Capture Zone Analysis

http://www.spokaneriverrescue.com/images/rescue-helo061.JPG

Capture Zone Analysis
Confined Aquifer

The equation to describe the edge of the capture zone for a confined aquifer when steady-state conditions have been reached is (Todd 1980; Grubb 1993):

$$x = \frac{-y}{\tan(2\pi Kbiy/Q)} \quad (10.16)$$

where

x and y	are directions defined on Figure 10.32
Q	is the pumping rate (L^3/T; ft^3/day or m^3/day)
K	is the hydraulic conductivity (L/T; ft/day or m/day)
b	is the initial saturated thickness of the aquifer (L; ft or m)
i	is the hydraulic gradient of the flow field in the absence of the pumping well (dimensionless)
tan(y)	is in radians

Capture Zone Analysis
Confined Aquifer

$$x_0 = -Q/(2\pi Kbi) \quad (10.17)$$

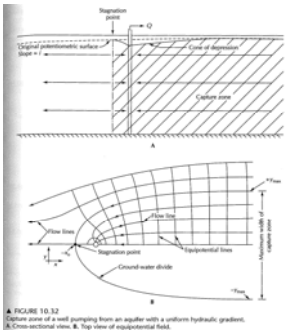
where x_0 is the distance from the pumping well to the down-gradient edge of the capture zone (L; ft or m).

2. The maximum width of the capture zone as x approaches infinity is given by

$$y_{max} = \pm Q/(2Kbi) \quad (10.18)$$

where y_{max} is the half-width of the capture zone as x approaches infinity.

Capture Zone Analysis Confined Aquifer



▲ FIGURE 10.32
Capture zone of a well pumping from an aquifer with a uniform hydraulic gradient. **A** Cross-sectional view. **B.** Top view of equipotential field.

Capture Zone Analysis Unconfined Aquifer

Grubb (1993) gave a solution for a capture zone in an unconfined aquifer. In this case one needs to know the head at two wells along the axis of the ground-water-flow direction. Let h_1 be the up-gradient head and h_2 be the down-gradient head, with L the distance between the two monitoring wells. In this case, the shape of the capture zone is given by

$$x = \frac{-y}{\tan\left[\pi K(h_1^2 - h_2^2)y/QL\right]} \tag{10.19}$$

where

x and y	are directions defined in Figure 10.32
Q	is the pumping rate (L^3/T; ft^3/day or m^3/day)
K	is the hydraulic conductivity (L/T; ft/day or m/day)
tan(y)	is in radians

The maximum width of the capture zone as x approaches infinity is given by

$$y_{max} = \pm\frac{QL}{K(h_1^2 - h_2^2)} \tag{10.20}$$

The position of the stagnation point where $y = 0$—that is, the down-gradient end of the capture zone—is given by

$$x_0 = \frac{-QL}{\pi K(h_1^2 - h_2^2)} \tag{10.21}$$

Capture Zone Analysis Example

Compute the capture zone of an interceptor well pumping at a rate of 190,000 ft^3/day from a confined aquifer with a hydraulic conductivity of 1500 ft/day, an original hydraulic gradient of 0.00300, and a saturated thickness of 75.0 ft.

Part A: Find the maximum width of the capture zone.

$$y_{max} = \pm\frac{Q}{2bKi}$$

$$= \pm\frac{190{,}000\ \text{ft}^3/\text{day}}{2 \times 75.0\ \text{ft} \times 1500\ \text{ft/day} \times 0.00300}$$

$$= \pm 281\ \text{ft}$$

Part B: Find the distance to the stagnation point.

$$x_0 = -\frac{Q}{2\pi Kbi}$$

$$= -\frac{190{,}000\ \text{ft}^3/\text{day}}{2 \times \pi \times 1500\ \text{ft/day} \times 75.0\ \text{ft} \times 0.00300}$$

$$= -89.6$$

Capture Zone Analysis: Example

Part C: Find the shape of the curve describing the capture zone. The following values are for one-half of the capture zone, which is symmetrical about the *x*-axis.

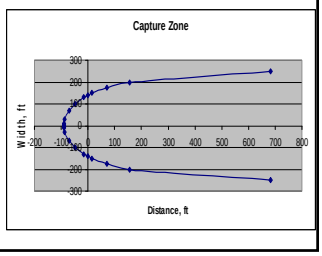
$$x = \frac{-y}{\tan\left(\frac{2\pi Khiy}{Q}\right)}$$

$$= \frac{-y}{\tan\left(\frac{2 \times \pi \times 1500\ \text{ft/day} \times 75.0\ \text{ft} \times 0.00300 \times y}{190{,}000\ \text{ft}^2\text{/day}}\right)}$$

$$= -\frac{y}{\tan(0.0112y)}$$

Remember that the tangent must be in radians.

y	x
250 ft	682 ft
200 ft	156 ft
175 ft	70.3 ft
150 ft	15.5 ft
140 ft	−1.2 ft
130 ft	−15.7 ft
100 ft	−48.9 ft
70 ft	−70.6 ft
30 ft	−86.2 ft
10 ft	−89.2 ft
1 ft	−89.6 ft



Advection

The diffusion of a solute through water is described by Fick's laws. Fick's first law describes the flux of a solute under steady-state conditions:

$$F = -D\,dC/dx \qquad (10.1)$$

where

F = mass flux of solute per unit area per unit time
D = diffusion coefficient (area/time)
C = solute concentration (mass/volume)
dC/dx = concentration gradient (mass/volume/distance)

The negative sign indicates that the movement is from greater to lesser concentrations. Values for D are well known for electrolytes in water. For the major cations and anions in water, D ranges from 1×10^{-9} to 2×10^{-9} m^2/s.

For systems where the concentrations may be changing with time, Fick's second law may be applied:

$$\partial C/\partial t = D\,\partial^2 C/\partial x^2 \qquad (10.2)$$

where $\partial C/\partial t$ = change in concentration with time.

