2pts

1. $\forall = 1 \, m^3$

$S_R = 0.2$ residual saturation
$n = 0.25$ porosity

Mass balance: original vol. of TCE in soils

$$= 1 \, m^2 \times 0.25 \times 0.2 = 0.05 \, m^3$$

Density of TCE $= 1.47 \, g/cm^3 = 1470 \, kg/m^3$

Initial mass TCE $= 1470 \, \dfrac{kg}{m^3} \cdot 0.05 \, m^3 = 74 \, kg \, TCE$

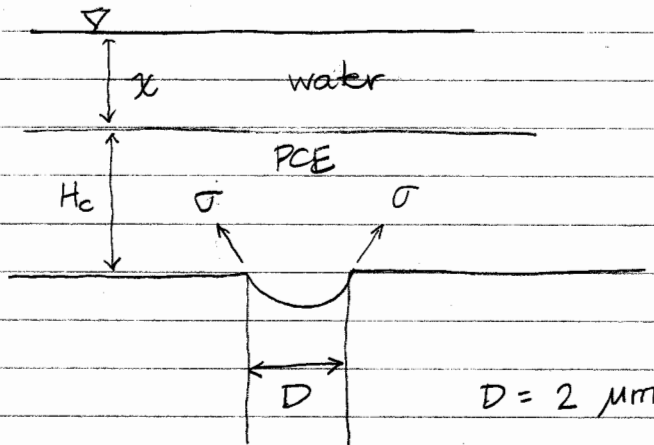Assume TCE dissolves into rain water to solubility $= 1100 \, mg/L$

Volume of rain $= 1 \, m^2 \times 500 \, mm/yr = 0.5 \, m^3/yr$

Mass carried by rain $= 0.5 \, m^3/yr \times 1000 \, mg/L \cdot 10^3 \, L/m^3$

$$= 0.5 \times 10^6 \, mg/yr = 0.5 \, kg/yr$$

Time to remove TCE $= \dfrac{74 \, kg \, TCE}{0.5 \, kg \, TCE/yr} = 150 \, years$

2.

Properties of PCE

$\rho_P = 1.63 \ g/cm^3$

$\sigma = 44.4 \ dyn/cm$

$1 \ dyn = 1 \ \dfrac{g \ cm}{sec^2}$

$D = 2 \ \mu m$

$$P_{NAPL} = \rho_w \, x \, g + \rho_P \, H_c \, g$$

$$P_{WATER} = \rho_w \, (x + H_c) \, g$$

a) $\quad \Delta P = (\rho_P - \rho_w) \, H_c \, g = \dfrac{2\sigma}{r} \quad$ for circular fracture

$$0.63 \ \dfrac{g}{cm^3} \ H_c \ 9.8 \ \dfrac{m}{s^2} = \dfrac{2 \ 44.4 \ \dfrac{g}{sec^2}}{1 \ \mu m}$$

$$H_c = \dfrac{2 \cdot 44.4}{0.63 \ \ 9.8} \ \dfrac{g/sec^2}{\mu m \ g/cm^3 \ m/s^2}$$

$$\dfrac{1}{10^{-6} m \ / (10^{-2})^3 m^3 \cdot m} = m$$

$$= 14 \ m$$

b) $\quad$ For linear fracture, σ is exerted on both sides of
fracture of length L

Hydrostatic pressure is exerted on opening DL

$$\Delta P \ DL = \sigma \ 2L \qquad\qquad \Delta P = \Delta \rho \, H_c \, g = (\rho_P - \rho_w) \, H_c \, g$$

$$H_c = \dfrac{2\sigma}{\Delta \rho \, g \, D} = 7.2 \ m \quad \left(\text{one half value for circular fracture}\right)$$

3. $i = 0.005$ $t = 10$ years

As first approximation, consider only advective travel. Thus, downstream wells need to extend to distance L:

$$L = ut = \frac{Ki}{n}t$$

For each type soil, use literature values of K and n *

soil	K (cm/s)	n_e	L
a. coarse sand	$9 \times 10^{-5} - 6 \times 10^{-1}$	0.2 - 0.35	48 Km
b. fine sand	$2 \times 10^{-5} - 2 \times 10^{-2}$	0.1 - 0.3	1600 m
c. silt	$1 \times 10^{-7} - 2 \times 10^{-3}$	0.34 - 0.61	94 m
d. clay	$1 \times 10^{-9} - 5 \times 10^{-7}$	0.34 - 0.60	2 cm

To be conservative, I used high value of K and low value of n from range in Daniel. L is computed to one-digit accuracy commensurate with accuracy of K.

