HOMEWORK

Chapter 2

2-1. A sample of silty sand in its natural condition had a volume of 220 cm^3 and weighed 481.2 g. After saturating the sample with water it weighed 546.9 g. The sample was then drained by gravity until it reached a constant weight of 445.7g. Finally the sample was oven dried at 105 °C after which it weighed 432.8 g. Note that the volume of the voids in the sample under natural conditions is the volume of water in the sample at saturation. Assuming the density of water is 1 g/cm^3, compute the following:

(a) water content (mass basis) under natural conditions, defined as the ratio of the mass of water to the mass of the sample under natural conditions.

(b) volumetric water content under natural conditions, defined as the ratio of the volume of water to the volume of the sample under natural conditions.

(c) saturation ratio under natural conditions, defined as the fraction of voids filled with water under natural conditions.

(d) porosity, defined as the ratio of the volume of voids to the volume of the sample under natural conditions.

(e) specific yield , defined as the ratio of the volume of water drained from the saturated sample due to gravity to the volume of the saturated sample.

(f) specific retention, defined as the ratio of the volume of water a sample can retain against gravity to the volume of the saturated sample, also equal to the difference between porosity and specific yield.

(g) dry bulk density, defined as the mass of the soil particles divided by the volume of the sample under natural conditions.

2-2. Three piezometers, A, B, and C are located 1000 m apart (in a straight line) in an unconfined aquifer. Fill in the blank spaces in the table below. Calculate the pressure head and elevation head at the base of the piezometer.

Piezometer	A	B	C
Ground surface (msl)(m)	450	435	430 -
Depth of piezometer (m)	___	___	70
Depth to water (m)	27	___	50
Pressure head (m)	53	___	___
Elevation head (msl)(m)	___	335	___
Total head (msl)(m)	___	400	___
Hydraulic gradient (m/m)	___	___	

2-3. Compute the discharge velocity, seepage velocity, and flow rate for water flowing through a sand column with the following characteristics

$$K = 10^{-4}\ \text{cm/s} \qquad \frac{dh}{dl} = 0.01$$

$$\text{Area} = 75\ \text{cm}^2 \qquad n = 0.20$$

2-4. The average water table elevation has dropped 5 ft due to the removal of 100,000 ac-ft from an unconfined aquifer over an area of 75 mi^2. Determine the storage coefficient for the aquifer.

2-5. A confined aquifer is 50 m thick and 0.5 km wide. Two observation wells are located 1.4 km apart in the direction of flow. The head in well 1 is 50.0 m and in well 2 the head is 42 m. The hydraulic conductivity K is 0.7 m/day.
(a) What is the total daily flow of water through the aquifer?
(b) What is the height of the piezometric surface 0.5 km from well 1 and 0.9 km from well 2?

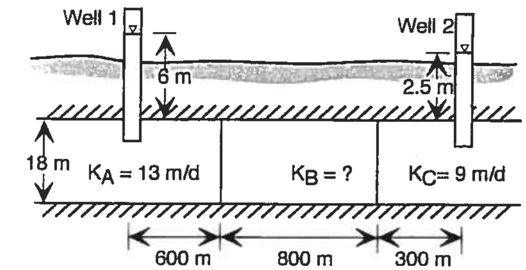
2-6. Three piezometers arranged in an aquifer as an equilateral triangle with sides of 1000 m. A is located to the east of Well B and Well C which are aligned in a north-south direction. The water surface elevations are measured for the three wells are as follows: A = 150m, B = 100m and C = 200m. Find the direction and two dimensional rate of flow within the triangle using graphical methods. The hydraulic conductivity of the aquifer is 5×10^{-7} cm/s.

2-7. Answer the following questions with reference to Figure 2.11(b) for a flow net under a dam with a sheet pile. Note that the numbers beside the equipotentials are labels only and not representative of head values.
(a) What are the values of equipotentials 17, 9, 2, and 0?
(b) What is the rate of seepage under the dam if the dam is 120 ft long and the hydraulic conductivity is 5 m/d?
(c) What is the rate of seepage under the dam if the upstream water level drops to 12 ft?

2-8. Refer to Figure 5.18 showing the potentiometric map for a shallow sand aquifer. The hydraulic conductivity of the unit is estimated to be 1.5×10^{-2} cm^2/s, porosity = 0.3.
(a) Which well would you expect to be most contaminated?
(b) What is the groundwater velocity and seepage velocity across the plume?
(c) Estimate how long the source has been contaminating the aquifer. You may ignore the effects of dispersion, diffusion and adsorption.
(d) Estimate the rate of flow across the plume.
(e) How would you explain contamination upgradient of the source?

2-9. Two observation wells 1700 m apart have been constructed in a confined variable 587 hydraulic conductivity in the direction (see Figure P2.9). The flow rate is 0.008 m^3/h per unit width of the confined aquifer. Well 1 is drilled in Soil A with hydraulic conductivity 13 m/d, and Well 2 is drilled in Soil C with hydraulic conductivity 9 m/d. The soil zone B is between the wells, 600 m from Well 1 and 300 m from Well 2. The potentiometric surface is 6 m above the upper confining unit in Well 1 and 2.5 m above the upper confining unit in Well 2. Evaluate the hydraulic conductivity of Soil B using Darcy's Law.

Figure P2.9



2-10. Three observation wells separated by 1000 m are drilled in a line in a confined aquifer with variable hydraulic conductivity in the x direction. The water surface elevation in Well 1 is 60 m and 52 m in Well 3. The hydraulic conductivity of the aquifer between Wells 1 and 2 is K_A, and between Wells 2 and 3 the hydraulic conductivity is K_B. Determine the water surface elevation in Well 2 for the following conditions:
(a) K_A = 10 m/d, K_B = 20 m/d
(b) K_A = 10 m/d, K_B = 50 m/d
(c) K_A = 50 m/d, K_B = 10 m/d

2-11. Two piezometers are located 1000 ft apart with the bottom located at depths of 50 ft and 350 ft, respectively, in a 400 ft thick unconfined aquifer. The depth to the water table is 50 ft in the deeper piezometer and 40 ft in the shallow one. Assume that hydraulic conductivity is 0.0002 ft/s.
(a) Use the Dupuit equation to calculate the height of the water table midway between the piezometers.
(b) Find the quantity of seepage through a section 25 ft wide in cfs.

