SAND2008-3902P

Groundwater Flow and Transport Class:

Introduction to Contaminant Hydrogeology

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Contaminant Hydrogeology

- Originally the science of groundwater hydrology was focused primarily on evaluation of groundwater as a resource
- More recently, issues of groundwater contamination have become more dominant in the field
- Undetected groundwater contamination can pose individual and population health risks
- Wide-spread groundwater contamination can threaten groundwater as a resource if the water quality in significant portions of the aquifer is degraded

Types of Contaminants

Table 10.4 Chemicals and organisms known to have caused ground-water contamination (various sources)

Metals	Nonmetals	Organics	Extractable Organic Compounds	Volatile Organic Compounds	Organisms
aluminum	acids	aldrin	tri-*n*-propylamine	benzene	*Giardia lamblia*
arsenic	ammonia	BOD	3- and/or 4-methyl phenol	1,2-dichloroethane	*Salmonella* sp.
barium	boron	chlordane	4-methyl benzoic acid	1,1,1-trichloroethane	*Shigella* sp.
cadmium	chloride	DDT	1,4-dioxane	1,1-dichloroethane	typhoid
chromium	cyanide	detergents	4-methyl-2-pentanol	1,1,2-trichloroethane	*Yersinin enterocolitica*
copper	fluoride	ethyl acrylate	*n,n*-dimethyl-formamide	chloroethane	viral hepatitis
iron	nitrate	gasoline	2-hexanone	1,1-dichloroethene	*E. coli*
lead	phosphate	hydroquinone	4-methyl-2-pentanone	cis-1.2-dichloroethene	
lithium	radium	lindane	1-methyl-2-pyrrolidinone	trans-1,2-dichloroethene	
manganese	selenium	paramethyl amino-phenol	2-hexanol	ethyl benzene	
mercury	sulfate	PBB	3,5-dimethyl phenol and/or 4-ethyl phenol	methylene chloride	
molybdenum	various radioactive isotopes	PCB	benzoic acid	tetrachloroethane	
nickel		DCPD (dicyclopenta-diene)	hexanoic acid	toluene	
silver		DIMP (diisopropyl-methyl-phospho-nate)	cyclohexanol	trichloroethene	
uranium		DBCP (dibromochloro-propane)	2-ethyl hexanoic acid	vinyl chloride	
zinc			octanoic acid	tetrahydrofuran	
			pentanoic acid	acetone	
			bis(2-ethylhexyl) phthalate	2-methyl-2-propanol	
			di-*n*-butyl phthalate	2-butanone	
			2,4-dimethyl phenol	2-butanol	
			isophorone	2-propanol	
			phenol		
			1,2-dichlorobenzene		

