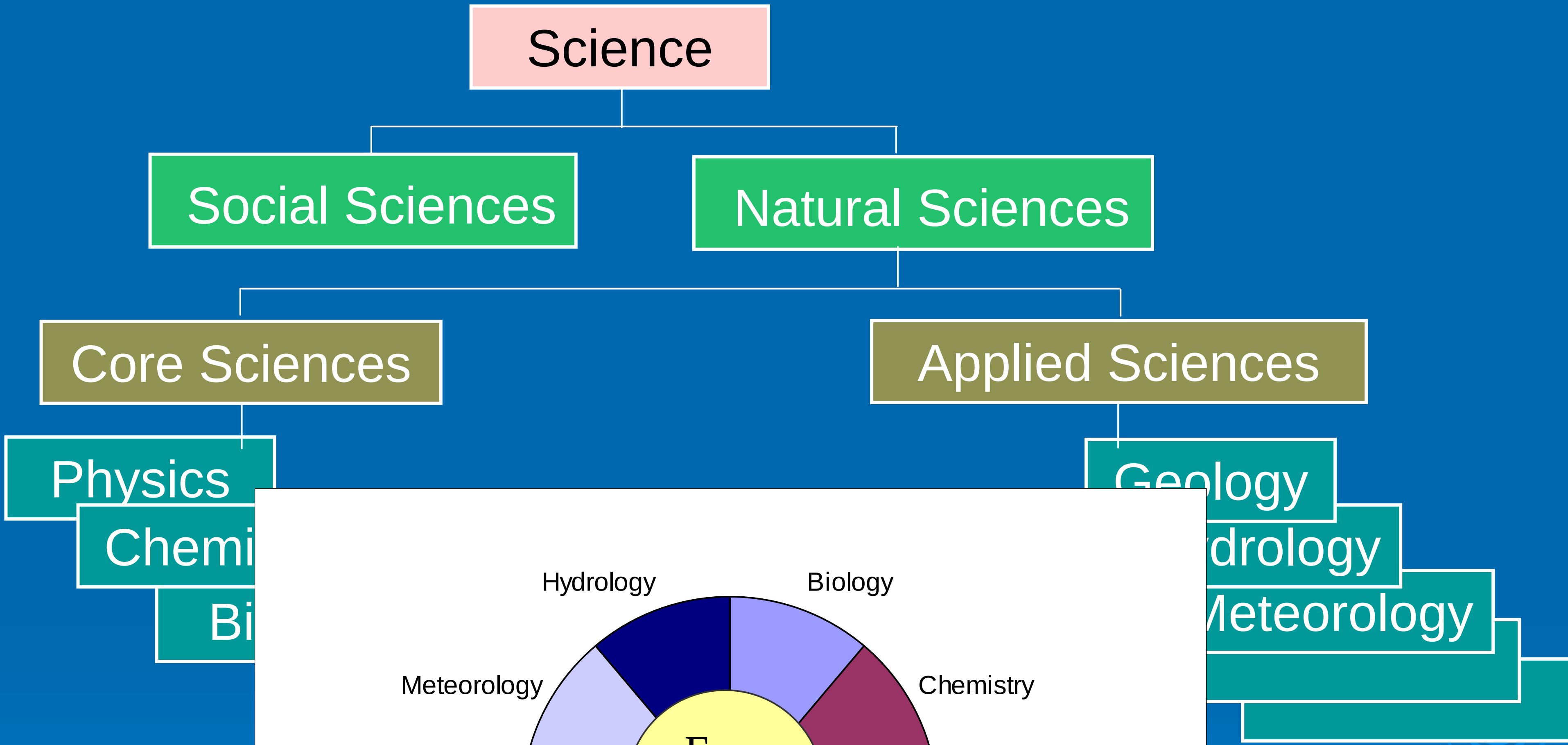
Fundamental Concepts in Environmental Engineering

Lecture Objectives

- To provide an overview of core areas in environmental engineering.
- To introduce important concepts in environmental engineering.
- To introduce the quantitative approach for environmental assessment and problem solving.

Environmental Science and Engineering



Science

Social Sciences

Natural Sciences

Core Sciences

Applied Sciences

Physics

Chemi

Bi

Geology

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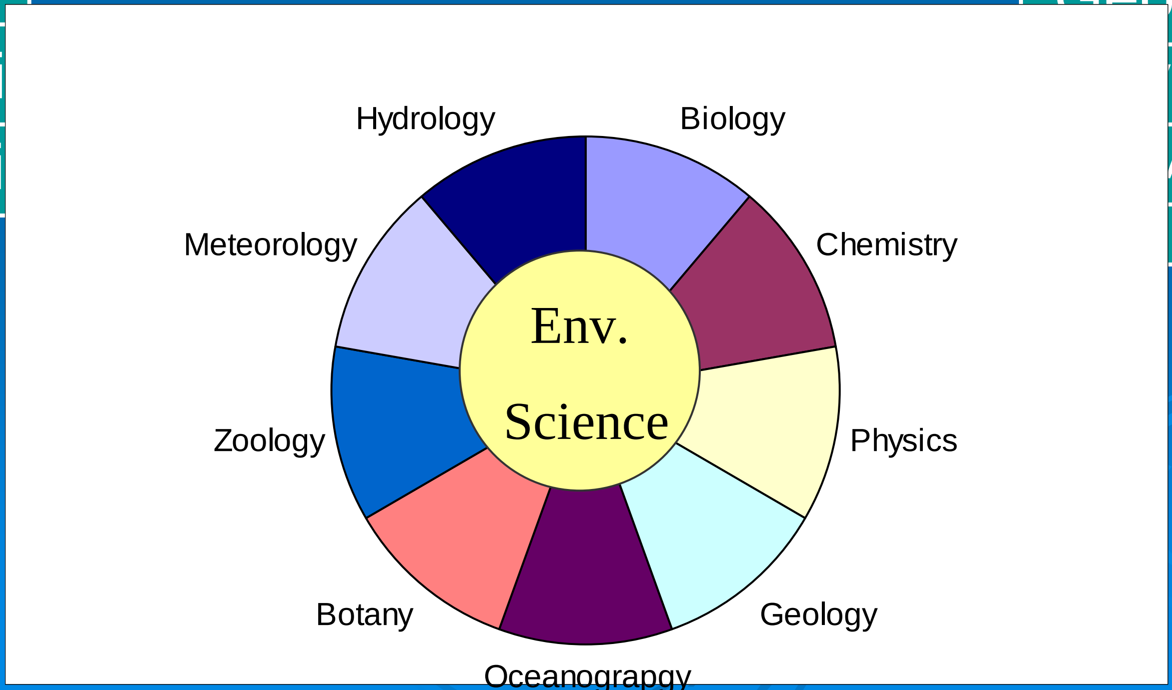
Meteorology

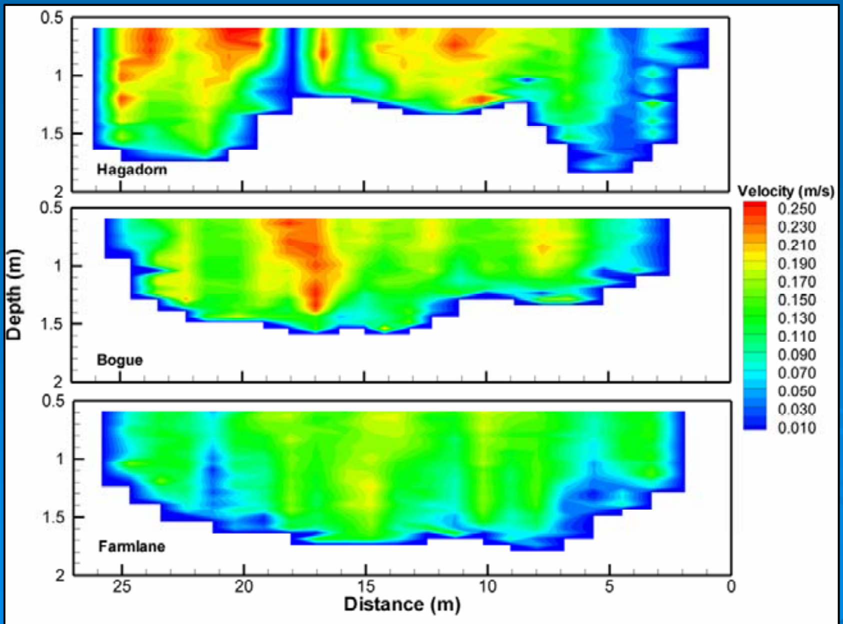


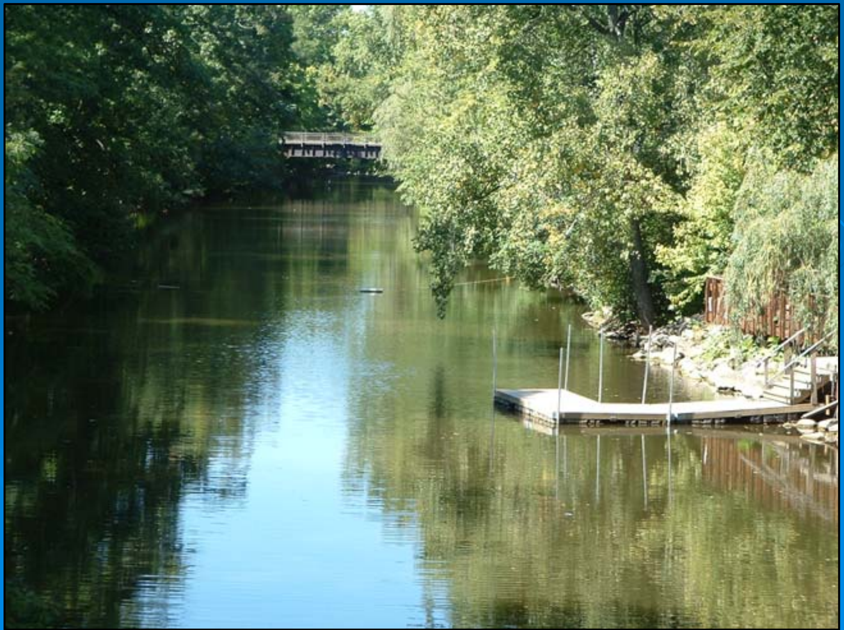
Core Areas in Environmental Engineering

- Water Resource Management
- Wastewater Treatment
- Water Quality and Water Treatment
- Solid Waste Management
- Air quality and Air Pollution control