2-12. Three geologic formations overlie one another with the characteristics listed below. A constant velocity vertical flow field exists across the three formations. The hydraulic head is 33 ft at the top of the formations (top of formation no. 1) and 21 ft at the bottom (bottom of formation no. 3). Calculate the hydraulic head at the two internal boundaries, that is, at the top and bottom of formation no. 2. Assume:

b_1 = 50 ft K_1 = 0.0002 ft/s
b_2 = 20 ft K_2 = 0.000005 ft/s
b_3 = 210 ft K_3 = 0.001 ft/s

2-13. A formation is composed of four horizontal, homogeneous, and isotropic strata overlying one another. The hydraulic conductivity in the top layer is 1×10^{-3} cm/s, 1×10^{-6} cm/s in the second layer, 1×10^{-2} cm/s in the third layer, and 1×10^{-4} cm/s in the bottom layer. Calculate the effective horizontal and vertical hydraulic conductivities for the entire formation if each layer is 3 m thick. Give an example of soil types that might make up this formation.

2-14. A soil sample 6 in. in diameter and 1 ft long is placed in a falling head permeameter. The falling head tube diameter is 1 in. and the initial head is 6 in. The head falls 1 in. over a two hour period. Calculate the hydraulic conductivity.

2-15. A constant head permeameter containing fine grained sand has a length of 12 cm, and an area of 30 cm^2. For a head of 10 cm, a total of 100 ml of water is collected in 25 min. Find the hydraulic conductivity.

2-16. Two observation wells, 450 m apart, have been constructed in a confined aquifer with a hydraulic conductivity of 5×10^{-4} cm/s and a porosity of 0.35. The average thickness of the aquifer between the wells is 45 m. Well 1 (water surface elevation of 95 m) lies to the east of Well 2 (water surface elevation of 94.6 m). A stream lies 900 m to the west of Well 2.
(a) Determine the flow rate per unit width of the aquifer.
(b) Calculate how long it would take groundwater contaminants to travel from Well 1 to the stream.
(c) Calculate the level of the potentiometric surface at a distance 600 m to the east of Well 1.

2-17. A conservative compound is discharged into a pond with water surface elevation of 100 m. The compound moves from the pond to a river (water surface elevation 99.3 m) 1.2 km away through a confined aquifer 12 m thick. The aquifer has a transmissivity of 0.05 m^2/s and a porosity of 0.30. Ignoring the effects of dispersion (see Chapter 6) and adsorption to the soil, and assuming immediate and complete mixing, how long would it take for the contaminant to reach the river? How would your answer differ if the aquifer was unconfined?

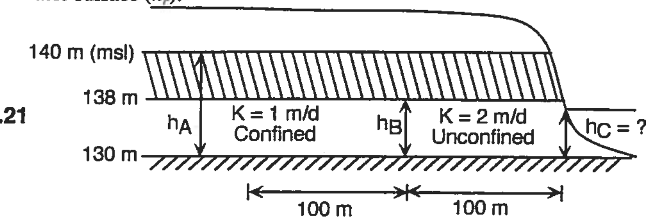
2-18. The base of a proposed landfill for paper-mill sludge is in a glacial till, 30 ft above an aquifer. The vertical hydraulic conductivity of the till is 1×10^{-7} cm/s, the vertical hydraulic gradient is 0.075, and the effective porosity is 0.30. If the leachate (contaminated fluid) drains from the landfill into the till, how many years would pass before the leachate reached the aquifer below? If the vertical hydraulic conductivity 3×10^{-6} cm/s, what would the travel time be?

2-19. A 3 m thick aquitard ($K_2 = 0.5$ m/d) separates an unconfined aquifer ($K_1 = 15$ m/d) from a leaky confined aquifer ($K_3 = 10$ m/d). The water table is above the potentiometric surface for the leaky confined aquifer. Three observation wells are drilled- one in the unconfined aquifer, one in the aquitard, and one in the leaky confined aquifer. The head in the leaky confined aquifer is 23 m and in the unconfined aquifer the head is 25 m. Using Darcy's Law calculate the head in the well at the top of the leaky confined aquifer (the base of the aquitard). Assume steady state conditions. The datum is at the base of the aquitard layer.

2-20. Two parallel rivers are separated by 1.5 km. The water surface elevations of the rivers are 60 m and 45 m and the datum is defined as the base of the river beds. A confined aquifer extends between the two rivers from elevation 0 m to elevation 30 m, and has a transmissivity of 210 m^2/d. The hydraulic conductivity of an unconfined aquifer on top of this formation is 10 m/d.
(a) Determine the combined flow rate between the two rivers.
(b) Determine the shortest time of travel for a contaminant to move from one to the other. Neglect dispersion effects and assume both aquifers have a porosity of 0.25.

2-21. A confined aquifer (hydraulic conductivity 1 m/d) flows into an unconfined aquifer (hydraulic conductivity 2 m/d) and then enters a shallow lake (as shown in Figure P2.21). The elevation of the lower confining unit for both aquifers is 130 m. The elevation of the base of the upper confining unit is 138 m. The upper confining unit is 2 m thick and extends across both aquifers. The thickness of the confined aquifer is 8 m. If the potentiometric surface at A is at an elevation of 140 m (h_A), find the elevation of the lake water surface (h_c).

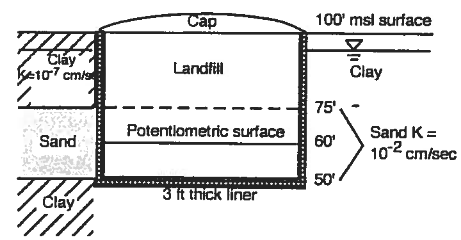
Figure P2.21



2-22. Two rivers are 1000 m apart. The water surface elevation of the first river is 30 m, and 25 m for the second river. The area between the rivers receives a recharge of 10 cm/y (after runoff). If the hydraulic conductivity is 0.8 m/d, find the location and elevation of the water divide and the daily seepage into each river. Sketch a flow net for the aquifer in the problem above.

2-23. A landfill liner is laid at elevation 50 ft msl (mean sea level) on top of a good unit. A clean sand unit extends from elevation 50 ft to elevation 75 ft, and another clay unit extends up to the surface located at elevation 100 ft. The landfill can be represented by a square with length of 500 ft on a side and a vertical depth of 50 ft from the surface. The landfill has a 3 ft thick clay liner with $K = 10^{-7}$ cm/s around the sides and bottom, as shown in Figure P2.23. The regional ground water level for the confined sand ($K = 10^{-2}$ cm/s) is located at depth of 10 ft below the surface. How much water will have to be continuously pumped from the landfill to keep the potentiometric surface at 60 ft elevation (msl) within the landfill? Assume mostly horizontal flow.

Figure P2.23



2-24. Repeat Problem 2.23 for the case where the clean sand unit extends below the landfill to an elevation of 25 ft msl. Assume water can flow through the sides and bottom of the clay liner

2-25. Repeat Example 2.3 for the case where net recharge $W = 10$ cm/yr. Repeat the example for the case where $W = 0$.

