Lecture Nine

Properties of hazardous wastes

9.1 Solubility

It is the extent of concentration (mg/L) to which a hazardous compound dissolves in a solvent. It determines whether the chemical can be found as a separate phase or dissolved, thus controlling fate and transport. Hydrophobic compounds tend to partition onto solids from emulsions and float at air-water interface, or sink to the bottom of aquifer. In general, solubility is inversely proportional to sorption, bioaccumulation and volatilization. It is affected by temperature (usually expressed at 25°C).

Solubility depends on molecular structure, size and forces of attraction. We can generalize by saying that size is inversely proportional to molar volume. E.g. – solubility of naphthalene $C_{10}H_{8}$, (128.17 $g \cdot mol^{-1}$) is 32 mg/L, while solubility of benzopyrene $C_{20}H_{12}$ (252.32 $g.mol^{-1}$) is 0.00038 mg/L.

9.2 Effective Solubility

It is the true solubility of a compound in mixture, denoted by S^i_e.

Effective Solubility $C_w = X_o\ S$

C_w = Effective solubility of the specific compound (mgL^{-1})

x_o = mole fraction (of chemical in fuel)

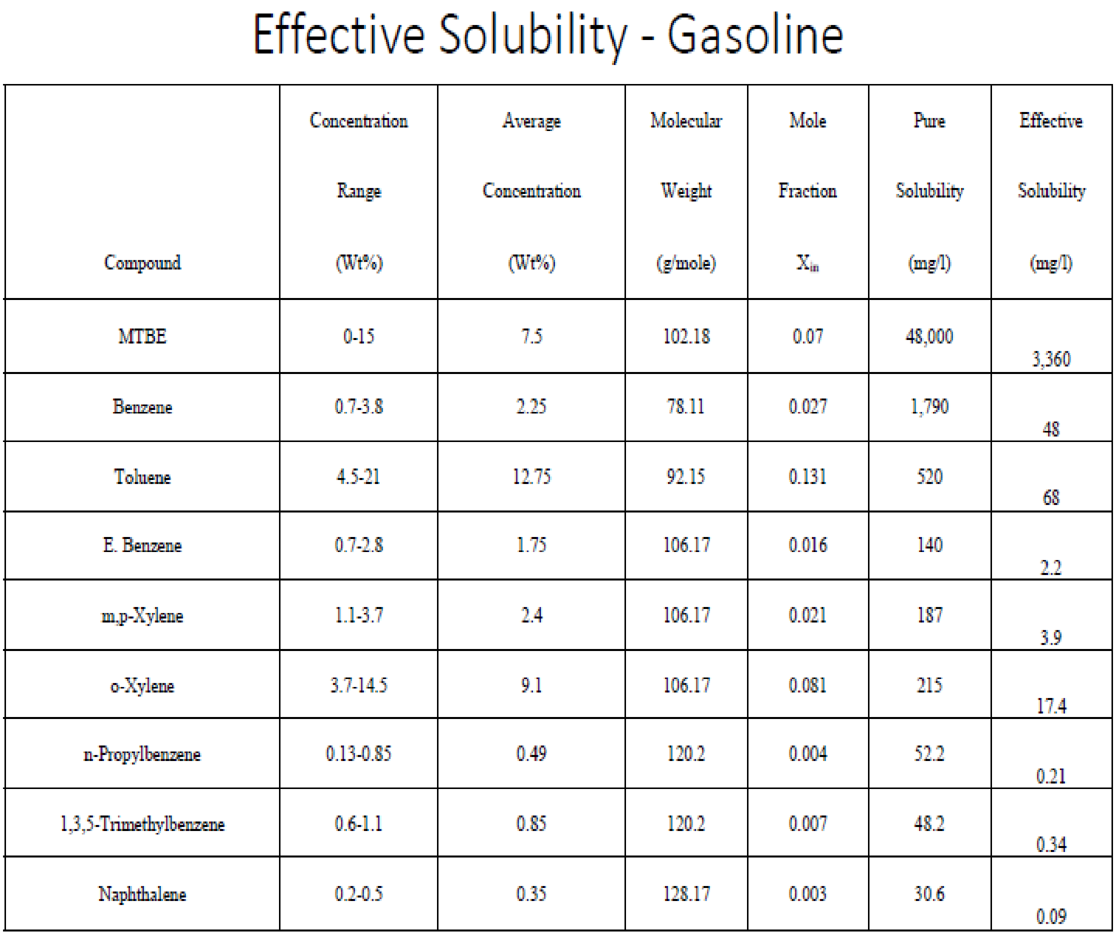
S = pure solubility of the specific compound in the total compound (mgL^{-1})

Mole Fraction $X_o = MF_x\ MW_o / MW_x$

MF_x = mass fraction of selected chemical in fuel

MW_o = average molecular weight of fuel ($gram.mol^{-1}$)

MW_X = molecular weight of selected chemical ($gram.mol^{-1}$)



Effective Solubility - Gasoline

Compound	Concentration Range (Wt%)	Average Concentration (Wt%)	Molecular Weight (g/mole)	Mole Fraction X_{in}	Pure Solubility (mg/l)	Effective Solubility (mg/l)
MTBE	0-15	7.5	102.18	0.07	48,000	3,360
Benzene	0.7-3.8	2.25	78.11	0.027	1,790	48
Toluene	4.5-21	12.75	92.15	0.131	520	68
E. Benzene	0.7-2.8	1.75	106.17	0.016	140	2.2
m,p-Xylene	1.1-3.7	2.4	106.17	0.021	187	3.9
o-Xylene	3.7-14.5	9.1	106.17	0.081	215	17.4
n-Propylbenzene	0.13-0.85	0.49	120.2	0.004	52.2	0.21
1,3,5-Trimethylbenzene	0.6-1.1	0.85	120.2	0.007	48.2	0.34
Naphthalene	0.2-0.5	0.35	128.17	0.003	30.6	0.09

9.3 Water solubility of weak acids/ bases

Weak acids dissociate into their ionized form.

