WATER QUALITY ENGINEERING

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Water Quality Management

- The control of pollution from human activities so that the water is not degraded to the point that it is no longer suitable for intended uses.
- How much is too much?

Effects of Pollutant in Rivers

- According to their physico-chemical or biological nature:
  - the addition of toxic substances;
  - the addition of suspended solids;
  - deoxygenation;
  - the addition of non-toxic salts;
  - heating the water;
  - the effect on the buffering system;
  - the addition of human, animal and plant pathogens.

Water pollutants and their sources

Pollutant category	Point sources		Non-point sources	
	Domestic sewage	**Industrial wastes**	**Agricultural runoff**	**Urban runoff**
Oxygen-demanding material	X	X	X	X
Nutrients	X	X	X	X
Pathogens	X	X	X	X
Suspended solids/sediments	X	X	X	X
Salts		X	X	X
Toxic metals		X		X
Toxic organic chemicals		X	X	
Endocrine-disrupting chemicals	X	X	X	
Heat		X		

Water quality management in Rivers

- **The objective:** to control the discharge of pollutants so that water quality is not degraded to an unacceptable extent below the natural background level.
- To control we need to:
  - measure the pollutants
  - predict the impact of the pollutants
  - determine the background water quality, and
  - decide the acceptable levels

Effect of pollutants on river

- The effect of pollutants on river communities depends on:
  - The type of pollutant
  - Its concentration in the water
  - The length of exposure to the community
  - The characteristics of the river

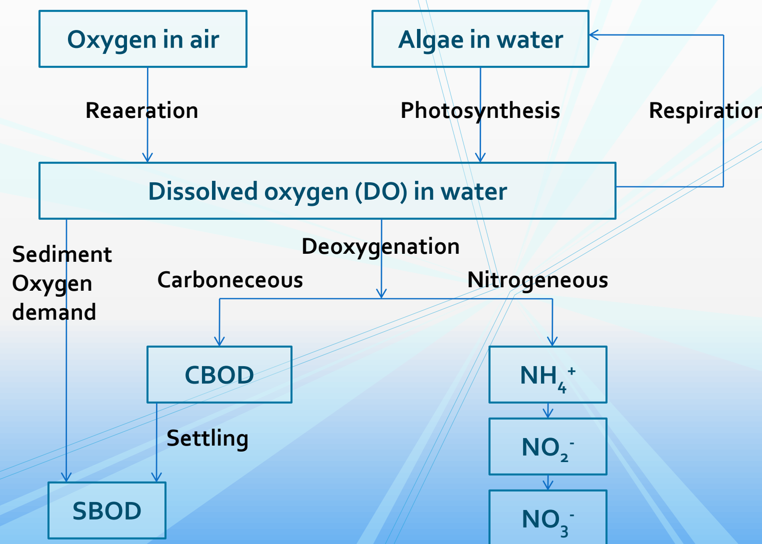
Total maximum daily loads (TMDL)

- A TMDL specifies the maximum amount of pollutant that a water body can receive and still meet water quality standards.
- Computed on a pollutant-by-pollutant basis
- **TMDL=ΣWLA + ΣLA + MOS**
  - WLA = waste load allocation for point sources
  - LA = waste load allocation for nonpoint sources
  - MOS = margin of safety

Effects of Oxygen-Demanding Wastes on Rivers

- Cause depletion of dissolved oxygen (DO)
- Oxygen replenished from the atmosphere and from photosynthesis by algae and aquatic plants
- consumed by organisms

Factor Affecting DO in Rivers



Biochemical Oxygen Demand

Theoretical oxygen demand (ThOD). The amount of oxygen required to oxidize a substance to carbon dioxide and water may be calculated by stoichiometry if the chemical composition of the substance is know.

