-X) = 1 + ERF(X)$

The EXCEL ERFC(X) function will exhibit an error if the X value is greater than 27. Use a logic statement to correct this. ERFC is 0 for all X values greater than 3.

EXAMPLE:

IF(X<0, 1+ERF(-X), IF(X<27, ERFC(X), 0))

ASSESSMENT OF MODEL

The Domenico model has numerous simplifying assumptions (listed below) and should only be used for screening scenarios. Interestingly, it is the basis for models which have added more complex (and realistic) biotransformation scenarios (BIOSCREEN and BIOCHLOR). BIOSCREEN incorporates the depletion of oxygen by BTEX transformation. BIOCHLOR incorporates the production of transformation by-products (i.e., TCE from PCE transformation).

- Uniform flow conditions
- Constant dispersivity (no scale effect)
- Equilibrium, reversible sorption

- First-order transformation rate

EMPIRICAL DATA

Except for MTBE, the following first-order transformation rates are taken from ranges given in Bedient et al. (1999). For MTBE, aerobic transformation rates have been estimated to be from one to two orders of magnitude lower than benzene rates in field studies.

Table 3. Contaminant Sorption and Transformation Parameters

Contaminant	Log K_{oc}	Aerobic λ (1/d)	Anaerobic λ (1/d)
Benzene	1.7	0.335	0.01
Toluene	2.06	0.262	0.02
Ethylbenzene	1.98	?	0.0015
Xylenes	2.11	0.11	0.001
MTBE	1.049	0.003	?
PCE	2.42	0.001	0.100
TCE	1.81	0.005	0.015
cDCE	1.5	?	0.047
Vinyl chloride	0.39	0.08	0.230

Commonly asked questions regarding the use of natural attenuation at federal facilities:

<http://www-erd.llnl.gov/rescue/Topics/AFCEE/>

Technical Guidelines for Evaluating Monitored Natural Attenuation of Petroleum Hydrocarbons and Chlorinated Solvents in Ground Water at Naval and Marine Corps Facilities http://enviro.nfesc.navy.mil/erb/erb_a/support/wrk_grp/artt/mna1198.pdf

CONCEPTUAL QUESTIONS

How do varying redox conditions affect the extent of various contaminant plumes?
 What contaminant plumes stabilize quickly and at a short distance from the source?
 How will the evidence of plume stabilization at short distances support the use of natural attenuation for a site?

What can happen to contaminant plumes with a change in redox state of the aquifer?

PROBLEMS AND PROJECTS

For all problems use the following aquifer parameters:

Hydraulic gradient, i	0.001
Hydraulic conductivity, K (ft/d)	150
Effective porosity, θ	0.25
Sediment density, ρ_s (g/cm^3)	2.65
Fraction organic carbon, f_{oc}	0.001
Longitudinal dispersivity, α_L (ft)	5.0
Transverse dispersivity, α_T (ft)	0.5
Vertical dispersivity, α_V (ft)	0.05

- Calculate the solute transport parameters in the following table. Show all calculations on a separate page and fill in the answers in the table.

Parameter	Value	
Average pore-water velocity, v (ft/d)		
Longitudinal dispersion coefficient, D_L (ft^2/d)		
Transverse dispersion coefficient, D_T (ft^2/d)		
Vertical dispersion coefficient, D_V (ft^2/d)		
Aquifer bulk density, ρ_b (g/cm^3)		
SORPTION PARAMETERS	K_d (cm^3/g)	Retardation factor, R
Benzene		
Toluene		
Ethylbenzene		
Xylenes		
MTBE		
PCE		
TCE		
cDCE		
VC		

2) Set up an EXCEL program that will simulate the centerline of groundwater plumes, $C(x,t)$, and be able to graph C vs. x for four different simulation times.

3) **BENZENE UNDER AEROBIC CONDITIONS.** Using your EXCEL program, simulate benzene in your aquifer under aerobic conditions. Use the effective solubility in Table 1 as your source concentration. Assume a source zone width of 175 ft and depth of 10 ft. Use the aerobic transformation rate for benzene in Table 2. Print the graph showing the plume centerline concentrations for 1, 5, 10 and 20 days since source has leaked [make sure you have the complete plume from near source to far edge]. At what time does the plume appear to stabilize? How far will concentrations above the MCL extend from the source area?

