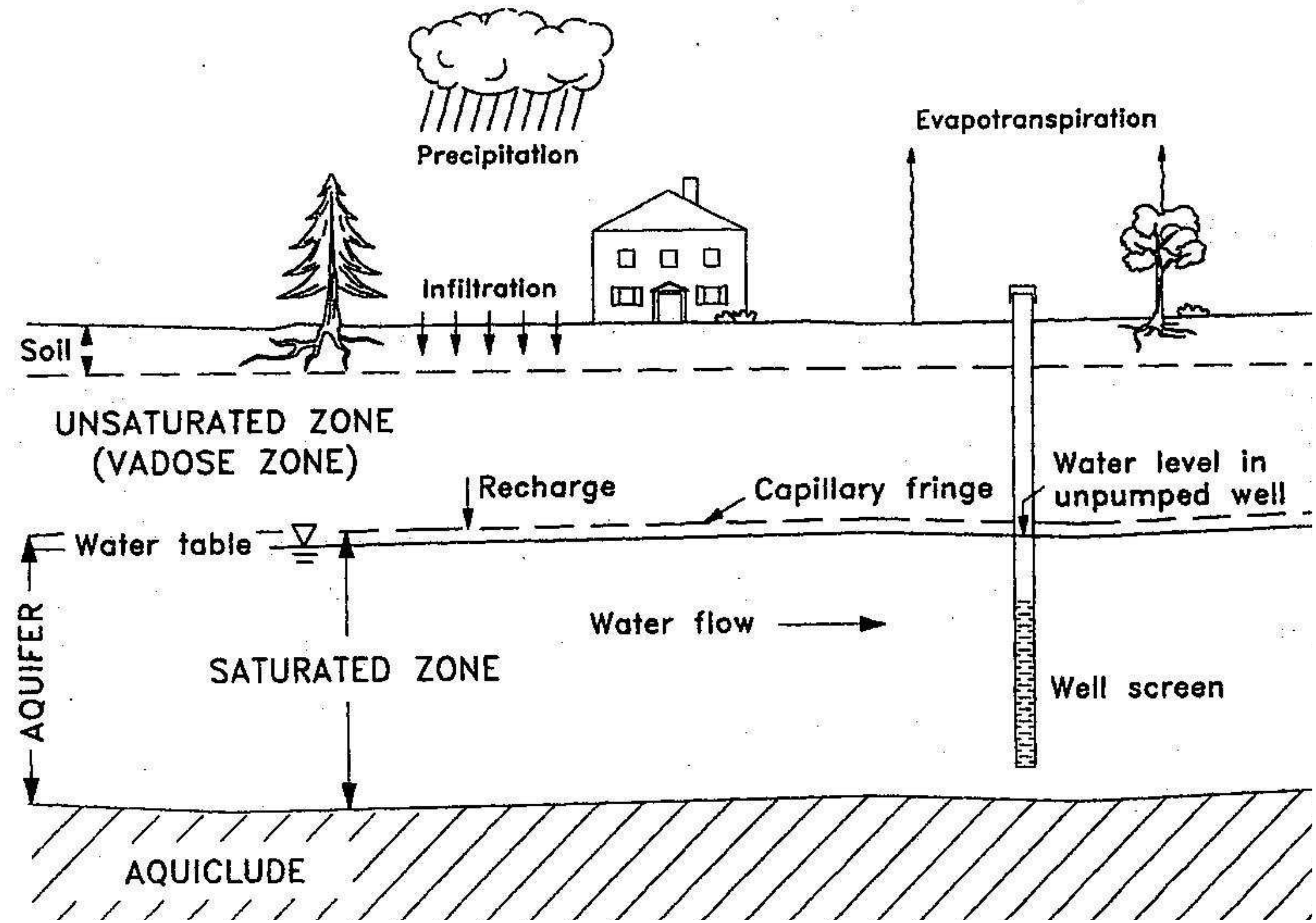
CE 435 (January 2018 Semester)

