

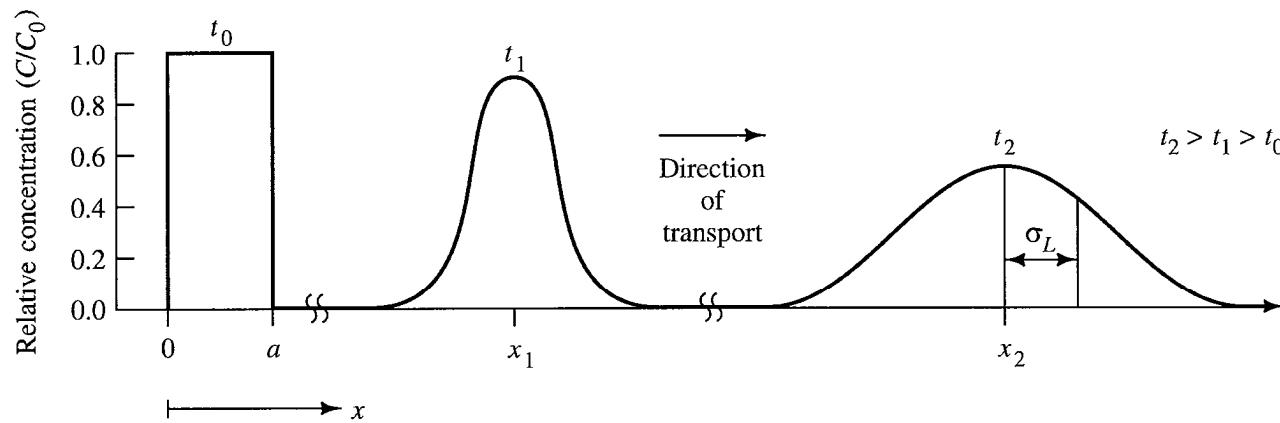
# **Groundwater Flow and Transport Class:**

## **Applied Contaminant Hydrogeology**

**June 20, 2008**

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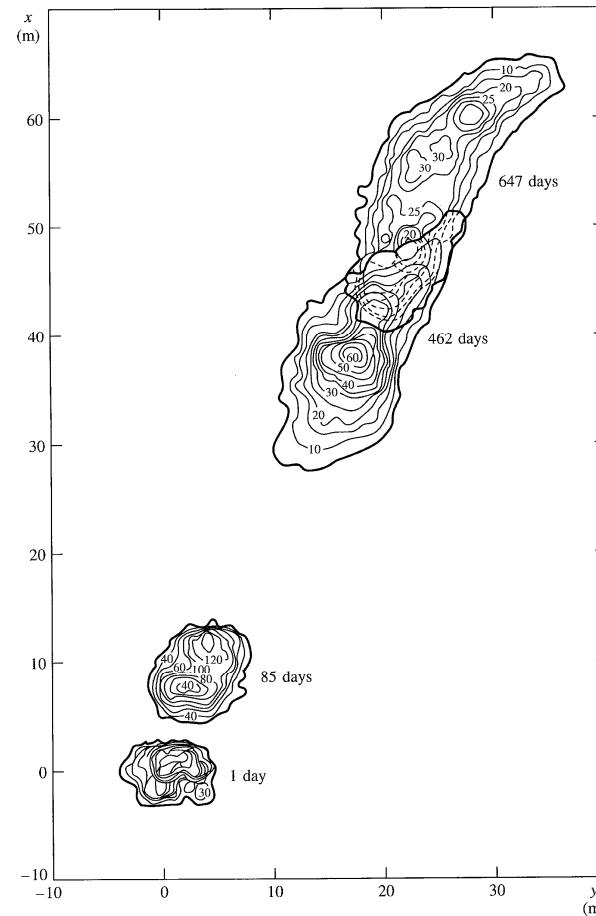
# Effects of Dispersion and Diffusion



**FIGURE 2.6** Transport and spreading of a solute slug with time due to advection and dispersion. A slug of solute was injected at  $x = 0 + a$  at time  $t_0$  with a resulting concentration of  $C_0$ . The ground-water flow is to the right.