2-26. Compute the flow rate through Figure 2.13 if the total head drop is 10 ft and $K = 1$ft/day

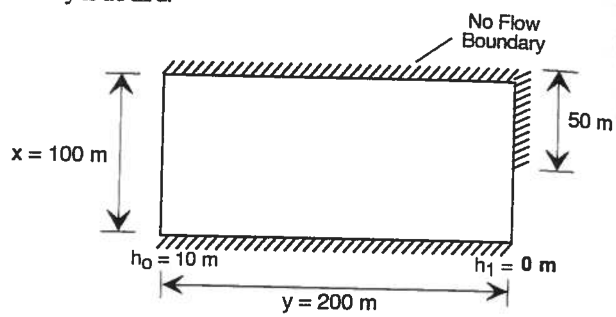
2-27. A confined aquifer slopes gradually from 20 m to 10 m in thickness over a length of 1 km. The slope of the potentiometric surface is 0.5 m/km and the hydraulic conductivity of the aquifer is 50 m/d. For a sloping aquifer, the continuity equation yields the following relation:

$$Q = \frac{(\phi_1 - \phi_2)/L}{\int \frac{dx}{T(x)}}$$

What is the flow rate through a 100 m wide section of the aquifer?

2-28. Sketch a quantitative flow net for the following confined a total flow per unit width if the hydraulic conductivity is 20 m/d.

Figure P2.28



Chapter 3

3-1. A well with a diameter of 18 in. penetrates an unconfined aquifer that is 100 ft thick. Two observation wells are located at 100 ft and 235 ft from the well, and the measured drawdowns are 22.2 ft and 21 ft, respectively. Flow is steady and the hydraulic conductivity is 1320 gpd/ft^2. What is the rate of discharge from the well?

3-2. A well of 0.5 m diameter is pumped from confined aquifer at 0.08 m^3/s. The drawdown recorded at Observation Well 1 (15 m from the pumping well) is 3.8m; at Observation Well 2 (50 m from the pumping well) the drawdown is 2.8m. What is the drawdown at the pumping well?

3-3. A single well pumps 1000 m^3/d in a confined aquifer of thickness 10 m and porosity 0.3. At the radius of influence of the well (1000 m) the head is 20 m. Assuming steady state conditions calculate the seepage velocity towards the well at a radius of 100 m, and a radius of 500 m.

3-4. **(a)** A well in a confined aquifer of thickness B pumps continuously at a rate Q. Using Darcy's Law in radial coordinates and the fact that the seepage velocity, $v_s = dr/dt$, show that the travel time for contaminants to move to the well of radius r_w, from a point on the radius of influence, R, is

$$t = (\pi B n/Q)(R^2 - r_w^2)$$

(b) A fully penetrating well of 0.8 m diameter and with a radius of influence of 100 m, is drilled in a confined aquifer 15 m thick. The aquifer has a transmissivity of 50 m^2/d and a porosity of 0.3. At what rate should the well be pumped if the time of travel for a contaminant to reach the well from the radius of influence is to be not less than 200 days. If the potentiometric surface was 15 m above the upper confining layer before pumping began, what is the steady state drawdown in the well?

3-5. A confined aquifer extends 3.5 km between the West River and the East River. The water surface elevations of the rivers are 230 m and 228.5 m respectively. The radius of influence of a fully penetrating pumping well located halfway between the rivers is 90 m. The well has a diameter of 0.5 m and pumps at a rate of 75 L/min. The elevation of the upper confining unit is 227 m and the aquifer is 25 m thick. The transmissivity of the aquifer is 80 m^2/d. Determine the steady state head 20 m to the east of the well.

3-6. In a fully penetrating well, the equilibrium drawdown is 30 ft with a constant pumping rate of 20 gpm. The aquifer is unconfined and the saturated thickness is 100 ft. What is the steady-state drawdown measured in the well when the pumping rate is 10 gpm? Assume radius of influence remains constant.

3-7. A fully penetrating well in an unconfined aquifer is pumped continuously so that the steady state drawdown is 15 m. The water table is at a height of 55 m from the bottom of the aquifer which has a hydraulic conductivity of 20 m/d. The diameter of the well is 0.25 m.

(a) If the pumping has no effect on the water table at a distance of 1.2 km, determine the pumping rate.

(b) Determine the drawdown in an observation well located 600 m from the pumping well.

(c) Determine the travel time from the observation well to the pumping well if the aquifer has a porosity of 0.4.

3-8. A fully penetrating well of radius r_w is located in the center of a circular confined aquifer of radius r_a and thickness B. The hydraulic conductivity of the aquifer varies with radius such that $K = K_i$ for $r_i \geq r \geq r_w$ and $K = K_2$ for $r_a \geq r \geq r_i$ If the piezometric head is maintained at h_w at $r = r_w$, and h_a at $r = r_a$ at what rate would the well be pumping?

3-9. Two wells are located 100 m apart in a confined aquifer with transmissivity $T = 2 \times 10^{-4}$ m^2/s and storativity $S = 7 \times 10^{-5}$. One well is pumped at a rate of 6.6 m^3/hr and the other at a rate of 10.0 m^3/hr. Plot drawdown as a function of distance along the line joining the wells at 1 hr after the pumping starts.

3-10. A Hvorslev slug test was performed in a confined aquifer with a piezometer screened over of 20 ft and a radius of 1 in. The radius of the rod was 0.68 in. The following recovery data for the well were observed. Given that the static water level is 7.58 ft and H_o = 6.88 ft, calculate the hydraulic conductivity.

TIME(s)	20	45	75	101	138	164	199
h (ft)	6.94	7.00	7.21	7.27	7.34	7.38	7.40

3-11. A well casing with a radius of 6 in. is installed through a confining layer into a formation with a thickness of 10 ft. A screen with a radius of 3 in. is installed in the casing. A slug of water is injected, raising the water level by 0.5 ft. Given the following recorded data for head decline, find the values of *T*, *K*, and *S* for this aquifer.

TIME(s)	5	10	30	50	80	120	200
h (ft)	0.47	0.42	0.32	0.26	0.10	0.05	0.01

3-12. A small municipal well was pumped for 2 hr at a rate of 15.75 L/s. An observation well was located 50 ft from the pumping well and the following data were recorded. Using the Theis method outlined in Example 3.3, compute *T* and *S*.