Environmental Pollution and Management:
Water Pollution

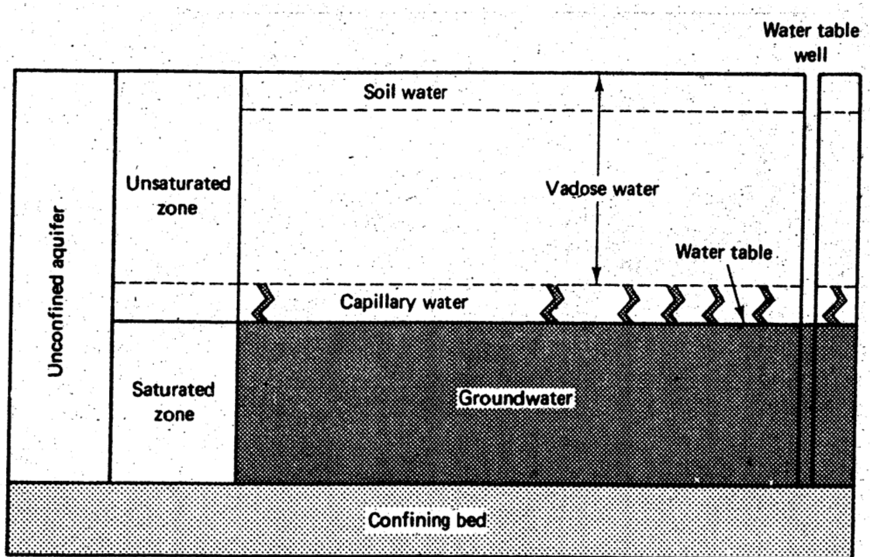
CN-5: Groundwater Pollution

Dr. M. Ashraf Ali
Professor of Civil Engineering, BUET

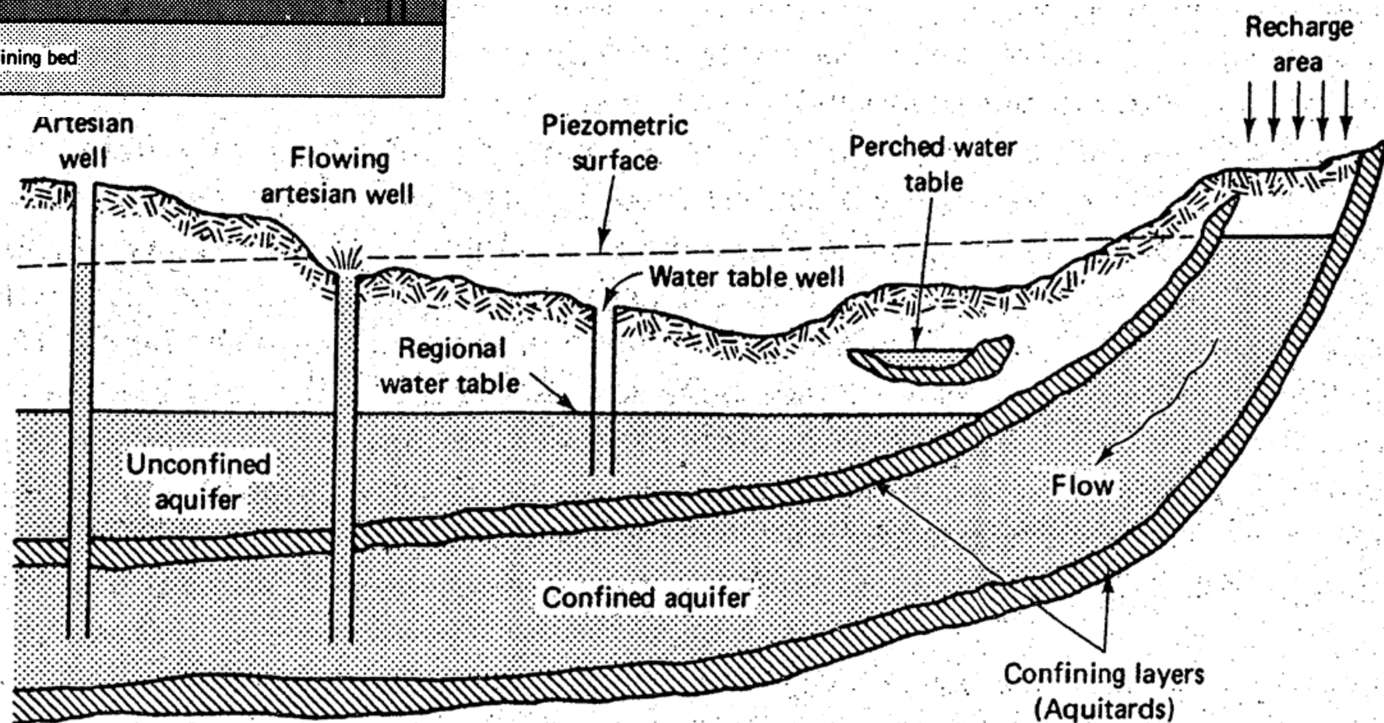
The Subsurface Environment



Aquifers



Water table well
Soil water
Unsaturated zone
Vadose water
Water table
Capillary water
Unconfined aquifer
Saturated zone
Groundwater
Confining bed



Recharge area
Artesian well
Flowing artesian well
Piezometric surface
Perched water table
Water table well
Regional water table
Unconfined aquifer
Flow
Confined aquifer
Confining layers (Aquitards)

Sources of Groundwater Contamination

-1) Land disposal of solid waste

-2) sewage disposal on land

-3) Land disposal of Chemical & Radioactive wastes

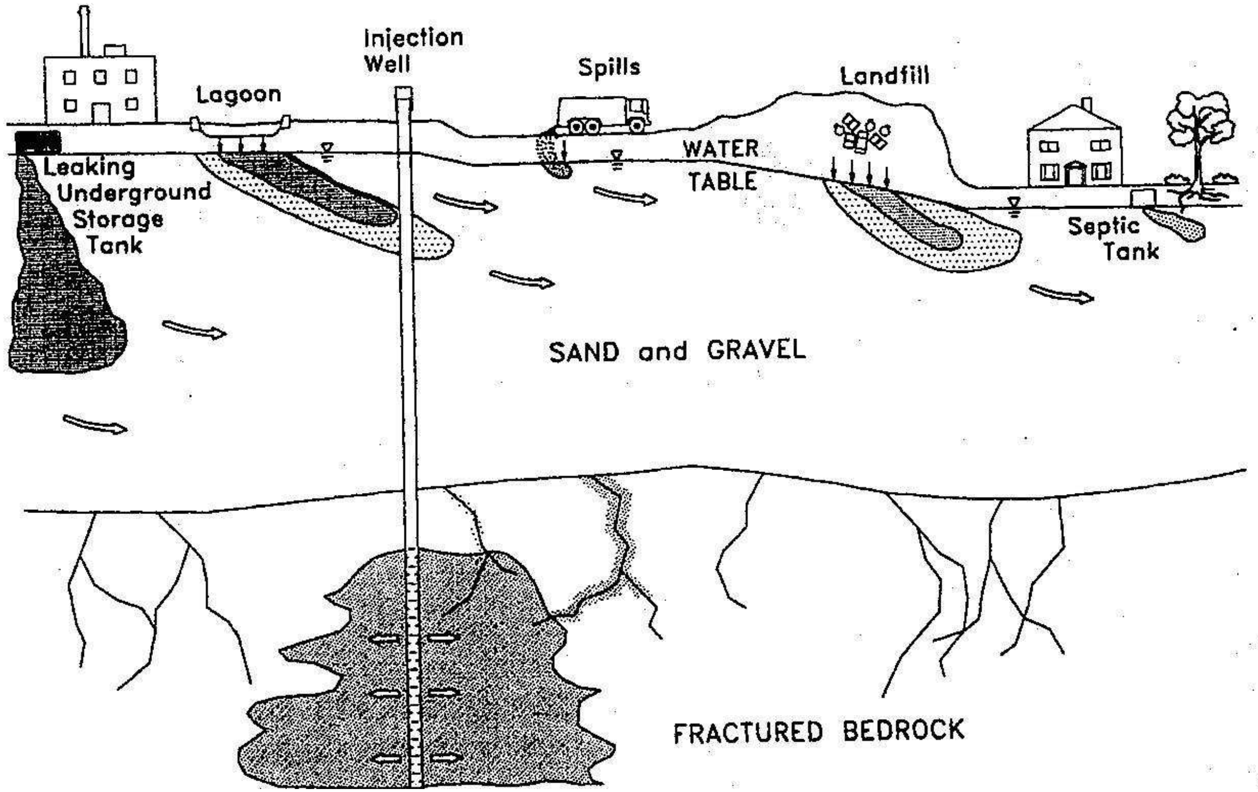
-4) mining operations, seepage from industrial waste lagoons

