Water quality II

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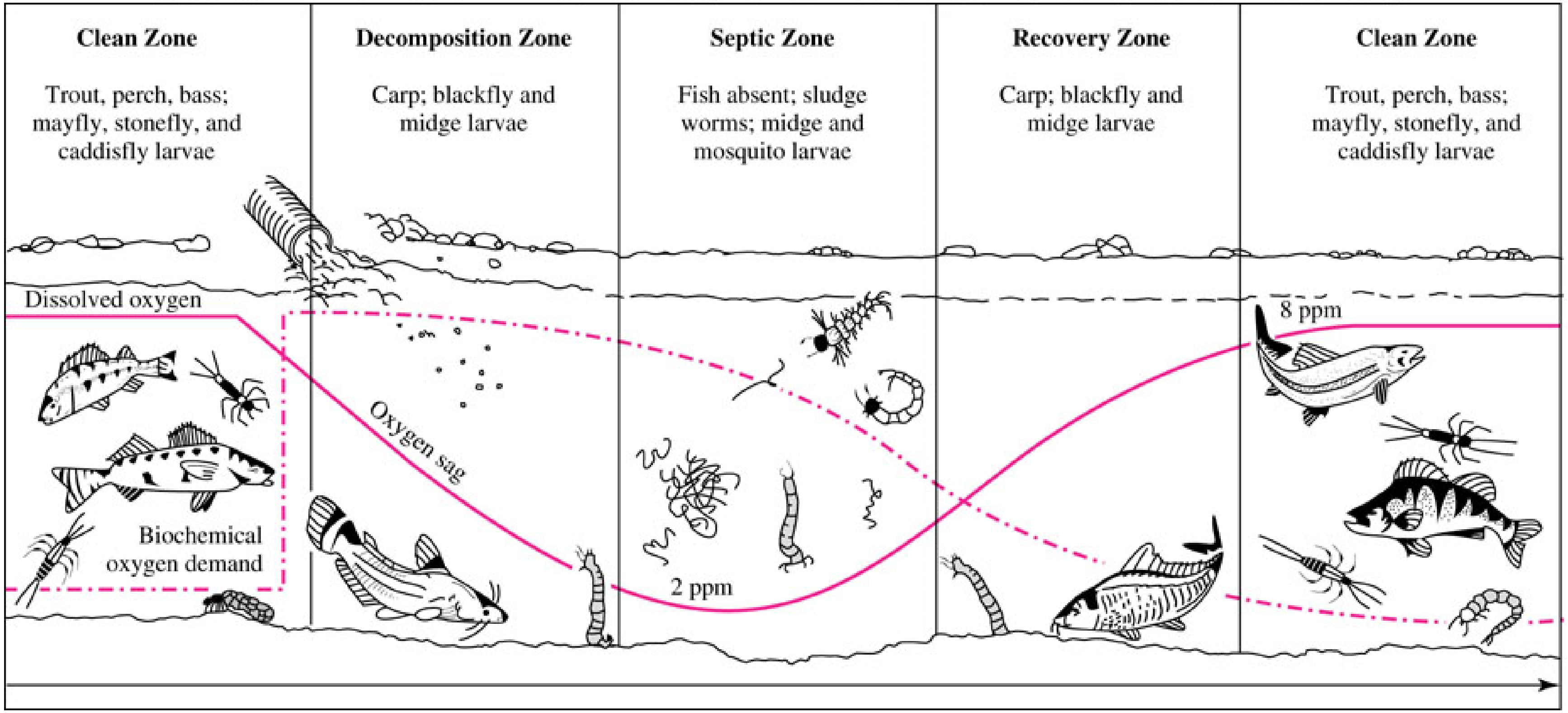
- DO dynamics in river
  - DO sag curve
  - Modeling DO in a river
  - Solution: Streeter-Phelps equation

