Water quality

Water quality

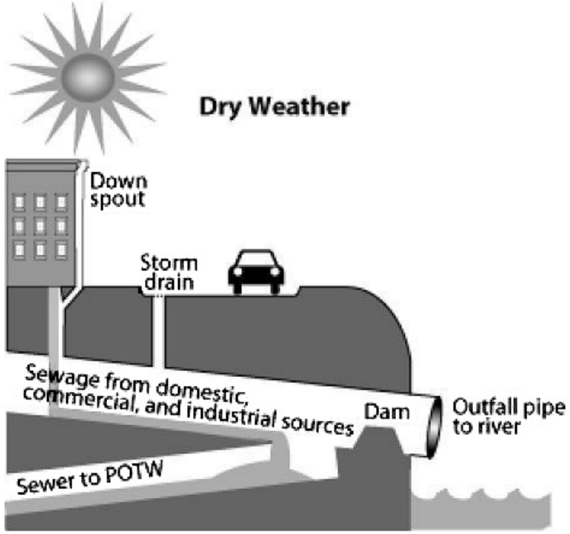
- Sources of water pollutants
- Types of water pollutants
- Oxygen demand: ThOD, COD, BOD
- DO dynamics in rivers
- Groundwater quality

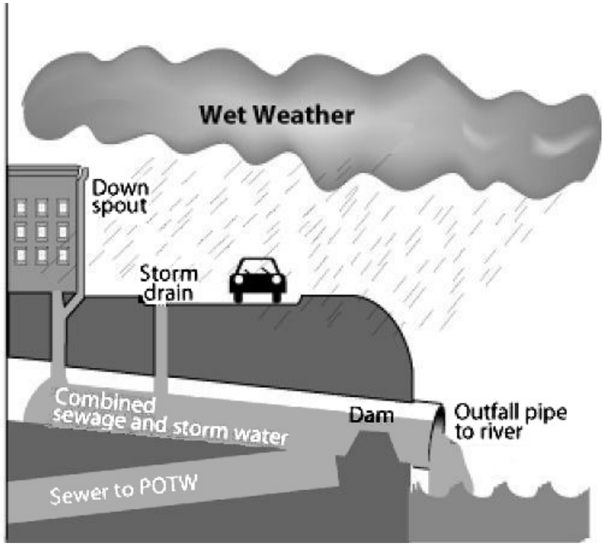
Sources of water pollutants

- **Point sources**: collected by a network of pipes of channels and conveyed to a single point of discharge
  - ex: domestic sewage, industrial wastewater
- **Nonpoint sources**: have multiple and diffuse discharge points
  - ex: urban and agricultural runoff

Combined sewer overflow (CSO)

- A nonpoint pollution problem
- Combined sewer system (↔ separate sewer system)
  - The sewage mixed with the storm water may go directly to the river (**C**ombined **S**ewer **O**verflow)
  - Generally no longer constructed in the developed world, but old cities may still have the combined sewer





USEPA (2004)

Types of water pollutants

Oxygen-demanding material

- Any substances that can be oxidized in the water resulting in the consumption of dissolved molecular oxygen (DO)

- Mostly biodegradable organic matter, but also includes inorganics (ex: ammonia)

- Low DO poses a threat to fish and other higher forms of aquatic life that requires oxygen

- Major source: human waste, food residue, industry (esp. food-processing & paper industries)

Nutrients

- Major: nitrogen (N) & phosphorus (P)
- Excessive nutrients → excessive algal growth
- Major source: agricultural runoff, human and animal excrement, P-based detergents, fertilizers, food-processing wastes
- Agricultural runoff may cause significant nutrient loadings to the water

Pathogens

- Bacteria, viruses, protozoa, and helminthes
- Excreted by diseased persons or animals
- Occurrence of pathogens in drinking water may cause outbreaks of gastrointestinal infections

1993 Milwaukee Cryptosporidiosis outbreak

The 1993 Milwaukee Cryptosporidiosis outbreak was a significant distribution of the Cryptosporidium protozoan in Milwaukee, Wisconsin, and the largest waterborne disease outbreak in documented United States history. The Howard Avenue Water Purification Plant was contaminated, and treated water showed turbidity levels well above normal. It was one of two water treatment plants for Milwaukee. The root cause of epidemic was never officially identified; initially it was suspected to be caused by the cattle genotype due to runoff from pastures. It was also thought that melting ice and snowmelt carrying *Cryptosporidium* may have entered the water treatment plants through Lake Michigan. MacKenzie et al. and the CDC showed that this outbreak was caused by *Cryptosporidium* oocysts that passed through the filtration system of one of the city's water-treatment plants, arising from a sewage treatment plant's outlet 2 miles upstream in Lake Michigan.