Water Resource Management

- Hydrological Processes (precipitation, evaporation, evapotranspiration etc)
- Watershed management and water budgeting
- Surface water hydrology (Flow in streams, rivers, estuaries, lakes and reservoirs.
- Groundwater hydrology and water exploration techniques.
- Flood and drought management, water conservation and harvesting





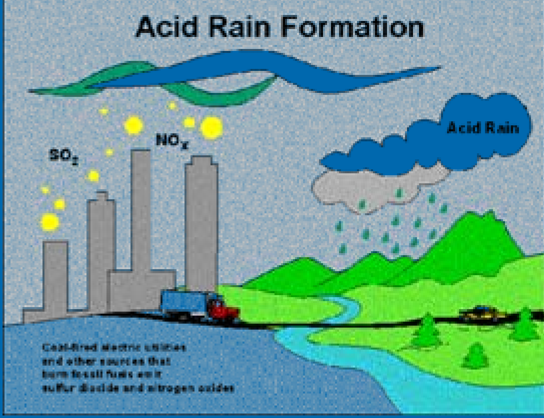
Water Quality and Water Treatment

- Physical, chemical and microbial quality
- Water pollutants, sources and their fate in the environment
- Water quality management in rivers, lakes and reservoirs
- Design of water treatment facilities

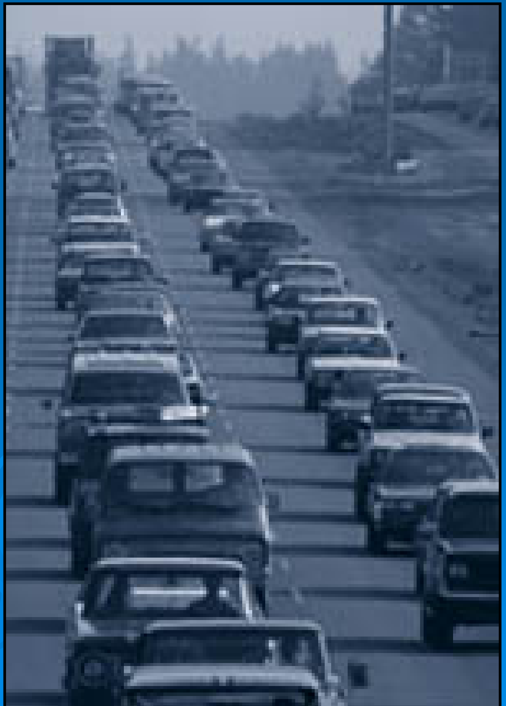
Wastewater Treatment

- Wastewater characterization
- Design of engineered systems for on-site disposal
- Municipal wastewater treatment system design
- Industrial wastewater treatment system design
- Sludge treatment and disposal

Air pollution

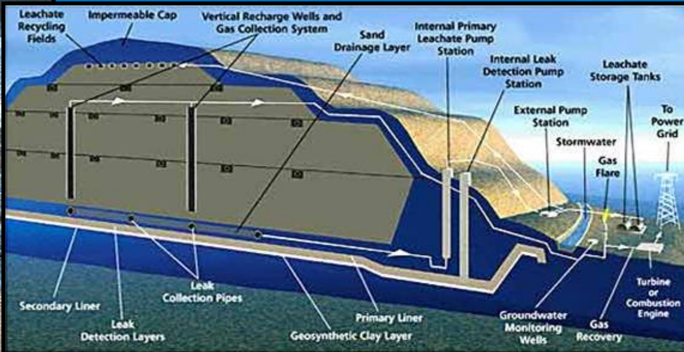


- Air pollutants and their effects
- Origin and fate of air pollutants
- Air pollution meteorology and atmospheric dispersion
- Air pollution control: indoors, mobile sources and stationary sources



Solid Waste Management

- Characterization and classification of solid waste by kind, composition and sources
- Collection, storage, transfer, and disposal
- Design and optimization collection and transfer mechanism
- Design of sanitary landfill
- Post closure landfill monitoring



Environmental Engineering- Key Elements

- **Systems approach** – includes multiple processes and interactions between these processes , defined by system boundaries
- **Based on chemistry** – environmental quality described by chemical composition
- **Quantitative** – the problem and the solution are described numerically
- **Driven by government policy**, set on the basis of risk

Systems Approach

- All systems are idealizations of the real world (defined by system boundaries)
- All systems have some structure or organization
- All systems show some degree of integration
- All systems function in some way, therefore, there are functional as well as structural relationships between the units (mass transfer)
- Scale of systems – From the global water cycle to water droplet

Chemical Substances

- Element or Compound?
  - Lead (Pb) **- element**
  - Formaldehyde (HCHO) - **compound**
- Inorganic or organic?
  - Hydrogen sulfide (H_2S) **- inorganic**
  - Benzene (C_6H_6) **- organic**
- Ionic or non-ionic?
  - Bicarbonate (HCO_3^-) **- ionic**
  - Silicon dioxide (SiO_2) **- non – ionic**
- Acid, base or salt?
  - Sulfuric acid (H_2SO_4) - **acid**
  - Sodium hydroxide (NaOH) - **base**
  - Sodium chloride (NaCl) - **salt**
- Gas, liquid, or solid?
  - Nitrogen dioxide (NO_2) - **gas**
  - Water (H_2O) - **liquid**
  - Calcium carbonate ($CaCO_3$) - **solid**

Concentration Units

- **Liquids**
  - most common - *mass of substance per unit volume of mixture*, e.g. mg/L, µg/L, g/m^3
  - alternatively - *mass of substance per mass of mixture*, e.g. ppm or ppb
  - occasionally - *molar concentrations*, e.g. moles/liter (M) or equivalents/liter (N)
- **Solids**
  - mass ratios (µg/kg)
  - weight percent (e.g., “4% by weight” means that 4 parts out of 100 of the mass is the contaminant species of interest.
  - 4% by weight means 0.04 kg per kg, or 40 g/kg.
- **Gases**
  - volume ratio - concentrations are independent of pressure and temperature changes

$$1\ \text{ppmv} = \frac{1\ \text{volume of gaseous pollutant}}{10^6\ \text{volumes of air}}$$

Stoichiometry

- **Stoichiometry** is the formation of balanced equations
- A balanced chemical equations describes:
  - Qualitative information on what reacts with what and what is formed
  - Quantitative information on how much reacts and how much is formed

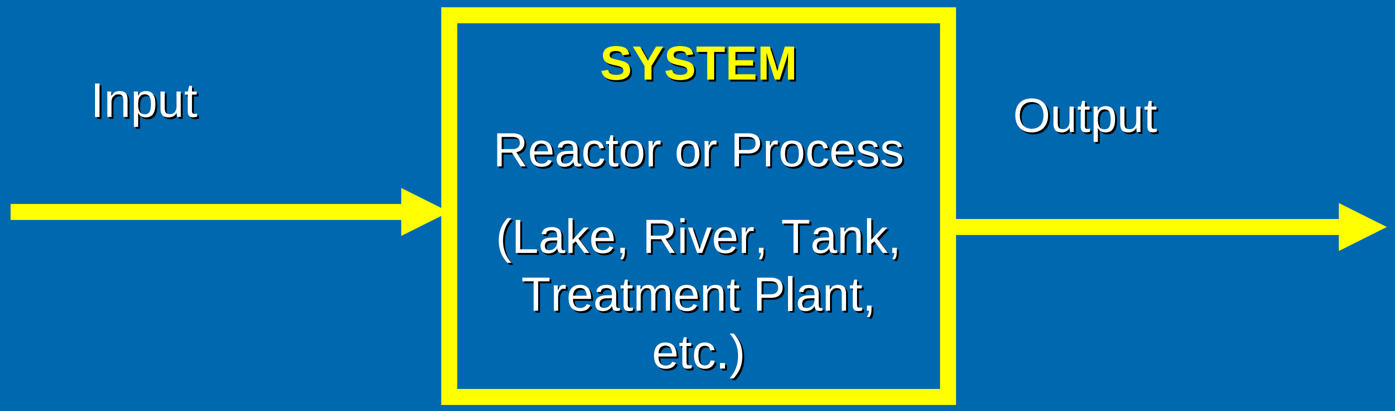
(unbalanced) $C_3H_8 + O_2 = CO_2 + H_2O$

(propane)

(Balanced) $C_3H_8 + 5\ O_2 = 3\ CO_2 + 4\ H_2O$

Each mole of propane requires 5 moles O_2

Mass Balance for Quantification



Input

SYSTEM

Reactor or Process

(Lake, River, Tank, Treatment Plant, etc.)