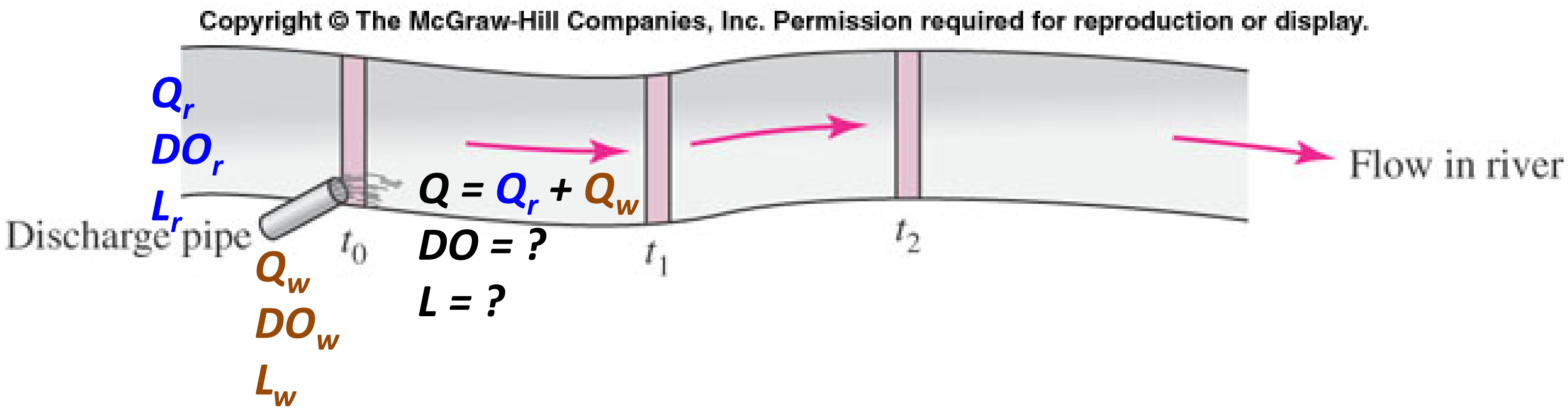
- Groundwater quality
  - Contamination issues
  - Contaminant transport mechanisms

Water quality in rivers: DO sag curve



- Factors causing DO depletion: BOD in water (upstream + waste)
- Factors causing DO increase: reaeration from the atmosphere (+ photosynthesis – neglected)

Modeling the DO along a river

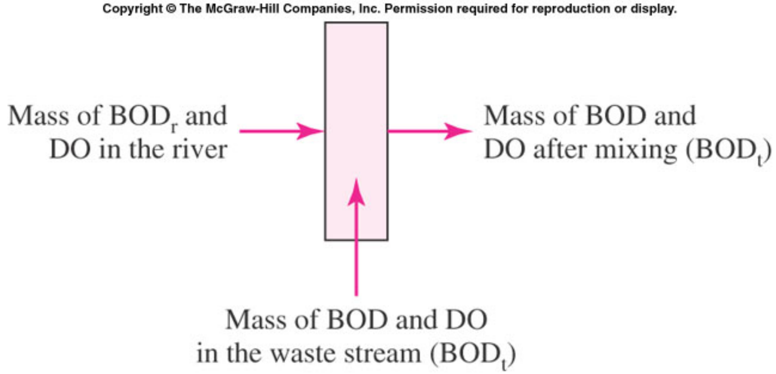


We will model the DO of a river receiving waste at time t_0. The river will be modeled as a PFR.

* The solution for this problem is known as "Streeter-Phelps equation", a well-known equation derived by Streeter and Phelps in 1925.

DO modeling: initial conditions

The DO and ultimate BOD at t_0 are calculated by a mass balance approach:



$$(Q_w + Q_r)DO_a = Q_w DO_w + Q_r DO_r$$

$$(Q_w + Q_r)L_a = Q_w L_w + Q_r L_r$$

DO_a = DO concentration right after mixing (mg/L)

L_a = ultimate BOD right after mixing (mg/L)

$$DO_a = \frac{Q_w DO_w + Q_r DO_r}{Q_w + Q_r} \qquad L_a = \frac{Q_w L_w + Q_r L_r}{Q_w + Q_r}$$

DO modeling: initial conditions (cont'd)

The temperature after mixing is calculated in the same way:

$$T_a = \frac{Q_w T_w + Q_r T_r}{Q_w + Q_r}$$

T_a = temperature after mixing (℃ or K)

T_w = temperature of the waste stream (℃ or K)

T_r = temperature of the river before mixing(℃ or K)

Oxygen deficit

- Oxygen deficit (*D*): the difference between the saturation DO value and the actual DO concentration

$$D = DO_s - DO$$

Therefore, the oxygen deficit right after mixing is calculated as:

$$D_a = DO_s - \frac{Q_w DO_w + Q_r DO_r}{Q_w + Q_r}$$

D_a = oxygen deficit right after mixing (mg/L)

Rate of reaeration, k_r

- Should depend on the stream velocity and depth
- The reaeration coefficient, k_r [day^{-1}]

$$k_r = \frac{3.9u^{1/2}}{h^{3/2}}$$

u = average stream velocity (m/s)

h = average stream depth (m)

- Rate of reaeration should also depend on oxygen deficit

$$Rate\ of\ reaeration = \left.\frac{d(DO)}{dt}\right|_{reaeration} = -\left.\frac{dD}{dt}\right|_{reaeration} = k_r D$$

- Effect of temperature on k_r: faster mass transfer at higher temp.