$$RCOOH \rightleftarrows RCOO^{-} + H^{+}$$

$$Activity\ coefficient,\ k_a = (\{RCOO^{-}\}\{H^{+}\}/\{RCOOH\})$$

For weak bases:

$$Ca^{2+} + 2OH^{-} \rightarrow Ca(OH)^{2}$$

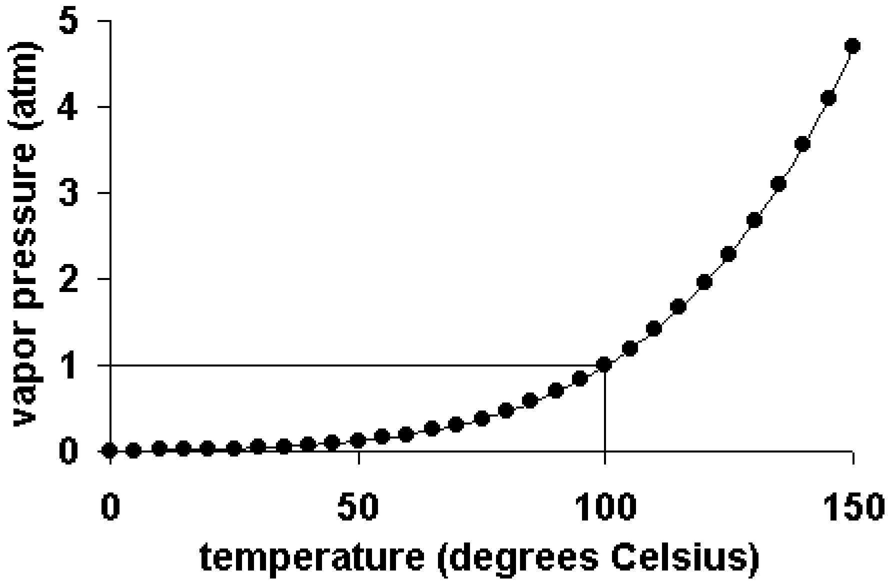
$$Solubility\ product,\ k_{sp} = [Ca^{2+}][OH^{-}]^{2}$$

9.4 Vapour Pressure

The vapor pressure of a liquid is the equilibrium pressure of a vapor above its liquid (or solid); that is, the pressure of the vapor resulting from evaporation of a liquid (or solid) above a sample of the liquid (or solid) in a closed container. Examples:

substance	**vapor pressure at 25^{o}C**
diethyl ether	0.7 atm
bromine	0.3 atm
ethyl alcohol	0.08 atm
water	0.03 atm

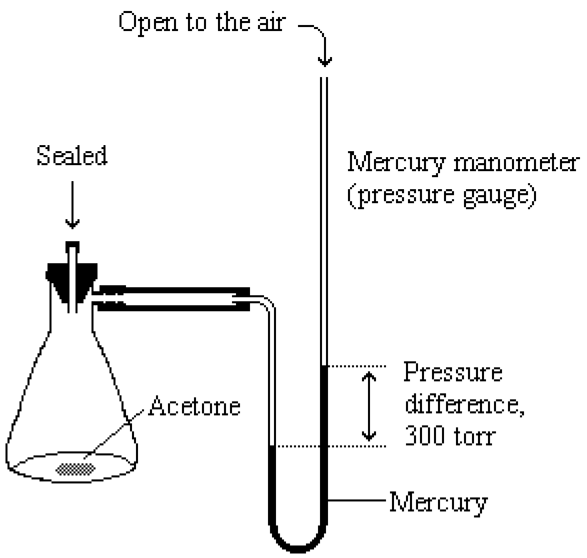
The vapor pressure of a liquid varies with its temperature, as the following graph shows for water. The line on the graph shows the boiling temperature for water.



As the temperature of a liquid or solid increases its vapor pressure also increases. Conversely, vapor pressure decreases as the temperature decreases. The vapor pressure of a liquid can be measured in a variety of ways. A simple measurement involves injecting a little of the liquid into a closed flask connected to a manometer.

The 300 torr increase in pressure is due to the evaporation of the liquid in the flask. The vapor pressure of the liquid is equal to the increase in pressure after the pressure stops changing.

Because the amount of liquid and vapor have stopped changing, we say the liquid and vapor are in equilibrium at this point.



Raoult's Law

$p_a = p_v X_a$ (for pure phase)

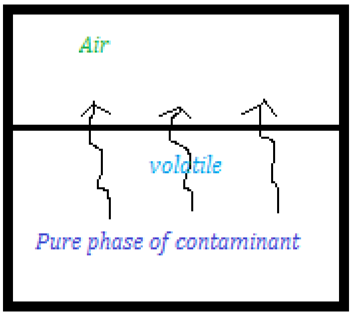


Fig. 1: Vapour pressure of a liquid contaminant

Where $p_a = partial\ pressure\ of\ contaminant\ a\ (atm)$

$p_v = vapour\ pressure\ of\ pure\ compound\ (atm)$

$X_a = mole\ fraction\ of\ a = moles\ of\ a/total\ number\ of\ moles$

Henry's Law

Henry's Law states that under equilibrium, partial pressure of a volatile gas above a liquid is proportional to the concentration of the compound in the liquid.

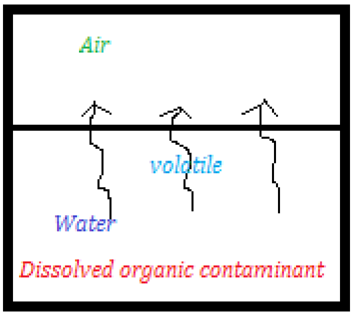


Fig. 2: Partitioning of a contaminant from water to air

Henry’s Constant $H\ (atm.m^3/mol)=P_g/C_l$

Where P_g is the partial pressure of the volatile gas above the liquid (atm) and C_l is the concentration of the compound in liquid (mol/m^3)

Dimensionless form of Henry’s constant $H'=C_a/C_w=H/RT$

Where C_a and C_w are the concentrations of the contaminant in air and water respectively.

Regression equation: $H=e^{A-(BT)}$

Where A and B are constants and T is the temperature

Example 1: Determine the Henry’s constant of toluene at 20°C. Vapour pressure is given to be 22 mm Hg and solubility is 515 mg/L.