TIME (min)	DRAWDOWN (ft)	TIME (min)	DRAWDOWN (ft)
1	1.5	15	14.9
2	4.0	20	17.0
3	6.2	40	21.4
5	8.5	60	23.1
7	10.0	90	26.0
9	12.0	120	28.0
12	13.7		

3-13. A well in a confined aquifer is pumped at a rate of 833 L/min for a period of over 8 hr. Time-drawdown data for an observation well located 250 m away are given below. The aquifer is 5 m thick. Use the Cooper-Jacob method to find value *K*, and *S* for this aquifer.

TIME (hr)	DRAWDOWN (m)	TIME (hr)	DRAWDOWN (m)
0.050	0.091	1.170	1.860
0.083	0.214	1.333	1.920
0.133	0.397	1.500	2.040
0.200	0.640	1.670	2.130
0.333	0.976	2.170	2.290
0.400	1.100	2.670	2.530
0.500	1.250	3.333	2.590
0.630	1.430	4.333	2.810
0.780	1.560	5.333	2.960
0.830	1.620	6.333	3.110
1.000	1.740	8.333	3.320

3-14. Drawdown, *s'*, was observed in a well located 100 ft from a pumping well that was pumped at a rate of 1.11 cfs for a 30 hr period. Use the Cooper-Jacob method to compute *T* and *S* for this aquifer.

Time(hr)	1	2	3	4	5	6	8	10	12	18	24	30
S(ft)	0.6	1.4	2.4	2.9	3.3	4.0	5.2	6.5	7.5	9.1	10.5	11.5

3-15. Repeat Problem 3.14 using the Theis method.

3-16. The drawdown in three observation wells was recorded after 24 hours of pumping from a well at 2300 m^3/d and the results are shown below. Calculate the transmissivity and storage coefficient of the aquifer using the Theis Method. You will need to plot drawdown versus r^2/t at a point in time for the three different radii and match the curves as before. Based on your estimate of the storativity, do you think the aquifer is confined or unconfined?

Well Number	Distance from Well (m)	Drawdown (m)
1	100	1.5
2	200	1.25
3	300	1.10

3-17. A well injects water into an aquifer at Q = 1.0 cfs. A river running north/south lies 300 ft west of the well. The confined aquifer with thickness of 10 ft has T = 3200 sq ft/day and S = 0.005. Observation wells are located 10, 50, 150, 300 and 450 ft west of the well.

(a) Compute the head buildup along the x-axis at the observation well locations after 6 hr of injection.

(b) Compute the Darcy velocity along the x-axis using simple graphical methods at the various well locations.

3-18. Use the Theis Method equations for the functions u and $W(u)$ to characterize the expected behavior of an areally infinite, homogeneous, horizontal, isotropic, confined aquifer. The aquifer has a transmissivity of 500 m^2/d and a storativity of 1×10^{-5}. The well is pumped continuously at 2500 m^3/d.

(a) What will be the drawdown 75 m away from the pumping well at 1, 10, 100, 1000, and 10,000 minutes after pumping begins?

(b) Estimate when the system will reach steady state.

(c) Estimate the steady state drawdown in the well.

(d) What will be the drawdown after one day at distances of 2, 5, 10, 50, 200, and 1000 m from the pumping well? Estimate the distance at which the pumping will have no effect on the potentiometric surface after one day of pumping.

3-19. A well at distance d from an impermeable boundary pumps at a flow rate Q. The head at any point (x, y) is given by the following expression:

$$h(x,y) = \frac{Q}{2\pi kb}\ln(r_1 r_2) + C$$

where C is a constant, r_I is the straight line distance from the well to point (x, y), and r_2 is the straight line distance from the image well to the point (x, y). The y-axis lies along the impermeable boundary. Use Darcy's Law to show that the discharge across the y-axis is zero.

3-20. A well is to be placed in an unconfined aquifer at a distance x from a stream. The well will be required to pump at a constant rate of 1.3×10^{-3} m^3/s. The aquifer has an average thickness of 10m and hydraulic conductivity of 1×10^{-2} cm/s. Regulations stipulate that the drawdown at a radius of 15 m from the well may not exceed 0.6 m.. Calculate x such that it is the smallest distance that satisfies the requirements.

3-21. A fully penetrating well pumps from a confined aquifer of thickness 20 m and hydraulic conductivity 10 m/d. There is no water table above the confined aquifer. The radius of the well is 0.25 m, and the recorded drawdown in the well is 0.5 m. Assume that the radius of influence of the well is 1250 m.

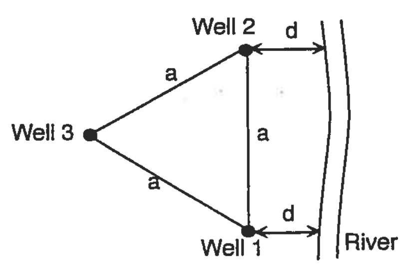
(a) Calculate the pumping rate if the well is 100 m from a stream.
(b) Calculate the pumping rate if the well is 100 m from an impermeable boundary.

3-22. An excavation site is to be dewatered by using four pumping wells located at the corners of a square with sides of 500 m. The wells are fully penetrating and have diameters of 0.5 m. What is the required flow rate in each well if the objective is to lower the original water table (h_0 = 100 m) by 5 m everywhere in the square site? Note that the maximum drawdown may not occur in the center of the square. The hydraulic conductivity of the aquifer is 1.5 m/d and the radius of influence for each well is 1000 m.

3-23. **(a)** Three fully penetrating wells in an unconfined aquifer form an equilateral triangle of side a. Two of the wells are a distance d from a long river. Each well has a radius r_w,. and pumps at a rate Q. At steady state the wells have a radius of influence of R and the water table is at an elevation of h_o. If the aquifer has a conductivity of K, derive an expression for the drawdown in the center of the triangle.

(b) What is the drawdown in the center of the triangle if the parameters are: a = 70 m, d = 100 m, K = 1.5 m/d, Q = 700 m^3/d, R = 600 m, h_0 = 50m

Figure P3.23



3-24. Walton (1960) gave data for an aquifer test in a well confined by a leaky aquitard 14 ft thick. Drawdown was measured in an observation well 96 ft away from a pumping well which was pumping at 25 gpm. For the following data, use Figure 3.13 to determine T, S and K'.

TIME (min)	DRAWDOWN (ft)	TIME (min)	DRAWDOWN (ft)
5	0.76	493	5.96
28	3.30	669	6.11
41	3.59	958	6.27
60	4.08	1129	6.40
75	4.39	1185	6.42
244	5.47		

3-25. An interceptor well fully penetrates a confined aquifer with a hydraulic conductivity of 0.5 cm/s. Before pumping began the aquifer had a hydraulic gradient of 0.001 and a saturated thickness of 27 m. The interceptor well pumps at a rate of 60 L/s. Define the capture zone of the interceptor well by calculating the maximum width and the distance to the stagnation point. Sketch the shape of the groundwater divide using at least ten points.