Advection proportional to Linear Velocity

The rate of flowing ground water can be determined from Darcy's law as

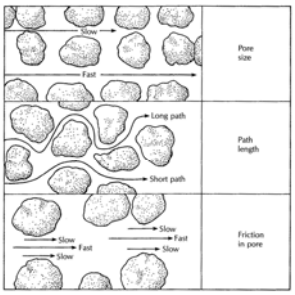
$$v_x = -\frac{K}{n_e}\frac{dh}{dl} \qquad (10.4)$$

where

v_x = average linear velocity
K = hydraulic conductivity
n_e = effective porosity
$\frac{dh}{dl}$ = hydraulic gradient

Contaminants that are advecting are traveling at the same rate as the average linear velocity of the ground water.

Longitudinal Dispersion



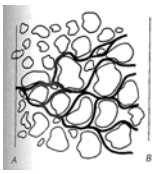
▲ FIGURE 10.8
Factors causing pore-scale longitudinal dispersion.

Lateral Dispersion

Lateral dispersion is caused by the fact that, as a fluid containing a contaminant flows through a porous medium, the flow paths can split and branch out to the side. This will occur even in the laminar flow conditions that are prevalent in ground-water flow (Figure 10.9).

The mechanical dispersion due to the preceding factors is equal to the product of the average linear velocity and a factor called the dynamic dispersivity (a_L).

$$\text{Mechanical dispersion} = a_L v_x \qquad (10.5)$$



◀ FIGURE 10.9
Flow paths in a porous medium that cause lateral hydrodynamic dispersion.

Hydrodynamic Dispersion

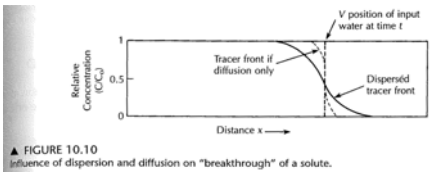
The processes of molecular diffusion and mechanical dispersivity cannot be separated in flowing ground water. Instead, a factor termed the coefficient of hydrodynamic dispersion, D_L, is introduced. It takes into account both the mechanical mixing and diffusion. For one-dimensional flow it is represented by the following equation:

$$D_L = a_L v_x + D^* \qquad (10.6)$$

where

D_L = the longitudinal coefficient of hydrodynamic dispersion
a_L = the dynamic dispersivity
v_x = the average linear ground-water velocity
D^* = the effective molecular diffusion coefficient

Diffusion/Dispersion and Breakthrough of a solute



▲ FIGURE 10.10
Influence of dispersion and diffusion on "breakthrough" of a solute.

Advection and Dispersion

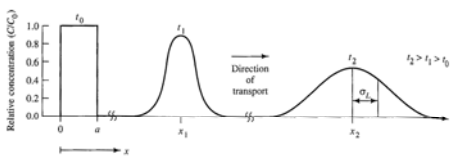
The one-dimensional equation for hydrodynamic dispersion (Beruch & Street 1967; Hoopes & Harleman 1967) is given by

$$D_L \frac{\partial^2 C}{\partial x^2} - v_x \frac{\partial C}{\partial x} = \frac{\partial C}{\partial t} \qquad (10.7)$$

where

D_L is the coefficient of longitudinal hydrodynamic dispersion
C is the solute concentration
v_x is the average ground-water velocity in the x-direction
t is the time since start of solute invasion

Advection and Dispersion



▲ FIGURE 10.11
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. *Source: C. W. Fetter,* Contaminant Hydrogeology. *Upper Saddle River NJ: Prentice Hall, 1999.*

Advection and Dispersion

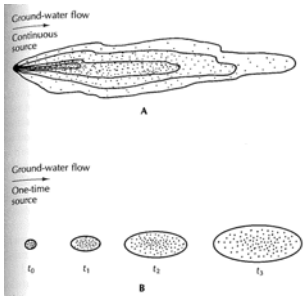
The concentration, C, at some distance, L, from a constant source of contamination at concentration, C_0, at time, t, is given by the following expression (Ogata 1970), where erfc is the complementary error function:

$$C = \frac{C_0}{2}\left[\text{erfc}\left(\frac{L - v_x t}{2\sqrt{D_L t}}\right) + \exp\left(\frac{v_x L}{D_L}\right)\text{erfc}\left(\frac{L + v_x t}{2\sqrt{D_L t}}\right)\right] \quad (10.8)$$

where

- C is the solute concentration (M/L^3, mg/L)
- C_0 is the initial solute concentration (M/L^3, mg/L)
- L is the flow path length (L; ft or m)
- v_x is the average linear ground-water velocity (L/T; ft/day or m/day)
- t is the time since release of the solute (T; day)
- D_L is the longitudinal dispersion coefficient (L^2/T; ft^2/s or m^2/s)

Advection and Dispersion



◀ FIGURE 10.12
A. The development of a contamination plume from a continuous point source. **B.** The travel of a contaminant slug from a one-time point source. Density of dots indicates solute concentration.

Length Dependence of Dispersion

ic dispersivity and flow length, and found that the following equation best describes the relationship.

$$a_L = 0.83(\log L)^{2.414} \quad (10.9)$$

where

- a_L is the apparent longitudinal dynamic dispersivity (L; ft or m)
- L is the length of the flow path (L; ft or m)

Advection and Dispersion: Example

A landfill is leaking leachate with a chloride concentration of 725 mg/L, which enters an aquifer with the following properties:

Hydraulic conductivity = 3.0×10^{-3} cm/s (3.0×10^{-5} m/s)

dh/dl = 0.0020

Effective porosity = 0.23

D^* = 1×10^{-9} m^2/s (estimated)

Compute the concentration of chloride in 1 y at a distance 15 m from the point where the leachate entered the ground water.

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Compute the concentration of chloride in 1 y at a distance 15 m from the point w entered the ground water.