Solution:

Toluene $C_6H_5\text{-}CH_3$ $Molecular\ weight=92g/mol$

$Vapour\ pressure=22\ mm\ Hg=22\ mm/760mm\ atm=0.0289\ atm$

$Solubility=515mg/L=515*0.001\ g/0.001\ m^3*92g/mol=5.59mol/m^3$

$Henry's\ constant\ H=VP/S=0.0289/5.59=5.2*10^{-3}\ atm.m^3/mol$

9.5 Partitioning

Partitioning is the distribution of chemicals between two different media/ phases. There are various partitioning coefficients, which empirically describe these phenomena.

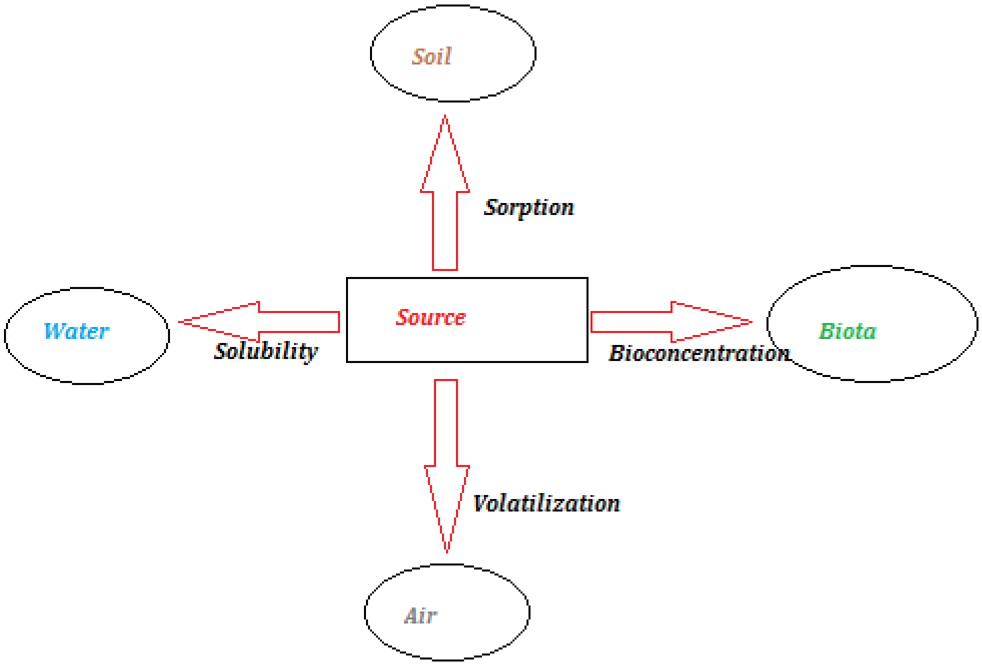


Fig. 3: Figure showing partitioning of hazardous waste to various media

9.5.1 Octanol-water partitioning coefficient

It is a measure of how an organic compound partitions between octanol and water. Octanol-water partitioning coefficient $K_{ow}=C_{octanol}/C_{water}$

9.5.2 Soil-water partitioning coefficient

Water is the preferred medium for contaminants. If the contaminant is in aqueous phase, it gets adsorbed by soil easily.

Soil-water partitioning coefficient $K_d=C_{soil}/C_{water}$ (for linear adsorption)

K_d is similar to adsorption coefficient and soil is the (heterogeneous) adsorbent.

9.5.3 Organic Carbon (OC) content

OC content, also known as humic content plays an important role in organic chemical partitioning. It is the fraction of organic carbon present in soil.

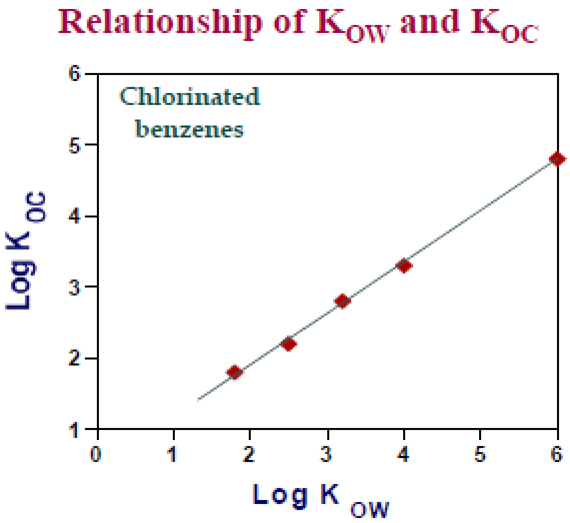
$K_{OC}=C_{OC}/C_{water}$ and $K_d=K_{OC}*f_{OC}$ (if $f_{OC}>f_{OC}^*$)

Where f_{OC} is the fraction of organic carbon present in soil (this is an important factor for partitioning) and f_{OC}^* is the critical organic carbon concentration

Organic content of soil is the main contributor towards sorption only if $f_{OC} > f_{OC^*}$.

f_{OC}^* is calculated from the surface area (Sa) of soil (empirical relation): $f_{OC^*}(\%) = Sa/200(K_{ow})^{0.84}$

The relationship between KOC and KOW is shown in Fig. below:



9.5.4 Contaminants in Biota

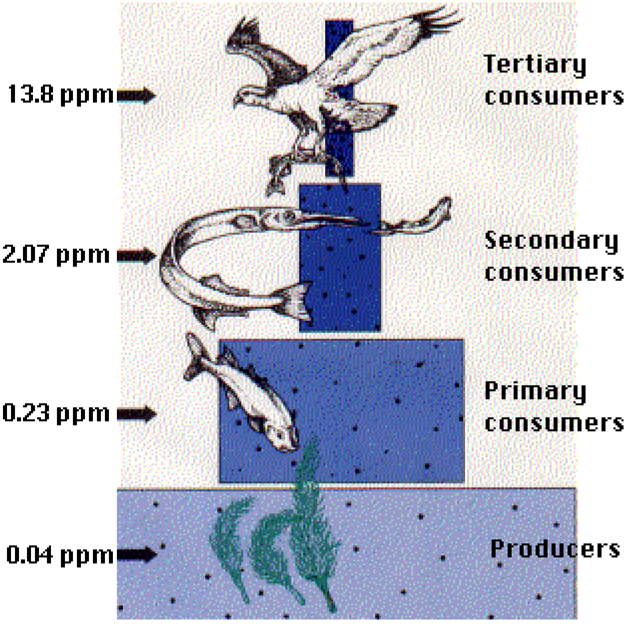
The partitioning coefficient between biota and water is also known as Bioconcentration Factor (BCF).