-5) Petroleum leakage and spills

-6) Agricultural activities.

-7) Natural sources (e.g., As in groundwater of Bangladesh).

Contamination Pathways and Sources



- Disposal of chemicals by burying them in drums or ponding them in lagoons
- Leaking underground storage tanks (NAPLs, DNAPLs)
- Septic tanks (non-industrial pollutants e.g. pathogens, N and P)
- Leakage of injection wells that were used to inject chemical wastes
- Agriculture

Transport processes of solutes in a porous media

Two important processes:

- ❑ **Advection, and**
- ❑ **Dispersion/ Hydrodynamic dispersion**

Advection: movement of solutes with bulk groundwater with velocity $\bar{v}$ (= avg. linear velocity or seepage velocity).

$$v = ki$$

$$Q = kiA$$

$$\bar{v} = \frac{kiA}{nA} = \frac{v}{n}.$$

K = Hydraulic conductivity

i = Hydraulic gradient $\left(\frac{dh}{dl}\right)$

n = porosity

Transport processes of solutes in a porous media …..

Dispersion / Hydrodynamic Dispersion:

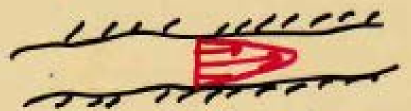
By this process, we can have solute proceed or fall behind the bulk phase.

Results from:

- molecular diffusion (Fick's law)
- mechanical mixing

mechanical mixing results from:

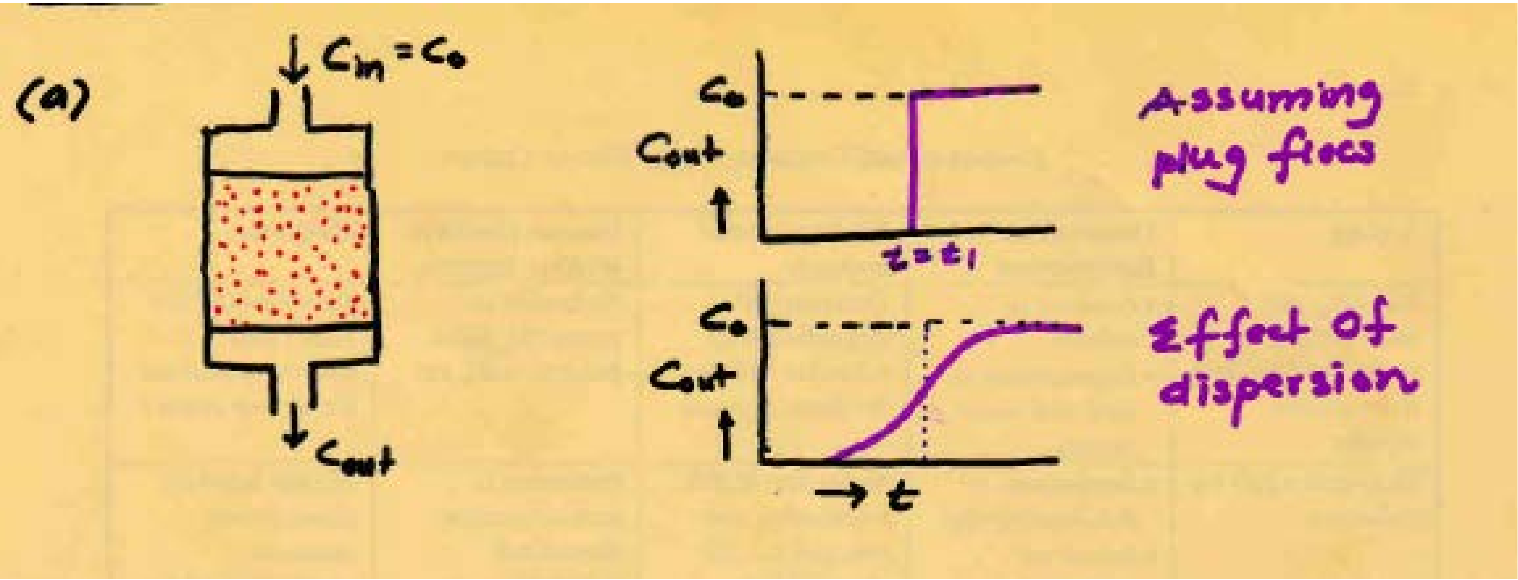
(i) Velocity variation within pore



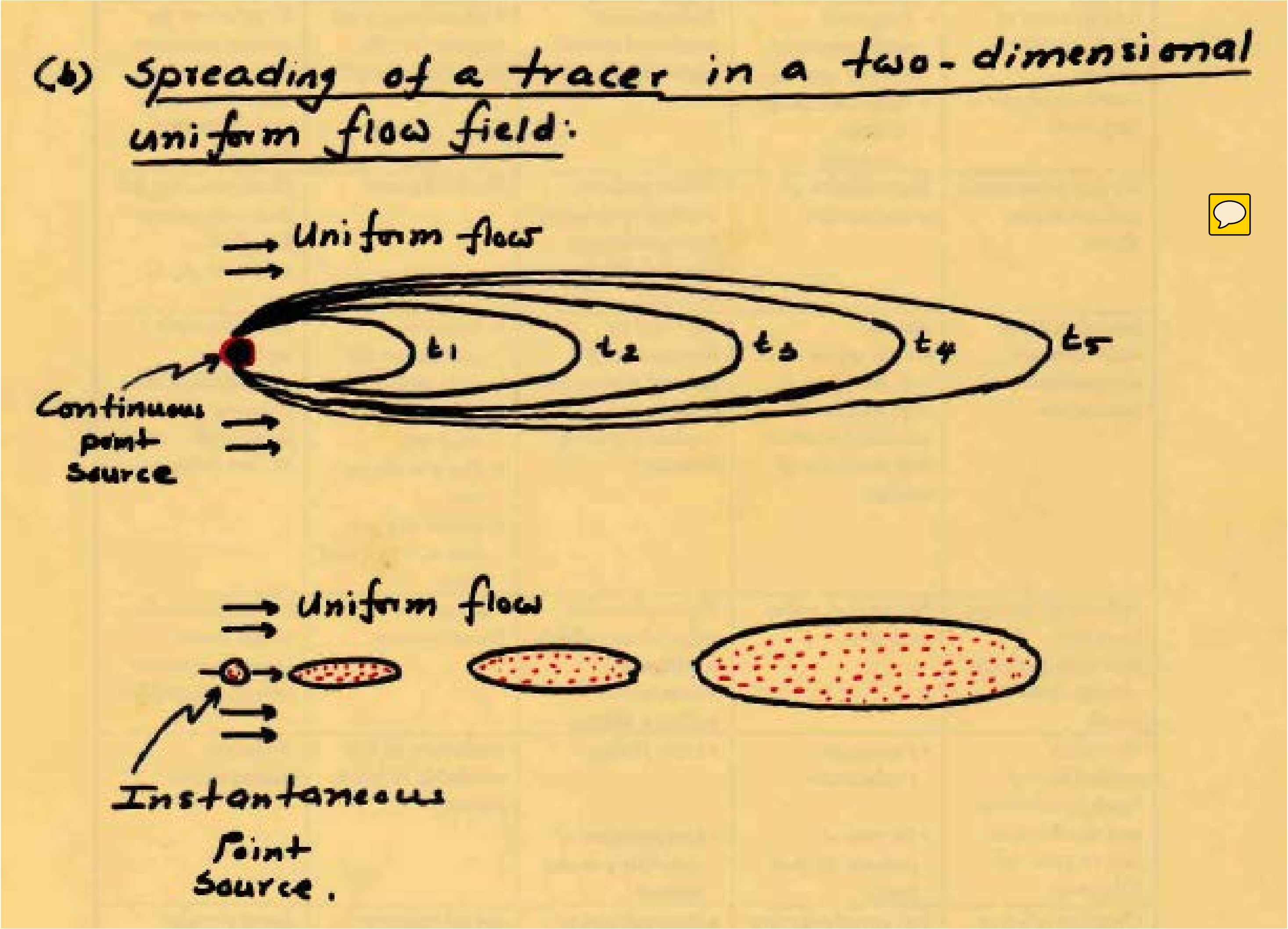
(ii) Velocity variation among pores (due to different sizes, shapes & orientation of pores).

(iii) Tortuosity:

Effect of dispersion



Effect of dispersion ……..



Hydrodynamic dispersion

Thus, Hydrodynamic dispersion = Mechanical mixing + Molecular diffusion

$$\therefore \quad D = \alpha \cdot \bar{v} + D^*$$

where, D = coefficient of hydrodynamic dispersion $[L^2/T]$

D^* = coefficient of molecular diffusion $[L^2/T]$

α = dispersivity $[L]$

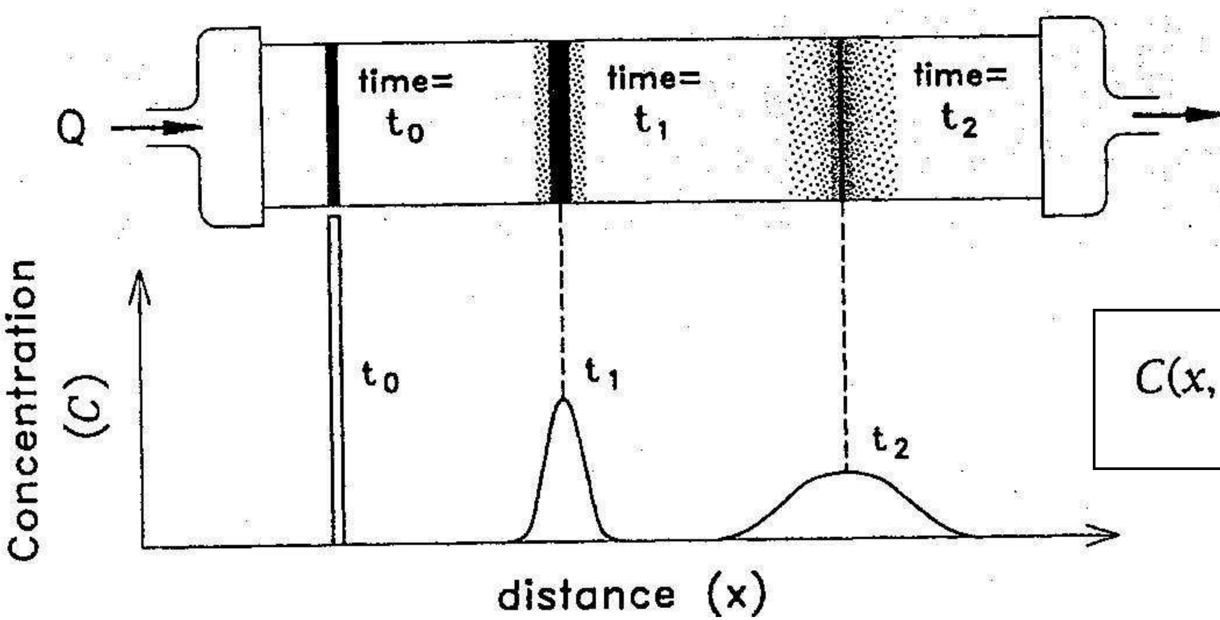
The term $\alpha \cdot \bar{v}$ (i.e., mechanical mixing) dominate at moderate to high velocities; while D^* (i.e., molecular diffusion) dominate at low velocities (e.g., in clay layer).