1. Determine average linear velocity.

$$v_x = \frac{K(dh/dl)}{n_e} = (3.0 \times 10^{-5}\ \text{m/s} \times 0.002)/(0.23)$$
$$= 2.6 \times 10^{-7}\ \text{m/s}$$

2. Determine the coefficient of longitudinal hydrodynamic dispersion.

   a. Find the value of a_L from Equation 10.9

$$a_L = 0.83\ (\log L)^{2.414}$$
$$= 0.83\ (\log 15\ \text{m})^{2.414}$$
$$= 1.23\ \text{m}$$

   b. Find the value of D_L.

$$D_L = a_L \times v_x + D^*$$
$$= (1.23\ \text{m} \times 2.6 \times 10^{-7}\ \text{m/s}) + 1 \times 10^{-9}\ \text{m}^2/\text{s}$$
$$= 3.2 \times 10^{-7}\ \text{m}^2/\text{s}$$

3. Restate the 1-y time of travel in seconds.

$$t = 1\ \text{y} \times 60\ \text{s/min} \times 1440\ \text{min/day} \times 365\ \text{days/y}$$
$$= 3.15 \times 10^7\ \text{s}$$

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Effective porosity = 0.23

D^* = 1×10^{-9} m

Compute the concentration of chloride in 1 y at a distar entered the ground water.

4. Substitute values into Equation 10.8.

C_0 = 725 mg/L

L = 15 m

t = 3.15×10^7 s

D_L = 3.2×10^{-7} m^2/s

v_x = 2.6×10^{-7} m/s

$$C = \frac{725}{2}\left\{\text{erfc}\left[\frac{15\ \text{m} - (2.6 \times 10^{-7}\ \text{m/s} \times 3.15 \times 10^7\ \text{s})}{2 \times (3.2 \times 10^{-7}\ \text{m}^2/\text{s} \times 3.15 \times 10^7\ \text{s})^{0.5}}\right]\right.$$
$$+ \exp\left(\frac{2.6 \times 10^{-7}\ \text{m/s} \times 15\ \text{m}}{3.2 \times 10^{-7}\ \text{m}^2/\text{s}}\right)$$
$$\left.\times\ \text{erfc}\left[\frac{15\ \text{m} + (2.6 \times 10^{-7}\ \text{m/s} \times 3.15 \times 10^7\ \text{s})}{2 \times (3.2 \times 10^{-7}\ \text{m/s} \times 3.15 \times 10^7\ \text{s})^{0.5}}\right]\right\}\text{mg/L}$$
$$= 362.5\left[\text{erfc}\left(\frac{15\ \text{m} - 8.19\ \text{m}}{6.3\ \text{m}}\right) + \exp(12.19) \times \text{erfc}\left(\frac{15\ \text{m} + 8.19\ \text{m}}{6.3\ \text{m}}\right)\right]\text{mg/L}$$
$$= 362.5\ [\text{erfc}(1.08) + \exp(12.9) \times \text{erfc}(3.68)]\ \text{mg/L}$$

The complementary error function can be determined from Appendix 13. Since the complementary error function of numbers greater than 3 is very small, we may ignore the second term of the equation.

$$C = 362.5 \times 0.127\ \text{mg/L}$$
$$= 46\ \text{mg/L}$$

Adsorption – Ions “stick” to porous media and thus don’t advect or disperse

When an adsorption relationship can be plotted as a straight line on log-log paper, it is described by the Freundlich isotherm as

$$\log C^* = j \log C + \log K_f \quad (10.10)$$

or

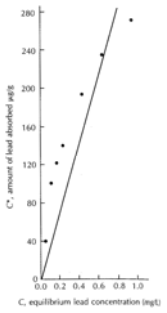
$$C^* = K_f C^j \quad (10.11)$$

where

C^* = mass of solute sorbed per bulk unit dry mass of soil
C = solute concentration
K_f, j = coefficients

Lead Adsorption

► FIGURE 10.13
Lead adsorption by Cecil clay loam at pH 4.5 and at 25°C described by a linear Freundlich equation through the origin. *Source: W. R. Roy, I. G. Krapac, S. F. J. Chou, & R. A. Griffin,* Batch-Type Adsorption for Estimating Soil Attenuation of Chemicals. *Technical Resource Document, EPA/530-SW-87-006, 1987.*

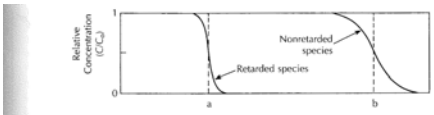


The slope of the curve on the log-log paper is represented by j. In a plot of C^* versus C, where the slope is a straight line, the relationship is linear, and j has a value of one. Under these conditions, the derivative of C^* with respect to C yields the relationship

$$dC^*/dC = K_d \quad (10.12)$$

where K_d is known as a **distribution coefficient.**

Influence of Adsorption



▲ FIGURE 10.14
Influence of retardation on movement of a solute front in a one-dimensional column.

Retardation

The K_d value can be used to compute the retardation of the solute front as it passes through the soil by the following equation:

$$\text{Retardation factor} = 1 + (\rho_b/\theta)\,(K_d) \qquad \textbf{(10.14)}$$

where

ρ_b is dry bulk mass density of the soil (M/L^3; gm/cm^3)

θ is volumetric moisture content of the soil (dimensionless)

K_d is distribution coefficient for the solute with the soil (L^3/M; mL/g)

If a solute is reactive, it will travel at a slower rate than the ground water owing to adsorption. The rate of solute movement can be determined by the retardation equation

$$v_c = v_x/[1 + (\rho_b/\theta)(K_d)] \qquad \textbf{(10.15)}$$

where

v_x is average linear velocity (L/T; ft/day or m/day)

v_c is velocity of the solute front. In a one-dimensional column the solute concentration is one-half of the original value ($C/C_0 = 0.5$) (L/T; ft/day or m/day)