Output

[accumulation rate]= [input rate] - [output rate] ± [reaction rate]

Mass of substance accumulated in system per unit time

=

Mass of substance entering system per unit time

-

Mass of substance leaving system per unit time

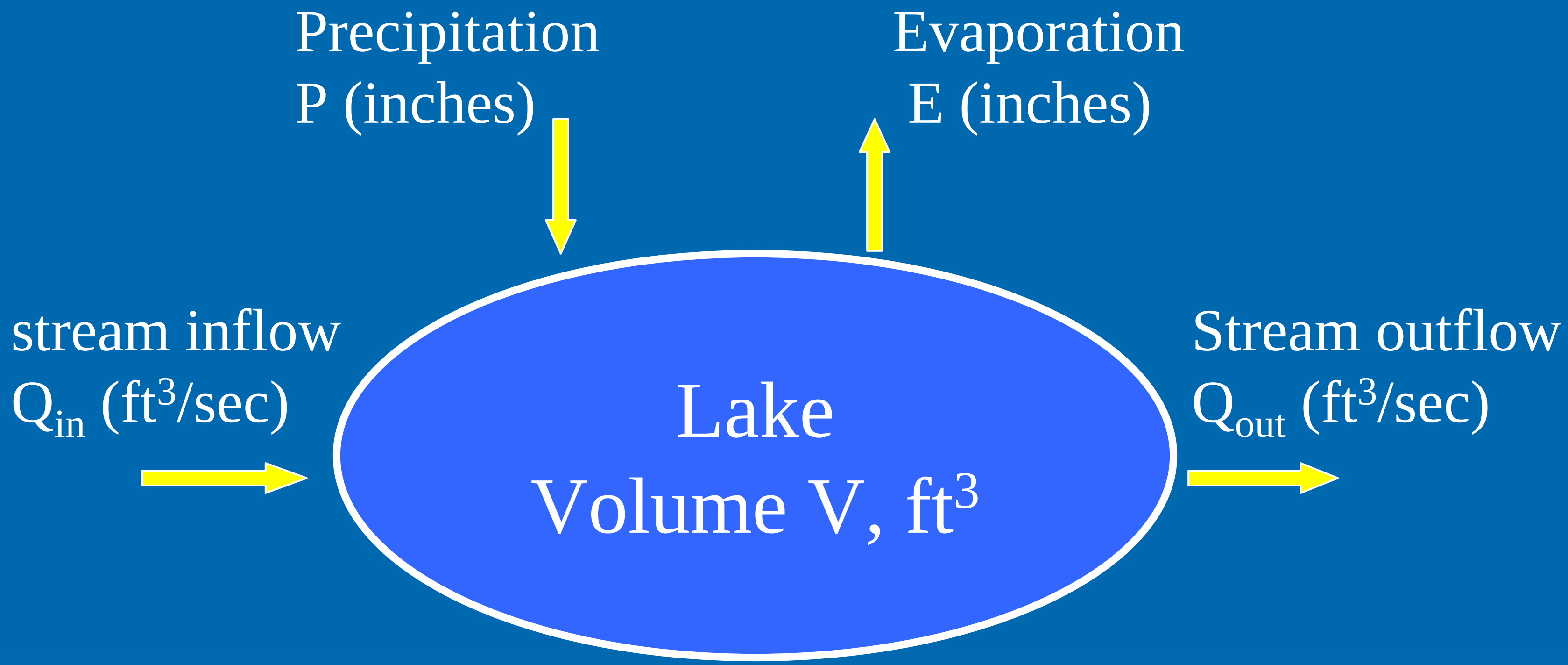
+

Mass of substance produced per unit time

-

Mass of substance consumed per unit time

Mass Balance on Water in a Lake



Precipitation
P (inches)

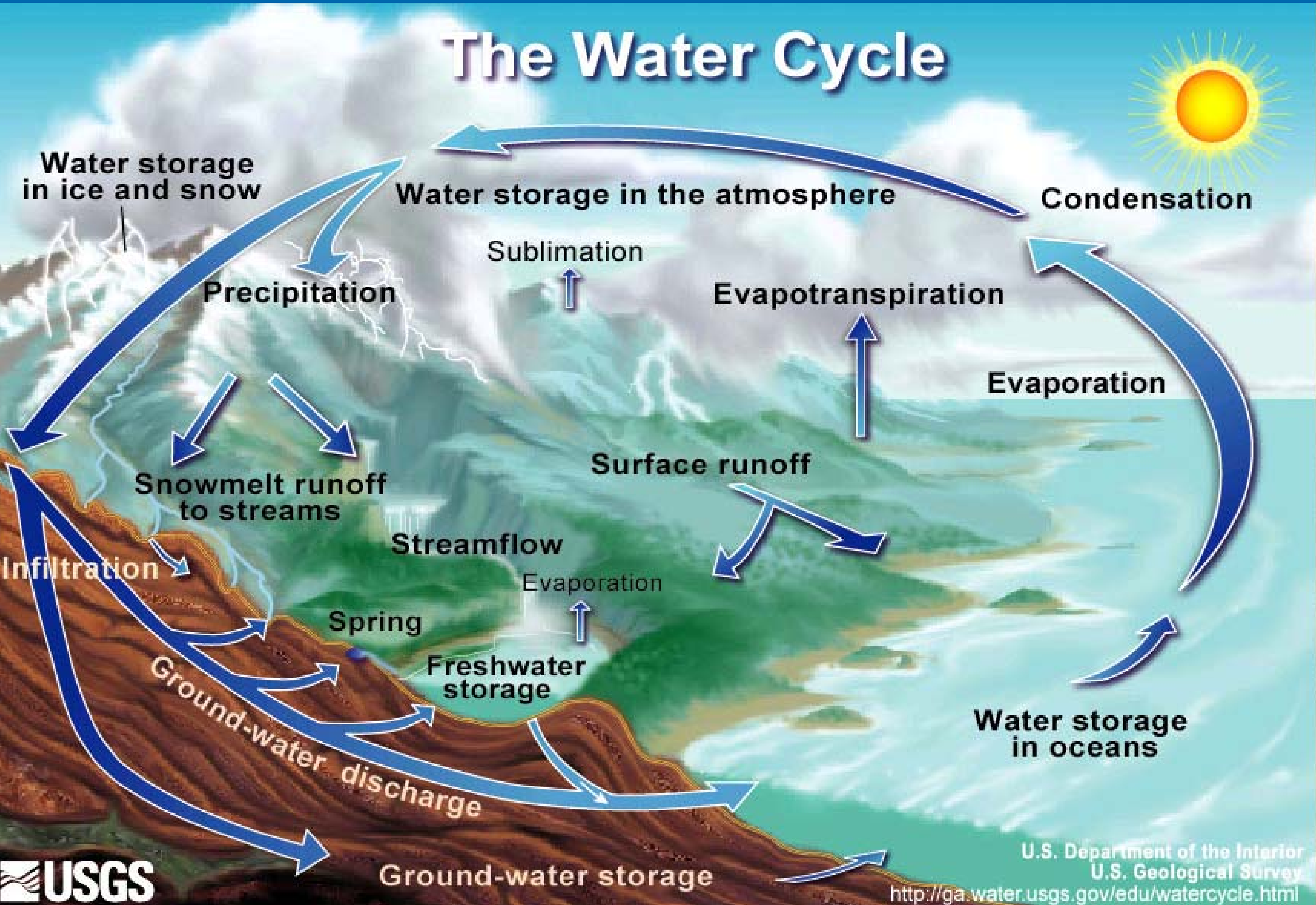
Evaporation
E (inches)

stream inflow
Q_{in} (ft^3/sec)

Lake
Volume V, ft^3

Stream outflow
Q_{out} (ft^3/sec)