Example

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

Solution

- Write balanced equation for the reaction

$C_6H_{12}O_6 + 6O_2 \Leftrightarrow 6CO2 + 6\ H2O$

- Compute the molecular weight
- Glucose (6C+12H+6O)=72+12+90=180
- Oxygen (12O)=192
- Thus, it takes 192 g of oxygen to oxidize 180 g of glucose
- The ThOD of 108.75 mg/L of glucose is

$$(108.75 mg/L)\left(\frac{192 g O_2}{180 g\ glu\cos e}\right) = 116 mg/L\ O_2$$

Chemical Oxygen Demand (COD)

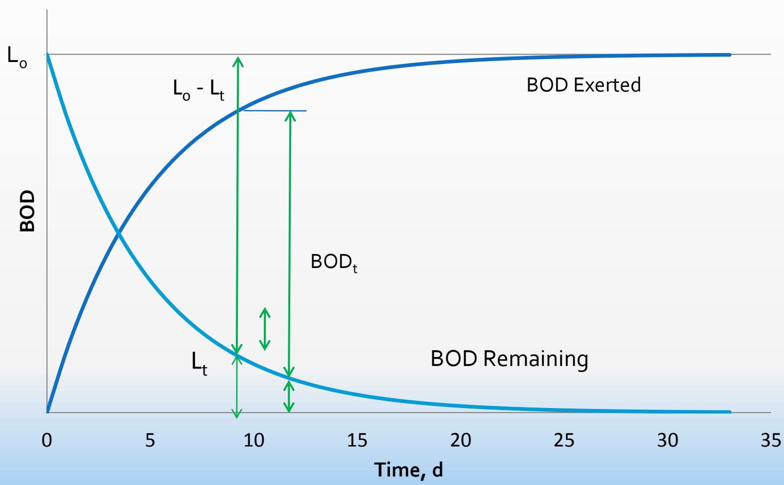
- The amount of oxygen needed to oxidize the wastes chemically.
- In the COD test, a strong chemical oxidizing agent (chromic acid) is mixed with a water sample and then boiled.
- The difference between the amount of oxidizing agent at the beginning of the test and that remaining at the end of the test is used to calculate the COD.

Biochemical Oxygen Demand (BOD)

If the oxidation of an organic compound is carried out by microorganisms using the organic matter as a food source.

$$\text{Organic matter} + O_2 \xrightarrow{\text{Microorganisms}} CO_2 + H_2O + \text{New Cells} + \text{Stable Products}$$

BOD Curve

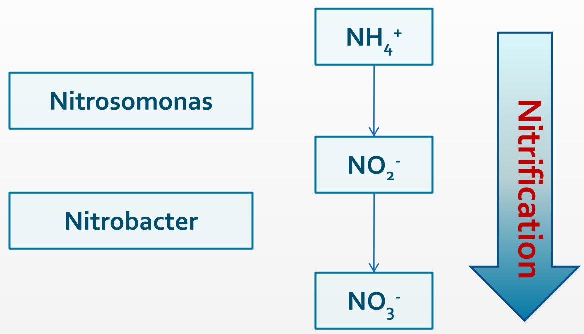


$$BOD_t = L_o(1 - e^{-kt})$$

Nitrogen Oxidation

- Proteins contain nitrogen that can be oxidized with the consumption of molecular oxygen.
- *Carbonaceous BOD* (CBOD): oxidation of carbon
- *Nitrogenous BOD* (NBOD): nitrogen oxidation.