For finer soils, diffusion could be more important than advection.

$$D_h = D_d^* + \alpha_L u$$

$$D_d^* \approx 10^{-9} \text{ m/s}$$

Based on chart from Gelhar et al. (1992) given in Lecture 2, for 1 to 10 m scale, $\alpha_L \approx 1$ m

* Techical Protocol for Evaluating Natural Attenuation of Chlorinated Solvents in Ground Water   Section C-3   pg. 206 of 248
http://www.epa.gov/ada/download/reports/protocol.pdf

3. (continued)

Velocities and dispersion coeffs are:

	u (m/yr)	$\alpha_L u$ (m²/s)	D_h (m²/s)
b. fine sand	7	2×10^{-7}	2×10^{-7}
c. silt	0.5	1×10^{-8}	1×10^{-8}
d. clay	0.004	1×10^{-10}	1×10^{-9}

Evaluate transport with equation given in Lecture 3:

$$c = \frac{c_0}{2} \, \text{erfc} \left(\frac{R_d x - ut}{\sqrt{4 R_d D_h t}} \right)$$

Assume $\frac{c}{c_0} = 0.01$ is threshold

$R_d = 1$ to be conservative

$$\frac{c}{c_0} = 0.01 = \frac{1}{2} \, \text{erfc} \left(\frac{x - ut}{\sqrt{4 D_h t}} \right)$$

$\text{erfc}(z) = 0.02$ at $z \approx 1.2$

$$\frac{x - u}{\sqrt{4 D_h t}} = 1.2$$

$$x = ut + 2.4 \sqrt{D_h} \sqrt{t}$$

Evaluate for different soils:

	u (m/yr)	D_h (m²/s)	D_h (m²/yr)	x
b. fine sand	7	2×10^{-7}	7	90 m
c. silt	0.5	1×10^{-8}	0.5	10 m
d. clay	0.004	1×10^{-9}	0.004	0.5 m

Note: diffusion dominates advection in clay, is about equal to advection in silt

Problem 3

$i =$ 0.005

$t =$ 10 years

$\alpha_L =$ 1 m

$D_d^* =$ 1.00E-09 m/s

	Soil	K (cm/s)	n_e	u (m/s)	u (m/yr)	L (m)	D_h (m²/s)	D_h (m²/yr)	x (m)
a.	coarse sand	1.00E-02	0.24	2.08E-06	6.57E+01	657.00	2.08E-06	6.57E+01	657
b.	fine sand	1.00E-05	0.24	2.08E-09	6.57E-02	0.66	3.08E-09	9.72E-02	0.7
c.	silt	1.00E-06	0.35	1.43E-10	4.51E-03	0.05	1.14E-09	3.60E-02	0.05
d.	clay	1.00E-08	0.4	1.25E-12	3.94E-05	0.0004	1.00E-09	3.16E-02	0.0006

$L = ut = (Ki/n_e)\, t$

$D_h = D_d^* + \alpha_L u$

3. (continued)

Benzene computation:

$$K_{oc} = 83 \ mg/\ell$$

f_{oc} —   check Technical Protocol
        can assume   a value of $f_{oc} \approx 0.001$ for all

$$\rho_b = 1.65 \ g/cm^3$$

$$n = 0.3$$

$$R_d = 1 + \frac{\rho_b \, f_{oc} \, K_{oc}}{n} \cong 1.5$$

Monitoring for benzene would only need to be about $\frac{2}{3}$ the distance of monitoring for MTBE.

4.

$K = 1.6 \times 10^{-4}$ cm/s $= 0.45$ ft/day

$i = 0.035$

$L = 400$ ft

$$u = \frac{Ki}{n}$$

assume n for clay-silt $= 0.3$ $\qquad \therefore u = 0.05 \frac{ft}{day}$

Ground-water travel time $= \dfrac{L}{u} = \dfrac{400 \, ft}{0.05 \, ft/d}$

$\qquad\qquad\qquad\qquad\qquad = 8000$ days $= 22$ years

Need to find retardation factors for PCE, TCA, xylene

From Table C.3.3 of Technical Protocol for Evaluating Natural Attenuation of Chlorinated Solvents in Ground Water

$\qquad f_{oc} \cong 0.002$ for glacial till

From Table A-1*. K_{oc} values are:

$\qquad$ PCE $\qquad K_{oc} = 364$ L/kg

$\qquad$ TCA $\qquad\qquad 152$

$\qquad$ X $\qquad\qquad\quad 240$

$\qquad$ TCE $\qquad\qquad 126$

Bulk density, $\rho_b = 1.65 \frac{g}{cm^3}$ (typical value) $= 1.65 \frac{kg}{L}$

Porosity, $\qquad n = 0.3$

Compound	K_{oc} (L/kg)	$R_d = 1 + \dfrac{\rho_b K_d}{n} = 1 + \dfrac{\rho_b K_{oc} f_{oc}}{n}$	Travel time (yrs)
PCE	364	3.0	66
TCA	152	1.8	40
X	240	2.3	51
TCE	126	1.7	37

Travel time $\qquad \dfrac{L}{u/R_d} = R_d \dfrac{L}{u}$

* From Chemical reference information in course reader

4. (cont)

Whether compounds reach brook depends on chemistry
PCE and TCE/A will degrade if conditions
are anaerobic
Xylene will degrade in aerobic

Given mix of chemicals at site, both anaerobic
and aerobic zones are possible — I would
expect chemicals to degrade over these long
travel times, but not necessarily from
areas of the site nearer the brook.