Chapter 6

6-1. Chloride was injected as a continuous source into a 1-D column 50 cm long at a seepage velocity of 10^{-3} cm/sec. The concentration measured after 1800 seconds from the beginning of the test was 0.3 of the initial concentration, and after 2700 seconds it reached 0.4 of the initial concentration. Find the coefficient of dispersion and longitudinal dispersivity.

6-2. Chloride has been injected into a 1-D column continuously. If the system has a Darcy velocity of 5.18×10^{-3} m/day, the porosity of the medium is 0.3, and the longitudinal dispersivity is 5 m,

(a) What is C/C_0 at 0.3 m from the point of injection after 5 days?
(b) Repeat (a) with a longitudinal dispersivity of 20 m.
(c) Comment on the difference in results.

6-3. The estimated mass from an instantaneous spill of benzene was 107 kg per m^2 of the 1-D aquifer. The aquifer has a seepage velocity of 0.03 m/day and a longitudinal dispersion coefficient of 9×10^{-4} m^2/day.

(a) Calculate the maximum concentration at t = 1 year.
(b) Calculate the benzene concentrations at t = 1 year, at one standard deviation on either side of the center mass of the plume.
(c) Plot the breakthrough curve vs. time at $x = (vt)$ (t = 1 year).
(d) Plot the breakthrough curve vs. distance at t = 1 year.
(e) Discuss the difference.

6-4. Match the breakthrough curves given in the diagram with the proper description given below. Curves represent responses to the injection of a tracer in 1-D soil columns. Choose the best match for each case or indicate none of the above (NA).

(a) Curve for a 1-D continuous injection where the constituents get sorbed to the medium.
(b) Curve for a 1-D continuous injection where plug flow is observed.
(c) Curve for an instantaneous source with longitudinal dispersion.
(d) Curve for an instantaneous source with no dispersion
(e) Curve for a 1-D continuous injection with longitudinal dispersion
(f) Curve for a 1-D continuous injection with longitudinal dispersion and biodegradation.
(g) Curve for a 1-D continuous injection in which a fracture existed along the soil column.

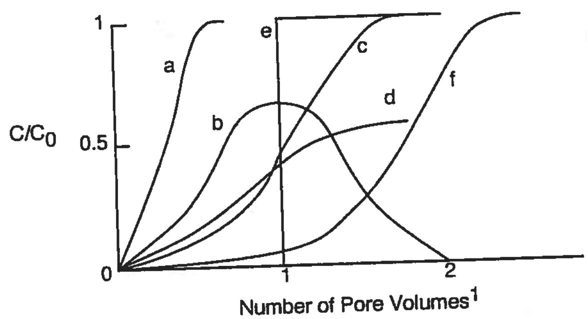


Figure P6.4

[1] A pore volume in a column is the volume of water that will completely fill all of the voids in the column.

6-5. Sketch (on the same graph) C/C_0 as a function of time for transport in a sand column from an instantaneous source for each of the following cases:

(a) Advection only
(b) Advection with low dispersion.
(c) Advection with high dispersion.
(d) Advection with high dispersion with biodegradation.
(e) Advection with high dispersion with retardation.

6-6. A continuous source has been leaking contaminant for 2 years into a 1-D aquifer. The steady state dilution attenuation factor DAF for the aquifer is 100. DAF = Concentration at source/concentration at receptor well. Source concentration = 1200 mg/L

(a) What is the concentration of benzene at a receptor well after 2 years.
(b) What is the concentration of benzene at a receptor well in 2 years, if there is first order decay at a rate of 0.01 (1/day).

6-7. An instantaneous release of biodegradable organics occurs in a 1-D aquifer. Assume that the mass spilled is 1.0 kg over a 10 m^2 area normal to the flow direction, α_x = 1.0 m, the seepage velocity is 1.0 m/day and the half life of the decaying contaminant is 33 years. Compute the maximum concentration at 100 m from the source.

6-8. For a 2-D aquifer, calculate the maximum concentration of a spike source of Tritium, H-3 (half life = 12.26 years) at 100 m from a well injecting 1.0 kg of mass over 10 m of well screen. The plume velocity is 0.5 m/day, α_x = 1.0 m, α_y = 0.1 m.

6-9. An accidental spill from a point source introduced 10 kg of contaminant mass to an aquifer. The seepage velocity in the aquifer is 0.1 ft/day in the x direction. The longitudinal dispersion coefficient D_L = 0.01 ft^2/day, the lateral and vertical dispersion coefficient, $D_y = D_z$ = 0.001 ft^2/day.

(a) Calculate the maximum concentration at x = 100 ft and t = 5 years.
(b) Calculate the concentration at point x = 200 ft, y = 5 ft, z = 2 ft, 5 years after the spill.

6-10. Domenico & Schwartz, 1998, developed a model for a planar source that accounts for the source geometry with longitudinal, lateral and vertical spreading. The steady state model was applied at the plane of symmetry where y = z = 0 (see Figure 6.8).

The model is to be applied to the case of a continuous source that has been leaking contaminant into an aquifer for 15 years. The source had a width Y and a depth Z of 6 m, the initial concentration of the source was 10 mg/L, the seepage velocity is 0.057 m/day, and the longitudinal, transverse and vertical dispersivities were estimated at 1 m, 0.1 m, 0.01 m respectively. Calculate the present contaminant concentration at x = 200 m from source, using the Domenico model.

6-11. A slug of contaminant was injected into a well for a tracer test (2-D). If the initial contaminant concentration is 1000 mg/L, the background seepage velocity in the aquifer is 0.022 m/day, the well radius is 0.05 m, the longitudinal dispersion coefficient is 0.034 m^2/day, and the transverse dispersion coefficient is 0.01 of the longitudinal dispersion coefficient.

(a) What is the maximum concentration reached after 24 hours?
(b) Plot the concentration vs. distance at t = 24 hours.

6-12. An underground storage tank (volume = 1.0 m^3) spills its contents of 1.0 kg of TCE in a 10 m thick sand aquifer. The seepage velocity is 1.0 m/day in the x direction. The longitudinal dispersivity is 1.0 m, the transverse and vertical dispersivities are 0.1 m. Assume R = 1.

(a) Calculate the maximum concentration at a distance of x = 500 m. Note: y=0, z=0 for maximum concentration.
(b) If the contaminant was uniformly spilled over the 10 m thickness of the aquifer, what is the maximum concentration at x = 500 m, y = 0, z = 0, with vertical dispersion = 0.
(c) Comment on the results.