Hydrodynamic dispersion …..

Hydrodynamic dispersion in the direction of bulk flow is called "Longitudinal dispersion" (given by D_L); dispersion ⊥ to bulk flow is called "transverse dispersion" (given by D_T).

Usually $D_L \gg D_T$.

1-D Dispersion of a pulse tracer in a Column



$$C(x, t) = \frac{M}{n\sqrt{4\pi D_L t}} e^{-(x-vt)^2/(4D_L t)},$$

Concentration at the center of mass when the center of mass is at a distance *x* from the origin (only applicable when longitudinal dispersion dominates the transport coefficient):

$$C(x) = \frac{M}{n\sqrt{4\pi\alpha x}}.$$

Problem: 1-D Dispersion

A column experiment is set up in the laboratory. Sand with a mean grain size of approx 0.5 mm is packed (porosity 0.3) into a cylindrical column, 1.5 m in length and 10 cm in dia. Water flows through the column with a seepage velocity of 1 m/hr. 5 mg of salt are injected into the column (pulse injection)

a. What will be the concentration of salt after an hour at a distance 0.9 m down the column?
b. When the tracer mass is centered 1.3 m down the column, what is the concentration of tracer at this location?

Solute Transport in Saturated Homogenous Porous Media: Continuous Source

The principal differential equation that describes transport of dissolved constituents in porous media is called "advection-dispersion equation".

1-D advection-dispersion equation (steady-state groundwater flow) for non-reactive (conservative) solutes is given by:

$$\frac{\partial c}{\partial t} = D_x \frac{\partial^2 c}{\partial x^2} - \bar{v}_x \cdot \frac{\partial c}{\partial x} \quad \text{——— (1)}$$

2-D advection-dispersion equation with flow aligned with x-axis (i.e., $\bar{v}_y = \bar{v}_z = 0$):

$$\frac{\partial c}{\partial t} = D_x \frac{\partial^2 c}{\partial x^2} + D_y \frac{\partial^2 c}{\partial y^2} - \bar{v}_x \frac{\partial c}{\partial x} \quad \text{——— (2)}$$

Solute Transport in Saturated Homogenous Porous Media: Continuous Source ....

Solution to Eq. 1 :

For continuous point source :

$$c(x,0) = 0 \; ; \; x \geq 0$$

$$c(0,t) = C_0 \; ; \; t \geq 0$$

$$c(\infty,t) = 0 \; ; \; t \geq 0$$

$$\frac{C}{C_0} = \frac{1}{2}\left[\mathrm{erfc}\left(\frac{x - \bar{v}_x t}{2\sqrt{D_x t}}\right) + \exp\left(\frac{\bar{v}_x \cdot x}{D_x}\right) \cdot \mathrm{erfc}\left(\frac{x + \bar{v}_x \cdot t}{2\sqrt{D_x t}}\right)\right] \quad \text{—— (3)}$$

where, erfc = complementary error function.

and $D_x = \alpha \cdot \bar{v}_x + D^{*}$

Solute Transport in Saturated Homogenous Porous Media: Continuous Source ……….

For low velocities, when $\bar{v}_x \simeq 0$ (e.g., in clay layer), Eq. (3) becomes.

$$\boxed{\frac{C}{C_0} \approx \operatorname{erfc}\left(\frac{x}{2\sqrt{D^* t}}\right)} \quad \text{——} \quad (4)$$

For large t (i.e., for very long time) or when velocity is large.

$$\boxed{\frac{C}{C_0} \approx \frac{1}{2}\operatorname{erfc}\left(\frac{x - \bar{v}_x \cdot t}{2\sqrt{D_x t}}\right)} \quad \text{——} \quad (5)$$

Complementary Error Function Table

TABLE 3-4 The Complementary Error Function[a]

x	erfc(x)	x	erfc(x)
0	1.0		
0.05	0.943628	1.1	0.119795
0.1	0.887537	1.2	0.089686
0.15	0.832004	1.3	0.065992
0.2	0.777297	1.4	0.047715
0.25	0.723674	1.5	0.033895
0.3	0.671373	1.6	0.023652
0.35	0.620618	1.7	0.016210
0.4	0.571608	1.8	0.010909
0.45	0.524518	1.9	0.007210
0.5	0.479500	2.0	0.004678
0.55	0.436677	2.1	0.002979
0.6	0.396144	2.2	0.001863
0.65	0.357971	2.3	0.001143
0.7	0.322199	2.4	0.000689
0.75	0.288844	2.5	0.000407
0.8	0.257899	2.6	0.000236
0.85	0.229332	2.7	0.000134
0.9	0.203092	2.8	0.000075
0.95	0.179109	2.9	0.000041
1.0	0.157299	3.0	0.000022

$$\mathrm{erfc}(x) = 1 - (2/\sqrt{\pi})\int_0^x e^{-\epsilon^2}d\epsilon$$

$$\mathrm{erfc}(-x) = 2 - \mathrm{erfc}(x)$$

[a] Adapted from Freeze and Cherry (1979).