Milwaukee Cryptosporidiosis outbreak (cont'd)

This abnormal condition at the water purification plant lasted from March 23 through April 8, after which, the plant was shut down. Over the span of approximately two weeks, 403,000 of an estimated 1.61 million residents in the Milwaukee area (of which 880,000 were served by the malfunctioning treatment plant) became ill with the stomach cramps, fever, diarrhea and dehydration caused by the pathogen. At least 104 deaths have been attributed to this outbreak, mostly among the elderly and immunocompromised people, such as AIDS patients.

(*Wikipedia, 2014*)

Suspended solids (SS)

- Particles carried by water
- When the water flow slows down, most SS settle down, but colloidal particles do not settle readily
- Cause turbidity in water and may destroy habitat for benthic organisms

Salts

- Often measured as total dissolved solids (TDS)
    - TDS measurement: (i) filter the water sample, (ii) evaporate water by heating the filtered water sample, (iii) weigh the solids remaining after evaporation
    - Most of the dissolved solids in water are salts
- Evaporation of water from reservoirs, canals, and during application to plants increases salinity
- Increased salinity causes reduction in crop yield & threats to aquatic life

Pesticides

- Herbicides, insecticides, fungicides, …
- Kills herbs, insects, fungi, … → why not toxic to humans?
- Migrates to surface water by runoff; to groundwater by infiltration

Pharmaceuticals and personal care products (PPCP)

- Of recent interest
- Substances used by humans and pets for health or cosmetic reasons and the products used to boost growth or health of livestock
- Sources: human activity, residues from manufacturing, residues from hospitals, illegal drugs, drug use to animals (antibiotics and steroids)

Drug Facts

Active ingredient **Purpose**

Triclosan 0.10% ....Antibacterial hand soap

Use • for handwashing to decrease bacteria on the skin

Warnings

For external use only

Keep out of reach of children. In case of accidental ingestion, drink a glass of water to dilute. If eye contact occurs, rinse thoroughly with water.

Directions • wet hands and forearms. Apply 5 ml or palmful to hands and forearms. Scrub thoroughly for 30 sec. and rinse.

INACTIVE INGREDIENTS: WATER, SODIUM LAURYL SULFATE, SODIUM LAURETH SULFATE, LAURAMINE OXIDE, ALCOHOL DENAT., SODIUM CHLORIDE, PPG-26, PEG-8 PROPYLHEPTYL ETHER, PEI-14 PEG-10/PPG-7 COPOLYMER, PHENOXYETHANOL, METHYLISOTHIAZOLINONE, FRAGRANCE, YELLOW 5, RED 33.

Questions? 1-800-725-3296

Endocrine disrupting chemicals (EDCs)

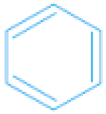
- Compounds mimicking hormones
- Examples:
  - polychlorinated biphenyls (PCBs): coolant, insulator, plasticizer
  - atrazine: pesticide
  - phthalates: plasticizer
  - bisphenol A (BPA): making plastics
  - natural and synthetic estrogen
    - contraceptive pills: 17α-ethynylestradiol (EE2)

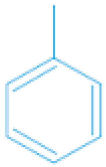
- May cause adverse effects at relatively low concentrations
- Can interfere with the regulation of reproductive and developmental processes or alter the normal physiological function of the endocrine system

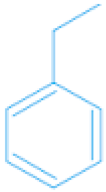
http://shopping.naver.com

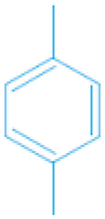
Other toxic organic chemicals

- **BTEX**
  - **B**enzene, **T**oluene, **E**thylbenzene, **X**ylene
  - Spills from gasoline and other petroleum products

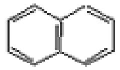

Benzene

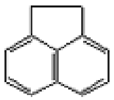

Toluene

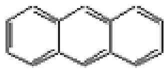

Ethylbenzene

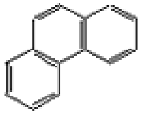

Xylene

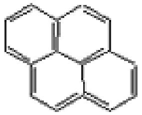
- **Polycyclic aromatic hydrocarbons (PAHs)**
  - Compounds with two or more fused benzene rings
  - Some are carcinogenic
  - Incomplete combustion, petroleum

