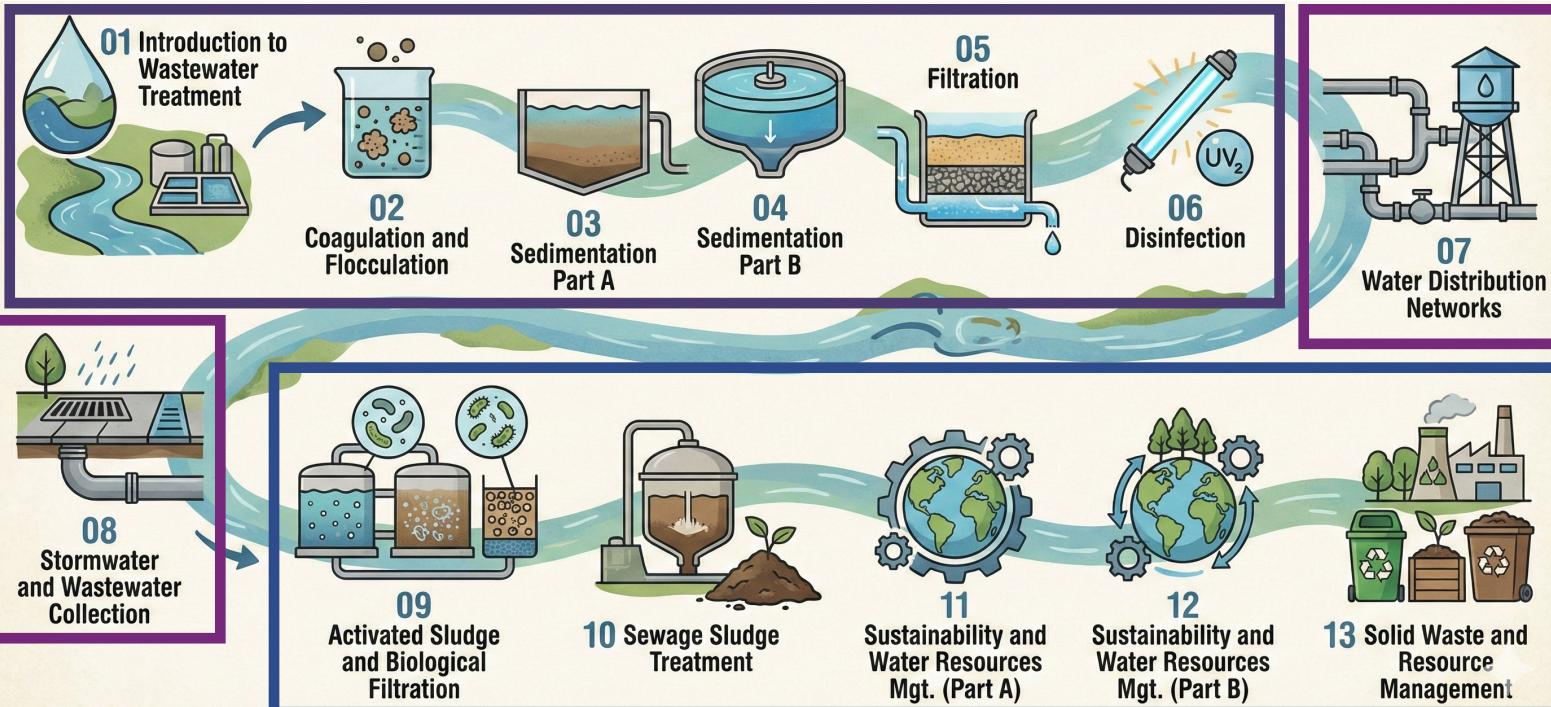


Table of Content



(L1 - L6: Traditional Water Treatment Process, L7 - L8: Water Distribution Network Management, L9 - L13: Post Treatment Phase)

NOTE THAT THIS NOTE IS ENTIRELY GENERATED BY AI, WITH LOTS OF MODIFICATION BY MYSELF, CORRECTING ERROR AND HALLUCINATIONS. HOWEVER I CANT GUARANTEE IT IS PERFECT AND THERE MIGHT BE SOME ERROR HIDDEN, AND I WOULD DEFINITELY APPRECIATE ANY REPORTS OF ERROR IF YOU CAN FIND ONE. THANKS.