Retardation Example

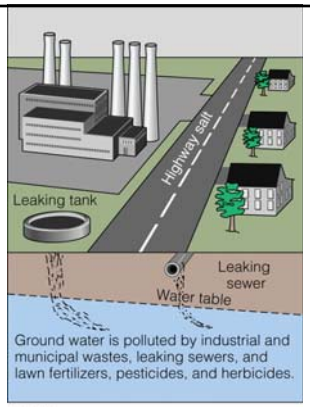
Compute the relative velocity of the solute front of a solute-soil system with a distribution coefficient of 10 mL/g, a ρ_b value of 1.75 g/cm^3, and θ of 0.20:

$$v_c = \frac{v_x}{1 + (\rho_b/\theta)(K_d)}$$

$$= \frac{v_x}{1 + \left(\frac{1.75\ \text{g/cm}^3}{0.20}\right)\left(10\frac{\text{mL}}{\text{g}}\right)\left(\frac{1\ \text{cm}^3}{1\ \text{mL}}\right)}$$

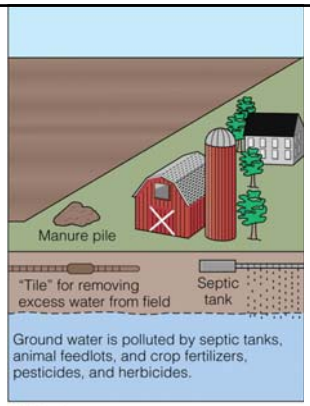
$$= \frac{v_x}{88.5}$$

$$= 0.011 v_x$$



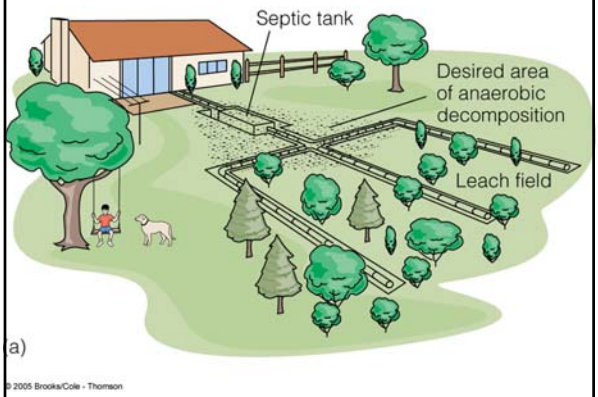
(a) Urban areas

Urban Pollution



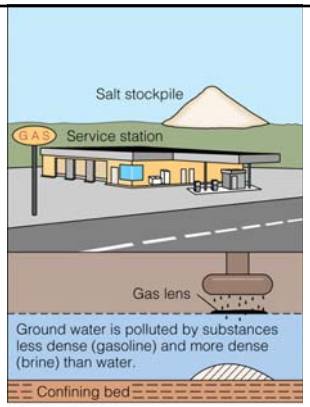
(b) Rural areas

Rural Pollution



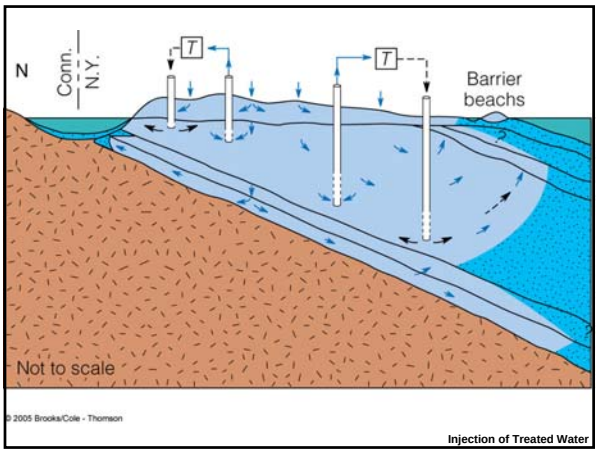
(a)

Septic Tank Field



(c) Density effects

Density



Injection of Treated Water

Organic Pollutants

Table 10.3 Solubility, K_{oc}, and mobility class for common organic pollutants

Compound	Solubility (mg/L)	K_{oc} (mL/g)	Mobility Class
1, 4-Dioxane	miscible	1	very high
4-hydroxy-4-methyl-2-pentanone	miscible	1	very high
acetone	miscible	1	very high
tetrahydrofuran	miscible	1	very high
N,N'-dimethylformamide		1	very high
N,N'-dimethylacetamide		2	very high
2-methyl-2-butanol	140000.	6	very high
2-butanol	125000.	6	very high
ethyl ether	84300.	8	very high
cyclohexanol	56700.	10	very high
3-methylbutanoic acid	42000.	12	very high
benzyl alcohol	40000.	12	very high
aniline	34000.	13	very high
2-hexanone (butylmethylketone)	35000.	14	very high
2-hydroxy-triethylamine		15	very high
2-methylphenol (o-cresol)	31000.	15	very high
2-methyl-2-propanol		16	very high

Organic Pollutants

Table 10.3 continued

Compound	Solubility (mg/L)	K_{oc} (mL/g)	Mobility Class
4-methylphenol (p-cresol)	24000.	17	very high
pentanoic acid	24000.	17	very high
cyclohexanone	23000.	18	very high
4-methyl-2-pentanone	19000.	20	very high
2, 4-dimethyl phenol	17000.	21	very high
4-methyl-2-pentanol	17000.	21	very high
methylene chloride	13200.	25	very high
isophorone	12000.	26	very high
phenol	82000.	27	very high
2-chlorophenol	11087.	27	very high
hexanoic acid	11000.	28	very high
chloroform	7840	34	very high
1,2-dichloroethane	8450.	36	very high
1,2-trans-dichloroethene	6300.	39	very high
chloroethane	5700.	42	very high
5-methyl-2-hexanone	5400.	43	very high
chloromethane	5380.	43	very high
1,1-dichloroethane	5100.	45	very high
1,1,2-trichloroethane	4420.	49	very high