# Effects of Dispersion and Diffusion

- **Hydrodynamic dispersion causes contaminant plume to spread over a larger area as it moves through the aquifer**
- **Spreading occurs mostly in the direction of movement (longitudinal dispersion)**
- **Maximum contaminant concentration in the plume decreases with travel distance (and travel time) because of dispersion**



**FIGURE 2.13** Vertically averaged chloride concentration at 1 day, 85 days, 462 days, and 647 days after the injection of a slug into a shallow aquifer. Source: D. M. Mackay et al. *Water Resources Research* 22, no. 13 (1986):2017–29. Copyright by the American Geophysical Union.



# Sorption

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- Many solutes can interact with the mineral grains in the aquifer during groundwater flow, leading to slower solute migration than the groundwater flow rate
- Sorption processes include adsorption, chemisorption, absorption (actually a diffusion process), and ion exchange
- Sorption processes can be rapid, leading to equilibrium conditions
- Sorption processes can be slow, in which case a kinetic sorption model is required to describe the process
- Sorption can be important to contaminant migration because it slows movement of contaminants allowing time for radioactive decay or chemical degradation



# Linear Sorption

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$$C^* = K_d C$$

$$\frac{\partial C}{\partial t} \left( 1 + \frac{B_d}{\theta} K_d \right) = D_L \frac{\partial^2 C}{\partial x^2} - v_x \frac{\partial C}{\partial x}$$

$$\left( 1 + \frac{B_d}{\theta} K_d \right) = R_f$$

$C^*$  = mass of solute sorbed on solids

$K_d$  = sorption coefficient

$B_d$  = bulk density

$\theta$  = porosity or moisture content

$R_f$  = retardation factor



# Sorption

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Freundlich Isotherm:

$$C^* = KC^N$$

Langmuir Isotherm:

$$\frac{C}{C^*} = \frac{1}{\alpha\beta} + \frac{C}{\beta}$$

$K$  = fitting constant

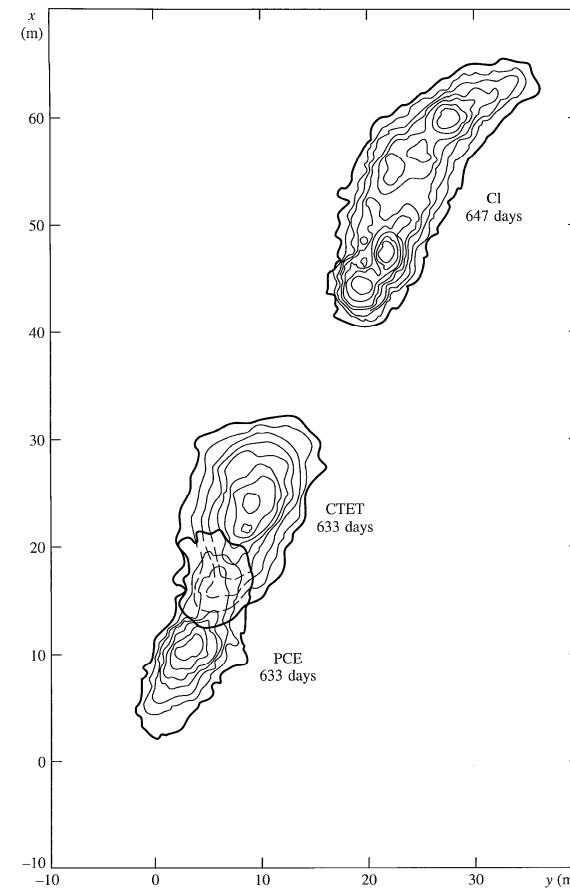
$N$  = exponent fitting constant

$\alpha$  = adsorption constant related to binding energy

$\beta$  = maximum amount of solute that can be sorbed

# Effects of Sorption

- Sorption of the contaminant on mineral grains in the aquifer leads to a retardation of the plume
- Even a moderate amount of sorption will lead to contaminant migration that is many times slower than the groundwater velocity



**FIGURE 3.16** Plumes of chloride, carbon tetrachloride, and tetrachloroethylene at the end of the experimental period. The plumes are based on depth-averaged values. Source: P. V. Roberts, M. N. Goltz, and D. M. Mackay, *Water Resources Research* 22, no. 13 (1986):2047–59. Copyright by the American Geophysical Union.