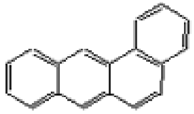

Naphthalene

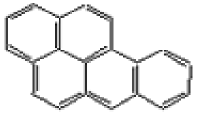

Acenaphthene


Anthracene


Phenanthrene

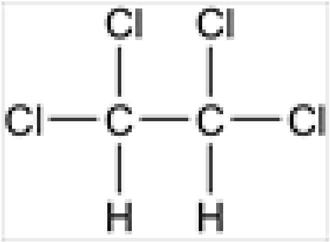

Pyrene

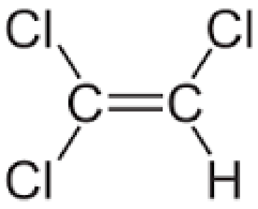

Benzophenanthrene

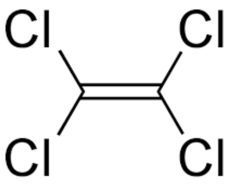

Benzo(a)pyrene

Other toxic organic chemicals (cont’d)

- **Chlorinated ethenes and ethanes**
  - Tetrachloroethane (**TCA**), trichloroethylene (**TCE**), tetrachloroethylene (**PCE**)
  - Solvents for dry cleaning and metal washing







***per**chloroethylene*

Arsenic

- Neither metal nor non-metal, but metalloid
- Source: mineral dissolution from weathered rocks and soils, mainly from iron oxides or sulfide minerals → arsenic contamination is often **a naturally occurring problem**
- Human carcinogen
- Significant groundwater contaminant in many regions of the world (ex: 33-77 million of Bangladesh's 125 million people are at risk of As poisoning from groundwater)
- Exist in quite high levels in Korea as well!

Toxic metals

- Cadmium (Cd), Chromium (Cr), Copper (Cu), Nickel (Ni), Lead (Pb), Mercury (Hg)
- Sources: industrial waste, wastewater treatment plants, stormwater runoff, mining operations, smokestack emissions, etc.
- Some heavy metals bioaccumulate and biomagnify (ex: mercury in tuna)

Toxic metals (cont'd)

- **Acid mine drainage (AMD)**
  - Water in mine operations gets acidic by a series of geochemical and microbial reactions
  - Generally metal solubility increases as pH lowers
  - Water contamination, ecosystem destruction, corrosion of infrastructure

- Outbreaks: recall from your middle school class!
  - Minamata, Japan – mercury
  - Toyoma, Japan – cadmium (itai-itai disease)

Heat

- Water used as coolants is discharged to the receiving waters
- May destroy the aquatic ecosystem
- Temperature increases → decrease in oxygen solubility and enhanced microbiological activity → oxygen depletion in rivers

Nanoparticles

- Particles of < 100 nm in dimension
- Examples
  - Naturally occurring humic material
  - TiO_2 particles in paints, varnishes, paper, plastics, creams, etc.
  - Carbon nanoparticles in tires, tennis rackets, video screens, etc.
  - Protein-based nanomaterials in the production of soaps, shampoos, and detergents
- Rapidly increasing production
- Toxicity and fate not well known

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Oxygen demand

- Indicators needed to predict the extent of oxygen depletion and to maintain sufficient levels of DO in rivers and streams

- **Theoretical oxygen demand (ThOD)**
  - the amount of oxygen required to oxidize a substance to CO_2 and H_2O calculated by stoichiometry
  - the chemical composition of the substance should be known

Theoretical oxygen demand

Q: Compute the ThOD of 108.75 mg/L of glucose ($C_6H_{12}O_6$).

Chemical oxygen demand (COD)

- A measured quantity – does not depend on the knowledge of the chemical composition of the substances in the water

- The organic compounds in a water is oxidized by a strong oxidizing agent such as potassium dichromate (K_2CrO_7) or potassium permanganate ($KMnO_4$)

- The difference between the amount of oxidizing agent at the beginning and the end of the test is used to calculate COD

Biochemical oxygen demand (BOD)

- The oxygen demand is measured by a bioassay
- The water sample is inoculated with bacteria that degrade organic matter in water
- The difference in DO in the water sample at the beginning and end of the test is used to calculate BOD

BOD Measurement

Step 1. Take the wastewater sample and dilute if needed. Fill the test bottle (usually 300 mL) with the (diluted) sample and a suspension of microorganisms (seed) if needed. Seal the bottle to prevent air intrusion/water evaporation.

$$Dilution\ factor = P = \frac{volume\ of\ wastwater\ sample}{volume\ of\ wastewater + dilution\ water}$$

The expected BOD of the diluted sample should be 2-6 mg/L.

** saturation DO concentration at 20℃: 9.17 mg/L*

BOD Measurement (cont'd)

Step 2. Prepare blank samples (control) containing only the dilution water and the seed.