$$\mathrm{erfc}(x) = 1 - \frac{2}{\sqrt{\pi}}\sum_{n=0}^{\infty}\frac{(-1)^n x^{2n+1}}{n!(2n+1)}.$$

$$\mathrm{erf}\,(\beta) = \frac{2}{\sqrt{\mu}}\int_0^{\beta} e^{-\epsilon^2}\,d\epsilon$$

$$\mathrm{erf}\,(-\beta) = -\mathrm{erf}\,\beta$$

$$\mathrm{erfc}\,(\beta) = 1 - \mathrm{erf}\,(\beta)$$

Table (approximate) for erf(x) and erfc(x)

x	erf(x)	erfc(x)
0	0.000	1.000
0.1	0.112	0.888
0.2	0.223	0.777
0.3	0.329	0.671
0.4	0.428	0.572
0.5	0.520	0.480
0.6	0.604	0.396
0.7	0.678	0.322
0.8	0.742	0.258
0.9	0.797	0.203
1	0.843	0.157
1.1	0.880	0.120
1.2	0.910	0.090

x	erf(x)	erfc(x)
1.3	0.934	0.066
1.4	0.952	0.048
1.5	0.966	0.034
1.6	0.976	0.024
1.7	0.984	0.016
1.8	0.989	0.011
1.9	0.993	0.007
2	0.995	0.005
2.1	0.997	0.003
2.2	0.998	0.002
2.3	0.999	0.001
2.4	0.999	0.001
2.5	1.000	0.000

Solute Transport in Saturated Homogenous Porous Media: Continuous Source …………

These solutions are useful for interpreting laboratory column experiments and solute transport under simplified condition.

For analysis of field problems where dispersion occurs in both longitudinal & transverse directions, solution of 2-D advection-dispersion equation are available in the literature. However, for such situations, numerical solutions are most widely used (using finite difference or finite element method).

Advective-Dispersive Transport with Chemical Reaction:

Important reactions include:

- 1) Adsorption/Ion exchange
- 2) Gas-water exchange (near surface)
- 3) Precipitation-dissolution
- 4) Oxidation-reduction
- 5) Biochemical reaction
- 6) Radioactive decay

Advective-Dispersive Transport with Chemical Reaction: 1-D Transport with Adsorption

Many organic and inorganic (e.g., heavy metals) solutes have strong affinity for soil and partition to the soil from aqueous phase. This is a reversible process.

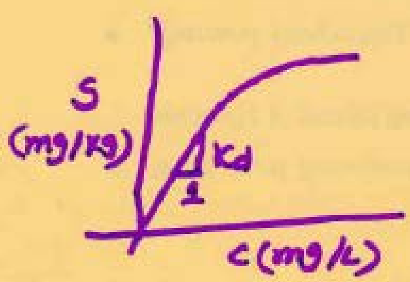
Adsorption/Sorption: attachment of solute

Desorption: detachment/release of solute

If c = dissolved (aqueous) conc. of solute

S = adsorbed conc.

Then, the relationship between S and c can often be expressed as follows:



at low concentration (c) of solute,

$$\frac{dS}{dc} = K_d = \text{distribution coefficient.}$$

Advective-Dispersive Transport with Chemical Reaction: 1-D Transport with Adsorption ……..

For homogeneous saturated porous media, with steady-state flow, the 1-D advection dispersion equation that includes the influence of adsorption-desorption is:

$$\frac{\partial c}{\partial t} = D_x \frac{\partial^2 c}{\partial x^2} - \bar{v}_x \frac{\partial c}{\partial x} + \frac{\rho_b}{n} \cdot \frac{\partial S}{\partial t} \quad \text{——— (c)}$$

where, ρ_b = bulk mass density of porous media

n = porosity

S = mass of chemical constituent adsorbed on solid mass of porous media per unit mass of solid.

$\frac{\partial S}{\partial t}$ = rate at which the constituent is adsorbed.

$\left[\frac{\rho_b}{n} \cdot \frac{\partial S}{\partial t}\right]$ represents the change in concentration in the fluid caused by adsorption-desorption

Advective-Dispersive Transport with Chemical Reaction: 1-D Transport with Adsorption ……..

now, $-\frac{\partial S}{\partial t} = \frac{\partial S}{\partial C} \cdot \frac{\partial C}{\partial t}$.

$\therefore -\frac{\rho_b}{n} \cdot \frac{\partial S}{\partial t} = \frac{\rho_b}{n} \cdot \frac{\partial S}{\partial C} \cdot \frac{\partial C}{\partial t}$.

$= \frac{\rho_b}{n} \cdot K_d \cdot \frac{\partial C}{\partial t}$.