# Non-Aqueous Phase Liquids

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**Table 10.6** Density and solubility in water of organic compounds

Compound	Specific Gravity <sup>a</sup>	Solubility <sup>b</sup> Milligrams compound/liter water (@ °C Temperature)
Acetone	0.79	Infinite
Benzene	0.88	1780 (20)
Carbon tetrachloride	1.59	800 (20), 1160 (25)
Chloroform	1.48	8000 (20), 9300 (25)
Methylene chloride	1.33	20,000 (20), 16,700 (25)
Chlorobenzene	1.11	500 (20), 488 (30)
Ethyl benzene	0.87	140 (15), 152 (20)
Hexachlorobenzene	1.60	0.11 (24)
Ethylene chloride	1.24	9200 (0), 8690 (20)
1, 1, 1-trichloroethane	1.34	4400 (20)
1, 1, 2-trichloroethane	1.44	4500 (20)
Trichloroethylene	1.46	1100 (25)
Tetrachloroethylene	1.62	150 (25)
Phenol	1.07	82,000 (15)
2-Chlorophenol	1.26	28,500 (20)
Pentachlorophenol	1.98	5 (0), 14 (20)
Toluene	0.87	470 (16), 515 (20)
Methyl ethyl ketone	0.81	353 (10)
Naphthalene	1.03	32 (25)
Vinyl chloride	0.91	1.1 (25)

<sup>a</sup>Source: R. Weast, "Handbook of Chemistry and Physics," 60th ed., CRC Press, Inc., 1979, 1980.

<sup>b</sup>From Verschueren, Karel. "Handbook of Environmental Data on Organic Chemicals." New York, Van Nostrand Reinhold, 1983. Numbers in parentheses = temperatures.

# Non-Aqueous Phase Liquids

- Non-aqueous phase liquids (NAPL) may be the wetting phase, in which case the water exists as isolated bodies in the porous medium
- If the NAPL is the non-wetting phase, then the water exists as a continuous body in the porous medium
- Wetting or non-wetting behavior is a function of the NAPL and the mineral grains