Step 3. Incubate the samples and blanks at 20°C in the dark. Usually the incubation time is 5 days.

Step 4. Measure the DO after incubation.

The BOD of the wastewater sample can be calculated as:

$$BOD_t = \frac{DO_{b,t} - DO_{s,t}}{P}$$

$DO_{b,t}$ = DO concentration in blank after t days of incubation

$DO_{s,t}$ = DO concentration in sample after t days of incubation

ThOD vs. COD vs. BOD

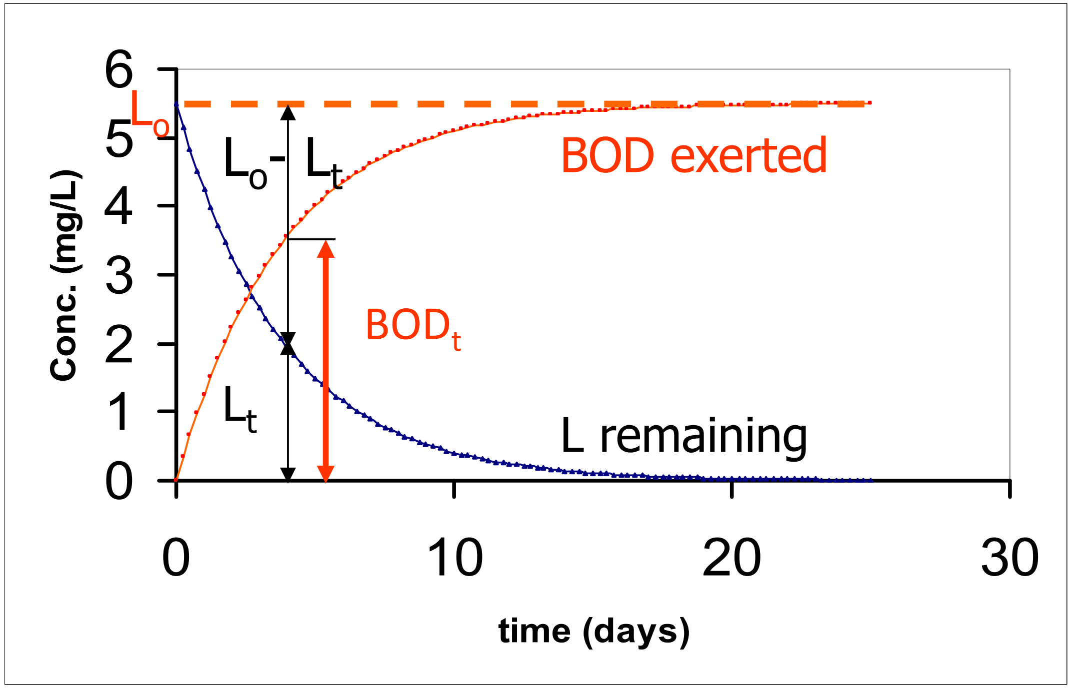
ThOD ≥ COD > BOD

- ThOD ≥ COD: some organic compounds may not be oxidized even with a strong oxidizing agent
- COD > BOD

During BOD measurement:

- some carbon is not oxidized, but used for bacterial growth
- some organic compounds are non-biodegradable, so not degraded
- some portion of biodegradable organic matter is converted to non-biodegradable materials

Modeling BOD



L = oxygen demand of remaining biodegradable organic chemicals (mg/L)

- L_t decreases with time and BOD_t increases with time
- $L_0 = L_t + BOD_t$
- L_0 (= BOD_∞): ultimate BOD

Modeling BOD (cont'd)

The degradation of organic compounds by microorganisms is modeled as a first-order reaction:

$$\frac{dL}{dt} = -kL$$

k = first-order reaction constant (day^{-1})

Integration of the equation gives:

$$L_t = L_0 e^{-kt}$$

As $BOD_t = L_0 - L_t$,

$$\boxed{BOD_t = L_0\left(1 - e^{-kt}\right)}$$

BOD rate constant

The magnitude of the BOD rate constant, *k* depends on:

1. Nature of waste: whether the waste is easily biodegradable or not

2. Ability of organisms to use waste: the microorganisms in the test bottle may not be ready to degrade the waste! (recall the “lag phase”)

3. Temperature effect

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

k_T = *BOD rate constant at temperature T℃ (day*$^{-1}$*)*

k_{20} = *BOD rate constant at 20℃ (day*$^{-1}$*)*

θ = *temperature coefficient*

(use 1.135 for 4-20℃ and 1.056 for 20-30℃)