Organic Pollutants

1,2-dichloropropane	3570.	51	high
benzoic acid	2900.	64	high
octanoic acid	2500.	70	high
heptanoic acid	2410.	71	high
1,1,2,2-tetrachloroethane	3230.	88	high
benzene	1780.	97	high
diethyl phthalate	1000.	123	high
2-nonanol	1000.	123	high
bromodichloromethane	900.	131	high
3-methylbenzoic acid	850.	136	high
trichloroethene	1100.	152	moderate
1,1,1-trichloroethane	700.	155	moderate
di-*n*-butyl phthalate	400.	217	moderate
1,1-dichloroethene	400.	217	moderate
carbon tetrachloride	800.	232	moderate
2-butanone (methylethylketone)	353.	235	moderate
4-methylbenzoic acid	340.	240	moderate
toluene	500.	242	moderate
tetrachloroethylene	200.	303	moderate
chlorobenzene	448.	318	moderate
1,2-dichlorobenzene	148.	343	moderate
o-xylene	170.	363	moderate
1,2,2-trifluoro-1,1,2-trichloroethane		372	moderate
styrene	162.	380	moderate
1,3-dichlorobenzene	118.	463	moderate
fluorotrichloromethane	110.	476	moderate
4,6-dinitro-2-methylphenol		477	moderate

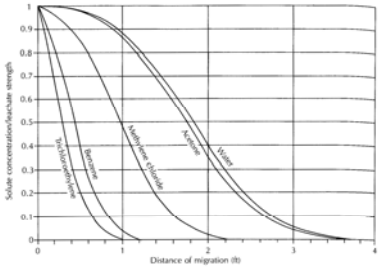
Organic Pollutants

N-nitrosodiphenylamine	35.1	982	low
3,5-dimethylphenol		1038	low
BHC-delta	31.5	1052	low
2,6-dimethylphenol		1060	low
1,2,4-trichlorobenzene	30.	1080	low
naphthalene	31.7	1300	low
4-ethylphenol		1986	low
dibenzofuran	10.	2140	slight
hexachloroethane	8.	2450	slight
acenaphthene	7.4	2580	slight
tri-*N*-propylamine		2610	slight
BHC-alpha	8.5	2627	slight
BHC-beta	2.7	3619	slight
hexachlorobenzene	0.035	3910	slight
hexachlorobutadiene	3.2	4330	slight
di-*n*-octyl phthalate	3.	4510	slight
butyl benzyl phthalate	2.9	4606	slight
fluorene	1.98	5835	slight
2-methylnaphthalene	25.4	8500	slight
bis(2-ethylhexyl)phthalate	0.6	12200	slight
toxaphene	0.4	15700	slight
heptachlor epoxide	0.35	17087	slight
endosulfan II	0.28	19623	slight
fluoranthene	0.275	19800	slight

Organic Pollutants

1,2-diphenylhydrazene (as azobenzene)	0.252	20947	immobile
endosulfan sulfate	0.22	22788	immobile
phenanthrene	1.29	23000	immobile
dieldrin	0.188	25120	immobile
anthracene	0.073	26000	immobile
BHC-gamma	0.15	28900	immobile
decanoic acid		39610	immobile
chlordane	0.056	53200	immobile
pyrene	0.135	63400	immobile
PCB-1254	0.042	63914	immobile
heptachlor	0.03	78400	immobile
endrin	0.024	90000	immobile
benzo(a)anthracene	0.014	125719	immobile
aldrin	0.013	132000	immobile
4,4'-DDE	0.01	155000	immobile
4,4'-DDT	0.0017	238000	immobile
4,4'-DDD	0.005	238000	immobile
benzo(*a*)pyrene	0.0038	282185	immobile
PCB-1260	0.0027	349462	immobile
chrysene	0.022	420108	immobile
benzo(*b*)fluoranthene		1148497	immobile
benzo(*k*)fluoranthene		2020971	immobile

Migration of Organic Pollutants



▲ FIGURE 10.16
Vertical migration, in feet per 100 y, of various synthetic organic compounds through a soil with a hydraulic conductivity of 1.6×10^{-5} cm/s, hydraulic gradient of 0.222, bulk density of 2.00 g/cm^3, particle density of 2.65, effective porosity of 0.22, and soil organic carbon content of 0.5%.

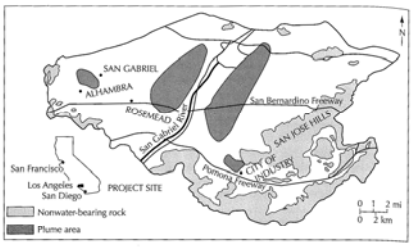
Common Groundwater Pollutants

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	*Yersinia 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	tetrachloroethene	
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	
			isopherone	2-propanol	
			phenol		
			1,2-dichlorobenzene		

Municipal Solid Water Landfill Leacates Wisconsin

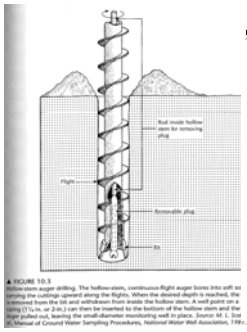
Parameter	Overall Range[a]	Typical Range (range of site medians)[a]	Number of Analyses
TDS	584–50430	2180–25873	172
Specific conductance	480–72500	2840–15485	1167
Total susp. solids	2–140900	28–2835	2700
BOD	ND–195000	101–29200	2905
COD	6.6–97900	1120–50450	467
TOC	ND–30500	427–5890	52
pH	5–8.9	5.4–7.2	1900
Total alkalinity ($CaCO_3$)	ND–16500	960–6945	328
Hardness ($CaCO_3$)	52–225000	1050–9380	404
Chloride	2–11375	180–2651	303
Calcium	200–2500	200–2100	9
Sodium	12–6010	12–1630	192
Total Kjeldahl nitrogen	2–3320	47–1470	156
Iron	ND–1500	2.1–1400	456
Potassium	ND–2800	ND–1375	19
Magnesium	120–780	120–780	9
Ammonia-nitrogen	ND–1200	26–507	263
Sulfate	ND–1850	8.6–500	154
Aluminum	ND–95	ND–95	9
Zinc	ND–731	ND–54	198
Manganese	ND–31.1	0.03–25.9	67
Total phosphorus	ND–274	0.3–117	454
Boron	0.87–13	1.19–12.3	15
Barium	ND–12.5	ND–5	73
Nickel	ND–7.5	ND–1.65	133
Nitrate-nitrogen	ND–250	ND–1.4	88
Lead	ND–14.2	ND–1.11	142
Chromium	ND–5.6	ND–1.0	138
Antimony	ND–3.19	ND–0.56	76
Copper	NA–4.06	NA–0.32	136
Thallium	ND–0.78	ND–0.31	70
Cyanide	ND–6	ND–0.25	86
Arsenic	ND–70.2	ND–0.225	112
Molybdenum	0.01–1.43	0.034–0.193	7
Tin	ND–0.16	0.16	3
Nitrite-nitrogen	ND–1.46	ND–0.11	20
Selenium	ND–1.85	ND–0.09	121
Cadmium	ND–0.4	ND–0.07	138
Silver	ND–1.96	ND–0.024	106
Beryllium	ND–0.36	ND–0.008	76
Mercury	ND–0.01	ND–0.001	111