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Types of Contaminants

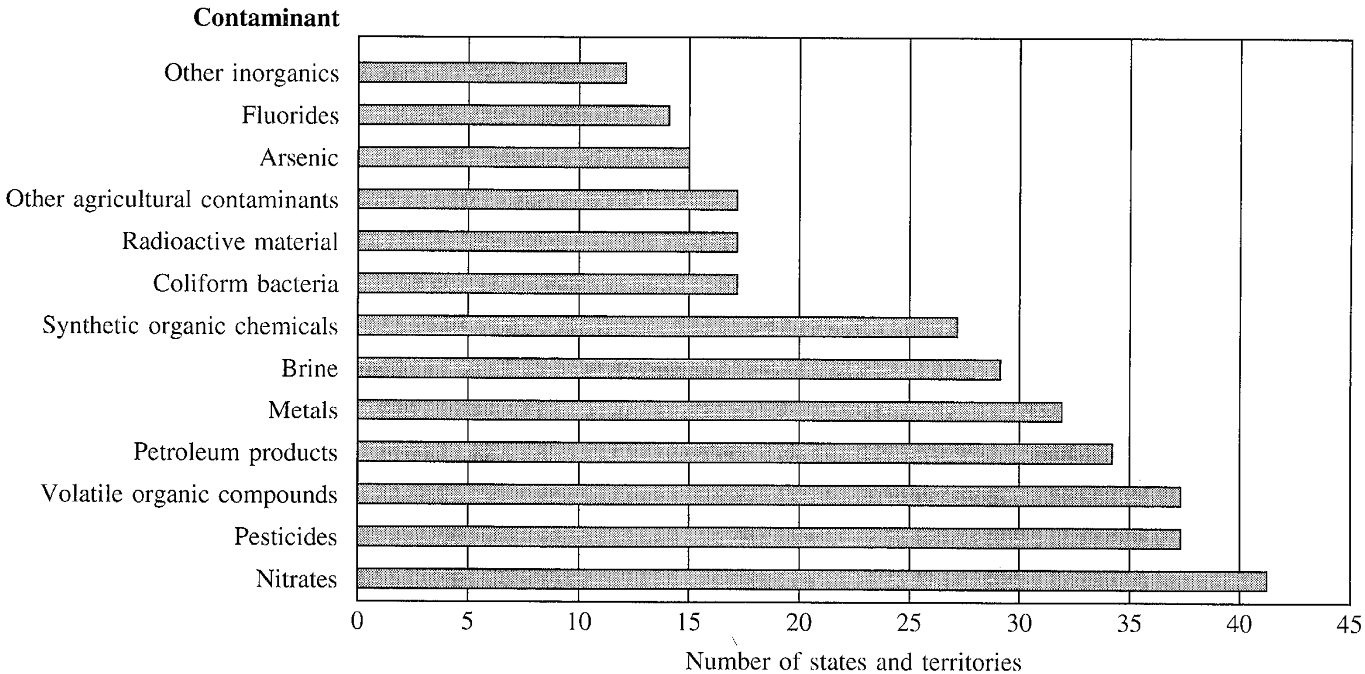

FIGURE 1.5 Frequency of various contaminants considered by states and territories of the United States to be a major threat to ground-water quality. *Source:* National Water Quality Inventory, 1988 Report to Congress, Environmental Protection Agency, 1990.