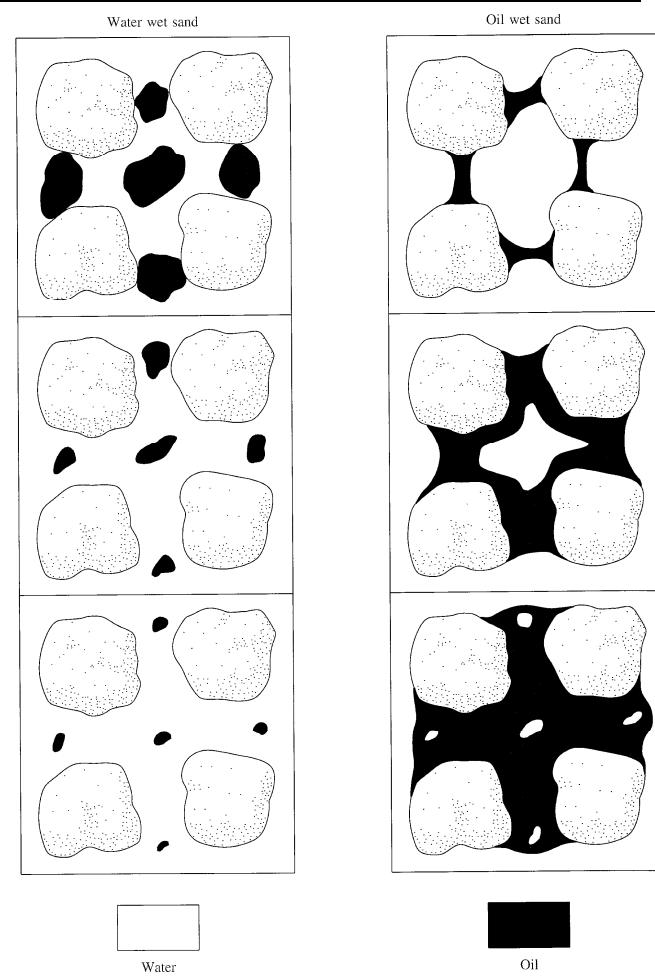
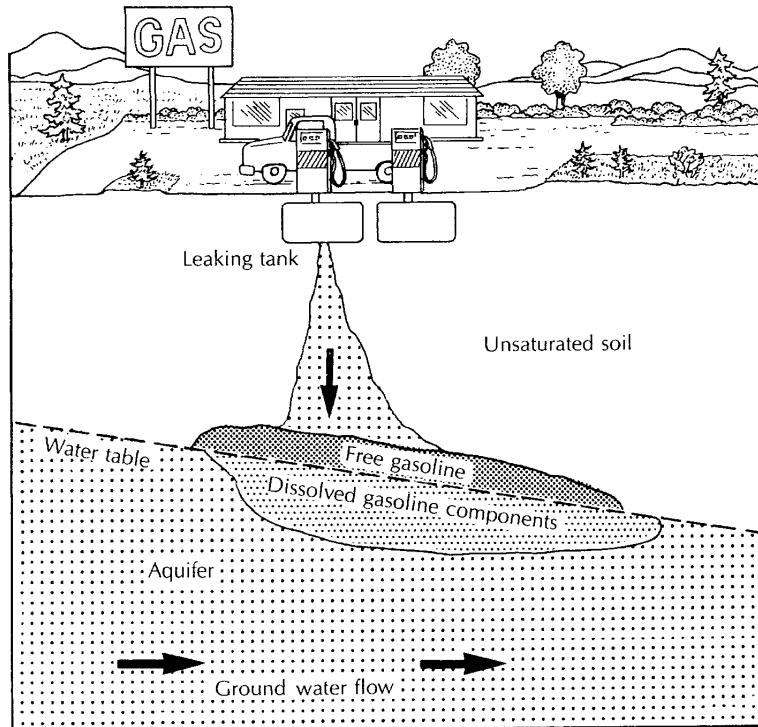


FIGURE 5.5 Different fluid saturation states for a porous media that contains water and oil.



# Non-Aqueous Phase Liquids

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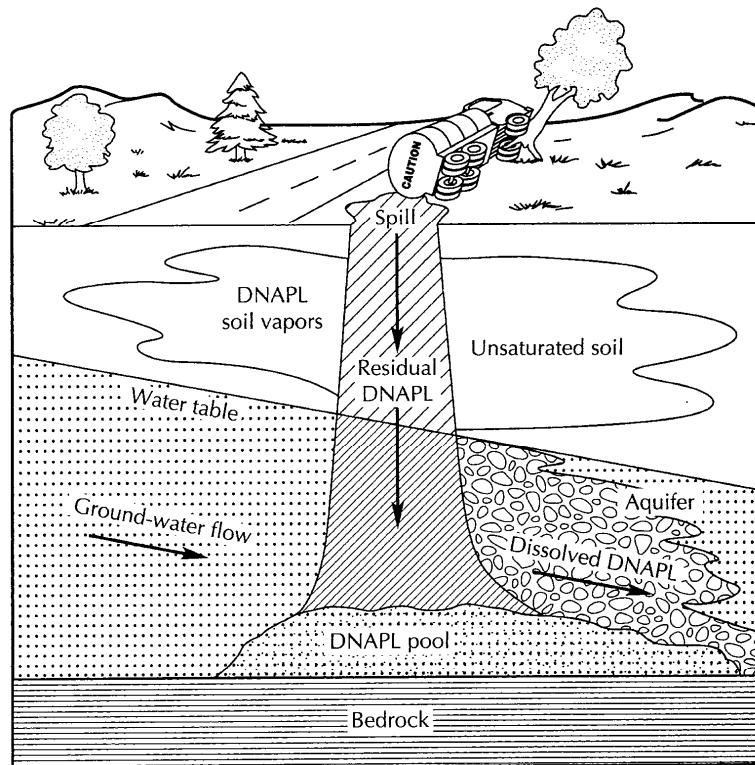
▲ FIGURE 10.19

Organic liquids such as gasoline, which are only slightly soluble in water and are less dense than water, tend to float on the water table when a spill occurs.