$$k_{r,T} = k_{r,20}\theta^{T-20}$$

$k_{r,T}$ = reaeration coefficient at temperature T (day^{-1})

$k_{r,20}$ = reaeration coefficient at 20℃, obtained from

$k_{r,20} = 3.9u^{1/2}/h^{3/2}$ (day^{-1})

θ = temperature coefficient (use 1.024)

Rate of deoxygenation, k_d

- Rate of oxygen consumption by microorganisms
- Assume that the first-order deoxygenation rate constant is equal to the BOD rate constant, *k*
- The assumption is valid for deep, slow-moving streams
- The rate of deoxygenation

$$Rate\ of\ deoxygenation = -\left.\frac{d(DO)}{dt}\right|_{deoxygenation} = \left.\frac{dD}{dt}\right|_{deoxygenation}$$
$$= k_d L$$

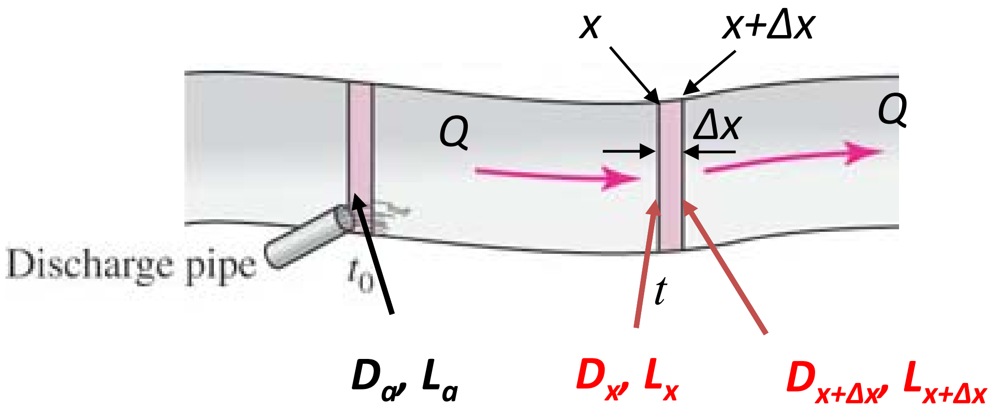
k_d = first-order deoxygenation rate constant [T^{-1}]

- Effect of temperature on k_d: use the equation for *k*!

$$k_T = k_{20}\theta^{T-20}$$

θ = 1.135 for 4-20 ℃ & 1.056 for 20-30 ℃

DO modeling: applying mass balance approach



Steady-state *D* (=DO_s-*DO*) balance for a thin plate at time *t* :

$$0 = QD_x - QD_{x+\Delta x} + k_d L_x \cdot \Delta V - k_r D_x \cdot \Delta V$$

ΔV = volume of the CV = A·Δx

(A = cross-sectional area)

With rearrangements and *Δx* → 0, we obtain:

$$\frac{dD}{dt} = k_d L - k_r D$$

DO modeling: governing eq. & solution

Governing equation:

$$\frac{dD}{dt} = k_d L - k_r D$$

+ Initial conditions:

at t=0, $D=D_a$ and $L=L_a$

Solution:

$$D_t = \frac{k_d L_a}{k_r - k_d}\left(e^{-k_d t} - e^{-k_r t}\right) + D_a\left(e^{-k_r t}\right)$$

D_t = oxygen deficit in a river after flowing downstream from the mixing point for time t

(Note $DO_t = DO_s - D_t$)

Critical point

- Critical point: the point where the DO is the lowest on the DO sag curve

$$t_c = \frac{1}{k_r - k_d} ln\left[\frac{k_r}{k_d}\left(1 - D_a \frac{k_r - k_d}{k_d L_a}\right)\right]$$

t_c = the time to the critical point [T]

- The critical deficit, D_c

$$D_c = \frac{k_d L_a}{k_r - k_d}\left(e^{-k_d t_c} - e^{-k_r t_c}\right) + D_a\left(e^{-k_r t_c}\right)$$

Modeling DO along a river

Q: A city disposes of 1.05 m^3/s of treated sewage having ultimate BOD of 28.0 mg/L and DO of 1.8 mg/L into a river. At the upstream from the outfall, the river flowrate is 7.08 m^3/s, and the ultimate BOD and DO of the river are 3.6 and 7.6 mg/L, respectively. At the river temperature, the saturation value of DO is 8.5 mg/L, the deoxygenation coefficient, k_d, 0.61 day^{-1}, and the reaeration coefficient, k_r 0.76 day^{-1}. The velocity of the river downstream from the outfall is 0.37 m/s.

1) Calculate the ultimate BOD and DO just downstream from the outfall. Assume complete mixing.
2) Calculate the DO 16 km downstream from the outfall.
3) Calculate the critical time, distance, and the minimum DO.