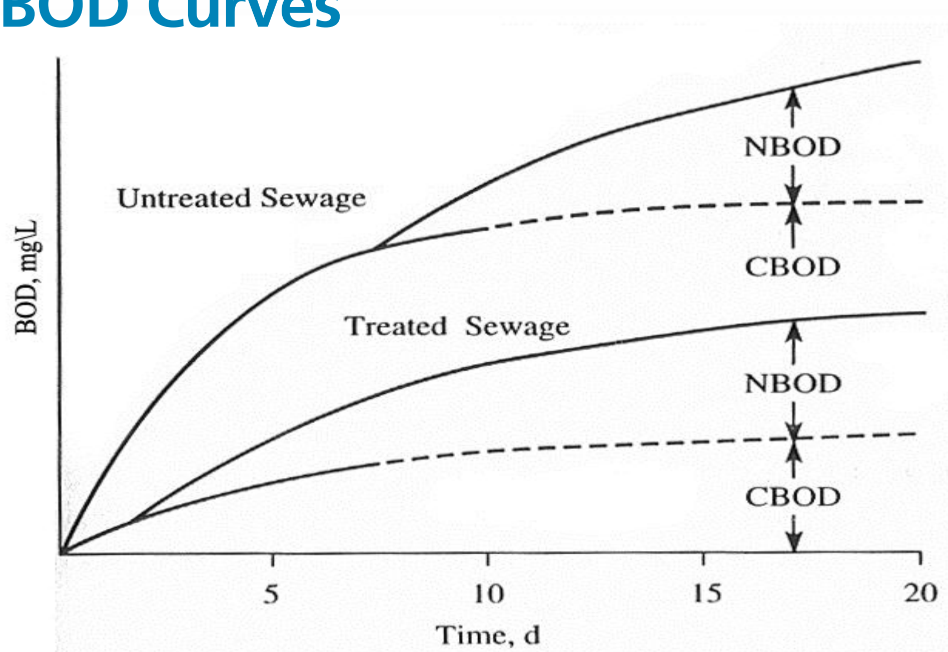
Nitrification



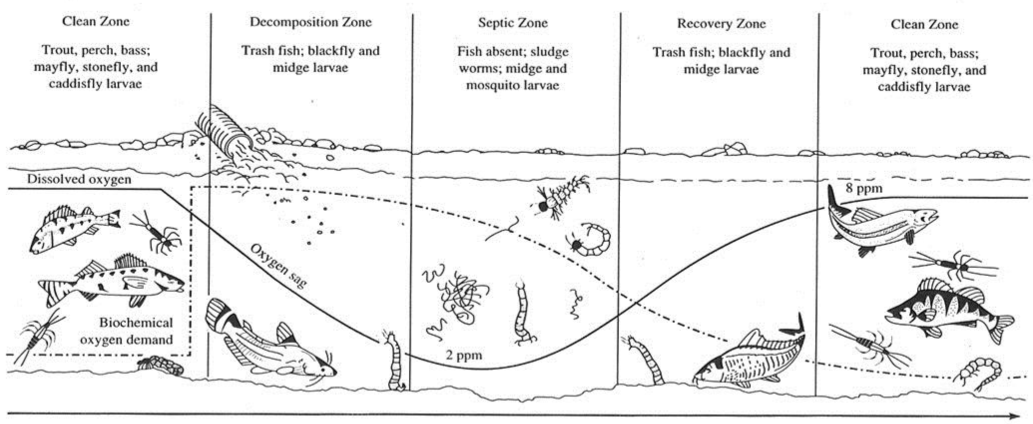
$$NH_4^+ + 2O_2 \xleftrightarrow{\text{Microorganisms}} NO_3^- + H_2O + 2H^+$$

$$NBOD = \frac{\text{grams of oxygen used}}{\text{grams of nitrogen oxidized}} = \frac{4X16}{14} = 4.57 g \frac{O_2}{g} N$$