$BCF\ (kg/L) = C_{biota}\ (g/kg)/C_{water}\ (g/L)$

It is an estimate of the amount of chemical that is likely to accumulate in aquatic organisms. The higher the lipid content in an organism, the more the accumulation.

9.5.4 Biomagnification

Is the incremental increase in a contaminant's concentration at each level of the food chain. This can be explained with the help of the following graphic:



The numbers are representative values of the concentration in the tissues of **DDT** and its derivatives (in parts per million, ppm)

Fig. 4: Biomagnification of DDT

Example 2: An insecticide chlordane is found in lake water at a concentration of 560 µg/L. Find the concentration of the insecticide in fish. Given BCF for chlordane is 14000 L/kg.

Solution: $C_{biota}=BCF*C_{water}=14000L/kg*(560*10^{-6}g/L)=7.84g/kg$

9.5.5 Sorption

Properties of the phase as well as properties of the contaminant affects sorption into soil. Sorption controls the rate at which the contaminants move across media.

9.5.5.1 Cation Exchange Capacity (CEC)

It is the quantity of cations sorbed per amount of soil. It is a property of the soil, not the contaminant. Generally, it can be said that bigger the charge of the cation, the better the attraction.

Trend in CEC: $Monovalent\ cations<Divalent<Trivalent\ and\ higher$

Also, higher CEC is observed in soils with higher clay/ organic matter.

9.5.5.2 Forces controlling sorption

- Vander Waal’s attraction force
- Electrostatic attraction (adsorption), electrostatic repulsion (desorption)
- Hydrogen bonding, Covalent bonds
- Dipole-dipole interaction
- Coulombic forces

Example 3: Determine the K_{OC}, K_d, C_s (sorbed phase concentration) for perchloroethylene in a soil-water system. Given f_{OC}=0.2% (found using TOC analyzer), logK_{ow}=2.79, K_{oc}=316, Sa=12 m^2/g, C_w=10 mg/L

Assuming linear sorption, find the concentration of PCE in soil.

Solution:

Check if $f_{OC}>f_{OC^*}$

$f_{OC^*}(\%)=Sa/200(K_{ow})^{0.84}=12/200*(616.59)^{0.8}=3.517*10^{-4}\%$

Therefore $K_d=K_{OC}*f_{OC}=316*0.002=0.632mLg$ $K_d=C_{soil}/C_{water}$

This implies $C_{soil}=0.632mL/g*10mg/L=6.32mg/kg$

9.6 Reasons for actual solubility in field being much lesser than the theoretical maximum solubility

1. Effective solubility

Solubility is proportional to mole fraction of contaminant.

2. Dilution

Dilution is the process of decreasing the concentration of a solute in solution, usually simply by mixing with more solvent. To dilute a solution means to add more solvent without the addition of more solute.

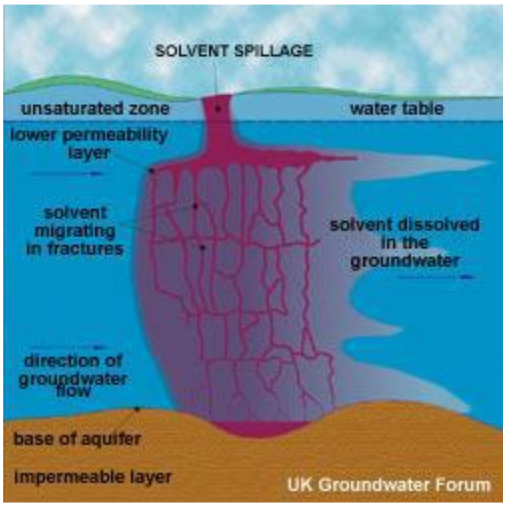


Fig. 5: Dilution of contaminant in ground water

3. Mass Transfer

There are two types of contaminant mass transfer which take place: equilibrium mass transfer (which reaches saturation) and rate limited mass transfer (when saturation is not reached). Rate limited mass transfer happens due to limited contact area/ time. Lesser contact area results in lesser solubility. Lesser contact time occurs when there is rapid movement of groundwater and there molecules of contaminant are small in size.

4. Remediation

Sometimes, it is observed that a concentration of a contaminant is greater than the concentration at saturated level.

$C > C_{saturated} > C_{effective}$

This is brought about by the presence of co-solvents and surfactants. Co-solvents refer to a group of intermediate solvents (such as methanol) that have the ability to dissolve pollutants, as well as dissolve in water.

5. Volatilization

Volatilization refers to the mass transfer of a contaminant from liquid to gaseous phase. It is important to monitor the migration of hazardous chemicals from waste sites and storage facilities (both above and below ground).

Factors contributing to concentration of contaminant in air:

- Vapour pressure and Henry’s Law (decides volatilization rate)
- Temperature
- Mixing (for e.g., fans/ blowers)
- Contact area (within the storage container)
- Ventilation rate (mixing from outside the room/ system)
- Rate limited mass transfer and dilution will play an important role

Rate of volatilization

Hanna-Davis equation for rate limited mass transfer in a closed container (close to source):

$Q_{vol}=MKA(VP-P)/RT$

Where $Q_{vol}=Rate\ of\ volatilization\ (g/s)$

$K=Mass\ transfer\ coefficient$ ($m^3/m^2/s$)

$A=Area$

$VP=Vapour\ pressure$

$P=Partial\ pressure\ above\ liquid$

$M=Molecular\ weight\ of\ contaminant$

For an open container, $P=atmospheric\ pressure$

The equation becomes: $Q_{vol}=MKA(VP)/RT$

Determination of Mass Transfer Coefficient:

Taking water as the reference: $Kw=0.83 cm/s$

If D is the diffusion coefficient and M the molecular weight of the contaminant: $K_1/K_2=(D_1/D_2)^{2/3}$

$D_1/D_2=\sqrt{}M_2/M_1$

Therefore $K_1/K_2=(M_2/M_1)^{1/3}$

Performing mass balance for volatilization and ventilation rates within a closed room (control volume):