Sources of Contamination

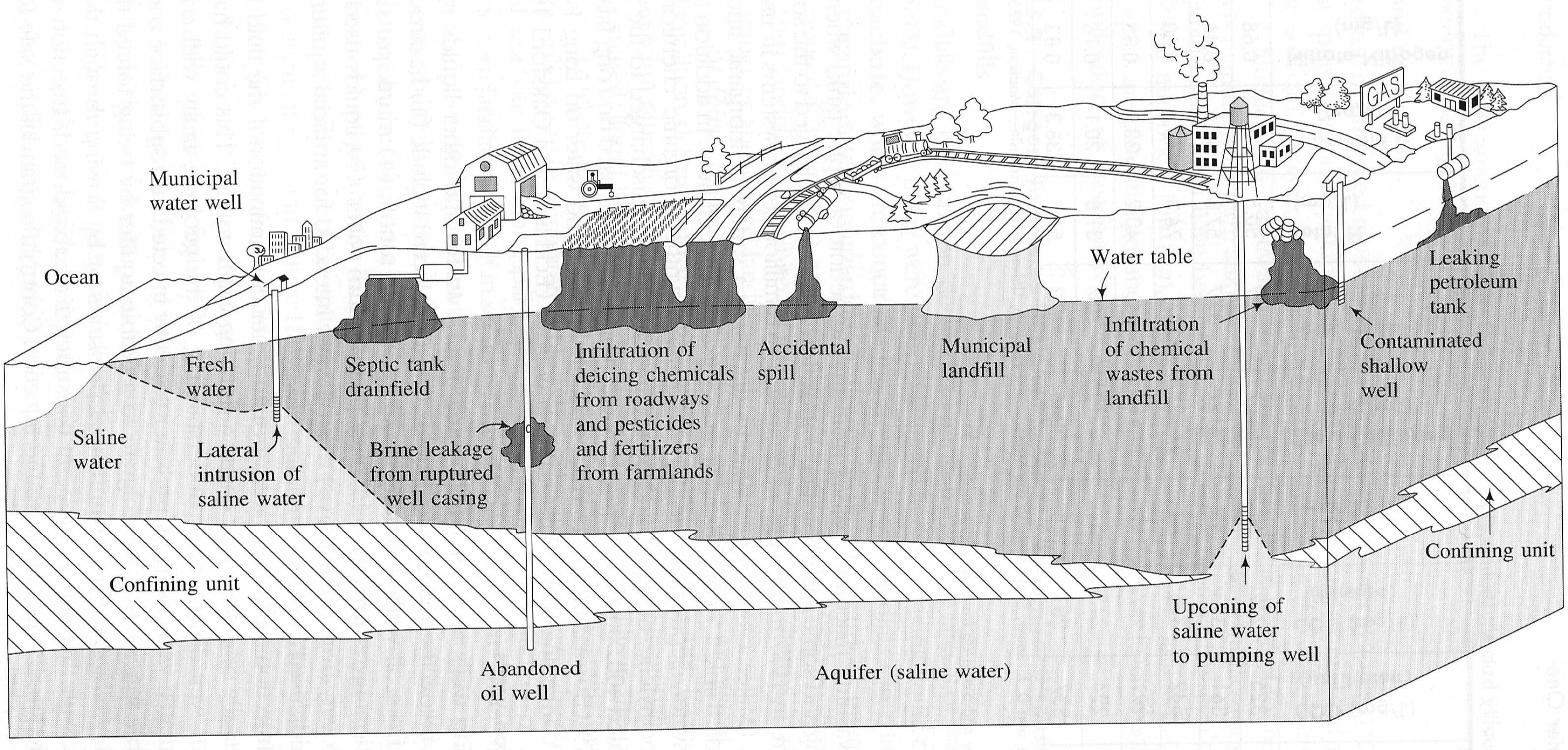

FIGURE 1.1 Mechanisms of ground-water contamination.