4) **MTBE UNDER AEROBIC CONDITIONS.** Using your EXCEL program, simulate MTBE in your aquifer under aerobic conditions. Use the effective solubility in Table 1 as your source concentration. Assume a source zone width of 175 ft and depth of 10 ft. Use the aerobic transformation rate for MTBE in Table 2. Print the graph showing the plume centerline concentrations for 100, 400, 1200 and 3000 days since source has leaked [make sure you have the complete plume from near source to far edge]. At what time does the plume appear to stabilize? How far will concentrations above the MCL (use the cancer health advisory) extend from the source area? How is this different from benzene?

PROJECT 1: GROUNDWATER CONTAMINATION FROM GASOLINE

Have a group of students simulate contaminant transport under a given redox state (aerobic or anaerobic) for all dissolved components emanating from gasoline (Table 1). Each student will be in charge of one contaminant and redox state. Have the students compile their data and sketch a cartoon scenario showing the plume extent and time of stabilization for all the contaminants emanating from gasoline for each redox condition. Present to the class and discuss the differences caused by aerobic vs anaerobic conditions. Have them think about and discuss limitations – can you assume an unlimited supply of oxygen for aerobic conditions? What would be a more realistic way to simulate?

PROJECT 2: GROUNDWATER CONTAMINATION FROM CHLORINATED SOLVENTS

Have a group of simulate contaminant transport under a given redox state (aerobic or anaerobic) for PCE and TCE. Select a source concentration about 10% of the aqueous solubility. Have the students compile their data and sketch a cartoon scenario showing the plume extent and time of stabilization for PCE and TCE. In reductive dechlorination, the following transformation chain occurs: $PCE \rightarrow TCE \rightarrow cDCE \rightarrow VC \rightarrow$ Simulate the transformation of cDCE and VC for the differing redox conditions (assume source concentration of 10% of the aqueous solubility). Present information to the class and discuss differences in rates of stabilization and plume extents. Discuss limitations of this simple model and what would make more sense for simulation of these coupled reactions.

SOLUTIONS

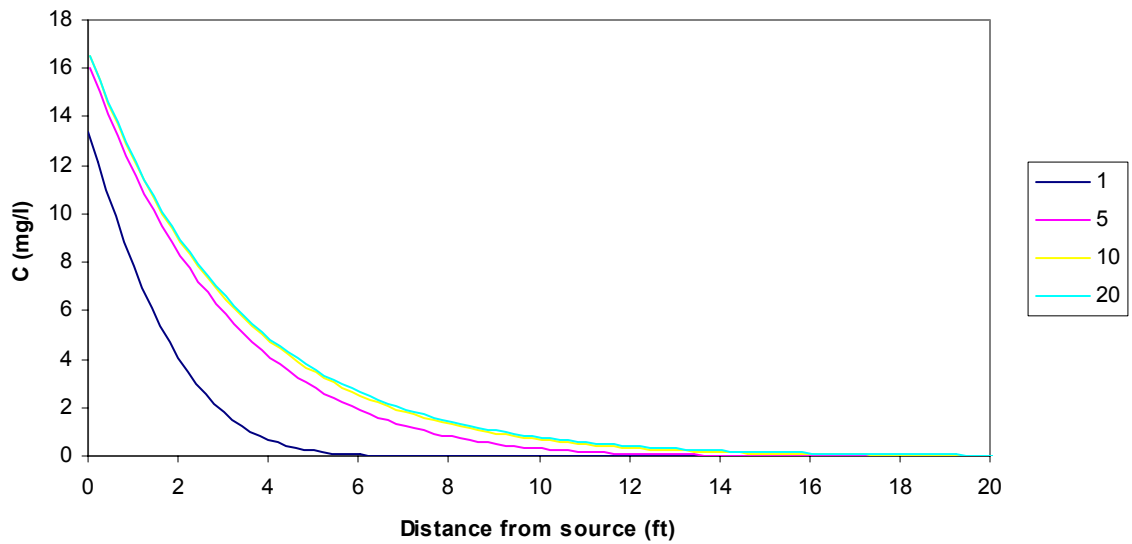
Problem 1.