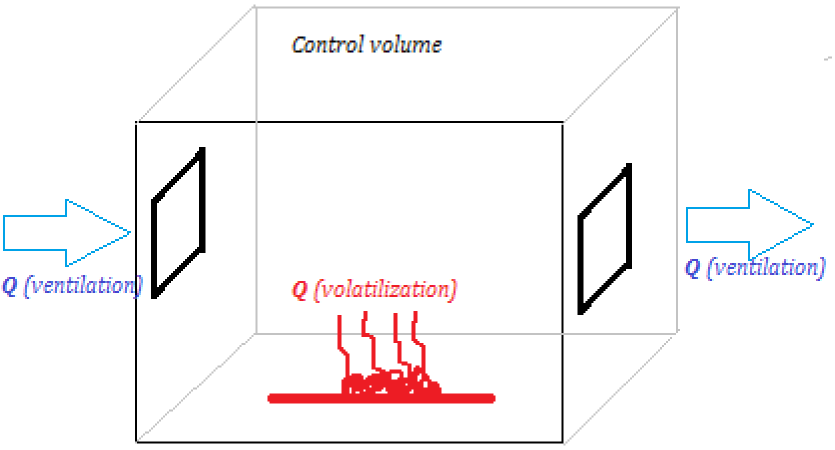


Fig. 6: Ventilation and volatilization flows in a closed room containing hazardous waste

$Accumulation=Flow\ in-flow\ out\pm change\ in\ system$

C represents concentration of contaminant (g/m^3), M_{vol} the volatilization rate (g/s), Q_{ven} the ventilation flow rate (m^3/s), V the control volume, k_m the mixing constant

$$V\frac{dc}{dt}=M_{vol}-k_m C Q_{ven}$$

There is no accumulation and no change in system (=0).

In other words, flow in is equal to flow out.

Therefore $C\left(\frac{g}{m^3}\right)=\frac{M_{vol}}{k_m Q_{ven}}$

Example 4: A cylindrical storage tank 1.5 m in diameter is left open in a volume of 220 m^3. It is known that the ventilation rate is 12 air-changes every hour. Determine the steady state concentration of toluene, when k_m is 0.2. The temperature is 20°C, atmospheric pressure 1 atm, vapour pressure of toluene 0.0289 atm.

Solution:

$$Air - change\ per\ hour = 220\,\frac{m^3}{hr}$$

$$Q_{ven} = 12\ air - changes\ per\ hour = \left(12 * \frac{220}{3600}\right)\frac{m^3}{s} = 0.733\ \frac{m^3}{s}$$

$$\text{Mass transfer coefficient } K = K_w.\left(\frac{M_w}{M_{toluene}}\right)^{\frac{1}{3}} = 0.0083\,\frac{m}{s} * \left(\frac{18}{92}\right)^{0.33} = 0.0048\,\frac{m}{s}$$

$$Q_{vol} = \frac{MKA(VP)}{RT}\ \text{for an open container}$$

$$Q_{vol} = M_{vol} = \frac{\left(\left(92\,\frac{g}{mol}\right) * \left(0.0048\,\frac{m}{s}\right) * (\pi 1.5^2\ m^2) * (0.0289\ atm)\right)}{(293\ K) * (8.205 * 10^{-5} m^3 atm K^{-1} mol^{-1})} = 0.75\,\frac{g}{s}$$

$$\text{Concentration of toluene } C\ \left(\frac{g}{m^3}\right) = \frac{M_{vol}}{k_m Q_{ven}} = \frac{0.75\frac{g}{s}}{0.2 * 0.733\,\frac{m^3}{s}} = 0.025\ \frac{g}{m^3}$$

9.7 Some relationships to describe movement of contaminant from soil

Dow's Equation

This first order equation describes volatilization of contaminant in surface soils.

Assuming first order: $-dc/dt\ is\ proportional\ to\ C\ (concentration)$

$-dc/dt = k_v C$

k_v is the volatilization rate constant.

On integrating:

$C_t = C_o e^{-k_v t}$ (C_t being concentration at time t, and C_o the initial concentration)

$k_v = 4.4 * 10^7 * VP/K_{OC}.S$

Where VP=$vapour\ pressure$ $(mm\ Hg)$, S=$solubility$ (mg/L), K_{OC}=$soil\ adsorption\ coefficient$ (mL/g)

9.7.1 Hamaker Equation

This equation describes volatilization of contaminant from deep aquifers. It is a semi-empirical equation.

$$Q_{vt} = 2C_o\sqrt{\frac{Dt}{\pi}}$$

$$Q_{vt} = \frac{volatilization}{unit\ area}\left(\frac{g}{cm^2}\right),\ C_o = initial\ concentration\ \left(\frac{g}{cm^3}\right)$$

$D = diffusion\ constant\ \left(\frac{cm^2}{s}\right)$ and $t = time\ (s)$

Example 5: A surface spill of endrine has occurred. Find the half-life of endrine and the time required for 99.9% volatilization. Given: logK_{OC}=4.11,VP=$7*10^{-7}$ $mm\ Hg$, S=0.24 mg/L

Solution:

For a surface spill, we use the Dow equation.

$$C_t = C_o e^{-k_v t}$$

Calculating half-life: $\frac{C_o}{2} = C_o e^{-k_v t_{0.5}}$

$$t_{0.5} = \frac{0.693}{k_v}$$

$$k_v = 4.4 * 10^7 * \frac{VP}{K_{OC}.S} = \frac{(4.4 * 10^7 * 7 * 10^{-7})}{12882 * 0.24} = 9.962 * 10^{-3}$$

$$t_{0.5} = \frac{0.693}{9.962 * 10^{-3}} = 69.56\ days{\sim}70\ days$$

For 99.9% volatilization:

$0.001C_o = C_o e^{-9.962*10^{-3}t}$, therefore $t = 924\ days.$

9.7.2 Fate and transport of contaminants in groundwater

Advection

The contaminant is physically carried by the medium (with the same velocity as the medium). Advection will transport contaminants at different rates in each stratum. Advective flux describing the bulk movement of the fluid carrying contaminant.