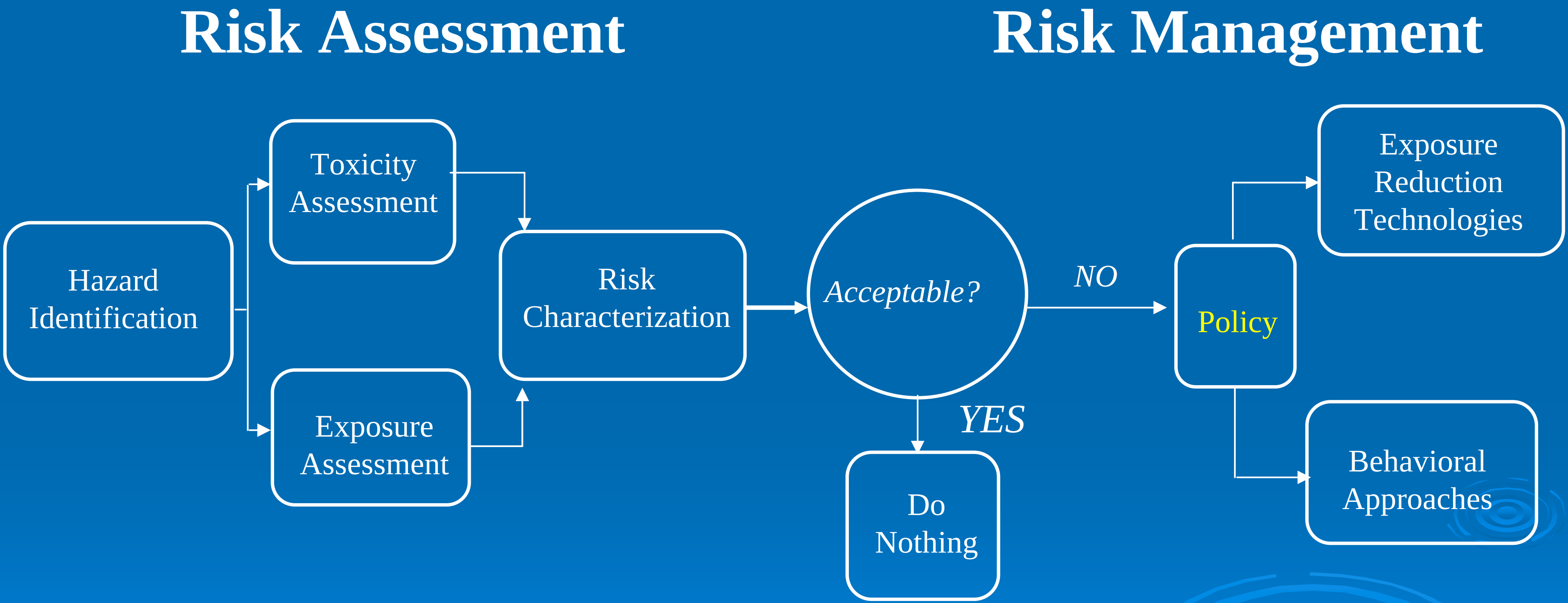
- [accumulation] = [input] – [output] ± [reaction]
- change in lake volume per unit time = inflow rate + precipitation rate – outflow rate - evaporation rate



The Water Cycle

U.S. Department of the Interior
U.S. Geological Survey
http://ga.water.usgs.gov/edu/watercycle.html

Risk



Risk Assessment

Risk Management

Hazard Identification

Toxicity Assessment

Exposure Assessment

Risk Characterization

Acceptable?

NO

Policy

Exposure Reduction Technologies

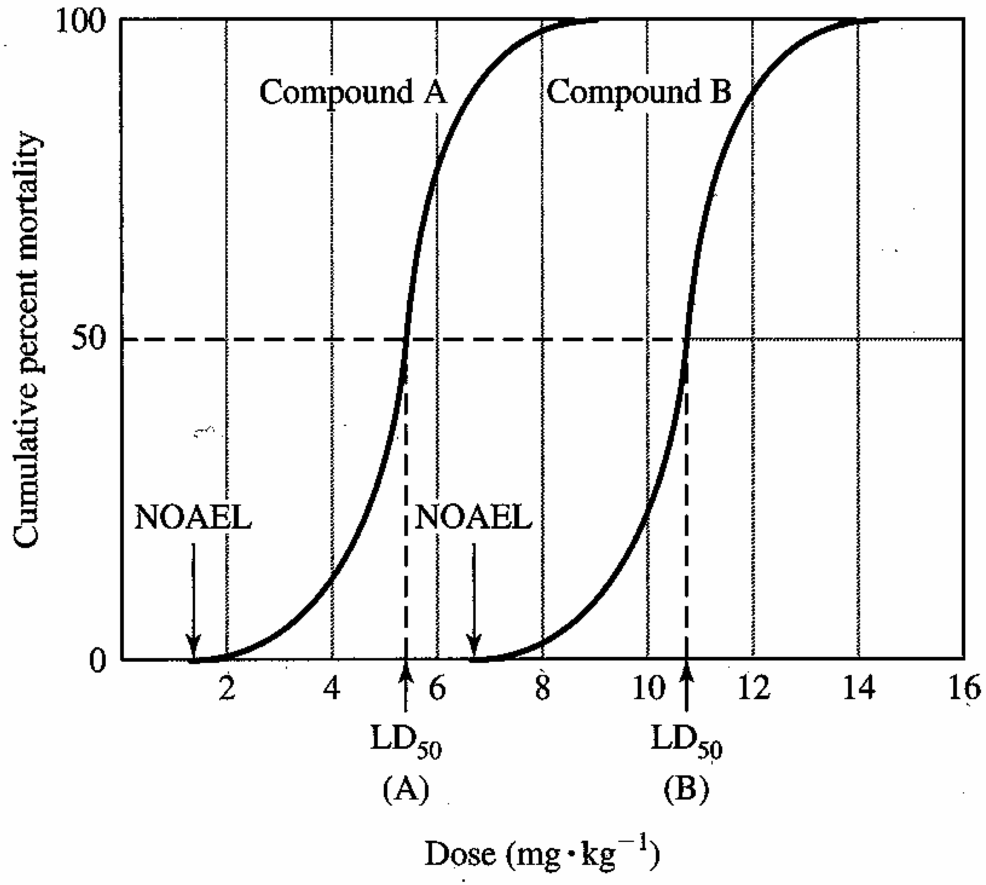
Behavioral Approaches

YES

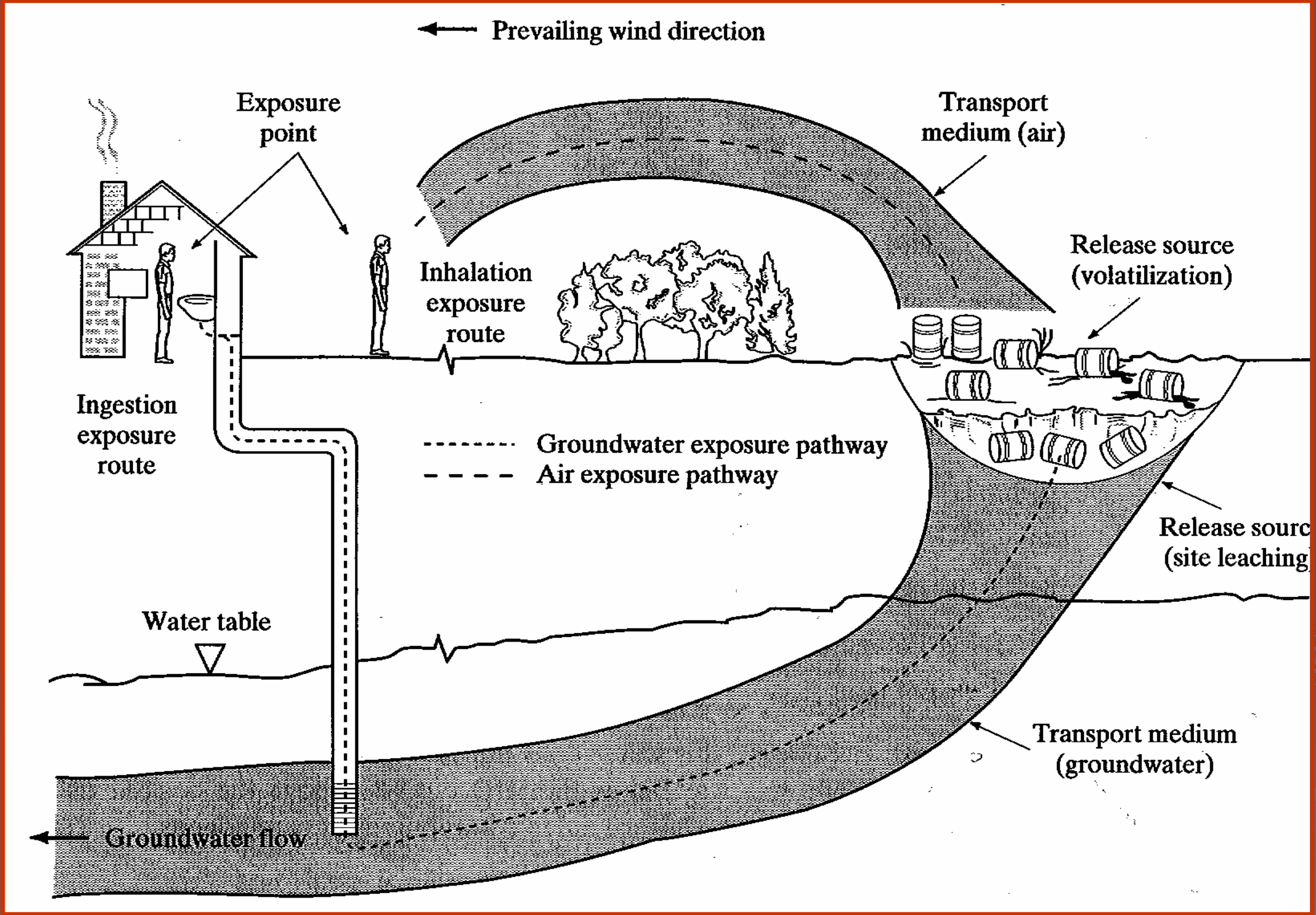
Do Nothing

Toxicity Assessment

Hypothetical dose-response curves for two chemical agents (A and B) administered to a uniform population. NOAEL = no observed adverse effect level.