Groundwater quality

- Contamination of groundwater (aquifer) can result from:
  - Discharge from improperly operated or located septic systems
  - Leaking underground storage tanks (USTs)
  - Improper disposal of hazardous and other chemical wastes
  - Spills from pipelines or transportation accidents
  - Recharge of groundwater with contaminated surface water
  - Leaking dumps and landfills
  - Leaking retention ponds or lagoons

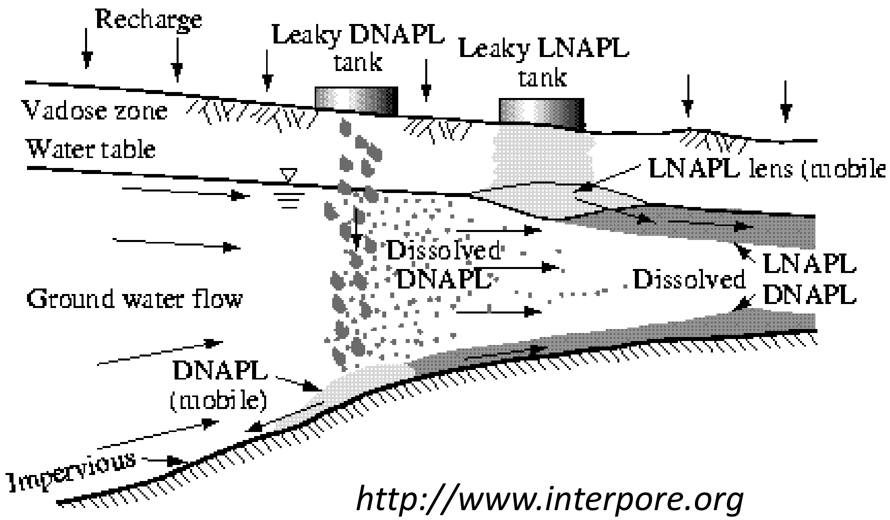
http://www.septicrepairny.com

http://www.apexenvirotech.com

Non-aqueous phase liquid (<u>NAPL</u>) in aquifer

- Many chemicals are only sparingly soluble in water
- They may migrate in aquifer as a separate non-aqueous phase

- **Light NAPL (LNAPL)**
  - lighter than water, float on the water table
  - example: gasoline (includes BTEX)
- **Dense NAPL (DNAPL)**
  - Denser than water, sink in the aquifer until reaching an impermeable layer
  - Example: TCE, PCE



http://www.interpore.org

Transport of dissolved contaminants

- **Advection**: transport of dissolved contaminants by average movement of groundwater (seepage velocity)
- **Dispersion**: spreading of contaminants by i) deviation of groundwater velocity from average and ii) molecular diffusion

- Many contaminants move slower than the groundwater seepage velocity because of: **sorption** (adsorption + absorption)
- Retardation coefficient: the extent to which chemicals are retarded in water

$$R = \frac{v'_{water}}{v'_{cont}}$$

R = retardation coefficient
v'_{water} = seepage velocity of groundwater
v'_{cont} = linear velocity of contaminant

Retardation coefficient

For neutral hydrophobic organic contaminants, the retardation coefficient, *R*, can be obtained by

$$R = 1 + \left(\frac{\rho_b}{\eta}\right) K_d$$

ρ_b = bulk density of soil (g/cm^3)
η = porosity of soil
***K_d** = sorption coefficient of the contaminant between soil and water (cm^3/g)*
= (conc. in soil at equilibrium) / (conc. in water at equilibrium)

As hydrophobic organic contaminants mainly sorb to organic matter in soil, the K_d can be written as

$$K_d = K_{oc} \cdot f_{oc}$$

***K_{oc}** = sorption coefficient to the organic carbon fraction of soil (g/cm^3)*
= (conc. in organic carbon at equilibrium) / (conc. in water at equilibrium)
f_{oc}= fraction of organic carbon in soil

Thus,

$$R = 1 + \left(\frac{\rho_b}{\eta}\right) K_{oc} \cdot f_{oc}$$

Transport of contaminants in groundwater

Q: A plume of benzene is migrating in groundwater flowing at a seepage velocity of 4.7×10^{-6} m/s. Using the following properties of the aquifer material and benzene, calculate the time for the center of the benzene plume to move 10 m in the direction of groundwater flow.

Aquifer material properties

Bulk density: 1.5 g/cm^3

Porosity: 0.4

Fraction of organic carbon: 0.02

Benzene property

Sorption coefficient to the organic carbon fraction: 27.0 cm^3/g

Reading assignment

Textbook Ch 9 p. 403-420, 435-439