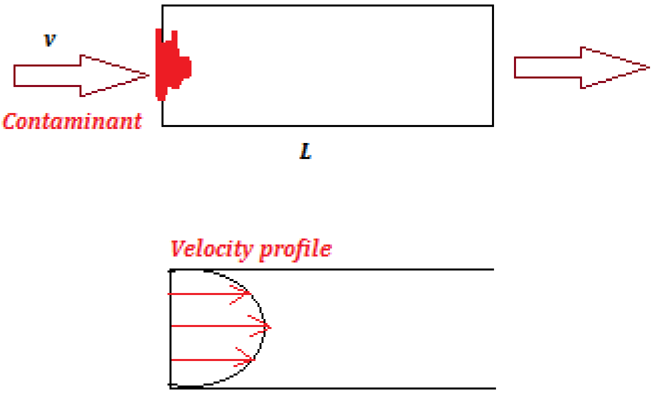


Fig. 7: Velocity profile of contaminant (once it is released) – similar to a Plug Flow Reactor

Diffusion

Diffusion is the process by which a contaminant will move from an area of greater concentration towards an area of lesser concentration. Diffusion will occur as long as a gradient exists.

Dispersion

Mechanical dispersion consists of two methods: longitudinal and transverse. Longitudinal dispersion occurs along the direction of flow path, while transverse dispersion occurs normal to the flow path and causes lateral spreading of the contaminant. Mechanical dispersion and diffusion combine in groundwater flow to create hydrodynamic dispersion. The process begins when a contaminant enters the aquifer. Once introduced, the advecting groundwater carries the mass of the contaminant with it, and in the process, the contaminant spreads, thereby decreasing the maximum concentration with time. However, the contaminant is now spread over a much wider area. Ground water behaves in a manner similar to *packed bed* + *PFR* type.

The adsorption of a solute onto the aquifer material (example – clay) results in reduction of concentration in the aqueous phase and a retardation of the velocity of contaminant migration. The degree of retardation experienced by a particular organic contaminant will depend on the f_{OC} of aquifer materials. The higher the f_{OC}, the more sites will be available for adsorption.

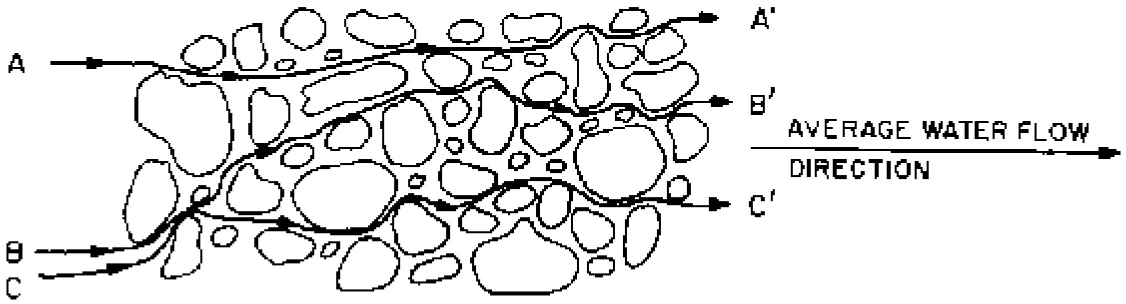


Fig. 8: Process of dispersion in groundwater flow (tortuous flow – flow through pores)

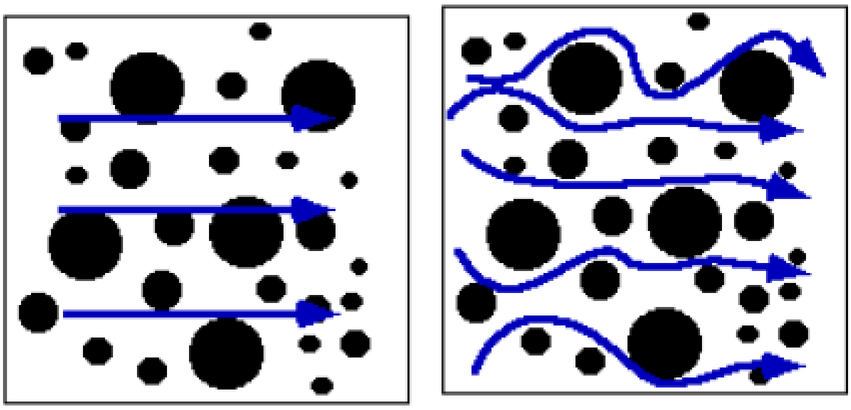


Fig. 9: Comparison between advective and dispersive transport of contaminants through groundwater

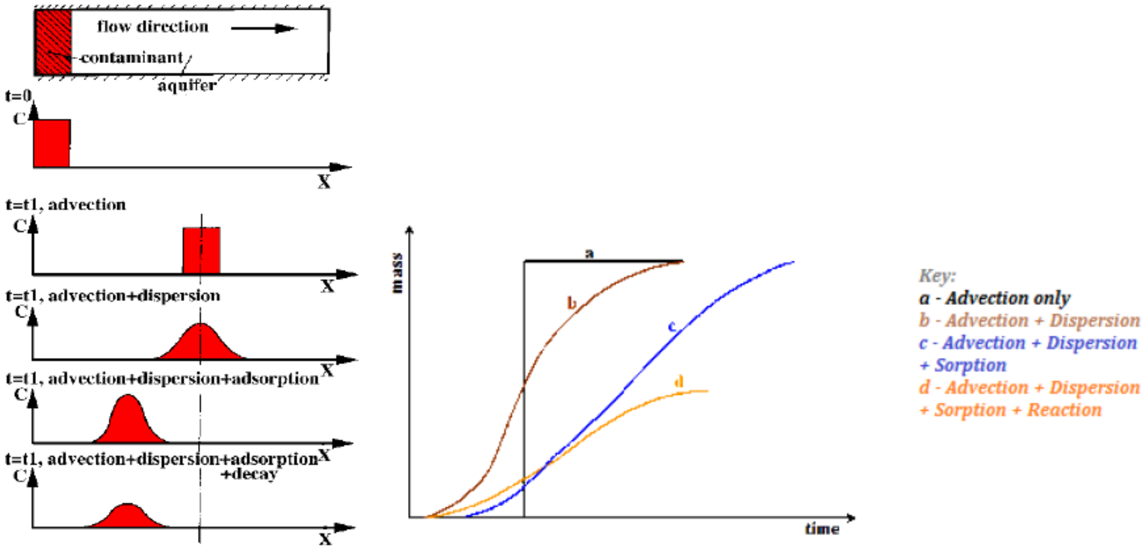


Fig. 10: Graphs showing different modes of contaminant transport

Retardation

Retardation, R is the slowing down of transport of contaminant. It can be denoted by:

$$R = \frac{velocity\ of\ water\ (seepage)}{velocity\ of\ contaminant} = \frac{v_s}{v_c}$$

If R>1, retardation or sorption is occurring.