Modeling BOD

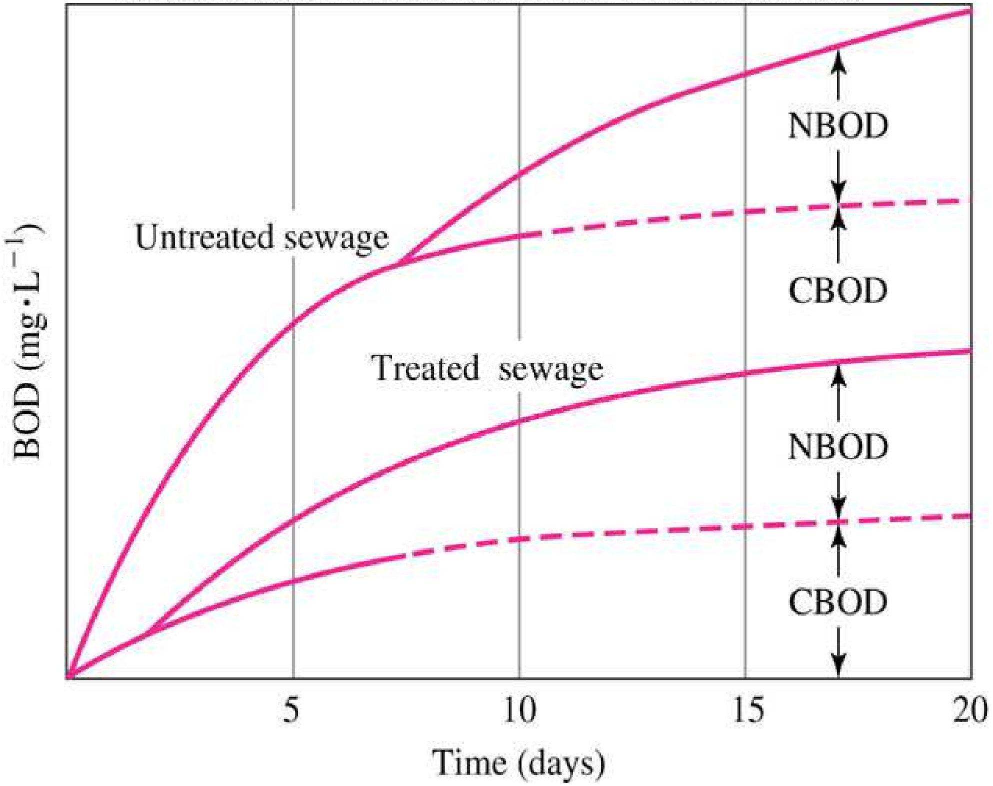
Q: The BOD_5 of a wastewater is 120 mg/L and the BOD rate constant is 0.115 day^{-1} at 20°C. What is the ultimate BOD? If the wastewater is incubated at 15°C with a supply of oxygen, how much oxygen will be used by microorganisms in three days?

Nitrogenous BOD

- So far, our assumption was that the oxygen demand is due to carbon oxidation only
- Organic compounds also contain reduced nitrogen
- The reduced nitrogen is released to form ammonium ion (NH_4^+)
- This may contribute significantly to overall oxygen demand by:

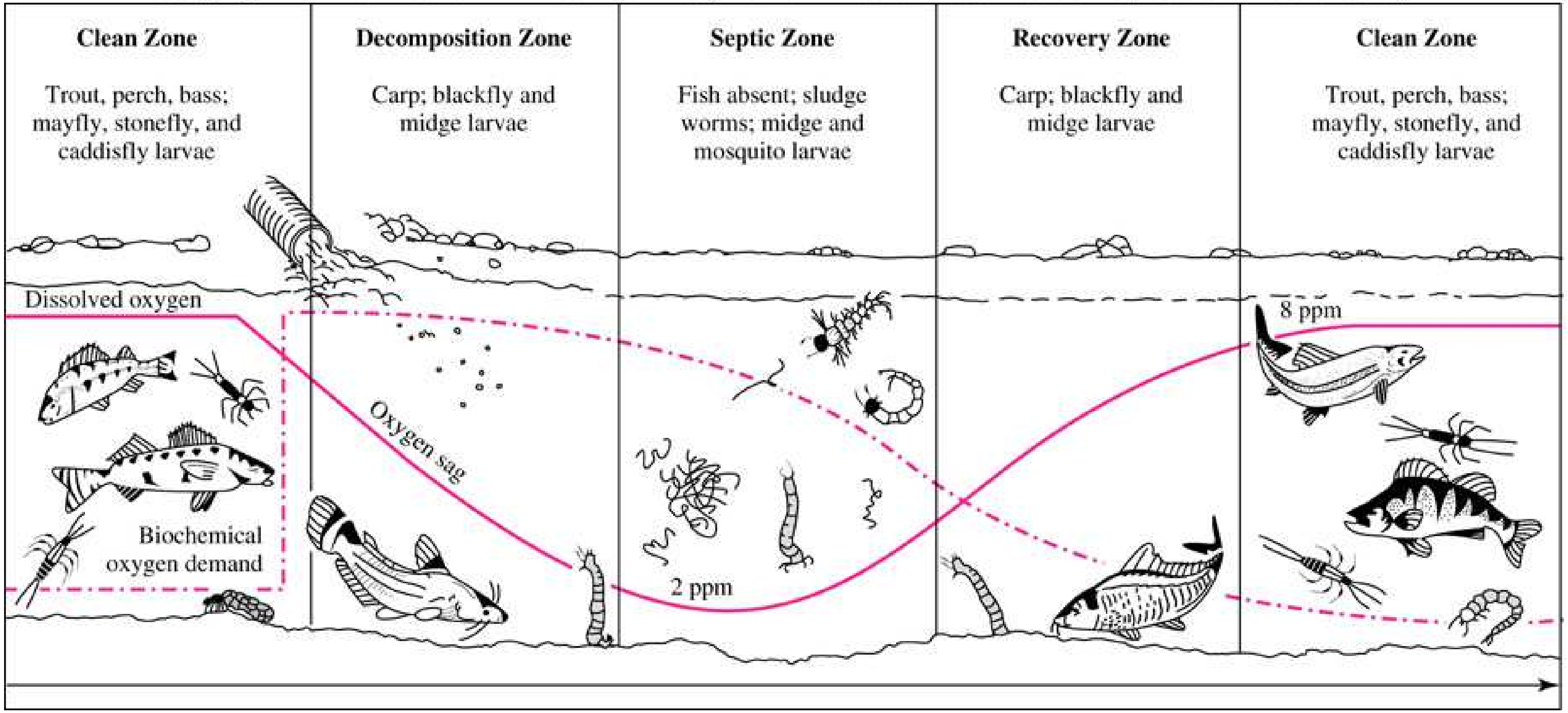
$$NH_4^+ + 2O_2 \longrightarrow NO_3^- + H_2O + 2H^+$$

BOD curve when NBOD is significant



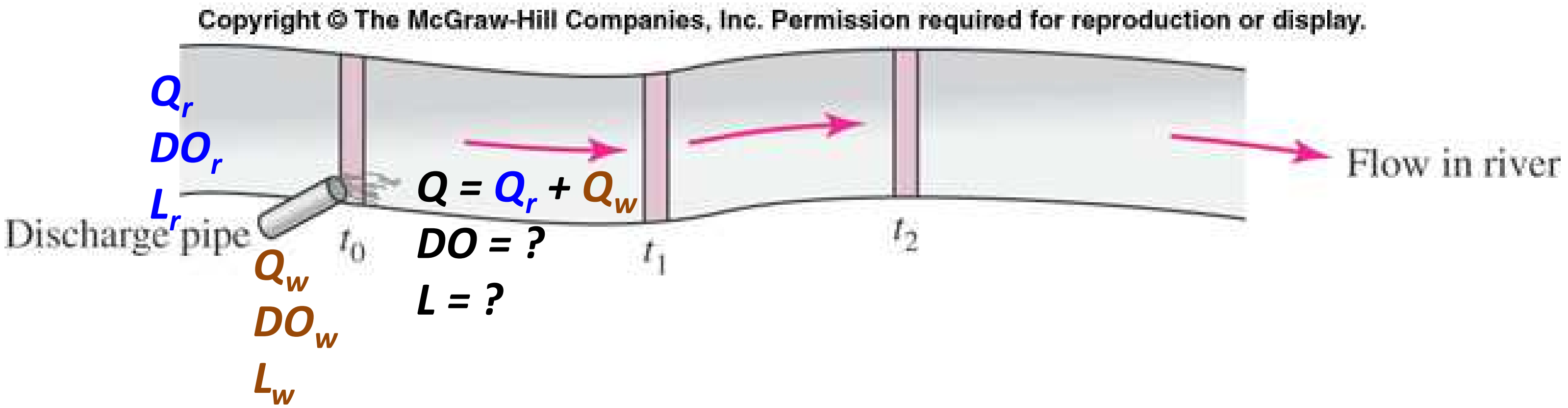
- Lag time exists because carbon-utilizing bacteria carbon is more prevalent at the beginning
- As CBOD goes down, the population of ammonia-utilizing bacteria increases, leading to NBOD consumption
- For treated sewage, the lag time is shorter, because there's not much food for carbon-utilizing bacteria