Exposure Assessment

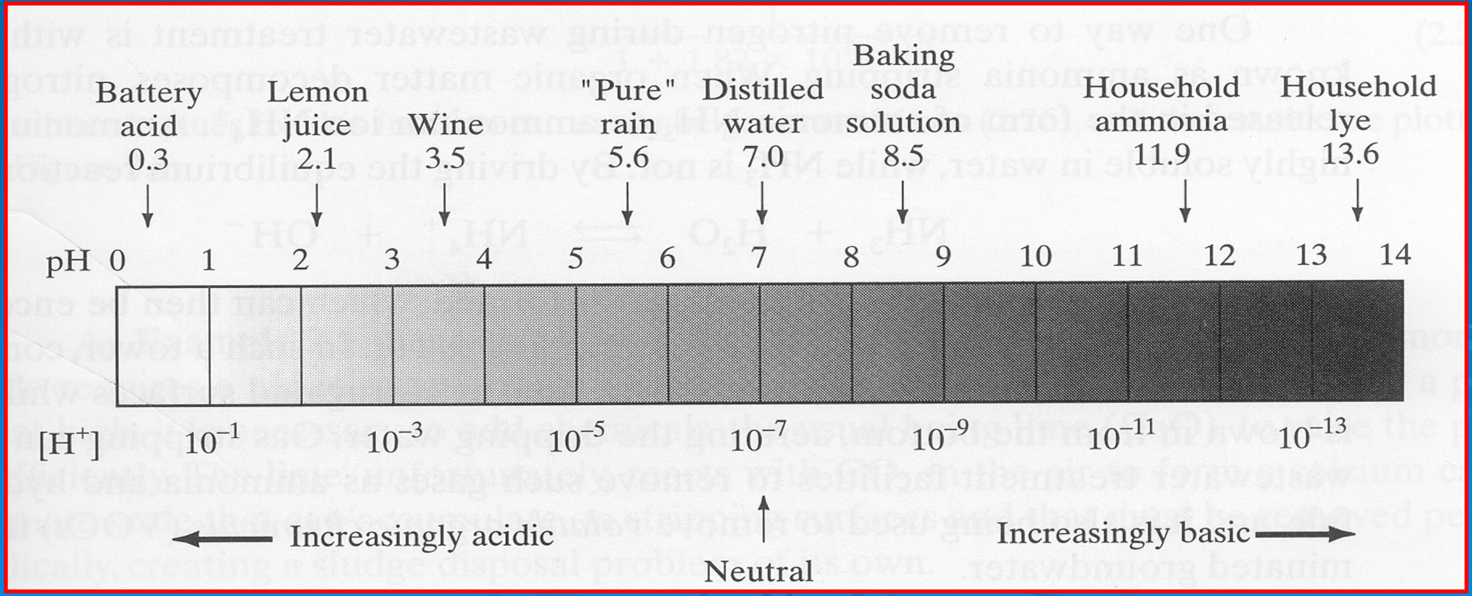


Significant Terms

- pH scale
- Dissolved oxygen (DO) and Biochemical oxygen demand (BOD)
- Contaminant fate and transport

pH Scale

- $\text{pH} = -\log_{10}[H^+]$
- Acidic solutions $[H^+] > [OH^-]$
- Basic solutions $[OH^-] > [H^+]$
- H^+ and OH^- can vary over many orders of magnitude so we use a log scale
- 1 pH unit corresponds to a 10 x concentration change



Significance of pH

- Sensitivity of the aquatic organisms to pH changes (waste neutralization before release of effluents to protect local ecosystems)
- Effects the equilibrium between a variety of chemical and biochemical reactions (chemical speciation)
  - Ammonia (NH_3) and ammonium ion (NH_4^+).
  - Hydrogen sulfide (H_2S) and bisulfide ion (HS^-).
  - Aluminum mobilization
- Effects the corrosivity potential of water
- Toxicity of most metals varies with pH
- Manipulation of the pH to drive out unwanted chemicals from the solution as precipitates or gases
  - Ammonia stripping (wastewater treatment)

$$\mathbf{NH_3 + H_2O \rightleftharpoons NH_4^+ + OH^-}$$

$$K_{NH_3} = \frac{[NH_4^+][OH^-]}{[NH_3]} = 1.82 \times 10^{-5}$$

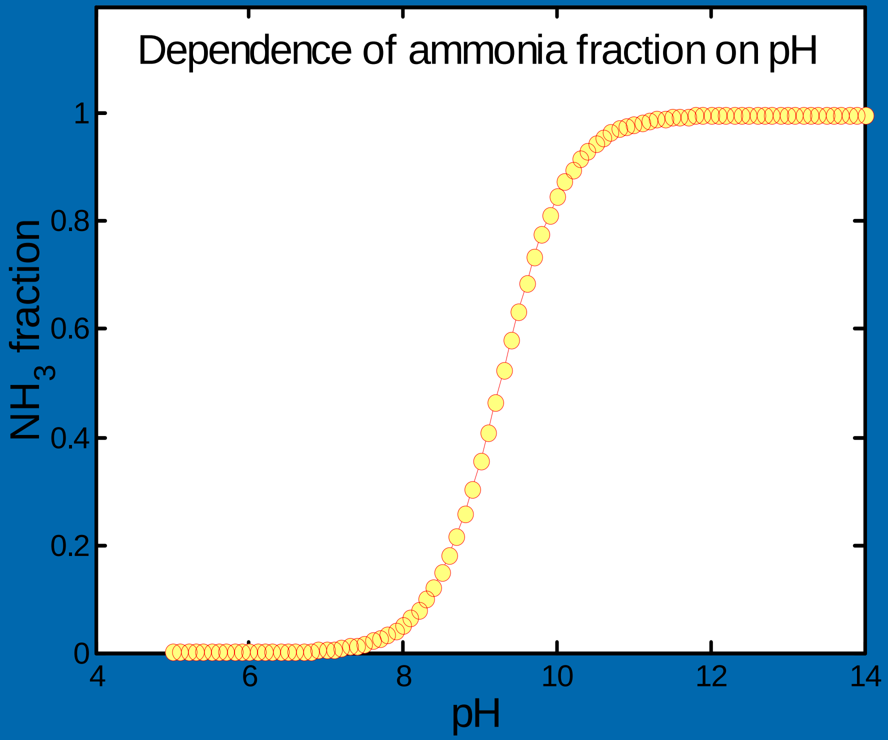
$$\mathbf{NH_3\ fraction} = \frac{[NH_3]}{[NH_3]+[NH_4^+]} = \frac{1}{1+[NH_4^+]/[NH_3]}$$

$$\mathbf{Also}\ [H^+]+[OH^-] = K_w = 10^{-14}$$

$$\mathbf{And}\ \frac{[NH_4^+]}{[NH_3]} = \frac{K_{NH_3}}{[OH^-]} = \frac{K_{NH_3}}{K_w/[H^+]},\ \mathbf{Therefore:}$$

$$\mathbf{NH_3\ fraction} = \frac{1}{1+\frac{K_{NH_3}}{K_w/[H^+]}} = \frac{1}{1+(1.82x10^{-5}x10^{-pH})/10^{-14}}$$

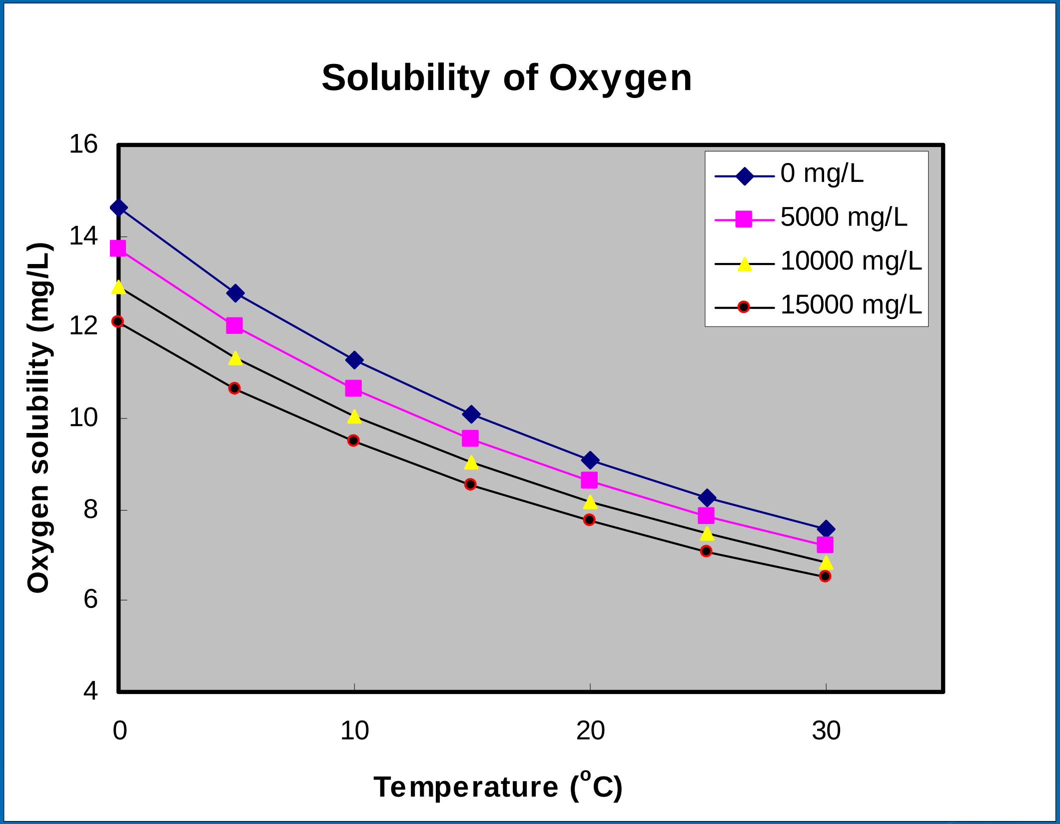
$$\mathbf{NH_3\ fraction} = \frac{1}{1+(1.82x10^{9-pH})}$$



To ensure that most is available in the form of ammonia and hence can be stripped, pH needs to be in excess of approximately 10.