$\therefore$ Eq. (6) becomes,

$$\frac{\partial C}{\partial t}\left(1 + \frac{\rho_b}{n} \cdot K_d\right) = D_x \cdot \frac{\partial^2 C}{\partial x^2} - \bar{v}_x \cdot \frac{\partial C}{\partial x} \quad \text{—(7)}$$

$$\Rightarrow \quad \frac{\partial C}{\partial t} \cdot R = D_x \cdot \frac{\partial^2 C}{\partial x^2} - \bar{v}_x \cdot \frac{\partial C}{\partial x} \quad \text{———(8)}$$

where, $R = \left(1 + \frac{\rho_b}{n} \cdot K_d\right)$ = Retardation factor

Advective-Dispersive Transport with Chemical Reaction: 1-D Transport with Adsorption ……..

$$\therefore \frac{\partial c}{\partial t} = \frac{D_x}{R} \cdot \frac{\partial^2 c}{\partial x^2} - \frac{\bar{v}_x}{R} \cdot \frac{\partial c}{\partial x}$$

$$\frac{\partial c}{\partial t} = D_x' \cdot \frac{\partial^2 c}{\partial x^2} - \bar{v}_x' \cdot \frac{\partial c}{\partial x} \quad \text{——— (9)}$$

Eq. (9) is same as Eq (1) except here

$$D_x' = \frac{D_x}{R} \text{ and } \bar{v}_x' = \frac{\bar{v}_x}{R}.$$

Solution to Eq. (9) is therefore the same as solution to Eq. (1); that is Eqs (3), (4). & (5) ~~are~~ can be used as solutions to Eq. (9) by replacing D_x by D_x' and $\bar{v}_x$ by $\bar{v}_x'$.

Advective-Dispersive Transport with Chemical Reaction: 1-D Transport with Adsorption ……..

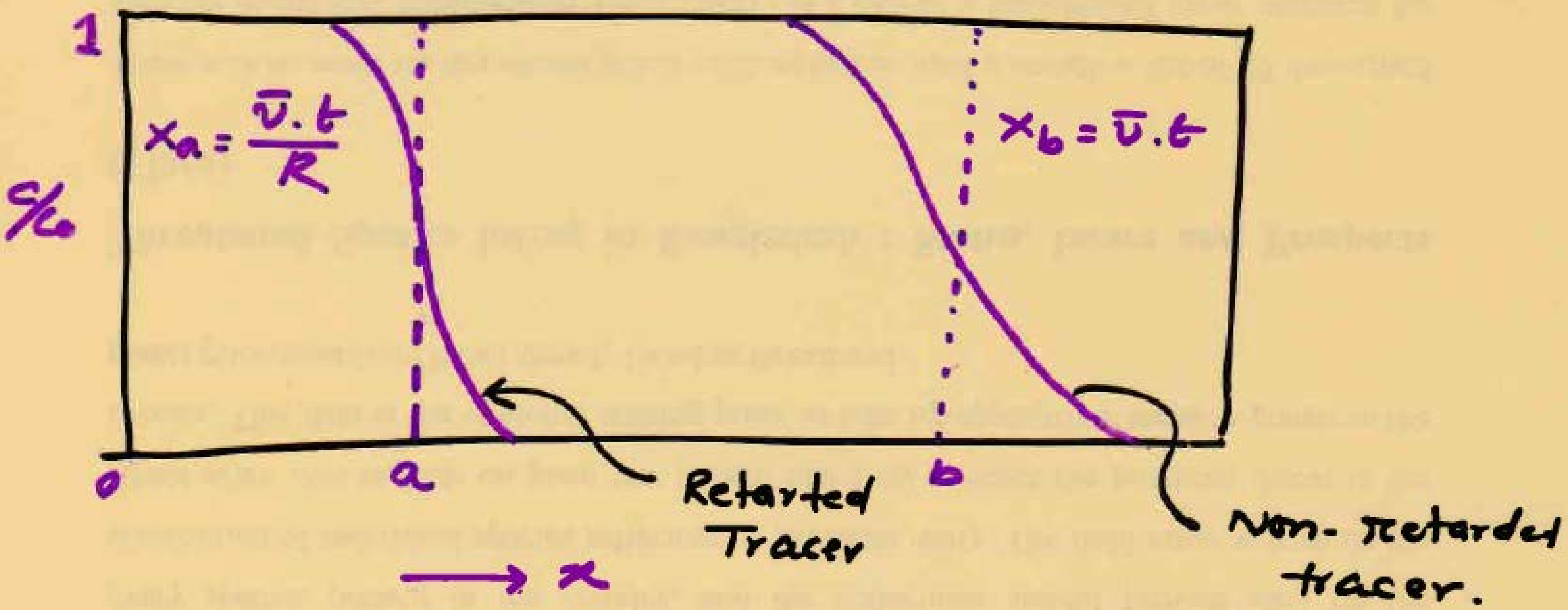


Fig. Advance of adsorbed and non-adsorbed solutes through a column of porous materials.