If R=1, there is no retardation.

Differential equations describing transport of contaminants through groundwater:

Two-dimensional transport equation:

Longitudinal dispersion coefficient

$$\frac{\partial C}{\partial t} = \frac{-v_s}{R}\frac{\partial C}{\partial x} + \frac{D_L}{R}\left(\frac{\partial^2 C}{\partial x^2}\right) + \frac{D_T}{R}\left(\frac{\partial^2 C}{\partial y^2}\right) - KC$$

Reaction

Advection Dispersion Diffusion

$$Velocity\ retarded = \frac{-v_s}{R}$$

One-dimensional transport equation:

$$R\frac{\partial C}{\partial t} = \underset{\underset{\text{Advection}}{\downarrow}}{-v_s\frac{\partial C}{\partial x}} + \underset{\underset{\text{Dispersion}}{\searrow}}{D_L\left(\frac{\partial^2 C}{\partial x^2}\right)} - \underset{\underset{\text{Reaction}}{\downarrow}}{k_1 C}$$

Analytical solution obtained:

$$R = 1 + \frac{\rho_b K_d}{n}$$

Where $\rho_b = bulk\ density\ of\ soil, K_d = sorption\ coefficient, n = porosity$

Pulse model:

Transformation occurs, but there is no sorption:

$$C(x,t) = \frac{Me^{-kt}}{\sqrt{4\pi D_x t}} \exp\left[\frac{-(x - v_x t)^2}{4D_x t}\right]$$

Where $M = mass\ spilled\ over\ a\ cross - sectional\ area\ \left(\frac{g}{m^2}\right)$

With sorption:

$$C(x,t) = \frac{Me^{-k't}}{\sqrt{4\pi D'_x t}} \exp\left[\frac{-(x - v'_x t)^2}{4D'_x t}\right]$$

With retardation:

$$C(x,t) = \frac{M}{\sqrt{4\pi D_x t}} \exp\left[\frac{-(x - v_x t)^2}{4D_x t}\right]$$

Wilson & Miller Equation (2-dimesnional):

$$C(x,t) = \frac{M'}{4\pi nt\sqrt{D'_x D'_y}} \exp\left[\frac{-(x - v'_x t)^2}{4D'_x t} + \frac{-y^2}{4D'_y t}\right]$$

Where $M = mass\ spilled\ over\ unit\ depth\ \left(\frac{g}{m}\right)$

Plume model:

For a continuous source, with sorption:

$$\frac{C(x,t)}{C_o} = \frac{1}{2}\{\exp(A_1).\operatorname{erf}(A_2) + \exp(B_1).\operatorname{erf}(B_2)\}$$

$$A_1 = \frac{x}{2D_x}(v_x - \sqrt{v_x + 4D_x K})$$

$$B_1 = \frac{x}{2D_x}(v_x + \sqrt{v_x + 4D_x K})$$

$$A_2 = \frac{x - t.\sqrt{v_x^2 + 4D_x K}}{2\sqrt{D_x t}}$$

$$B_2 = \frac{x + t.\sqrt{v_x^2 + 4D_xK}}{2\sqrt{D_xt}}$$

If there is retardation: v_x is replaced by $v_x{}'$ where $v_x' = \frac{v_x}{R}$. Similar D_x and K are replaced by $D_x{}'$ and K′.

Also, $\text{erf}(x) = \frac{2}{\pi}\int_0^x dx$ and $\text{erf}(-x) = -\text{erf}(x)$

Darcy’s Law

Darcy’s Law gives an expression for groundwater flow through porous media.

The rate at which groundwater flows is equal to the product of the hydraulic conductivity multiplied by the hydraulic gradient.

$V=KA(G)$, where V is the groundwater velocity, K the hydraulic conductivity (related to porosity and permeability of aquifer), A the cross-sectional area, and G the hydraulic gradient (difference in pressure head divided by distance travelled).

Transport of contaminants through air

Contaminant properties through atmosphere depends on many factors such as plume properties, wind, and atmospheric turbulence.

Advection

The bulk movement of fluid is denoted by flux:

$$J_{adv} = v * C\ (atmosphere)$$

$$J_{adv} = n * v * C(sub\ surface)$$

Where $v = average\ fluic\ velocity, n = porosity, C = concentration\ of\ contaminant$