Lecture 1: Introduction to Wastewater Treatment

FOUNDATIONAL CONCEPTS: SOLIDS & ORGANICS

UNDERSTANDING THE SOLIDS MATRIX

Diagram illustrating the classification of solids:

- ALL SOLIDS** (represented by a circle) is divided into **SUSPENDED** (represented by a cloud) and **DISSOLVED** (represented by small circles).
- SUSPENDED** solids are further categorized:
 - ORGANIC (VOLATILE)**: Solids that will burn at ignition 550°C (represented by a flame icon).
 - INORGANIC (FIXED)**: Ash that remains after ignition (represented by a furnace icon).
- ORGANIC (VOLATILE)** is subdivided into **TOTAL SOLIDS (TS)** and **INORGANIC (SOLUBLE)**.
- INORGANIC (SOLUBLE)** is subdivided into **particulate** (e.g., bacteria) and **soluble** (e.g., sugar).
- particulate** is subdivided into **particulate organic** (e.g., bacteria) and **particulate inorganic** (e.g., sand, silt).
- soluble** is subdivided into **soluble organic** (e.g., sugar) and **soluble inorganic** (e.g., salts).

Definitions:

- T : Total
- S : Solids or Suspended
- D : Dissolved
- V : Volatile
- F : Fixed

CALCULATION GUIDE 1: SOLIDS ANALYSIS

EXAMPLE PROBLEM WALKTHROUGH (BASED ON A 100 mL (0.1 L) SAMPLE)

Given data:

- EMPTY DISH: 81.923 g
- DISH + DRY SOLIDS: 82.015 g (TS)
- DISH + ASH: 81.975 g (FS)
- EMPTY DISH: 81.923 g
- DISH + DRY SOLIDS (AT 105°C): 82.015 g
- DISH + ASH (AT 550°C):

Calculated values:

- Mass = 82.015 - 81.923 = 0.092 g (92 mg).
- Concentration = $\frac{92 \text{ mg}}{0.1 \text{ L}} = 920 \text{ mg/L}$

CALCULATION GUIDE 2: BOD ANALYSIS

BASIC BOD FORMULA

$$\text{BOD}_5 = \frac{D_1 - D_2}{P}$$

Definitions:

- D₁: Initial Dissolved Oxygen (DO)
- D₂: Final DO
- P: Dilution Factor

BOD KINETICS FORMULA

$$L_t = L_u(1 - 10^{-kt})$$

Definitions:

- L_t: BOD at time t (days)
- L_u: Ultimate BOD
- k: Reaction rate constant

Graph showing BOD kinetics over time.

BOD vs. COD: MEASURING ORGANIC CONTENT

BIOCHEMICAL OXYGEN DEMAND (BOD): Measures the oxygen consumed by microorganisms to deplete organic matter. $\text{BOD}_5 < \text{BOD}_{20} < \text{COD}$

CHEMICAL OXYGEN DEMAND (COD): Measures the oxygen equivalent to chemically oxidize organic matter using a strong chemical agent, taking only a few hours.

Key finding: If $\text{BOD}_5/\text{COD} > 0.5$, the wastewater is considered easily biodegradable and suitable for biological treatment.

1. CALCULATE TOTAL SOLIDS (TS) CONCENTRATION

Mass = 82.015 - 81.923 = 0.092 g (92 mg).
 Concentration = $\frac{92 \text{ mg}}{0.1 \text{ L}} = 920 \text{ mg/L}$

2. CALCULATE VOLATILE SOLIDS (VS) CONCENTRATION

Mass Lost = 82.015 - 81.975 = 0.040 g (40 mg).
 Concentration = $\frac{40 \text{ mg}}{0.1 \text{ L}} = 400 \text{ mg/L}$

3. CALCULATE FIXED SOLIDS (FS) CONCENTRATION

FS = TS - VS. Or you can straightaway calculate "Dish + Ash" - "Dish".
 Concentration = 920 - 400 = 520 mg/L

EXAMPLE PROBLEM WALKTHROUGH

Given data:

- 5 mL WASTEWATER SAMPLE ADDED TO 300 mL BOTTLE
- INITIAL DO = 8.4 mg/L
- FINAL DO = 3.7 mg/L
- k = 0.1 d⁻¹

Calculated values:

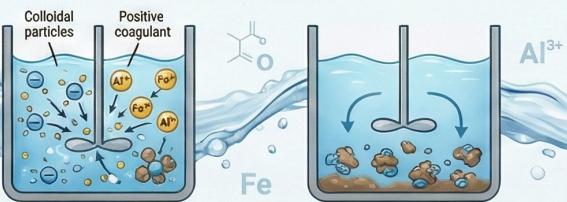
- 1. CALCULATE DILUTION FACTOR (P)**
 $P = \frac{\text{Volume of Wastewater}}{\text{Total Volume}} = \frac{5 \text{ mL}}{300 \text{ mL}} = 0.0167$
- 2. CALCULATE BOD₅**
 $\frac{8.4 - 3.7}{0.0167} = 282 \text{ mg/L}$ 282 mg/L
- 3. CALCULATE ULTIMATE BOD (L_u)**
 $L_u = \frac{282}{1 - 10^{-0.1 \times 0.145}} = 412 \text{ mg/L}$
- 4. CALCULATE 20-DAY BOD (L₂₀)**
 $L_{20} = L_u(1 - 10^{-kt}) = 412 * (1 - 10^{-(0.1 \times 20)}) = 408 \text{ mg/L}$

*IF INSTEAD OF WEIGHT OF DISH, IT'S WEIGHT OF GLASS FIBRE FILTER DISH:
 THE RESULTS WOULD BE TSS, VSS, AND VSS (CAUSE WHAT LEFT ON THE FILTER IS SUSPENDED SOLIDS)

Graph showing BOD kinetics over time for different organic matter types (high k, low k, carbonaceous).

Lecture 2: Coagulation and Flocculation

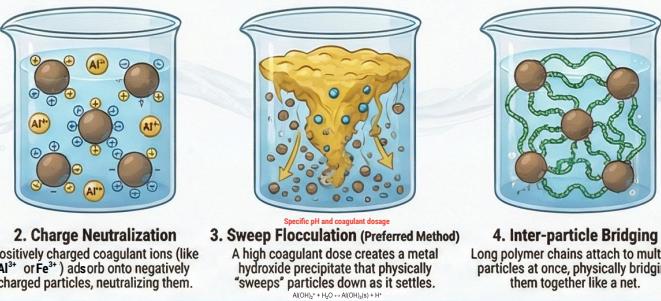
The Two-Step Process: Coagulation vs. Flocculation



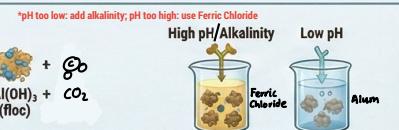
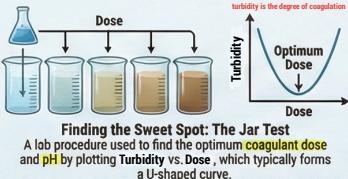
Coagulation: Destabilize Particles
The addition of chemicals (coagulants) under fast mixing conditions to neutralize the charge of colloidal particles. (colloidal particles are usually negatively charged)

Flocculation: Build Flocs
A slow mixing process that causes destabilized particles to collide and form larger, settleable aggregates called "floc".

The 4 Mechanisms of Coagulation (Exam Favorite)



Practical Application & Key Concepts



When to Use Ferric Chloride
For water with high pH or high alkalinity, Ferric Chloride is often preferred over Alum because it works effectively over a wider pH range.

Exam Calculation 1: Alkalinity Consumption

Problem: 30 mg/L of Alum (Molar Mass 600) is added to water with 100 mg/L of Alkalinity (Molar Mass 100). 1 mole of Alum consumes 3 moles of Alkalinity. Find the final alkalinity.

$$\text{Step 1: Convert Alum Dose to Moles/L}$$

$$\frac{30 \text{ mg/L}}{600,000 \text{ mg/mol}} = 0.00005 \text{ mol/L of Alum.}$$



$$\text{Step 2: Calculate Alkalinity Consumed}$$

$$0.00005 \text{ mol/L Alum} \times 3 = 0.00015 \text{ mol/L of Alkalinity consumed.}$$



$$\text{Step 3: Convert Consumed Alkalinity to mg/L}$$

$$0.00015 \text{ mol/L} \times 100,000 \text{ mg/mol} = 15 \text{ mg/L of Alkalinity consumed.}$$

$$\text{Step 4: Final Alkalinity}$$

$$\text{Initial (100 mg/L) - Consumed (15 mg/L)} = 85 \text{ mg/L remaining.}$$

Exam Calculation 2: Velocity Gradient (G)

The Velocity Gradient (G) Equation

$$G = \sqrt{\frac{P}{\rho V}}$$

G is mixing intensity, P is power, ρ is viscosity, and V is tank volume. A typical range for G is 20-70 s⁻¹.