Sources of Contamination

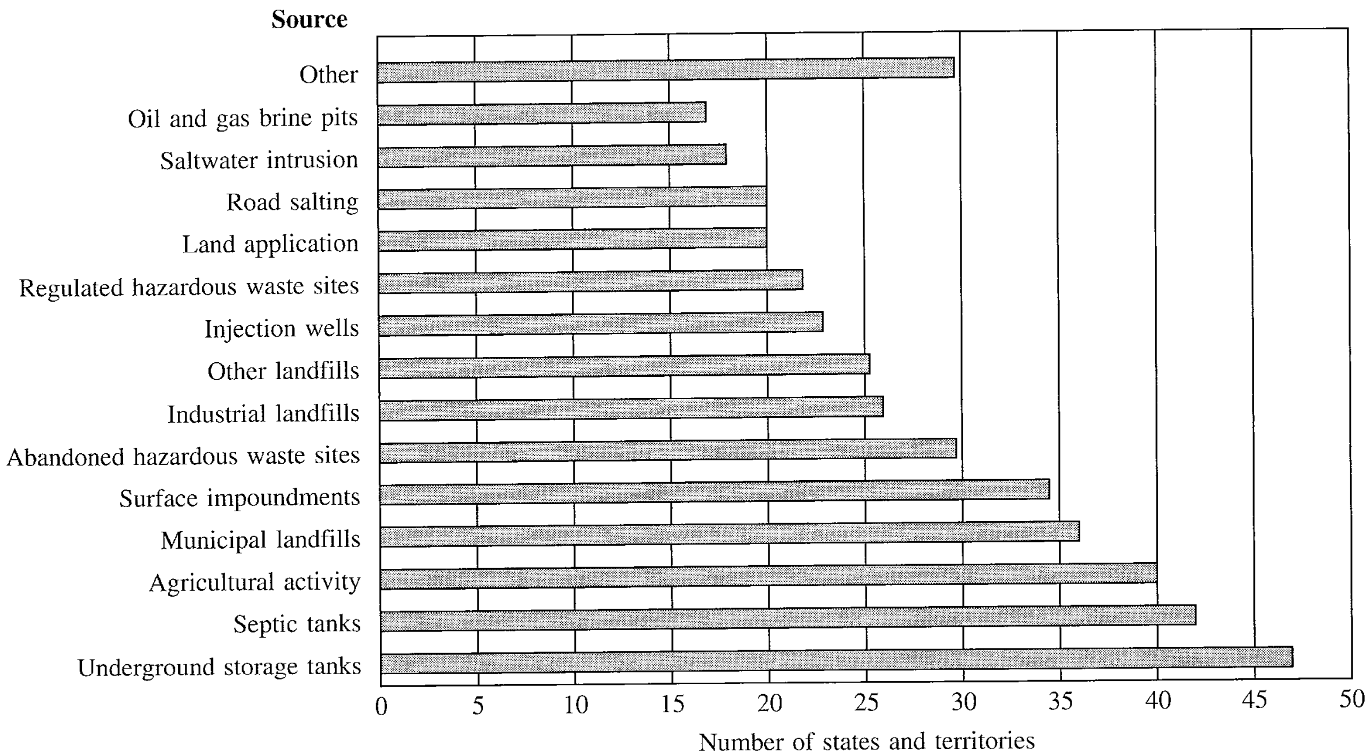

FIGURE 1.2 Frequency of various contamination sources considered by states and territories of the United States to be major threats to ground-water quality. *Source*: National Water Quality Inventory, 1988 Report to Congress, Environmental Protection Agency, 1990.

Sources of Contamination

- Waste landfills are common sources of groundwater contamination
- High chloride concentrations result from dissolution in waste and indicate flow directions
- Chloride plume is generally a good proxy for contamination with other chemicals from the landfill

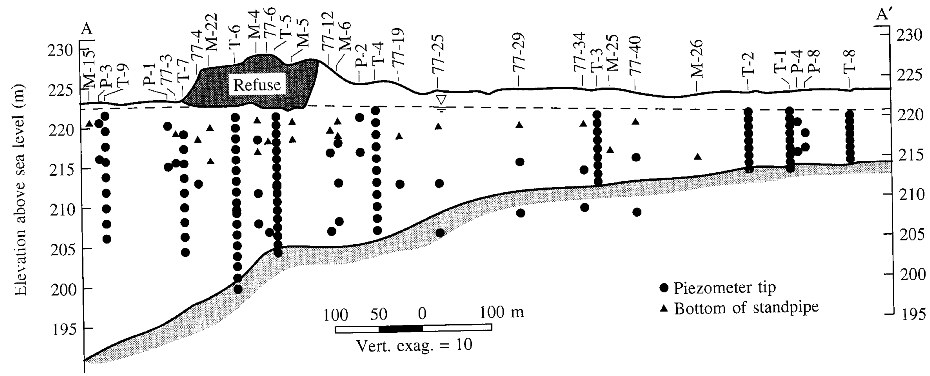

FIGURE 2.33 Cross section of aquifer at the Borden landfill showing the location of multilevel monitoring devices. *Source:* E. O. Frind and G. E. Hokkanen, *Water Resources Research* 23, no. 5 (1987):918–30. Copyright by the American Geophysical Union.

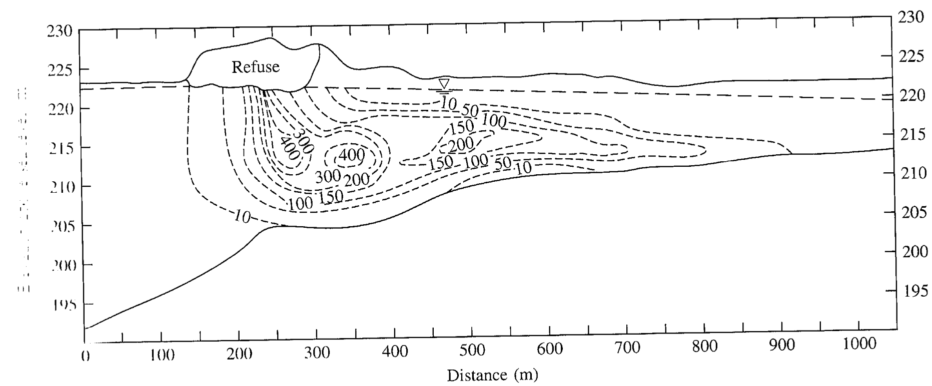

FIGURE 2.34 Chloride plume along the Borden landfill cross section in 1979. Values are in milligrams per liter. *Source:* E. O. Frind and G. E. Hokkanen, *Water Resources Research* 23, no. 5 (1987):918–30. Copyright by the American Geophysical Union.