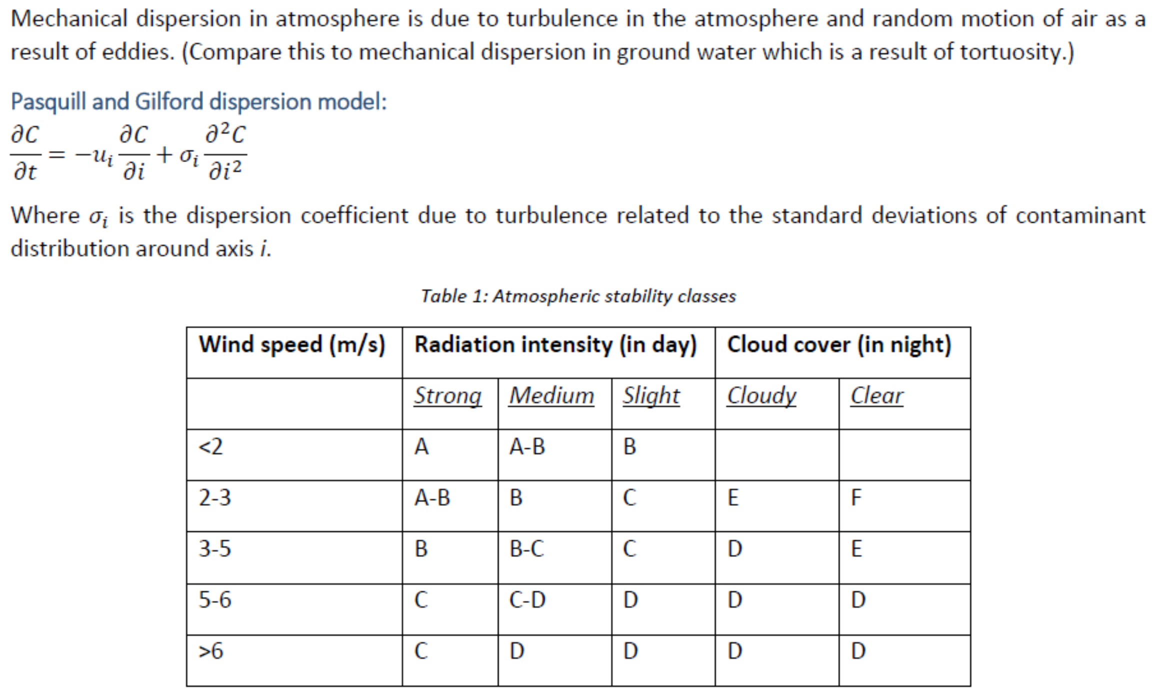
Dispersion

Dispersive flux:

$$J_{disp} = -D\frac{\partial C}{\partial x}\ (atmosphere)$$

$$J_{disp} = -nD\frac{\partial C}{\partial x}\ (sub\ surface)$$

Dispersion coefficient $D = D_{mechanical} + D_{molecular}$



Mechanical dispersion in atmosphere is due to turbulence in the atmosphere and random motion of air as a result of eddies. (Compare this to mechanical dispersion in ground water which is a result of tortuosity.)

Pasquill and Gilford dispersion model:

$$\frac{\partial C}{\partial t} = -u_i \frac{\partial C}{\partial i} + \sigma_i \frac{\partial^2 C}{\partial i^2}$$

Where σ_i is the dispersion coefficient due to turbulence related to the standard deviations of contaminant distribution around axis *i*.

Table 1: Atmospheric stability classes

Wind speed (m/s)	Radiation intensity (in day)			Cloud cover (in night)	
	Strong	Medium	Slight	Cloudy	Clear
<2	A	A-B	B		
2-3	A-B	B	C	E	F
3-5	B	B-C	C	D	E
5-6	C	C-D	D	D	D
>6	C	D	D	D	D

Puff model:

This model is used to describe an instantaneous spill in the atmosphere.

Contaminant concentration at ground level with velocity *u* in the X-direction is given by:

(Assuming concentrations in Y and Z directions are 0)

$$C(x,t) = \frac{Q_m}{\pi u \sigma_y \sigma_z}$$

Ground level concentration with only concentration in Z-direction as 0:

$$C(x,y,t) = \frac{Q_m}{\pi u \sigma_y \sigma_z} \exp\left[-\frac{1}{2}\left(\frac{y^2}{\sigma_y^2}\right)\right]$$

Steady state concentration along all 3 dimensions:

$$C(x,y,z,t) = \frac{Q_m}{\pi u \sigma_y \sigma_z} \exp\left[-\frac{1}{2}\left(\frac{y^2}{\sigma_y^2} + \frac{z^2}{\sigma_z^2}\right)\right]$$

Example 6: A hazardous waste spill site has released 10 kg TCE into the air. If the spill occurred with the sky being mostly overcast and a wind velocity of 7 m/s in the X-direction; determine the concentration of TCE 0.5 downwards.

Solution:

From Table 1, we can see that the stability class in this case is D.

From data sources (for a particular stability class): $\sigma_y = \sigma_x = 42\ m, \sigma_z = 20\ m$

$$Time\ of\ travel = \frac{500m}{7\frac{m}{s}} = 71.43\ s$$

$$C(x,t) = \frac{Q'_m}{\sqrt{2}\pi^{\frac{3}{2}}\sigma_x\sigma_y\sigma_z}\exp\left[-\frac{1}{2}\left(\frac{x-ut}{\sigma_x}\right)^2\right]$$

$$C(500{,}71.43) = \frac{\left(10\ kg * 10^6\frac{mg}{kg}\right)}{1.414 * 5.56 * 42 * 42 * 20} * \exp\left[-\frac{1}{2}.\frac{(500-7*71.43)^2}{42^2}\right] = 36\frac{mg}{m^3}$$

Health Effects of Hazardous Waste

A hazardous waste can have adverse health effects in any of the following scenarios:

☐ A large amount is released at once

☐ A small amount if released intermittently in the same location

☐ The substance does not get diluted

☐ The substance is very toxic

Humans, plants and animals can come into contact with hazardous waste by either inhalation, ingestion, or dermal exposure.

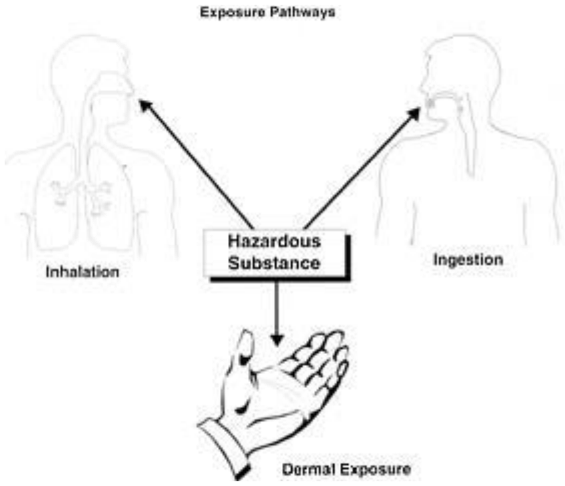


Fig. 12: Exposure pathways

Exposure can be acute or chronic.

Table 2: Different types of exposure to hazardous waste

Acute exposure	**Chronic exposure**
Single exposure for short time period	Repeated exposure over long periods of time
E.g. burn on your finger from an acid	E.g. leaking dumpsite which results in contaminated groundwater (health effects include cancer, liver and kidney failure, slow physical and mental development)