6-13. A finite source of chloride is released at x = 0 into a 1-D aquifer over a 1 year period. The plume moves at a seepage velocity of 0.2 m/day, α_x = 2 m. Assume that the solution can be found by using an imaginary negative concentration source beginning at the end of the release period. Develop the equation for concentration $C(x,t)$ if C_0 = 1000 mg/L. Find the maximum concentration at x = 100 m.

6-14. The concentration of organic waste in a landfill is 100 mg/L. The pit is placed in a clay layer, $K = 10^{-6}$ cm/sec underlain by a sand layer, $K = 2 \times 10^{-2}$ cm/sec. The two units are separated by a thin impermeable silty layer. The top surface of the clay layer is at elevation 9.15 m above MSL for which the water table is at 8.5 m above MSL. The top surface of the sand layer is at elevation 6.1 m, for which the piezometric surface is 7.6m above MSL. The pit bottom lies at elevation 8.4 m above MSL. The slope of the piezometric surface is 0.01. The porosity of the 2 layers is 0.25, and the longitudinal dispersivity is estimated at 0.3 m. An observation well is located 300 m from the pit. (See Figure P6.14.)

(a) Calculate the seepage velocity for the clay layer. How long does it take the contaminant to reach the sand layer.

(b) Calculate the seepage velocity for the sand layer. What is the contamination level in the well after 15 years from the beginning of the release, assuming a 1-D model.

(c) What would happen to the concentration in the well if lateral dispersion exists in the sand aquifer in addition to longitudinal dispersion.

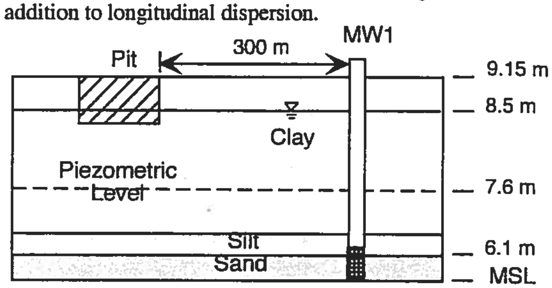


Figure P6.14

6-15. From example 6.4, multiply the vertical scale of Figure 6.10a times 2 and repeat the problem.

6-16. Prove that the plume described in Eq. (6.27) takes the form of a two dimensional Gaussian (normal) distribution as described below, and evaluate α_x and α_y

$$P = [1/(2\pi\sigma_x\sigma_y)]\exp(-[(x-x_0)^2/(2\sigma_x^2)] - [(y-y_0)^2/(2\sigma_y^2)])$$

6-17. A well 300 ft west of a river (which runs north/south) injects waste chloride at a rate of 30,000 ft^3/day into a confined aquifer. The head in the aquifer and river prior to pumping was 100 ft. Aquifer characteristics include T = 1,000 ft^2/ day, thickness of 20 ft, and n = 0.25. A farmer's well pumps water supply from the same aquifer 300 ft east of the river (on the other side) at 20,000 ft^3/day. Both wells have a radius of influence of 1000 ft.

(a) Compute the heads and velocities at 100 and 200 ft from the pumping well.

(b) Will chloride arrive at the pumping well?

(c) Find the average seepage velocity from the injection well to the river along the shortest line of travel. Use any convenient approximation method.

6-18. A tank of TCE located directly below a water table is known to be continuously leaking at concentration of 10,000 μg/L of TCE. The source can be assumed to be a vertical plane 5 m wide and 3 m deep located just below the water table. Dispersivity in the x, y, and z directions can be assumed to be 10 m, 3 m, and 0.3 m. Hydraulic gradient of the water table is 0.001 and the porosity is 0.3. The hydraulic conductivity K ranges from 2.0×10^{-2} to 5.0×10^{-2} cm/sec.
What is the highest concentration predicted to occur at a receptor located at x = 100 m, y = 5 m, and z = 3 m, where x is longitudinal, y is transverse, and z is vertical? Evaluate the results at t = 1 year, 3 years and 6 years. What level of remediation would be required to keep the receptor level below 5 μg/L for the range of K values indicated at t = 6 yr?

6-19. (a) From the chloride data presented in Figure 6.12b of a 2-D experiment at the Borden landfill, estimate the average seepage velocity in the aquifer, where porosity averages 0.3. Explain how you would compute the longitudinal and transverse dispersivity for the site from the field data (do not perform this calculation). What equation would you use ?

(b) Adsorption of carbon tetrachloride was tested at the site and retardation is defined as the ratio of velocity of a natural tracer (chloride) to that of the retarding chemical. Roughly estimate the retardation factor of carbon tetrachloride (CTET) from the data in Figure 7.3b. All contaminants originated from the source location (0,0) at time zero.

6-20. Refer to the figure from the Borden Landfill natural gradient test. Assume that day 1 represents the input of chloride into the aquifer with C_0 = 892 mg/L over a 20 m^2 area. The plumes of chloride in 2-D for day 85, 462 and 647 are plotted on Figure 6.12b. Note that the latter two plumes overlap each other.

(a) Roughly sketch the longitudinal distribution of chloride concentration for day 85, 462, and 647 on a single graph of concentration vs. distance measured from the peak conc. of each curve.

(b) Use the 2-D equation for a pulse input to compute α_L and α_T (dispersivity) based only on the observed peak conc. for day 647 (Eq. 6.27). Use seepage V = 30 m/yr, C_0 = 892 mg/L, *area* = 20 m^2, and t = 647 days. Assume that the ratio of α_L to α_T is 10/1.

6.21 A landfill next to a river has been leaking chromium continuously for 20 years, creating a plume of contamination. The gradient of ground water flow is towards the river, as shown in the figure below. Well concentration data is provided along with water level readings. Assume that chromium acts as a conservative tracer in this aquifer where longitudinal dispersivity =1.0 m. Landfill, ground water, and river data are provided in the following table and Figure P6.21. K = 10^{-3} cm/sec; n = 0.4; b = 20 ft; Q(river) = 200 cfs; Concentration of Cr at point A (upstream) = 0 mg/L.

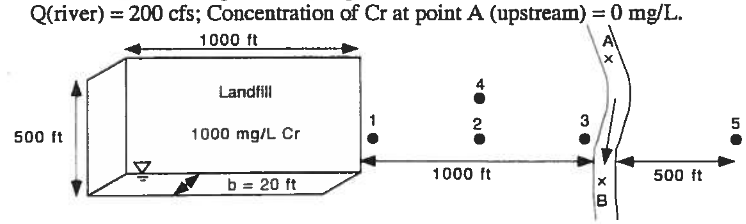


Figure P6.21

Well	Water elevation (ft)	Cr Concentration (mg/L)
1	100	1000
2	90	no data
3	80	no data
4	90	0
5	100	0

(a) Find the predicted concentration of Cr in well 3 (at t = 20 years).
(b) Find the concentration of Cr in the river at point B (immediately downstream) Consider the flow from both sides of the river.