Sources of Contamination

- Landfills typically contain organic waste that consumes available oxygen within the landfill and in the proximal groundwater plume
- Variations in the redox conditions in the plume can have important impacts on contaminant degradation, contaminant mobility, and water quality

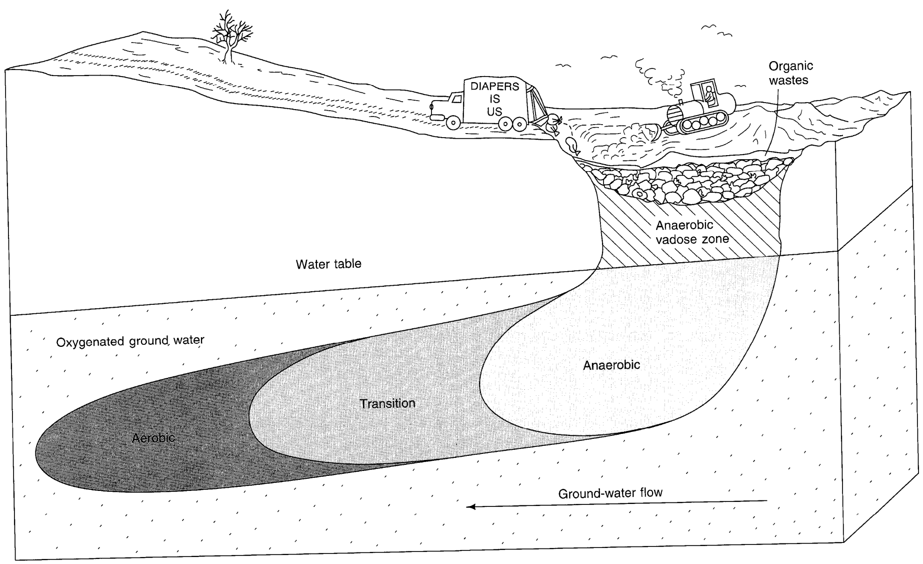

FIGURE 6.15 Geochemical zonation of the leachate plume from a landfill receiving organic waste.

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Impacts of Redox Conditions

- **Water chemistry and important redox species vary along the flow path in a landfill plume**
- **The nature of microbial growth and metabolism also varies along the flow path**
- **Types of microbial activity are important because of their role in contaminant degradation**