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



Q_r
DO_r
L_r

Q_w
DO_w
L_w

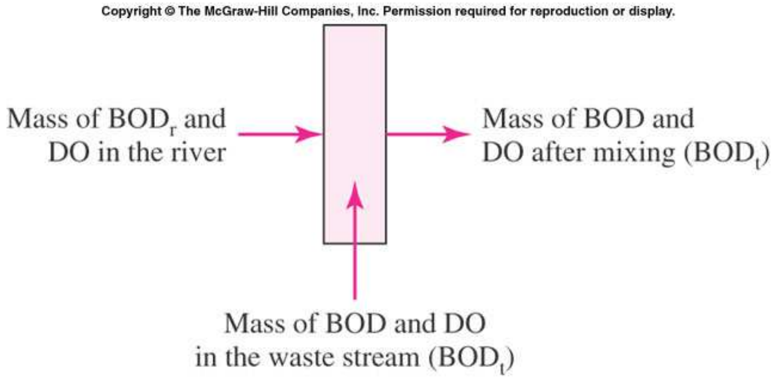
$Q = Q_r + Q_w$
$DO = ?$
$L = ?$

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

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

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

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

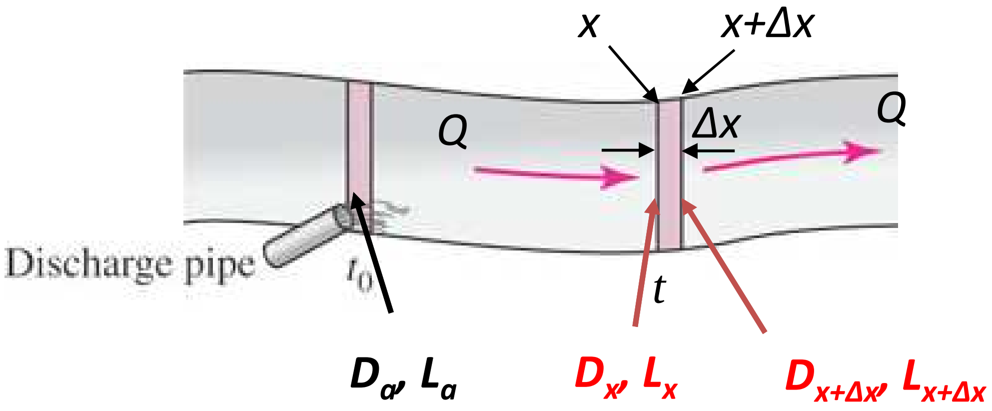
k_d = *first-order deoxygenation rate constant* [T^{-1}]

- 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

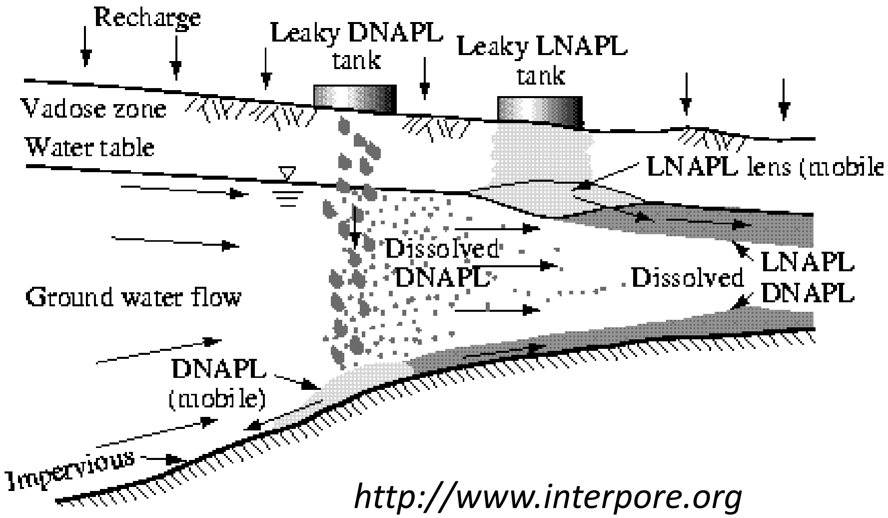
http://www.septicrepairny.com

http://www.apexenvirotech.com

Non-aqueous phase liquid (NAPL) 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 x 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. 378-418, 435-439