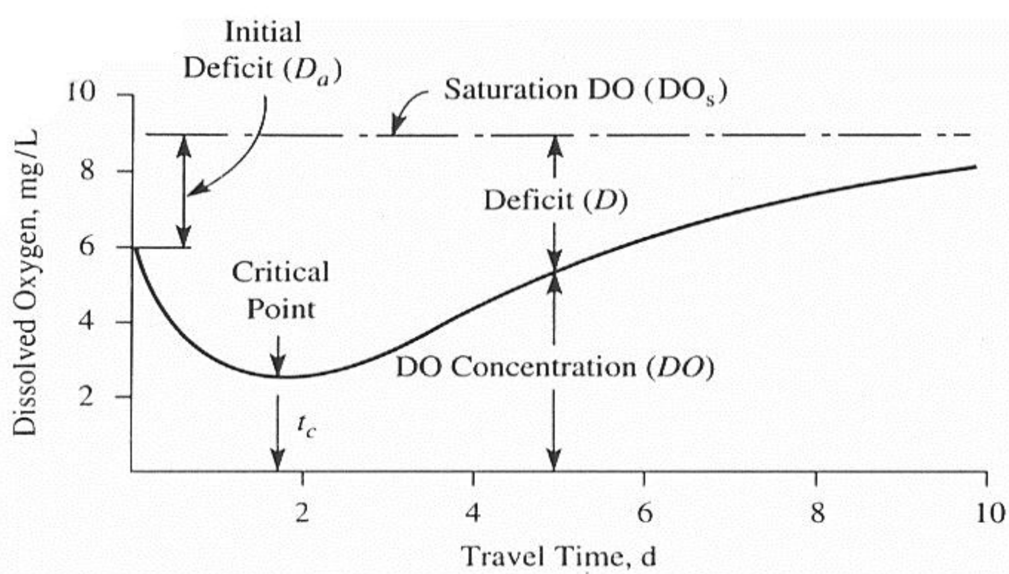
BOD Curves



DO Sag Curve

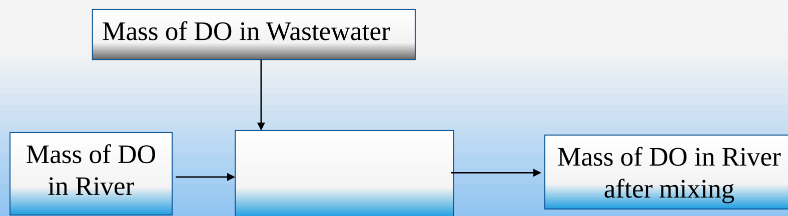


DO Sag Curve



Mass-Balance Approach

- Three conservative mass balances may be used to account for initial mixing of the waste stream and the river.
- DO, CBOD, and temperature all change as the result of mixing of the waste stream and the river.



DO and BOD after mixing

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

Where Q_w = volumetric flow rate of wastewater, m^3/s
Q_r = volumetric flow rate of river, m^3/s
DO_w = dissolved oxygen concentration in the wastewater, g/m^3
DO_r = dissolved oxygen concentration in the river, g/m^3
L_w = ultimate BOD of the wastewater, mg/L
L_r = ultimate BOD of the river, mg/L
L_a = initial ultimate BOD after mixing mg/L

Example

A certain college discharges 17,360 m^3/d of treated wastewater into a nearby river. The treated wastewater has a BOD_5 of 12 mg/L and k of 0.12 d^{-1} at 20°C. The river has a flow rate of 0.43 m^3/s and an ultimate BOD of 5.0 mg/L. The DO of the river is 6.5 mg/L and the DO of the wastewater is 1.0 mg/L. Compute the DO and initial ultimate BOD after mixing.

The temperature after mixing

- It is found by solving a heat balance equation rather than a mass balance
- Loss of heat by hot bodies = gain of heat by cold bodies).
- The final river temperature after mixing is thus calculated as:

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

Oxygen Deficit

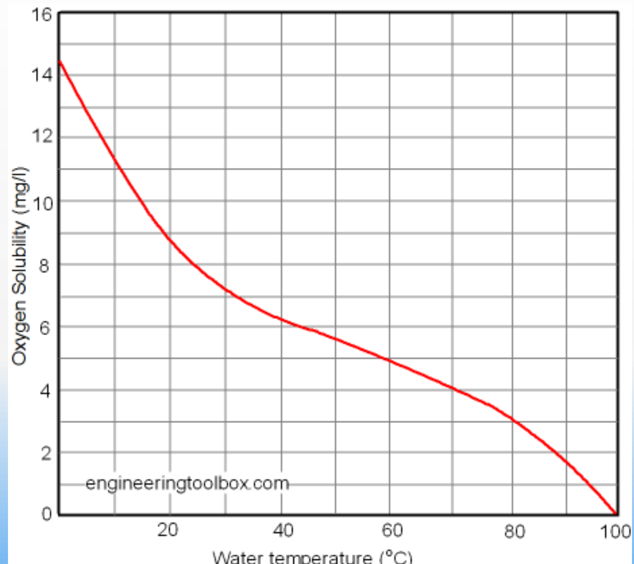
- The oxygen deficit is the amount by which the actual dissolved oxygen concentration is less than the saturated value with respect to oxygen in the air:
  - $D = DO_s - DO$
  - Where D = oxygen deficit, mg/L
  - DO_s = saturation concentration of dissolved oxygen at the temperature of the river after mixing, mg/L
  - DO = actual dissolved oxygen concentration, mg/L