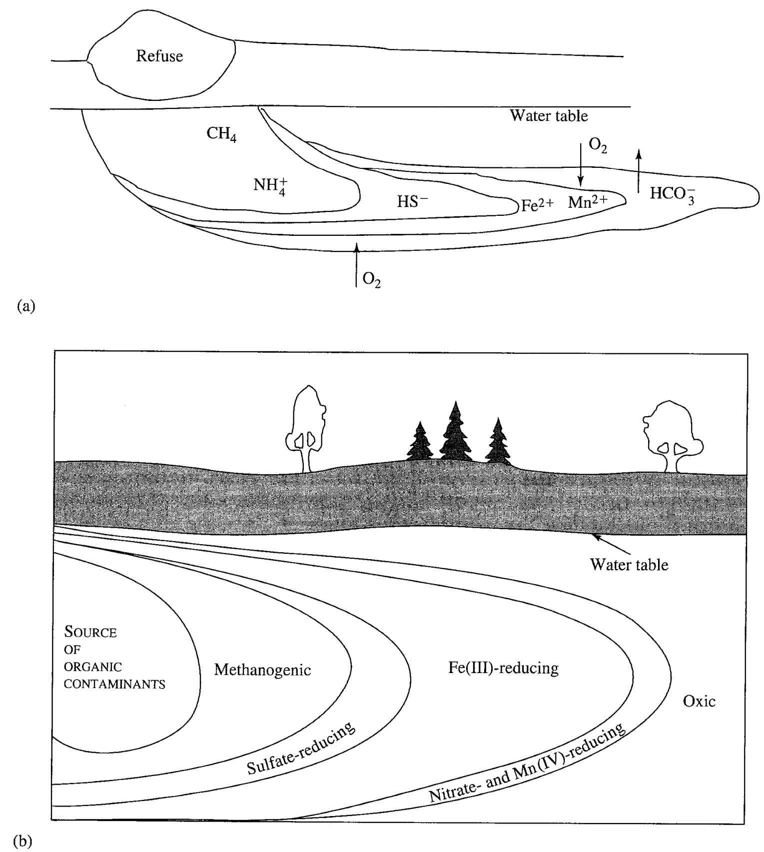

Figure 11.16 Schematic cross-sections of groundwater systems contaminated by organic-rich wastes. **(a)** Development of redox zones down gradient from a landfill in the groundwater flow direction (Baedecker and Back 1979). **(b)** Possible sequence of redox zones encountered in the groundwater flow direction from a source of organic contamination. After D. R. Lovley, F. H. Chapelle, and J. C. Woodward, Use of dissolved H_2 concentrations to determine distribution of microbially catalyzed redox reaactions in anoxic groundwater. *Envir. Sci. & Technol.* 28(7):1205–10. Copyright 1994 by American Chemical Society.