6-22. A well fully penetrates an aquifer which has a uniform depth of 10 m. 100 grams of benzene is spilled into the well and is immediately dissolved and mixed into the water in the well. The seepage velocity = 30 m/yr in the x direction, the longitudinal dispersivity = 1.0 m, and the transverse dispersivity is 0.1 m.
Using the following aquifer characteristics, calculate the retardation factor R for benzene in this aquifer. Bulk density = 1.8 g/cm^3, porosity = 0.3, organic carbon fraction = 1%, K_{ow} for benzene = 135 L/kg
(a) Which equation should you use for calculating benzene concentrations downgradient of the well (1-D, 2-D, or 3-D; spike or continuous)
(b) What is the maximum benzene concentration at t = 1 year? Where is this maximum located?
(c) What is the benzene concentration at t = 1 year, 3 meters away from the center of mass in the x direction?
(d) What is the benzene concentration at t = 1 year, 3 meters away from the center of mass in the y direction?
(e) Comment on how the dispersivity affects the concentration of benzene 3 m away in the x and y directions.

6-23. Repeat Example 6.la from Chapter 6, using a retardation factor (R = 2.5) for benzene.

6-24. Repeat Example 6.2 from Chapter 6 for benzene (with a retardation factor, R = 2) for a 10,000 μg/L spill.

6-25. Bromide (Br$^-$), a common field tracer, is injected continuously at a concentration of 500 mg/L and a flowrate of 5 L/min from a well (6 inches in diameter) into a confined aquifer with a hydraulic conductivity of 2×10^{-4} cm/s and a gradient of 0.009. The porosity is 0.3 and α_x = 1 m, α_y = 0.1m A receptor well is located 2 meters downgradient of the injection well. You may neglect the z-direction as the well is assumed to be fully penetrating the aquifer.
(a) Plot out the Br$^-$ concentration versus time for the receptor well.
(b) For t = 24 hours, plot the concentration as a function of distance.

6-26. Chromium is a common contaminant associated with metal plating operations. Chromium was continuously released from a small metal shop for 5 years at a concentration of 5000 mg/L into an aquifer with a porosity of 0.3, α_x = 1 m, and α_y = 0.1 m. the aquifer is a fine sand (2.4×10^{-3} cm/s). Groundwater flow is to the south with a gradient of 0.01. A nearby resident placed a shallow well (fully screened) for watering a garden 1000 feet south and 50 feet east of the discharge location. The EPA MCL for chromium is 0.1 mg/L. Assume that there is no degradation. Calculate the maximum possible concentration in the well if the depth of the source zone was 1 foot and the width of the source zone was
(a) 6 inches (b) 12 inches (c) 36 inches

6-27. Several drums of radioactive waste leaked into an aquifer. with α_x = 1 m, α_y = 0.1m, and α_y = 0.04m. The drums contained 1000 ci Sr–90 and 300 ci Cs–137 (see table 4.5) The linear groundwater velocity is 10 cm/day. Sr–90 has a half life of 28 years, and Cs–137 has a half life of 33 years. A river is located 1000 feet downgradient of the drums. Calculate the time it takes for Sr–90 and Cs–137 to reach the river and determine what the maximum concentration will be at a point near the river bank.

6-28. A tracer study is to be performed at a field site to determine hydraulic conductivity. Slug tests indicate that the site has a conductivity between 10^{-3} and 10^{-4} cm/s. The aquifer is confined with a thickness of 15 ft. Bromide has been selected for the tracer (field detection limit of 0.1 mg Br$^-$/L using the Phenol Red colorimetric method). The tracer is injected at a concentration of 1000 mg/L for 12 hours into a fully screened well with a 6 inch diameter and then monitored at various receptor wells to determine hydraulic conductivity and dispersivity. The tracer test needs to be finished within 3 weeks.
(a) Choose the location for five monitoring wells around the injection well. Since this is for design purposes, assume porosity of 0.3, α_x = 1 m, and α_y = 0.1 m.
(b) Design a sampling schedule for the test taking into account the cost associated with taking a round of samples and the resolution necessary to determine the hydraulic conductivity and dispersivity. Remember that you do not know the exact hydraulic conductivity and dispersivity beforehand.

Chapter 8

8-1. Example 8.2 in the text presents a biodegrading plume (assume that it is all benzene) which then receives 20 and 40 mg/L of oxygen into the aquifer. Answer the following questions regarding the benzene plume.
(a) What is the average seepage velocity in the plume with the pump/treat system on? What is the flow rate across the plume assumed to be 2500 ft wide?
(b) Each well in the pump and treat system is pumping 1 gpm. How does this combined flow compare to the average flow across the plume without pumping?
(c) What mass of oxygen in Kg is transported into the plume over the two year period assuming a concentration of 8.0 mg/L in the groundwater.
(d) If there is 15 inches of rainfall per year, with an O_2 concentration of 8.0 mg/L, what mass of additional benzene will be degraded over that contained in Fig. 8.6.
(e) Why does the plume shape change in Fig. 8.6 after biodegradation?

8-2. Set up a BIOPLUME II or III model for the input data given in example 8.2
(a) Change pump locations by 2 cells
(b) Change pump rates by a factor of 2
(c) Change O_2 concentrations by a factor of 2
(d) Change the gradient across the plume by a factor of 2
(e) Compare your results with example 8.2 and discuss.

Chapter 11

11-1. A contaminated site has been surveyed and a contaminated region 100 ft × 150 ft × 15 ft deep was delineated. The average concentration of total petroleum hydrocarbons (TPH) on soil is 10,000 mg/Kg .

(a) What is the total mass of contaminants at the site in kilograms? Assume the density of the soil is about 128 lb per cubic foot (specific gravity = 2).

(b) Using the results from (a), estimate the total volume of petroleum hydrocarbons released assuming 50% of the hydrocarbons have been lost to volatilization, biodegradation, and dissolution (report the answer in gallons). Assume that the hydrocarbon released at the site was gasoline with a specific gravity of 0.8, and that the density of the gasoline did not change over time in the soil.

(c) Estimate the residual saturation of the hydrocarbon-soil system. Assume a soil porosity of 0.35.