# Non-Aqueous Phase Liquids

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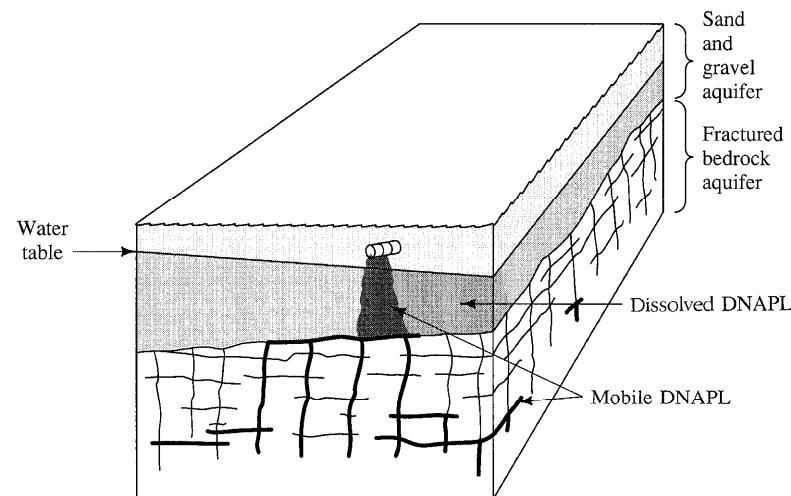


▲ FIGURE 10.20

Organic liquids such as trichloroethylene, which are only slightly soluble in water and are more dense than water, may sink to the bottom of an aquifer when a spill occurs.

# Non-Aqueous Phase Liquids

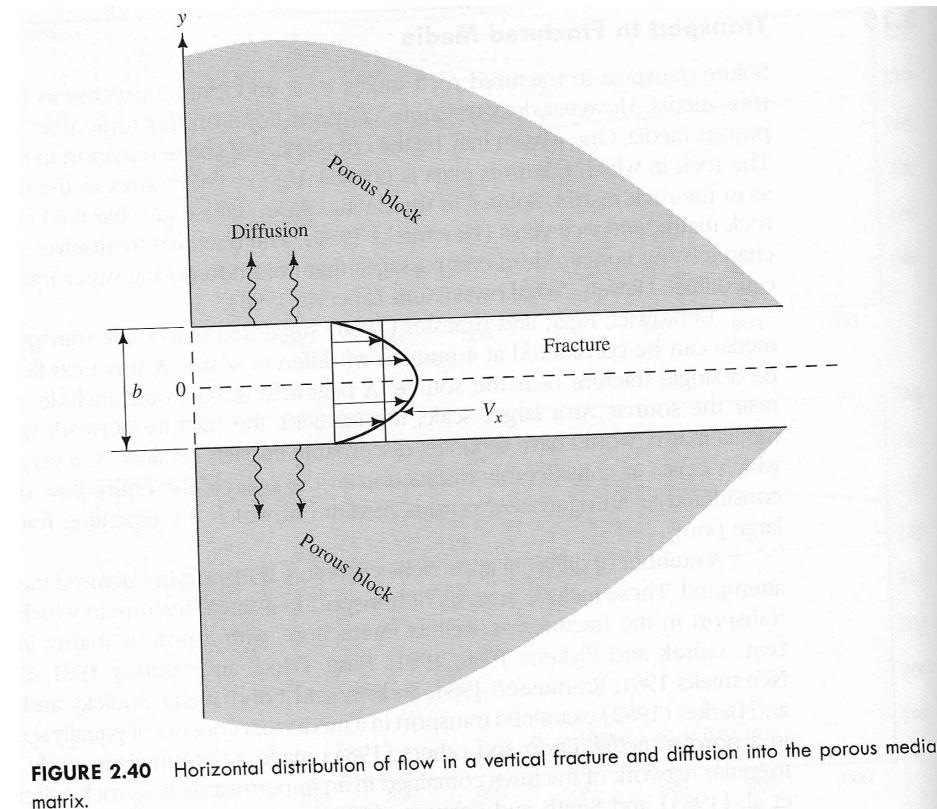
- DNAPL contamination of fractured aquifers represents a serious challenge for aquifer remediation
- DNAPL migration in fractures is difficult to characterize and predict
- DNAPL probably cannot be recovered from fractured bedrock