Impacts of Redox Conditions

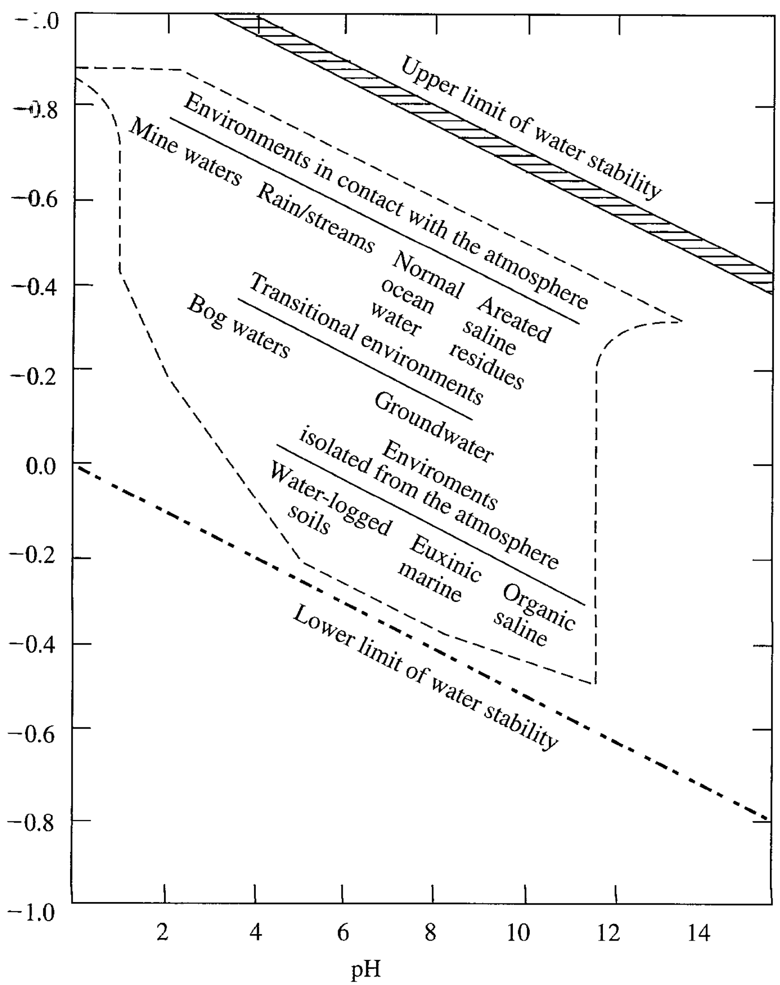

Figure 11.4 Approximate position of some natural environments in terms of Eh and pH. The dashed line represents the limits of measurements in natural environments, as reported by Baas-Becking et al. (1960) and shown in Fig. 11.3. The crosshatched area defines theoretical conditions under which waters are calculated to contain dissolved oxygen at or above a detection limit of 5 μg/L. Modified after R. M. Garrels and C. L. Christ (1965). Solutions, minerals and equilibria. Copyright © 1965 by Freeman, Cooper and Company. Used by permission.

Advective-Dispersive Transport

Advection:

$$\frac{\partial C}{\partial t} = -v_x \frac{\partial C}{\partial x}$$

$$v_x = \frac{K}{n_e}\frac{dh}{dx}$$

K = hydraulic conductivity
h = hydraulic head
C = solute concentration
n_e = effective porosity
v_x = average linear velocity
t = time

Advective-Dispersive Transport

Diffusion:

$$\frac{\partial C}{\partial t} = D^* \frac{\partial^2 C}{\partial x^2}$$ (Fick's second law)

$$D^* = \omega \cdot D_d$$

D^* = effective diffusion coefficient
D_d = molecular diffusion coefficient
ω = coefficient related to tortuosity

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Advective-Dispersive Transport

Diffusion:

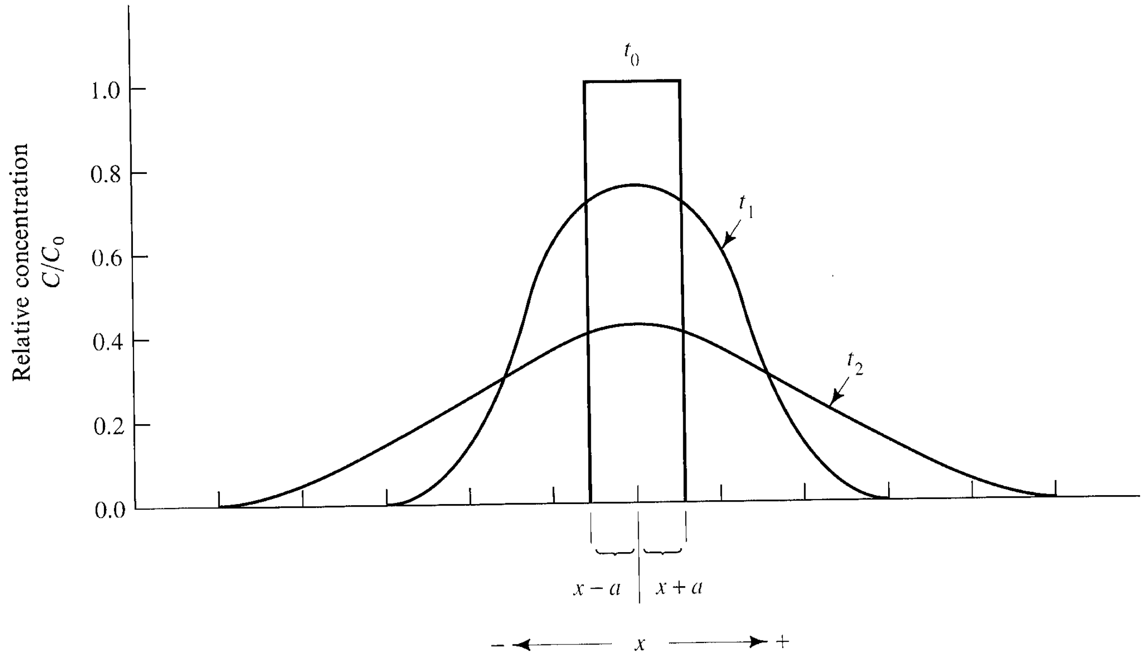

FIGURE 2.1 Spreading of a solute slug with time due to diffusion. A slug of solute was injected into the aquifer at time t_0 with a resulting initial concentration of C_0.