Dissolved Oxygen (DO)

- Composition of air (78% N, 21% O_2 + other gases in trace amounts)
- Gases dissolve in water based on "Henry's law"
- Oxygen solubility is a function of **Temperature and salinity**



Oxygen Demand

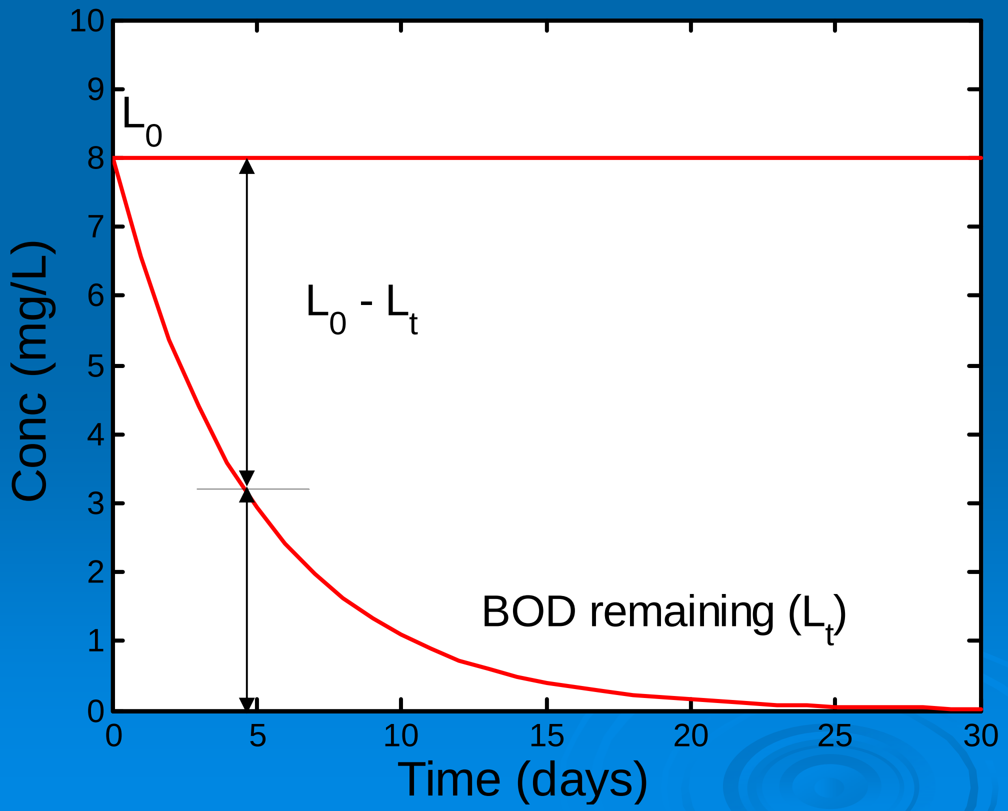
- **Theoretical oxygen demand (ThOD)** - O_2 required to completely oxidize a chemical substance to CO_2 and H_2O. Based on stoichiometry.
- **Chemical oxygen demand (COD)** – O_2 required to completely oxidize a chemical substance to CO_2 and H_2O using a strong chemical oxidant (standard test).
- **Biochemical oxygen demand (BOD)** - The amount of oxygen required by microorganisms to oxidize organic wastes aerobically (i.e., in presence of oxygen).
  - Expressed as mg of O_2 required per liter of wastewater (mg/L)
  - Two components:
    - **Carbonaceous** biochemical oxygen demand (CBOD)
    - **Nitrogenous** biochemical oxygen demand (NBOD)

BOD$_5$ Measurement

- Take sample of waste; dilute with oxygen saturated water; add nutrients and microorganisms (seed)
- Measure dissolved oxygen (DO) levels over 5 days
- Temperature 20° C
- In dark (prevents algae from growing)
- Final DO concentration must be > 2 mg/L
- Need at least 2 mg/L change in DO over 5 days

Modeling BOD Reactions

Assume rate of decomposition of organic waste is proportional to the waste that is left in the flask



L_t = BOD remaining at any time t

L_0 = Ultimate BOD (i.e., no BOD has been exterted so far)

$$\frac{dL_t}{dt} = -kL_t$$

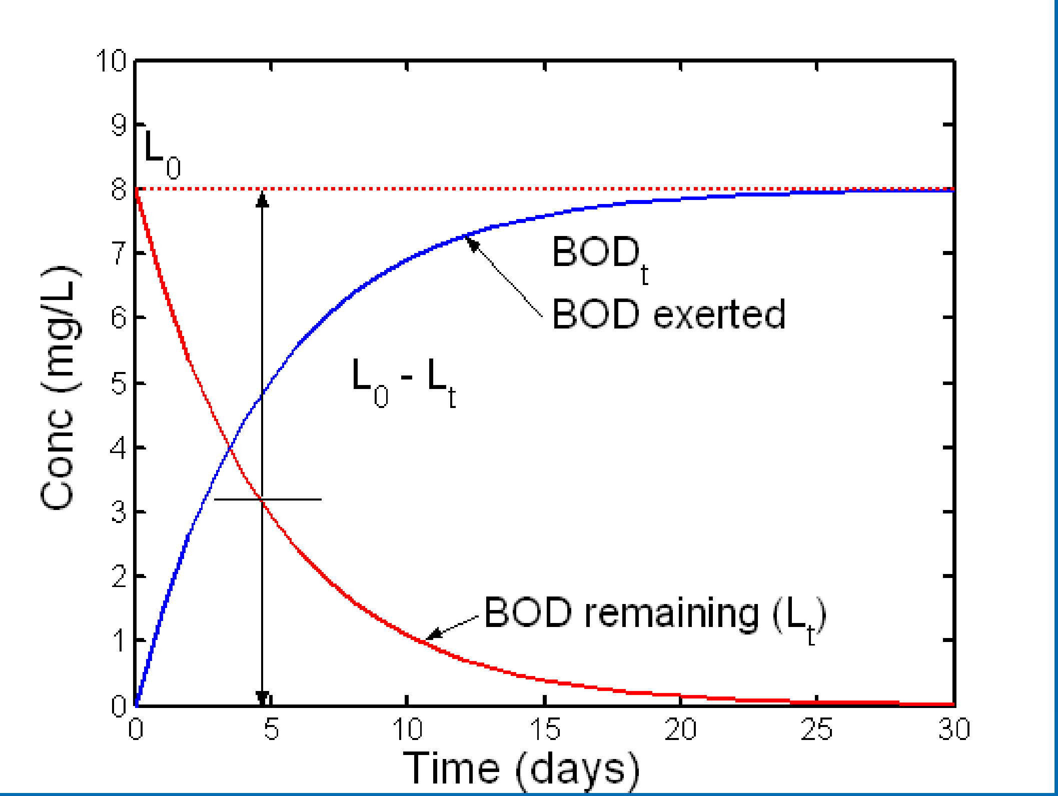
Solving from time time t=0 to time t,

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

Where :

k = BOD rate constant (time^{-1})

Ultimate BOD



At any time t,

$L_0 = L_t + BOD_t$

or

$BOD_t = L_0 - L_t$

Since $L_t = L_0 e^{-kt}$, therefore

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

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

BOD reaction rate constant *k*

- Indicates the rate of biodegradation
- As k increases, the rate at which DO is used, increases
- Depends on a number of factors:
  - **Nature of the waste** (e.g. starches and simple sugars degrade easily while cellulose doesnot)
  - **Ability of microorganisms** to degrade the waste in question
  - **Temperature**. The As temperature increases, metabolism increases, utilization of DO also increases

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

$\theta = 1.135$ if T is between 4 - 20 ^{o}C

$\theta = 1.056$ if T is between 20 - 30 ^{o}C

$\theta = 1.047$ (Most commonly used value)