Solvent/Degreaser Plumes



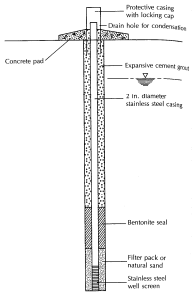
▲ FIGURE 10.1
Plumes of contaminated ground water in the 170-mi² San Gabriel groundwater basin, southern California. Contaminants, which include trichloroethylene, perchloroethylene, carbon tetrachloride, and other suspected carcinogens, are found in more than 88 municipal supply wells to depths as great as 1000 ft (300m). Multiple sources of contamination are responsible for the common industrial solvents and degreasers found in the ground water. *Source: J. J. Kosowatz & M. J. Sponseller,* Engineering News Record *217, no. 21 (Nov. 21, 1986): 28–29.*

Monitoring Wells

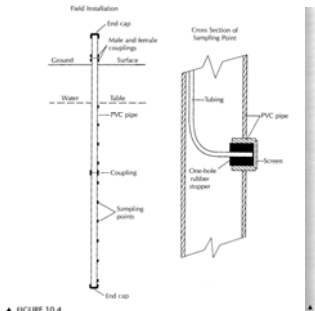


▲ FIGURE 10.3
Hollow-stem auger drilling. The hollow-stem, continuous-flight auger bores into soft soil carrying the cuttings upward along the flights. When the desired depth is reached, the plug is removed from the bit and withdrawn from inside the hollow stem. A well point on a casing (1¼ in. or 2 in.) can then be inserted to the bottom of the hollow stem and the auger pulled out, leaving the small-diameter monitoring well in place. *Source:* M. L. Scot [illegible], Manual of Ground Water Sampling Procedures, *National Water Well Association, 198[illegible].*

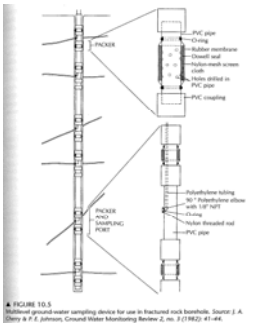
► FIGURE 10.2
Typical ground-water monitoring well.



Groundwater Sampling



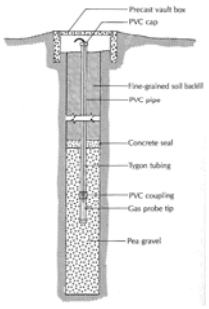
▲ FIGURE 10.4
Multilevel ground-water sampling device for use in sandy soil. *Source: J. F. Pickens et al.,* Ground Water Monitoring Review *1, no. 1 (1981): 48–51.*



▲ FIGURE 10.5
Multilevel ground-water sampling device for use in fractured rock boreholes. *Source: J. A. Cherry & P. E. Johnson,* Ground Water Monitoring Review *2, no. 3 (1982): 41–44.*

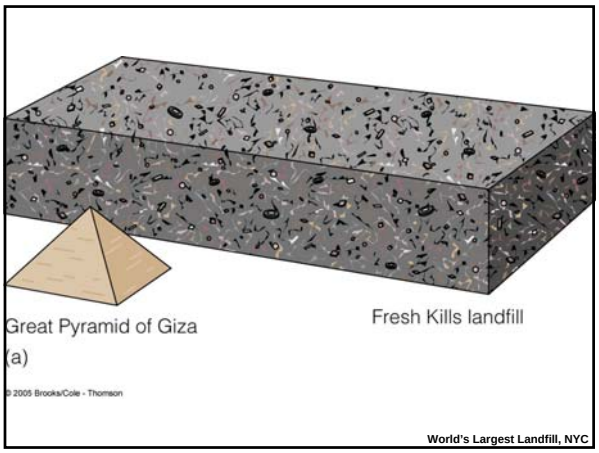
Gas Monitoring Well

► FIGURE 10.6
Gas monitoring well in vadose zone.
Source: L. S. Wilson, Ground Water Monitoring Review *3, no. 1 (1983): 155–66.*