Initial Deficit (D_a)

The initial deficit = the difference between saturated DO and the concentration of the DO after mixing:

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

Dissolved oxygen in water



Example

Calculate the initial deficit of the river after mixing with the wastewater from the college (previous example). The stream temperature is 10°C and the wastewater temperature is 20°C.

Solution

- Saturation dissolved oxygen can be read from table. Thus at 10°C DO_s = 11.33 mg/L
- From the previous example DO_{mix} = 4.75 mg/L
- Therefore, initial deficit DO, D_a = 11.33-4.75
- D_a=6.58 mg/L

DO Sag Equation

- Taking a mass balance of DO as a reactive substance expressed as the deficit we get the Streeter-Phelps oxygen sag curve

Rate of increase Of the deficit	=	Rate of deoxygenation	-	Rate of oxygenation

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

dD/dt = the change in oxygen deficit (D) per unit time, mg/L.d

k_d = deoxygenation rate constant, d^{-1}

k_r = reaeration rate constant, d^{-1}

L = ultimate BOD of river water, mg/L

D = oxygen deficit in river water, mg/L

DO Sag Equation

- By integrating the previous Eq., and using the initial conditions (at t = 0, D = D_a) we obtain the DO sag equation:

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

D = oxygen deficit in river water after exertion of BOD for time, t, mg/L
L_a = initial ultimate BOD after river and wastewater have mixed, mg/L
t = time of travel of wastewater discharge downstream, d

DO Sag Equation

- When k_d = k_r we have a reduced equation:

$$D = (k_d t L_a + D_a)(e^{-k_d t})$$

Deoxygenation Rate Constant. It difference from the BOD rate constant because there are physical and biological differences between a river and a BOD bottle.

$$k_d = k + \frac{v}{H}\eta$$

Where k_d = deoxygenation rate constant at 20ºC, d^{-1}
v = average speed of stream flow, m/s
k = BOD rate constant determined in laboratory at 20ºC, d^{-1}
H = average depth of stream, m
η = bed-activity coefficient (from 0.1 to 0.6 or more.)

Example

Determine the deoxygenation rate constant for the reach of the river (For the previous examples) below the wastewater outfall (discharge pipe). The average speed of the stream flow in the river is 0.03 m/s. The depth is 5.0 m and the bed-activity coefficient is 0.35.

Solution

- From the previous examples we have k = 0.12d^{-1}
- The deoxygenation constant at 20°C is

$$k_d = 0.12d^{-1} + \frac{0.03\,m/s}{5.0\,m}(0.35) = 0.12\,d^{-1}$$

- The deoxygenation constant is at 20°c, but the Stream temperature is 10°c. Thus we must correct it

$$k_d\ at\,10^o C = (0.1221d^{-1})(1.135)^{10-20} = 0.034d^{-1}$$

Reaeration

- The value of k_r depends on the degree of turbulent mixing, which is related to stream velocity, and on the amount of water surface exposed to the atmosphere compared to the volume of water in the river.
- A narrow, deep river will have a much lower k_r than a wide, shallow river.

$$k_r = \frac{3.9v^{0.5}}{H^{1.5}}$$

k_r = reaeration rate constant at 20°C, day^{-1}
v = average stream velocity, m/s
H= average depth, m

The Critical point

- The lowest point on the DO sag curve, which is called the critical point, indicates the worst conditions in the river.
- The time to the critical point (t_c) can be calculated by differentiating and setting DO sag equation to zero

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

- when $k_d = k_r$:

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

Example

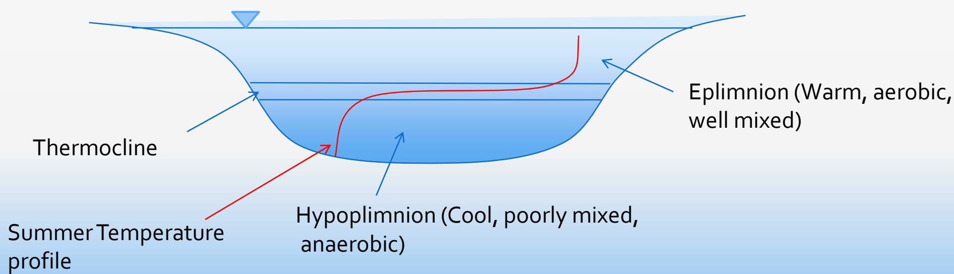
Determine the DO concentration at a point 5 km downstream from the college discharge into the river (for the previous examples). Also determine the critical DO and the distance downstream at which it occurs.

Water Quality in Lakes

The study of lakes is called limnology

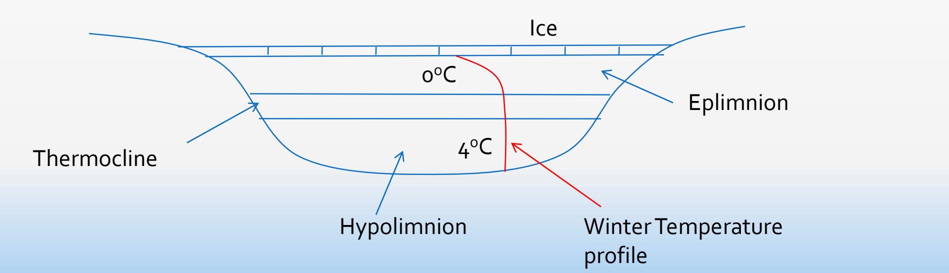
Stratification and Turn over

- Lakes in temperate zone become stratified during summer and overturn (turnover) in the fall.



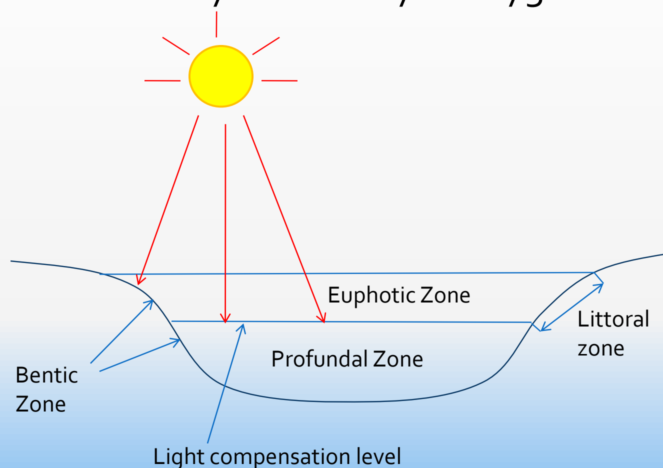
Stratification and Turn over

- During winter there is turnover at 4°C



Biological Zones

- Determined by availability of oxygen and light

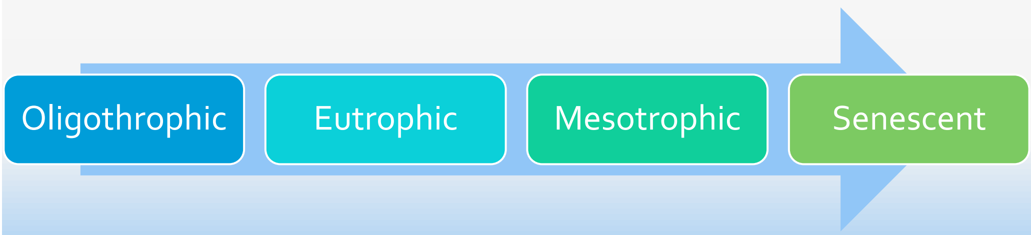


Lake Productivity

- Lake productivity is a measure of its ability to support a food web.
- Generally measured by algal growth
- Increased productivity reduces water quality
- Based on productivity we can classify lakes as
  - Oligothrophic: low level of productivity
  - Eutrophic: high level of productivity
  - Mesotrophic: intermediate productivity
  - Senescent: old and shallow lakes with thick organic sediment and rooted plant

Eutrophication

Eutrophication is a natural process in which lakes gradually become shallower and more productive through the introduction and cycling of nutrients.