Problem: Calculate G for a tank ($V=1600 \text{ m}^3$) with a power input of 1080 W and water viscosity of $1.002 \times 10^{-3} \text{ kg/m}\cdot\text{s}$. Flow(Q)=800L/d

$$G = \sqrt{\frac{P}{\rho V}} = \sqrt{\frac{1080}{1.002 \times 10^{-3} \times 1600}} = 25 \text{ s}^{-1}$$

To find Gt, first find retention time, t:

$$Q = \frac{V}{t}, t = \frac{V}{Q} = \frac{1600}{1.002 \times 10^{-3}} = 1728 \text{ s}$$

$$Gt = 25 \times 1728 = 43,200 \quad (\text{Typical } Gt = 10^4 \text{ to } 10^5)$$

Pro Tip: Exam Variation

Solving for Tank Dimensions
Some questions give you the optimal G (from a graph) and ask you to calculate a required tank dimension, like Depth.

How to Solve:
1. Read optimal G from the provided graph.

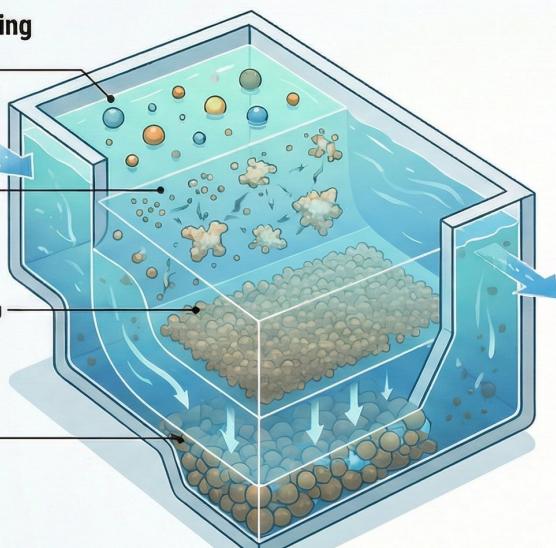
2. Rearrange the formula to solve for Volume: $G^2 \cdot \frac{P}{\rho V} \Rightarrow V = \frac{P}{\rho G^2}$

3. Calculate V, then find the missing dimension e.g., Depth = V / (Length × Width)

Lecture 3: Sedimentation Part A - Discrete Settling

The 4 Types of Settling

Type I: Discrete Settling
Individual particles settle independently without interacting. Their size, shape, and density remain constant.
(Example: Grit removal)



Type II: Flocculent Settling
Particles collide and aggregate (flocculate) as they settle, increasing in size and settling faster with depth.
(Example: Alum or Iron floc)

Type III: Hindered (Zone) Settling
Particle concentration is high, causing them to hinder (block) each other and settle as a unified "blanket" with clear water above.
(Example: Sludge thickening)

Type IV: Compression Settling
Concentration is so high that particles are in physical contact. Settling occurs as the weight of the particles squeezes water out.
(Example: Bottom of a sludge tank)

Key Concepts & Formulas for Ideal Settling

(covered next chapter)



Surface Overflow Rate (v_o)

This is the critical design parameter representing the upward velocity of water. It is calculated as

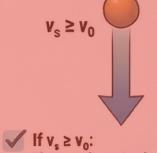
$$v_o = \frac{\text{Flow Rate (Q)}}{\text{Surface Area (A)}}$$

Stokes' Law (for Settling Velocity, v_s)

$$v_s = \frac{g(S-1)d^2}{18v}$$

g = Gravity (9.81 m/s²)
S = Specific Gravity of particle (in meters)
d = Particle Diameter (in meters)
v = Kinematic Viscosity of water (m²/s)
→ If given dynamic viscosity, η : $v_s = M/d^2$

The Removal Rule



If $v_s \geq v_o$: The particle settles faster than the upward velocity. Result: 100% Removal.

If $v_s < v_o$: The particle settles slower than the upward velocity. Result: Partial Removal. The percentage removed is $(v_s/v_o) \times 100$.

Theory Explained: Why Coagulation Works

Velocity is Proportional to Diameter Squared ($v_s \propto d^2$). This relationship from Stokes Law is the key. Coagulation combines small particles into larger flocs, significantly increasing diameter (d).

Double the Size, Settle 4x Faster
Because of the squared relationship, a small increase in particle diameter leads to a massive increase in settling velocity, making treatment much more efficient.