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Advective-Dispersive Transport

Hydrodynamic Dispersion:

$$D_L = \alpha_L v_i + D^*$$

$$D_T = \alpha_T v_i + D^*$$

D_L = longitudinal hydrodynamic dispersion
D_T = transverse hydrodynamic dispersion
α_L = longitudinal dispersivity
a_T = transverse dispersivity

Advective-Dispersive Transport

- **Dispersion is dominated by diffusion at low groundwater velocities (Pe < ~1)**
- **Dispersion is dominated by hydrodynamic dispersion (dispersivity) at higher groundwater velocities (Pe > ~1)**
- **Transport in most groundwater flow systems is dominated by hydrodynamic dispersion**
- **Dispersivity generally increases with increasing length of flow path**

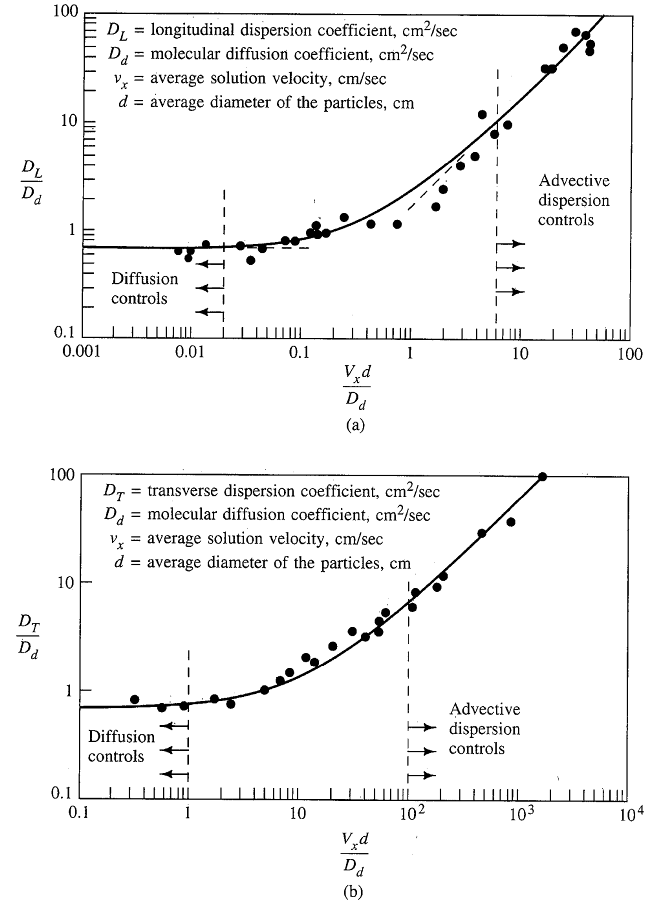

FIGURE 2.7 Graph of dimensionless dispersion coefficients versus Peclet number, $P = v_x d/D_d$. (a) D_L/D_e versus P and (b) D_T/D_e versus P. *Source:* T. K. Perkins and O. C. Johnson, *Society of Petroleum Engineers Journal*, 3 (1963):70–84. Copyright 1963, Society of Petroleum Engineers.

Advection-Dispersion Equation

$$D_L \frac{\partial^2 C}{\partial x^2} + D_T \frac{\partial^2 C}{\partial y^2} - v_x \frac{\partial C}{\partial x} = \frac{\partial C}{\partial t}$$

Two-Dimensional Transport

D_L = longitudinal diffusion coefficient

D_T = transverse diffusion coefficient

Advection-Dispersion Equation

$$C = \frac{C_0}{2}\left[erfc\left(\frac{L - v_x t}{2\sqrt{D_L t}}\right) + \exp\left(\frac{v_x L}{D_L}\right) erfc\left(\frac{L + v_x t}{2\sqrt{D_L t}}\right)\right]$$

Analytical Solution for One-Dimensional Transport
(Ogata and Banks 1961)

D_L = longitudinal diffusion coefficient
C_0 = source concentration
L = distance from source
erfc = complimentary error function