Nitrogenous BOD

- Many other compounds, such as proteins, consume oxygen. When living things die, nitrogen tied to complex organic molecules is converted to ammonia by bacteria and fungi
- The ammonia is then converted to nitrate by a two-step process by different bacteria in each step. This process of converting ammonia to nitrate as a whole is termed as "Nitrification"

$$2NH_3 + 3O_2 \xrightarrow{\text{Nitrosomonas}} 2NO_2^- + 2H^+ + 2H_2O \text{............(Step 1)}$$

$$2NO_2^- + O_2 \xrightarrow{\text{Nitrobacter}} 2NO_3^- \text{..(Step 2)}$$

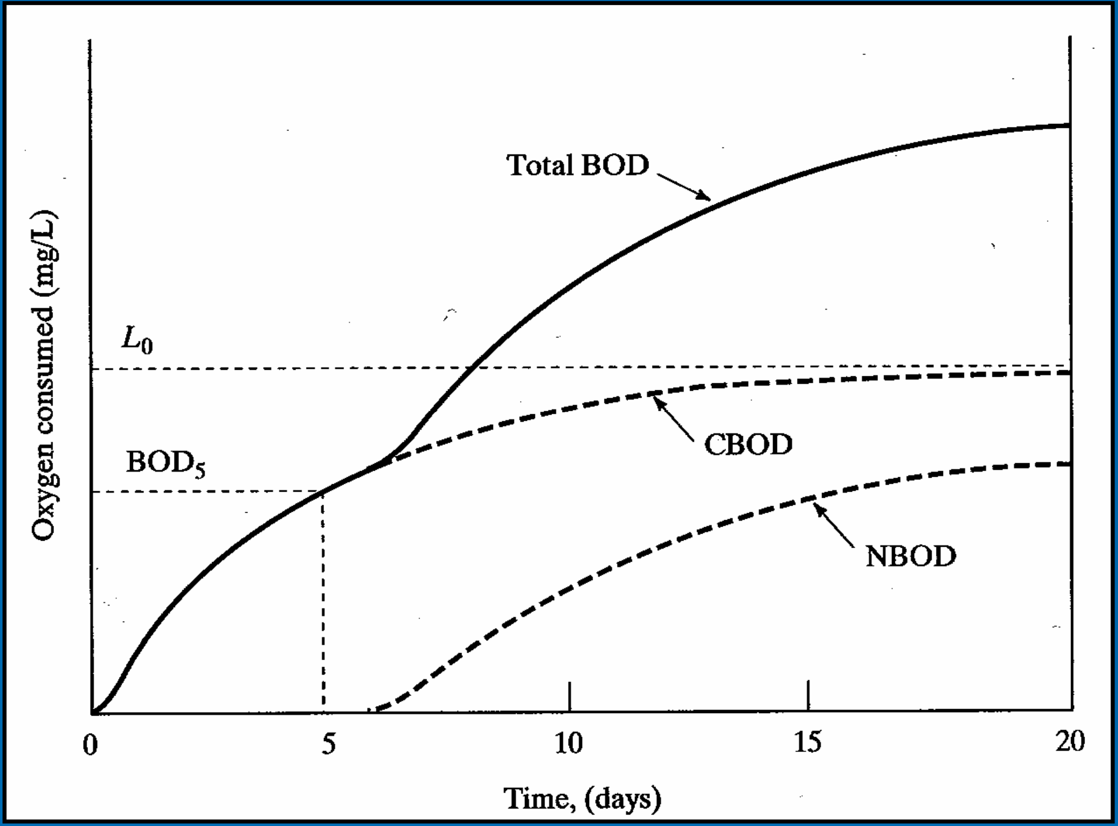
Over all reaction:

$$NH_3 + 2O_2 \longrightarrow NO_3^- + H^+ + H_2O$$

$$\text{Theoretical NBOD} = \frac{\text{grams of oxygen used}}{\text{gram of Nitrogen oxidized}}$$

$$\text{Theoretical NBOD} = \frac{2 \text{ x } 32}{14} = 4.57 \ \frac{\text{g } O_2}{\text{g of N}}$$

Nitrogenous BOD



- **NBOD** doesnot begin to exert for **5-8** days, so 5 day tests are not affected
- Typical values for untreated domestic waste water:

ultimate-**CBOD** = 250 - 350 mg/L

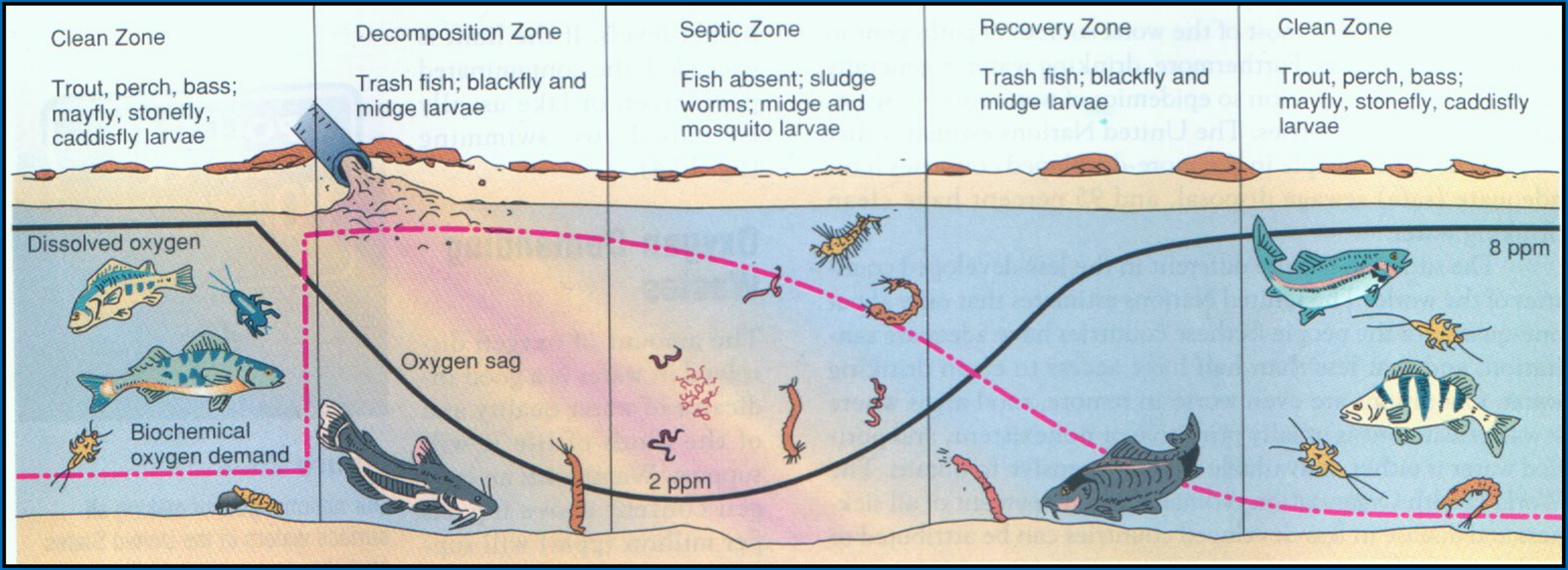
ultimate-**NBOD** = 70 - 230 mg/L

TKN (Total Kjeldahl Nitrogen) is the total concentration of organic and ammonia nitrogen in wastewater (Typical values: 15-50 mg/L as N)

NBOD is also considerable (70-230 mg/L)

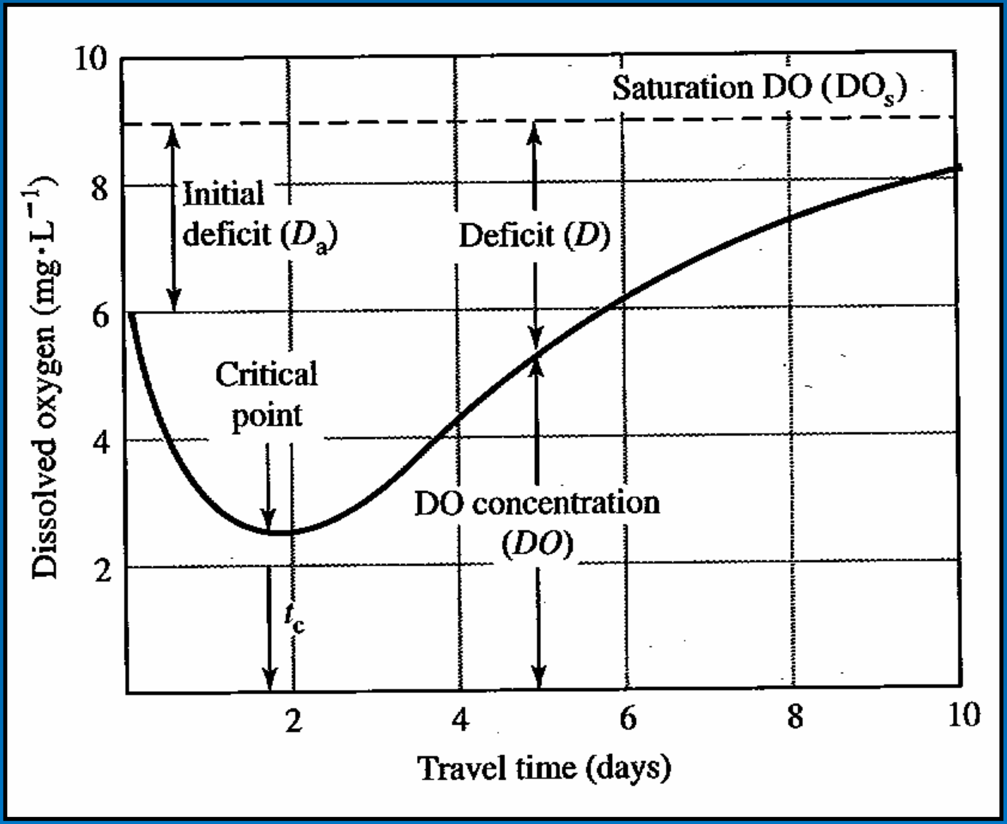
Ultimate NBOD ≈ 4.57 x TKN

Dissolved Oxygen (DO) Depletion in Surface Waters



(From: Environmental Science: A Global Concern, 3rd ed. by W.P Cunningham and B.W. Saigo, WC Brown Publishers, © 1995)