Parameter	Value	
Average pore-water velocity, v (ft/d)	0.6	
Longitudinal dispersion coefficient, D_L (ft ² /d)	3.0	
Transverse dispersion coefficient, D_T (ft ² /d)	0.3	
Vertical dispersion coefficient, D_V (ft ² /d)	0.003	
Aquifer bulk density, ρ_b (g/cm ³)	1.99	
SORPTION PARAMETERS	K_d (cm ³ /g)	Retardation factor, R
Benzene	0.05	1.4
Toluene	0.11	1.9
Ethylbenzene	0.10	1.8
Xylenes	0.13	2.0
MTBE	0.01	1.1
PCE	0.26	3.1
TCE	0.07	1.6
cDCE	0.03	1.2
VC	0.002	1.0

Problem 2. See benzeneaerobic.xls file

Problem 3. Print the graph showing the plume centerline concentrations for 1, 5, 10 and 20 days since source has leaked [make sure you have the complete plume from near source to far edge].

Plume Centerline



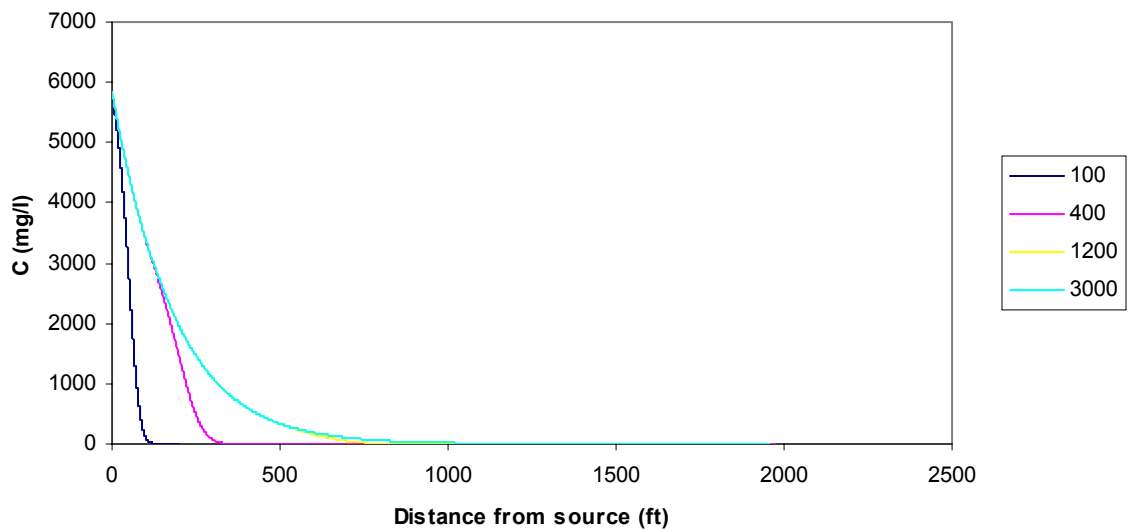
At what time does the plume appear to stabilize? 10 days

How far will concentrations above the MCL extend from the source area? 22 ft (read from EXCEL data table – see benzeneaerobic.xls)

Problem 4. Print the graph showing the plume centerline concentrations for 100, 400, 1200 and 3000 days since source has leaked [make sure you have the complete plume from near source to far edge].

See mtbeaerobic.xls for worksheet solution:

Plume Centerline



At what time does the plume appear to stabilize? After approximately 1,200 days (3.3 years)

How far will concentrations above the MCL (use the cancer health advisory) extend from the source area?

About 1,828 ft (read from mtbeaerobic.xls data table)

PROJECT 1: GROUNDWATER CONTAMINATION FROM GASOLINE

Findings should include differing plume extents and stabilization times for each component. Shorter plume extents and stabilization times for BTEX under aerobic conditions. Coupling the utilization of oxygen during aerobic conditions and switching to an anaerobic transformation rate upon oxygen depletion would be more valid. Have students investigate BIOSCREEN manual and code for more information on this technique.

PROJECT 2: GROUNDWATER CONTAMINATION FROM CHLORINATED SOLVENTS

Findings should include more extensive plumes for chlorinated solvents and byproducts than for BTEX. Coupling reactions so PCE degradation produces TCE which then degrades to produce cDCE, etc. would make more sense than having to assume a source concentration for TCE, cDCE and VC when they are present as PCE-transformation byproducts. Have students investigate BIOCHLOR manual and code for more information on this technique.

SUGGESTIONS

For upper-division classes, explore the more complex scenarios in the EPA models:

BIOSCREEN – <http://www.epa.gov/ada/csmos/models/bioscrn.html>

BIOCHLOR – <http://www.epa.gov/ada/csmos/models/biochlor.html>

Model manuals and simulation examples allow for easy utilization of these codes by students.

REFERENCES

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