Retardation of Solutes due to Adsorption

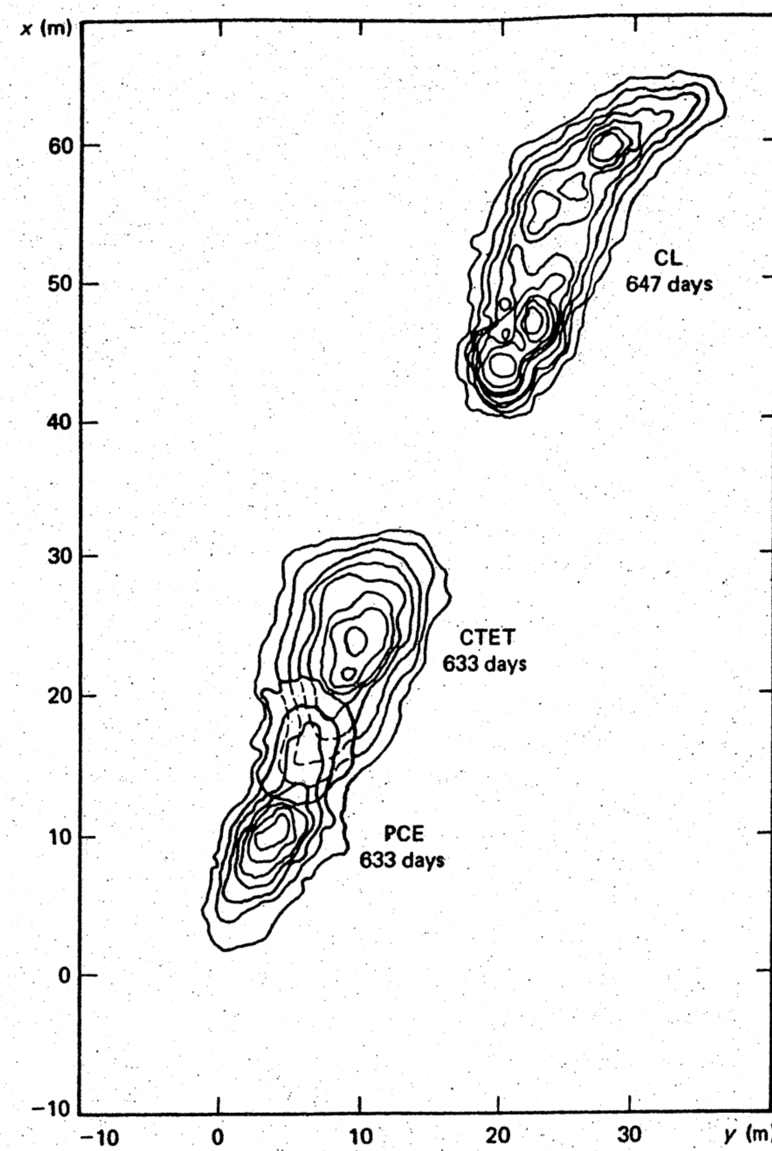
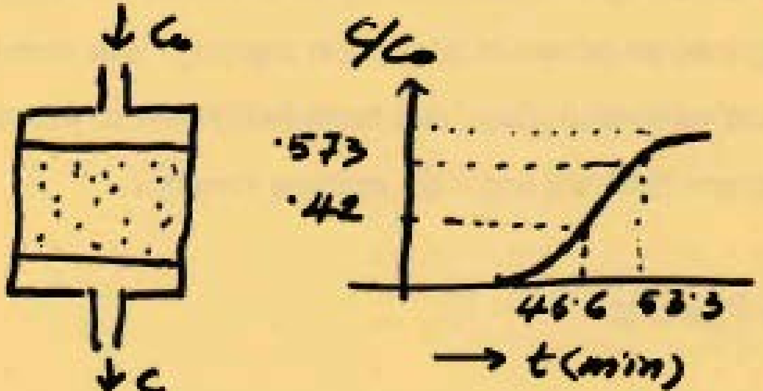


Figure 4.24 Plume separation for chloride (CL), carbon tetrachloride (CTET), and tetrachloroethylene (PCE) 21 months after injection into an actual aquifer. (*Source:* Roberts, Goltz, and Mackay, 1986. "A Natural Gradient Experiment on Solute Transport in a Sand Aquifier, 3, Retardation Estimates and Mass Balances for Organic Solutes." *Water Resources Research* 22(13):2047–2058, © by the American Geophysical Union.)

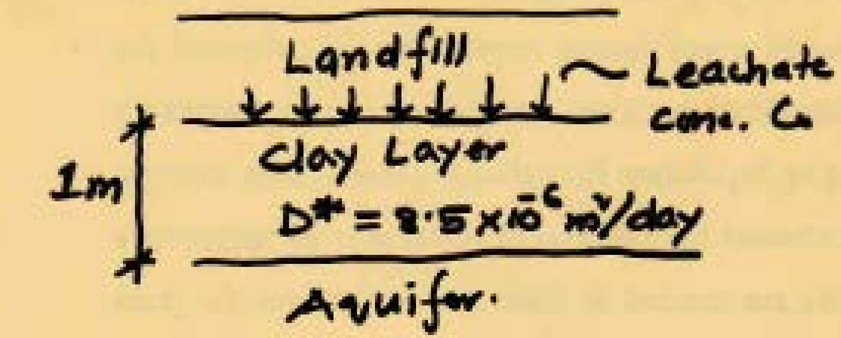
Problems

Ex. 1 A non-reactive (conservative) solute is sent through a column (filled with relatively homogeneous sand) 30 cm in length at a velocity of 1×10^{-2} cm/s. The $C/C_0 = 0.42$ point arrived after 46.6 minutes; the $C/C_0 = 0.573$ point arrived after 53.3 minutes. Estimate dispersivity of sand (neglect molecular diffusion).



Problems

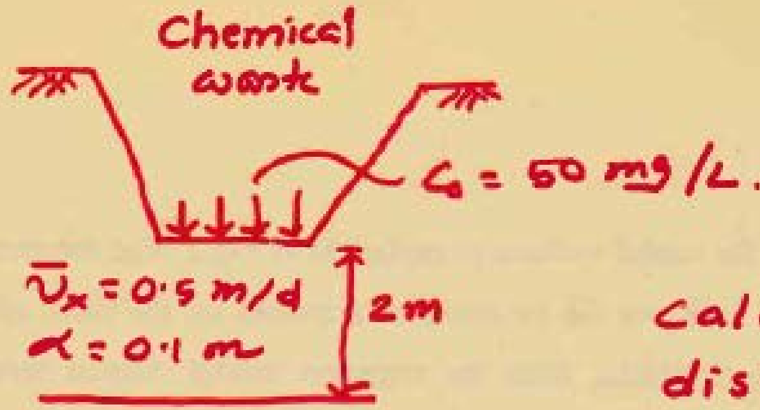
Ex. 2



Estimate the time when contaminant concentration in the aquifer will be 20% of that in the landfill.

Problems

Ex. 3



calculate conc. at a distance 2m from the bottom of the waste pond after 3 days assuming vertical 1-D transport. (assume conservate contaminont and neglect molecular diffusion).