Dissolved Oxygen Sag Curve

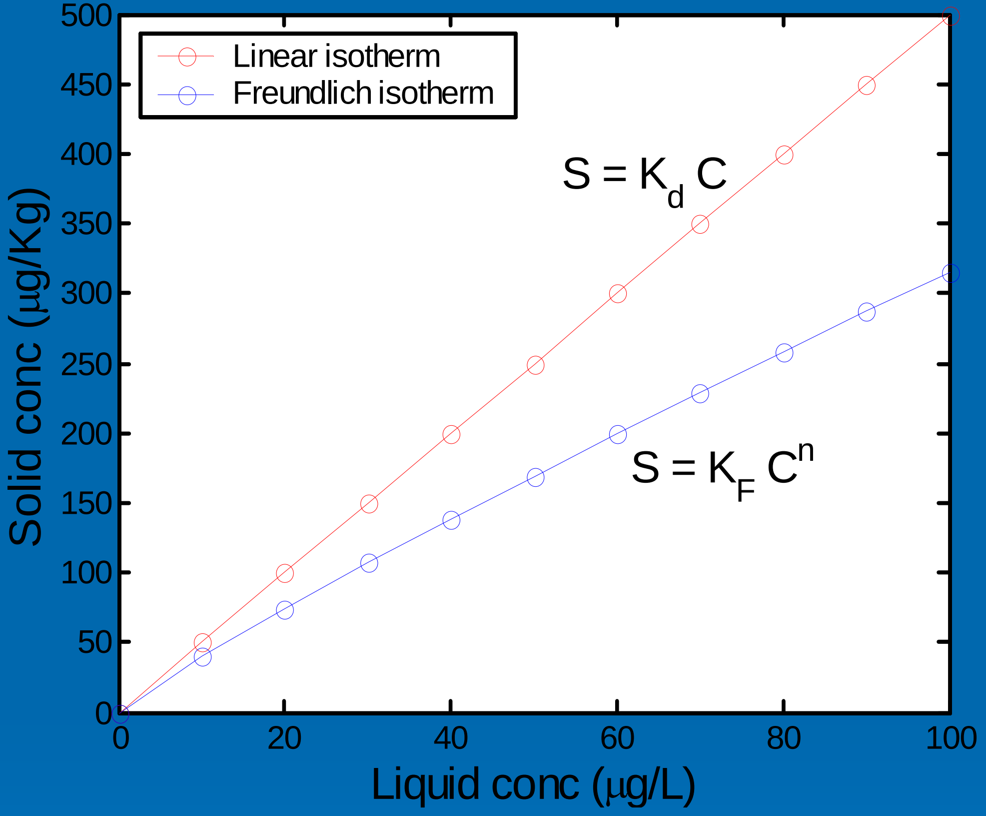


- Originally developed by H.W. Streeter and E.B. Phelps in 1925
- River described as "plug-flow reactor"
- Mass balance is simplified by selection of system boundaries
- Oxygen is depleted by BOD exertion
- Oxygen is gained through reaeration

Contaminant Fate and Transport

- Mass balance approach
- Need to describe the system
  - Surface (overland, surface water)
  - Sub-surface (vadoze zone, saturated zone)
- Assumptions depending upon the simplicity or complexity of the system and objectives
- Mathematical models for:
  - Ground water flow and transport
  - Surface water flow and transport
  - Use of GIS
  - Selection of model based on objectives, level of analysis and data availability

Soil-water Partitioning



K_d = Linear partitioning coefficient

K_F = Freundlich coefficient

S = Sorbed phase concentration

C = Liquid phase concentration

$K_{oc} = K_p/f_{oc}$

Where:

K_{oc} = organic carbon normalized partition coefficient (L/kg)

f_{oc} = mass fraction of organic carbon in soil (dimensionless)

Conservative Pollutant in Water

- Now, consider a chemical that enters and leaves a lake via the stream, but not by evaporation or precipitation, and which does not degrade

$$\frac{dM}{dt} = (Q_{in}C_{in}) - (Q_{out}C_{out})$$

$$\left(\frac{g}{sec}\right) = \left(\frac{m^3}{sec}\,\frac{mg}{L}\right) - \left(\frac{m^3}{sec}\,\frac{mg}{L}\right)$$

M = mass of chemical (g)
t = time (sec)
Q = flow rate (m^3/sec)
C = concentration (mg/L)

Are units consitent ?

$$\frac{dM}{dt} = \left(Q_{in}C_{in} - Q_{out}C_{out}\right)\frac{\cancel{m^3}}{sec}\,\frac{\cancel{mg}}{\cancel{L}} \; x\, 10^3\,\frac{\cancel{L}}{\cancel{m^3}} \; x10^{-3}\,\frac{g}{\cancel{mg}}$$

$$\left(\frac{g}{sec}\right) = \left(\frac{g}{sec}\right)$$

Units on both side of equation are consistent

Non-conservative Pollutants

- Most pollutants degrade over time and the rate of decay is proportional to the amount present
- Simplest way to describe is by a first-order reaction

$$\frac{dC}{dt} = -kC$$

- [accumulation]= [input] – [output] ± [reaction]

$$V\frac{dC}{dt} = Q_{in}C_{in} + Q_wC_w - Q_{out}C_{out} - kC_{out}V$$

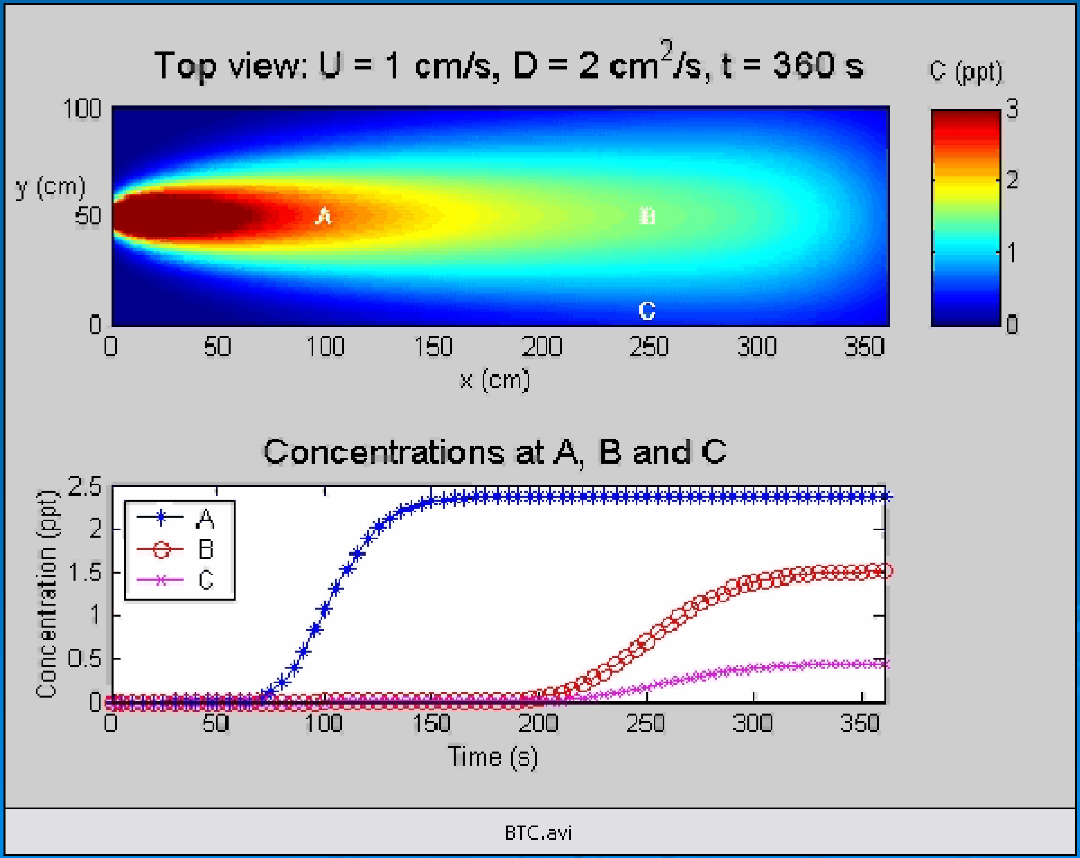
$$At\ steady-state,\ \frac{dC}{dt} = 0,\ therefore$$

$$0 = Q_{in}C_{in} + Q_wC_w - Q_{out}C_{out} - kC_{out}V$$

$$For\ a\ transient\ case,\ \frac{dC}{dt} \neq 0,$$

so we need to solve the differential equation

Contaminant Transport



Thank you