1.061 / 1.61 Transport Processes in the Environment
Fall 2008

Problem 9.1

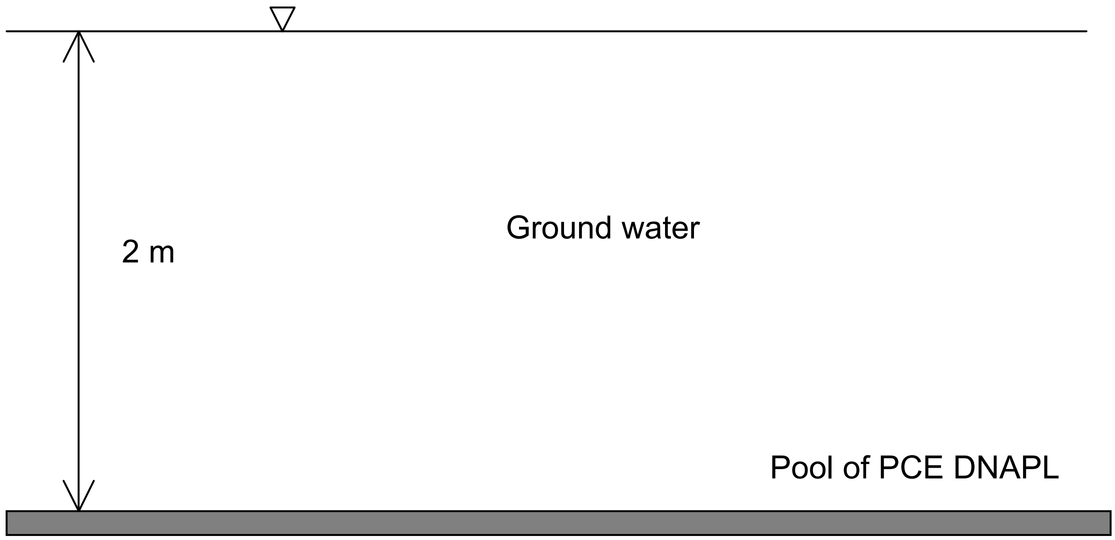
A smokestack of height H = 20 m releases two gases, dichlorodifluoromethane (Freon 12) and trichloroethene (TCE), each at a rate of 5 kg/min. Freon 12 is conservative. TCE undergoes first-order degradation in the atmosphere at a rate of $k_{TCE} = 0.1\ day^{-1}$, producing the highly toxic chemical phosgene ($C(=O)Cl_2$). Assume that the wind blows steadily and uniformly at 5 m/s in the positive x direction. The atmospheric turbulence is homogeneous but anisotropic, with the vertical diffusivity, $D_Z = 0.1\ m^2s^{-1}$, smaller than the horizontal diffusivities, $D_X = D_Y = 1\ m^2s^{-1}$. For both gases the ground acts as a no-flux boundary. Find the maximum concentration of Freon and TCE 10-km downwind of the stack.

Problem 9.2

A small channel is h = 5 cm deep and b = 10 cm wide. It carries flow at $U = 10\ cms^{-1}$. The stream-wise coordinate is x. The vertical coordinate is z, with z = 0 at the bed and positive upward. A continuous source of dye is injected at a rate of $\dot{m} = 1\ gs^{-1}$ at mid-depth and mid-width, and at x = 0. Assume that the channel has no dye upstream of the injection point. The bed of the channel is a perfect absorber for the dye, such that the concentration of dye in equilibrium with the bed is zero, and thus C(z=0) = 0. The molecular diffusivity for the dye is $D = 10^{-5}\ cm^2s^{-1}$. What is the maximum concentration in the channel 20 m downstream of the source?

Problem 9.3

Dense non-aqueous phase liquids (DNAPLs) are liquids that are heavier than water and have very low solubility in water. Typical DNAPLs include chlorinated solvents like the dry-cleaning fluid perchloroethylene (PCE), also called tetrachloroethylene or tetrachloroethene. When a DNAPL enters an aquifer it will sink under gravity until it encounters a layer of low permeability, such as clay. It then spreads into a thin layer. Consider the pool of PCE depicted below which was created at time t = 0. For t < 0 the PCE concentration in the aquifer is zero. For t > 0, PCE slowly diffuses into the water above. The coefficient of diffusion is $D = 4.4 \times 10^{-9}\ m^2s^{-1}$. The ground water is stagnant and the aquifer is 2 meters thick above the DNAPL. PCE has a solubility in water of 150 mg/L. The Maximum Contaminant Level (MCL) for PCE in drinking water is 5 ppb. When will the concentration of PCE throughout the aquifer be above the MCL?



Problem 9.4

You have identified a point source of TCE that is contaminating a small stream. The stream is h=20 cm deep, b=80 cm wide and flows at U = 10 cm/s. At the source (x = 0) the TCE mixes quickly across the channel depth and width with the resulting initial concentration, $C(x=0)=C_o=10$ ppb. You wish to determine if there are additional sources of TCE to the river. Because TCE is volatile and the concentration in the atmosphere is negligible, you know there is a flux of TCE from the river to the atmosphere. The Henry's Law constant for TCE is $H_{TCE} = 0.42$, indicating that the flux is water-side controlled. Because of the flux to the atmosphere, you expect the TCE concentration to decline downstream. Indeed, 2 km downstream of the known source $C_{2km} = 5$ ppb. To determine the rate of water-air exchange for the TCE you inject and measure the concentration of Propane [$H_{propane} = 0.42$] along the stream. From this study you find that $K_{propane} = 1.5 \times 10^{-4}\ s^{-1}$. The molecular diffusion coefficients for TCE and Propane in water are $D_{w,\ TCE} = 0.75 \times 10^{-5}\ cm^2s^{-1}$ and $D_{w,\ Propane} = 1.3 \times 10^{-5}\ cm^2s^{-1}$.