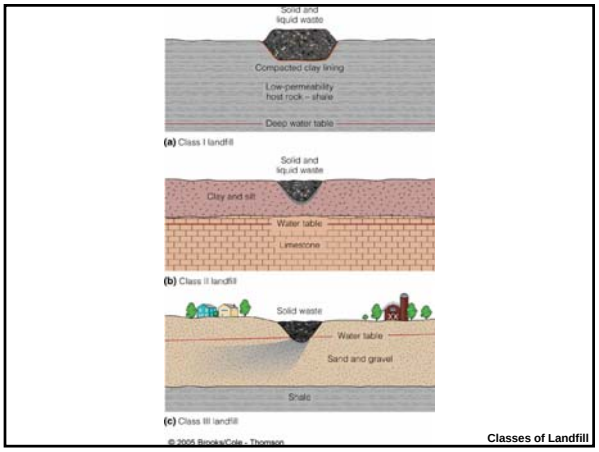


Full, graded landfill prior to planting

Fresh Kills Landfill, NYC



World's Largest Landfill, NYC

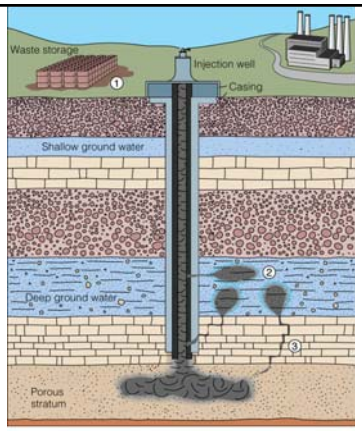


Classes of Landfill

TABLE 15.1 Classifications of Disposal Sites and Waste Groups

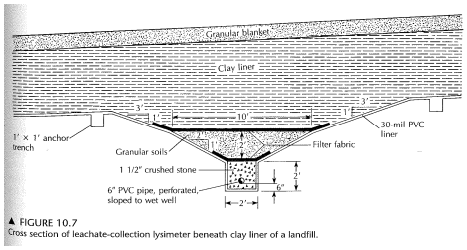
Geology of Disposal Sites	
Class I	No possibility of discharge of leachate to usable waters. Inundation and washout must not occur. The underlying lining material, whether soil or synthetic, must be essentially impermeable; that is, it must have a permeability less than 0.3 cm/year. All waste groups may be received (Figure 15.5, part a).
Class II	Site overlies or is adjacent to usable ground water. Artificial barriers may be used for both vertical and lateral leachate migration. Geologic formation or artificially constructed liners or barriers should have a permeability of less than 30 cm/year. Groups 2 and 3 waste may be accepted (Figure 15.5, part b).
Class III	Inadequate protection of underground- or surface-water quality. Includes filling of areas that contain water, such as marshy areas, pits, and quarries. Only inert Group 3 wastes can be accepted (Figure 15.5, part c).
Constituents of Waste Groups	
Group 1	Consists of but not limited to toxic substances that could impair water quality. Examples are saline fluids, toxic chemicals, toilet wastes, brines from food processing, pesticides, chemical fertilizers, toxic compounds of arsenic, and chemical-warfare agents.
Group 2	Household and commercial garbage, tin cans, metals, paper products, glass, cloth, wood, yard clippings, small dead animals, and hair, hide, and bones.
Group 3	Non-water-soluble, nondecomposable inert solids such as concrete, asphalt, plasterboard, rubber products, steel-mill slag, clay products, glass, and asbestos shingles.

Methane-extraction well



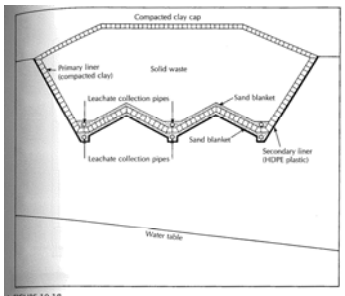
Deep Well Injection of Hazardous Waste

Leachate Collection System

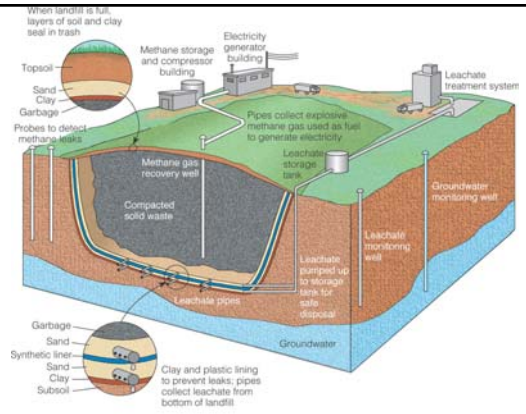


▲ FIGURE 10.7
Cross section of leachate-collection lysimeter beneath clay liner of a landfill.

Landfill Design

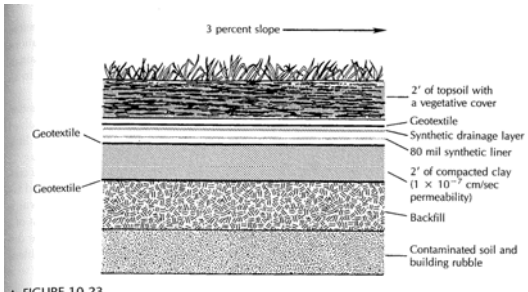


▲ FIGURE 10.18
Double-lined landfill with leachate collection system. The primary liner consists of 5 ft of compacted clay soil with hydraulic conductivity of no more than 1×10^{-7} cm/s. The secondary liner is flexible membrane such as 40-mil HDPE plastic. The leachate collection system consists of 6-thick sand layers with perforated pipes, which drain to a leachate collection tank.



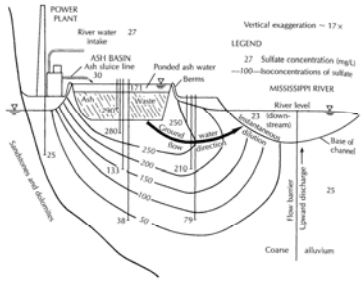
Landfill design with Lechate and Methane controls

Multimedia Landfill Cap



▲ FIGURE 10.23
Design of a low-permeability multimedia cap to cover waste. Fill material is used above waste to create a 3% slope if the waste material or land surface over the waste material is not sloped.

Leaching of Sulfate

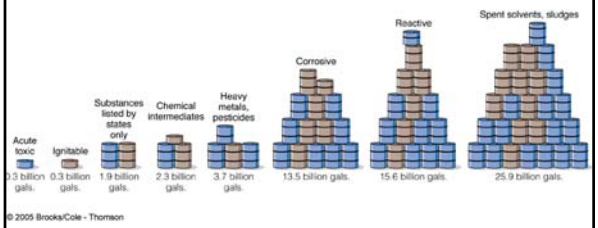


▲ FIGURE 10.17
Plume of ground water contaminated with high-sulfate leaching from a fly ash landfill located below the water table. *Source: Daniel R. Viste.* Proceedings, First Annual Conference of Applied Research and Practice on Municipal and Industrial Waste (Madison: University of Wisconsin, 1978), pp. 327–40.