Cultural Eutrophication is caused by human activity by speeding up the natural process

Algal Growth Requirement

- Carbon: from dissolved CO_2 in water
- Nitrogen: usually as NO_3^-, comes from atmosphere or industrial waste
- Phosphorus: from external sources as inorganic form (PO_4^{3-})
- Trace elements

The limiting Nutrient

- Justin Liebig's law of the minimum: "*growth of a plant is dependent on the amount of foodstuff that is presented to it in minimum quantity*."
- Phosphorus is the limiting nutrient in lakes.
- Should be below 0.010 to 0.015 mg/L to limit algae.

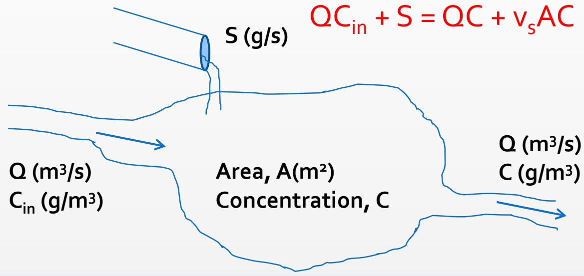
Control of Phosphorus

- Reducing the input from the source
  - Rock weathering
  - Human activity
- Precipitating with alum
- Removing phosphorus-rich sediments by dredging.

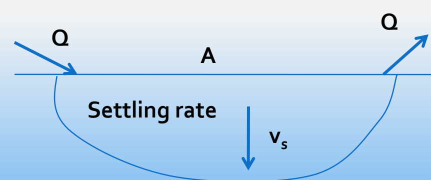
A simple phosphorus model

- Rate of addition of P = Rate of removal of P

$QC_{in} + S = QC + v_sAC$



Well-mixed lake phosphorus mass balance



A simple phosphorus model

$QC_{in} + S = QC + v_sAC$

The steady-state concentration becomes

$$C = \frac{QC_{in} + S}{Q + v_s A}$$

The settling rate, v_s, is empirically determined quantity. Usually it is around 10 to 16 m/yr.

Example: Phosphorus loading

A phosphorus-limiting lake with surface area equal to $80 \times 10^6\ m^2$ is fed by a $15.0\ m^3/s$ stream that has a phosphorus concentration of 0.010 mg/L. In addition, effluent from a point source adds 1 g/s of phosphorus. The phosphorus settling rate is estimated at 10 m/yr.

a. Estimate the average total phosphorus concentration.
b. What rate of phosphorus removal at the wastewater treatment plant would be required to keep the concentration of phosphorus in the lake at acceptable level of 0.010 mg/L?

Solution

a. Phosphorus loading from the incoming stream

$QC_{in} = 15\ m^3/s \times 0.01\ mg/l \times (1g/L)/(mg/L) = 0.15\ g/s$

The estimated settling rate:

$$v_s = \frac{10\, m/yr}{365\, d/yr \times 24\, hr/d \times 3600\, s/hr} = 3.17 \times 10^{-7}\ m/s$$

The steady-state concentration of phosphorus:

$$C = \frac{QC_{in} + S}{Q + v_s A} = \frac{(0.15 + 1.0)\, g/s}{15\, m^3 s + 3.17 \times 10^{-7}\, m/s \times 80 \times 10^6\, m^2}$$

$= 0.028\ g/m^3 = 0.028\ mg/L$

Solution

b. To reach 0.010 mg/L, the phosphorus loading from the point source must be

$S = C(Q + v_sA) - QC_{in}$

$= 0.010\ g/m^3(15\ m^3/s + 3.17 \times 10^{-7} m/s \times 80 \times 10^6 m^2)$

$- 15\ m^3/s \times 0.010\ g/m^3$

$= 0.25\ g/s$

The point source efficiency currently supplies 1.0 g/s, so 75 % removal of phosphorus is needed.