Determine if additional sources of TCE exist along the reach x = 0 to 2 km.

Problem 9.5

A small pond is h = 1 m deep with a surface area A. Three chemicals are spilled into the pond and rapidly mixed over the volume. The chemicals are the pesticide Lindane (w/ Henry's Law constant $H_L = 2.2 \times 10^{-5}$), the solvent Toluene ($H_T = 0.28$), and Napthalene ($H_N = 0.04$). Assume that mixing is sufficient to maintain a uniform concentration of each chemical within the bulk of the lake volume, i.e. below the laminar sub-layer at the surface.

Molecular diffusivity in air, $D_a = 10^{-5}\ m^2s^{-1}$ for all chemicals

Molecular diffusivity in water, $D_w = 10^{-9}\ m^2s^{-1}$ for all chemicals

Turbulent diffusivity in water, $D_{tw} = 10^{-3}\ m^2s^{-1}$

Waterside laminar sub-layer, $\delta_w = 100\ \mu m$

Airside laminar sub-layer, $\delta_a = 10$ mm

a) Sketch the profile of C (z) for each chemical. Indicate the concentration at z = 0, the air-water interface; at $z = -\delta_w$; at $z < -\delta_w$; and at $z = +\delta_a$. Assume that the atmosphere is a perfect sink for each chemical, such that $C_a = 0$ for $z > +\delta_a$.

b) Write an equation for the mass flux at the air-water interface for each chemical.

c) For each chemical determine the time at which only 5% of the original mass remains.

d) For which chemicals is the assumption of a uniform concentration within the bulk fluid appropriate?

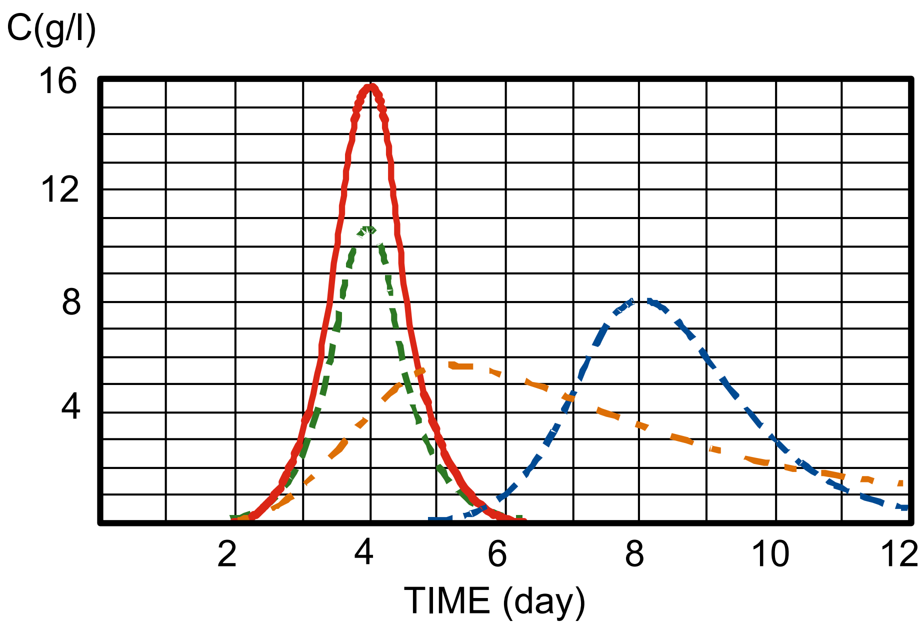
Problem 9.6
A mixture containing an equal mass of four chemicals is released as a pulse into a groundwater aquifer. The concentration of each chemical is measured in the pore water at a monitoring well located 8-m from the injection. Match the following descriptions to the correct curves.

Chemical 1 is a conservative tracer that does not react or degrade.

Chemical 2 does not adsorb to the grains, but is degraded by microbes living in the aquifer. What is the rate of degradation, K_d [day^{-1}]?

Chemical 3 readily adsorbs to organic material. The rate of adsorption/desorption is so rapid that the water/organic matter partitioning is always at equilibrium. What fraction of this chemical is associated with the pore water, *i.e.* is in the mobile phase?

Chemical 4 adsorbs to organic material, but at a rate that is much slower than that of chemical 3, such that the solid/water partitioning is never at equilibrium. What is the order of magnitude of the rate constant describing the adsorption/desorption reaction?



Problem 9.7

Between midnight and 2 am, illegal dumpers empty two five-gallon drums containing 2 kg of Toluene into a shallow abandoned well. Within 24 hours the Toluene is distributed vertically over the shallow (5 m thick), sandy aquifer. Evidence of the dumping is discovered two days later, and you are asked to assess the risk to a drinking well located 1 km directly downstream, if no remediation is done. Previous tests on this aquifer indicate the following:

Mean pore velocity, u = 1 m /day
Isotropic, Homogeneous Dispersivity, K = 0.1 m^2/day.
Porosity, n = 0.3
Solids density, ρ_S = 2.6 g/mL.

Toluene partitions rapidly to aquifer solids and has a solid-water partitioning coefficient of

$$K_d = 0.5 \frac{g_{toluene} / kg_{solid}}{g_{toluene} / L_{water}}.$$

Assume that the partitioning of Toluene is everywhere in equilibrium.

a) Write an appropriate transport equation.
b) Estimate the total concentration, C(t), at the drinking well.
c) Estimate the peak concentration in the pore water at the well and the duration of exposure.