AMD, Mike Horse Mine, Montana

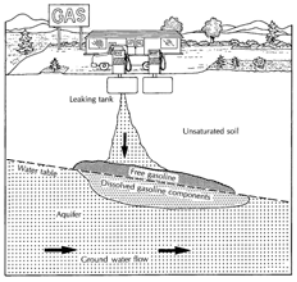
Organic Compounds

Compound	Specific Gravity[a]	Solubility[b] 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)



U.S. Toxic Waste

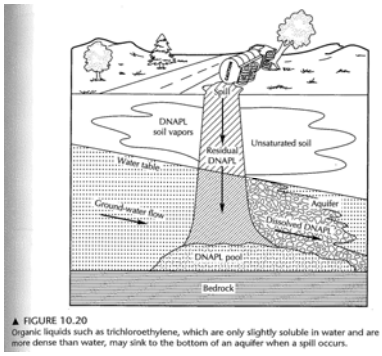
Light, Slightly Soluble Organic Liquids (e.g., gasoline)



▲ 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.

Dense Non-Aqueous Phase Liquids

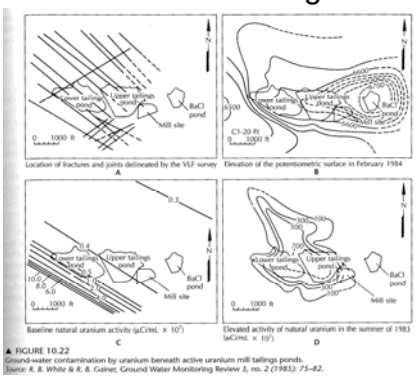
a liquid that is denser than water and does not dissolve or mix easily in water



▲ 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.

▲ FIGURE 10.21
Plumes of 1,1,1-trichloroethane in shallow ground water in South Brunswick Township, New Jersey. The plume to the southwest has traveled to the east and has reached a public water-supply well. Source: P. M. Bass & W. F. Abbott, Ground Water 18 (1980): 664–72.

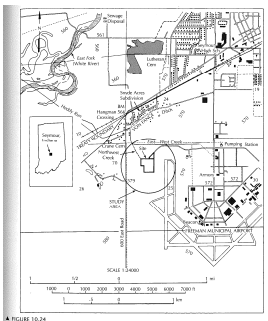
Movement of Solute along Fractures



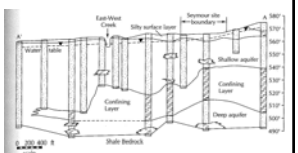
▲ FIGURE 10.22
Ground-water contamination by uranium beneath active uranium mill tailings ponds.
Source: R. B. White & R. B. Gainer, Ground Water Monitoring Review 5, no. 2 (1985): 75–82.

Love Canal, Niagara Falls, NY

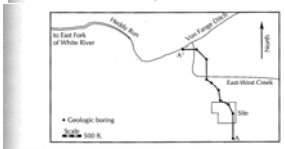
Superfund Site



▲ FIGURE 10.24
Vicinity of the Seymour Recycling Corporation Superfund site. Source: CH2M-Hill, Feasibility Study Report, Seymour Recycling Corporation Hazardous Waste Site, U.S. Environmental Protection Agency, 1990.

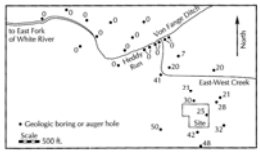


▲ FIGURE 10.26
Southeast to northwest geological cross section through the Seymour Recycling Corporation Hazardous Waste Site. The elevation scale on the right is in feet above mean sea level.

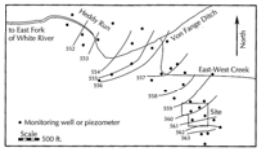


▲ FIGURE 10.27
Location of the geological cross section shown on Figure 10.26.

Superfund Site

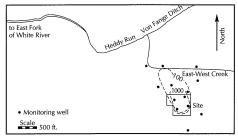


▲ FIGURE 10.25
Thickness, in feet, of the confining layer as measured in borings in the vicinity of the Seymour Hazardous Waste Site.

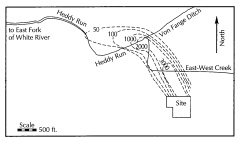


▲ FIGURE 10.28
Elevation of the water table in the vicinity of the Seymour Recycling Corporation Hazardous Waste Site. Elevations are in feet above mean sea level.

Superfund Site



▲ FIGURE 10.29
Extent of the 1,4-dioxane plume on December 1984. Concentrations in μg/L.



▲ FIGURE 10.30
Extent of the 1,4-dioxane plume in 1990. Concentrations in μg/L.

Semivolatile compounds	Maximum concentration μg/L
2,4-dimethylphenol	780
Phenol	4,800
Benzoic acid	20,000
2-methylphenol	190
4-methylphenol	6,000
bis(2-ethylhexyl)phthalate	17
2-chlorophenol	10 K
Isophorone	120
Benzyl alcohol	200 K
Pentachlorophenol	10 K
Benzo(a)anthracene	10 K
Chrysene	20 K
Napthalene	100 K
1,2-dichlorobenzene	100 K
Volatile compounds	
Chloroethane	14,000
1,2-dichloroethane	3,200
1,1,1-trichloroethane	93,000
1,1,2-trichloroethane	2,300
Tetrachloroethene	500 K
1,1-dichloroethene	2,600
Trans-1,2-dichloroethene	240,000
Trichloroethene	500 K
Chloroform	3,300
Methylene chloride	32,000
Vinyl chloride	19,000
Acetone	37,000
Benzene	9,700
Ethylbenzene	500 K
Toluene	18,000
2-butanone	31,000
2-hexanone	9,800
4-methyl-2-pentanone	12,000
Total xylenes	500 K