**FIGURE 5.27** Movement of a DNAPL into a fractured bedrock aquifer that underlies a sand and gravel aquifer.

# Transport in Fracture Media

- **Groundwater velocity in fractured media are generally very high due to the low value of fracture porosity**
- **Diffusion of contaminants from the fracture into the porous rock matrix can be an important mechanism for the retardation of contaminant migration**
- **Matrix diffusion provides access to the sorption capacity of the rock matrix also**



**FIGURE 2.40** Horizontal distribution of flow in a vertical fracture and diffusion into the porous media matrix.

# Contaminant Monitoring

- Monitoring wells should be constructed to protect from surface contamination
- Well screen length should not be excessive because this can lead to artificial dilution of contaminant concentrations during pumping
- Filter pack, well casing, and well screen should not be chemically reactive with contaminants of interest

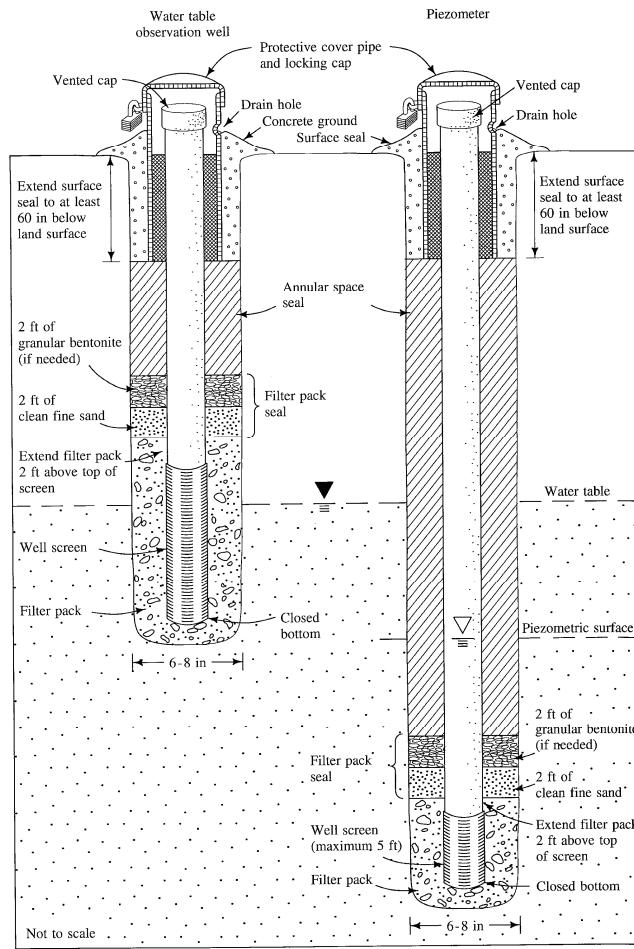


FIGURE 8.8 Construction details of a water table observation well and piezometer. Source: Wisconsin Department of Natural Resources.



# Contaminant Monitoring

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- Soil vapor can be sampled from the unsaturated zone using well construction similar to water wells
- Soil moisture can be sampled from the unsaturated zone using a suction lysimeter in which a vacuum is created within a ceramic porous cup to extract liquid from partially saturated soil