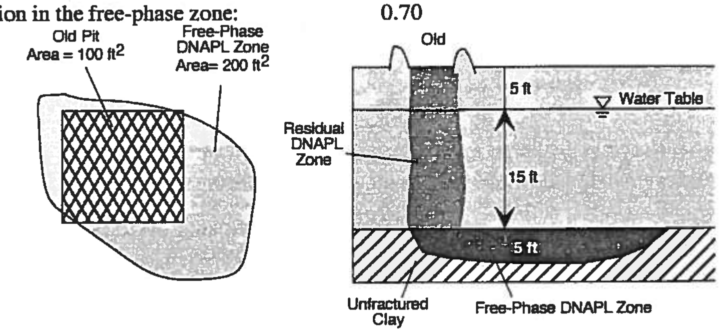
11-2. A sampling program at a Superfund site indicated the following DNAPL zones:

- A "pool" of free-phase DNAPL in a stratigraphic depression in an unfractured clay. The pool is 200 ft^2 in area and averages 5 ft in thickness.
- A zone of residual DNAPL extending directly underneath an old pit 100 ft^2 in area. The residual zone extends through the 5 ft thick unsaturated zone and 15 ft through the saturated zone until it reaches the DNAPL pool.

Other Data: Laboratory tests of mgs of hydrocarbons on the soil and engineering judgment provided the following saturation data:

Residual saturation in the unsaturated zone:	0.10
Residual saturation in the saturated zone:	0.35
Saturation in the free-phase zone:	0.70

Figure P11.2



Plan View Profile View

(a) What is the estimated total volume of DNAPL at the site?

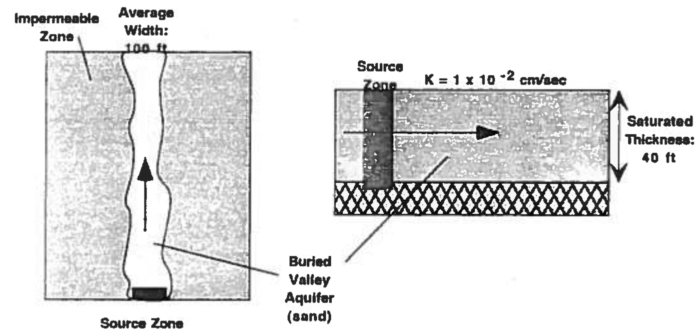
(b) How much is pumpable from a theoretical basis?

(Assume a typical porosity value of 0.3. This should be considered an upper range estimate of the total recoverable volume. Actual volumes are usually much lower).

11-3. A source zone contains about 2000 drums of residual DNAPL comprised of TCE (Trichloroethylene). The porosity is 0.4 and the total mass of DNAPL is 1.3×10^5 kg. The average down gradient dissolved hydrocarbon concentration is 100 mg/L. If there is no adsorption, biodegradation, or natural attenuation of any kind, what is a ballpark estimate for the maximum length of contaminant plume that would result?

Hint: Do not use the advection dispersion equation. Assume the entire depth and width of the aquifer downstream of the source contains dissolved hydrocarbons at 100 mg/L. Calculate the maximum length of the plume when all of the DNAPL is dissolved into the aquifer.

Figure P11.3



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11-4. Gasoline is found in a monitoring well with a specific gravity of 0.8. If a total of 6 ft of gasoline is found in the well, what is the estimated actual thickness of the LNAPL in the formation?

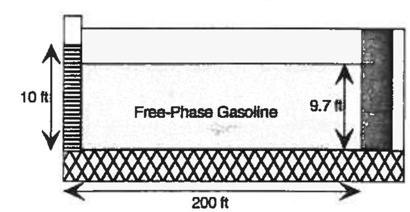
11-5. A large gasoline release completely displaces the water in an shallow sandy aquifer at an old refinery. A large recovery trench is installed to recovery the free-product gasoline.

Using Darcy's law, what is the estimated recovery rate of LNAPL in gpm (gallons per minute)?

Note that hydraulic conductivity can be converted to intrinsic permeability by using 1 cm/sec ~ 1×10^3 darcies = 10^{-5} cm^2. Use values in units of cm^2 for intrinsic permeability and poise (not centipoise; 1 cp = 0.01 poise) for dynamic viscosity in Eq. 11.9.

Profile View

Figure P11.5



Trench Length: 100 ft.

Hydraulic Conductivity of Sand: 1×10^{-2} cm/sec

Density of Gasoline: 0.8 fm/cm^3

Dynamic viscosity: 0.45 centipoise

11-6. Assume that Figure 11.14 represents the residual saturation curve for the system for this system (even though gasoline is not a DNAPL). If there is 20% of water in the system shown in Problem 11-5 (therefore saturation of gasoline = 0.8),

(a) What would the relative permeability be?
(b) What percentage reduction in gasoline recovery would there be?
(c) Would there be any water recovery?
(d) When the NAPL reaches residual saturation, what is the relative permeability for NAPL and for water?

11-7. Using the capillary number relationship (Eq. 11.13), estimate the hydraulic gradient required to initiate movement of gasoline trapped at residual saturation in a gravel aquifer with a hydraulic conductivity of 1×10^{-1} cm/sec.

- Assume the dynamic viscosity of water is 1 cp, or 0.01 g/cm-sec.
- Assume the interfacial tension for gasoline is 50 dyne/cm
- (1 dyne = 1 gm cm/sec^2). Use the capillary number curve for sandstone in Fig. 11.16 as representative data for this system.

Is your answer the same as is shown if Fig. 11.17?

11-8. A contaminated area in the saturated zone has approximately 250 kg of gasoline trapped as a residual NAPL. If you needed to remediate this area back to background conditions within a 6 month timeframe, how could one use in-situ biodegradation to reach the 6 month cleanup objective?

- Assume that you can design a groundwater injection/extraction system that will flush the contaminated area with oxygenated (but otherwise untreated) water. Therefore the only removal mechanism will be the in-situ biodegradation, and the flushing zone will serve as an underground bio-reactor.
- Assume the groundwater Darcy velocity is 5 m/day and the oxygen/hydrocarbon consumption ratio by the native microorganisms is 2 mg O_2/mg NAPL. See Example 11.7 for any other required data.
- Note that the solubility of oxygen in water at 20 °C is 9.2 mg/L when the water is in equilibrium with air (21% O_2) and proportionally higher when in contact with pure oxygen)

Is it possible to dissolve this much oxygen into the reinjection stream using air? Using pure oxygen?

11-9. A DNAPL mixture is estimated to consist of 110,000 mg/kg 1,2 dichloroethane, 5,000 mg/kg trichloroethene, and the rest long chained alkanes such as decane. What is the effective solubility of these chemicals when water is in contact with this DNAPL?

Chemical	Molecular Weight (g/mole)	Solubility (mg/L)
1,2 DCA	72	8,690
TCE	131	1,000
Decane	142	Insoluble

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