Oxygen demand

Slide#26 solution)

Reaction stoichiometry:

$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$

MW of glucose = 180 g/mole

ThOD of 108.75 mg/L glucose:

$$108.75\, mg\ glucose/L\ \times \frac{(6\times32)\ g\ O_2/mole\ glucose}{180\ g\ glucose/mole} = \boldsymbol{116\ mg\ O_2/L}$$

Modeling BOD

Slide#35 solution)

i) Ultimate BOD

$BOD_t = L_0(1 - e^{-kt})$

$L_0 = \frac{BOD_5}{1-e^{-5\,d \times k}} = \frac{120\ mg/L}{1-e^{-5\,d \times 0.115\,d^{-1}}} = \boldsymbol{274\ mg/L}$

ii) BOD$_3$ at 15^{o}C

$k_{15} = k_{20}\theta^{15-20}$, θ=*1.135 at 4-20^{o}C*

$k_{15} = 0.115\ day^{-1} \times 1.135^{15-20} = 0.0611\ day^{-1}$

$BOD_3 = 274\ mg/L \times \left(1 - e^{-0.0611\ day^{-1} \times 3\ day}\right) = \boldsymbol{45.9\ mg/L}$

Modeling DO along a river

Slide #48 solution)

i) L_a and DO_a

$$L_a = \frac{28.0\ mg/L \times 1.05\ m^3/s + 3.6\ mg/L \times 7.08\ m^3/s}{(1.05+7.08)\ m^3/s} = \mathbf{6.8\ mg/L}$$

$$DO_a = \frac{1.8\ mg/L \times 1.05\ m^3/s + 7.6\ mg/L \times 7.08\ m^3/s}{(1.05+7.08)\ m^3/s} = \mathbf{6.9\ mg/L}$$

ii) DO 16 km downstream

Initial deficit, $D_a = DO_s - DO_a$ = 8.5 mg/L – 6.9 mg/L = 1.6 mg/L

$$t = \frac{16000\ m}{0.37\ m/s \times 86400\ s/day} = 0.50\ days$$

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

$$= \frac{0.61\ day^{-1} \times 6.8\ mg/L}{(0.76-0.61)\ day^{-1}}\left(e^{-0.61\ day^{-1} \times 0.50\ days} - e^{-0.76\ day^{-1} \times 0.50\ days}\right)$$

$$+1.6\ mg/L \times \left(e^{-0.76\ day^{-1} \times 0.50\ days}\right)$$

Modeling DO along a river

$$= 2.6\ mg/L$$

$DO_t = DO_s - D_t = 8.5\ mg/L - 2.6\ mg/L = \mathbf{5.9\ mg/L}$

iii) t_c, L_c & DO_c

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

$$= \frac{1}{(0.76 - 0.61)\ day^{-1}} ln\left[\frac{0.76\ day^{-1}}{0.61\ day^{-1}}\left(1 - 1.6\ mg/L \frac{(0.76 - 0.61)\ day^{-1}}{0.61\ day^{-1} \times 6.8\ mg/L}\right)\right]$$

$$= \mathbf{1.07\ days}$$

$$L_c = 1.07\ days\ \times 0.37\ m/s\ \times 86400\ s/day = 34200\ m = \mathbf{34.2\ km}$$

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

$$= \frac{0.61\ day^{-1} \times 6.8\ mg/L}{(0.76 - 0.61)\ day^{-1}}\left(e^{-0.61\ day^{-1} \times 1.07\ days} - e^{-0.76\ day^{-1} \times 1.07.days}\right)$$

$$+1.6\ mg/L \times \left(e^{-0.76\ day^{-1} \times 1.07\ days}\right)$$

Modeling DO along a river

$$= 2.8\, mg/L$$

$DO_c = DO_s - D_c = 8.5\ mg/L - 2.8\ mg/L =$ **$5.7\ mg/L$**

Transport of contaminants in groundwater

Slide #53 solution)

$$R = 1 + \left(\frac{\rho_b}{\eta}\right) K_{oc} \cdot f_{oc} = 1 + \frac{1.5\frac{g}{cm^3}}{0.4} \cdot 27.0\ cm^3/g \cdot 0.02 = 3.03$$

$$v'_{cont} = \frac{v'_{water}}{R} = \frac{4.7 \times 10^{-6} m/s}{3.03} = 1.55 \times 10^{-6}\ m/s$$

$$t = \frac{10\ m}{1.55 \times 10^{-6}\ m/s \times 86400\ s/d} = 75\ days$$