Exam Problem Walkthrough: Calculating Settling Distance

- Convert All Units to SI
- Calculate Settling Velocity (v_s)

Ensure all measurements are in meters (m) and seconds (s). (Example: 0.2 mm becomes 0.2 x 10⁻³ m; 10 minutes becomes 600 s).

- CRUCIAL CHECK - Reynolds Number
- Stokes' Law is only valid for laminar flow ($Re < 1$). You must check this for full marks.

Formula: $Re = (v_s \cdot d) / v$.

(Example: $Re = 0.67$, which is < 1, so the law is valid).

- Calculate Distance Settled
- Use the simple formula: Distance = Velocity x Time.

(Example: $0.00282 \text{ m/s} \times 600 \text{ s} = 2.29 \text{ meters}$).

Question: How far would a discrete spherical particle of diameter 0.2 mm and specific gravity 1.2 settle in 10 minutes? Water temp is 15°C (Kinematic viscosity $v = 1.14 \times 10^{-6} \text{ m}^2/\text{s}$).

Advanced Exam Method: Total Removal Calculation

- Calculate v_s for Each Particle Size
- Compare Each v_s to the Tank's v_o
- Calculate Removal for Each Fraction

For a given table of particle fractions, use Stokes' Law to find the settling velocity for every particle diameter listed.

- Calculate Total Removal

Sum the removals:
Total = $\sum (mass \text{ fractions for removed particles}) + \sum (mass \text{ fraction of partially removed particle} \times [v_s/v_o] \times 100)$.

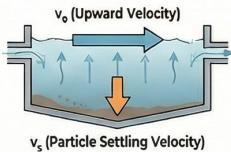
(covered next chapter)

Lecture 4: Sedimentation Part B - Analysis & Design

Why actual % of particle removal is less than settling column test?

- Inlet/outlet turbulence
- Wind effects
- Differences from temperature gradients
- Equipment movement (may cause velocity gradients)
- Settling tank hydraulics (possible short-circuiting)
- Sludge storage volume is insufficient

CORE CONCEPTS & TANK DESIGNS



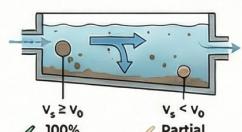
What is Surface Overflow Rate (SOR or v_o)

The "speed limit" for settling. Particles must settle faster than the upward velocity of the water (v_o) to be effectively removed.

Calculated as Flow Rate (Q) / Surface Area (A).

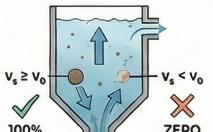
Horizontal Flow vs. Upflow Clarifiers

Horizontal Flow



Horizontal flow tanks are more efficient because they can partially remove slow-settling particles.

Upflow Clarifier



ZERO removal if $v_s < v_o$, as slow particles are carried out with the upward flow.

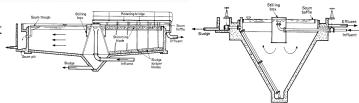
Common Tank Types



Rectangular (Horizontal)
Inlet at one end, outlet weir at the other, with a sludge scraper on the bottom.

Radial (Circular)
Central inlet, water flows outwards to weirs on the edge, with a rotating bridge scraper.

Upflow (Hopper Bottom)
Funnel shaped tank where water enters low and flows up, with sludge collecting in the pointed bottom.



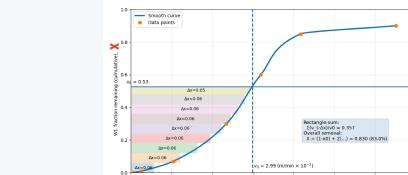
HOW TO CALCULATE TOTAL REMOVAL (GRAPHICAL METHOD)

(this is a settling column test)

The Master Equation for Total Removal (X)

$$\text{Total Removal} = \left(\frac{\text{Removal of Fast Particles}}{\text{Fast Particles}} \right) + \left(\frac{\text{Partial Removal of Slow Particles}}{\text{Slow Particles}} \right)$$

$$\text{Formula: } X = (1 - x_0) + \sum_{i=1}^{n-1} \frac{v_s}{v_o} dx_i; \text{ or } X = (1 - x_0) + \sum_{i=1}^{n-1} \Delta x \cdot \frac{v_s \cdot v_{s,avg}}{v_o}$$



NOTE: If question gives a table as below,

Particle size (mm): 0.10 0.08 0.07 0.06 0.04 0.02 0.01

Mass fraction greater than size (%): 10 15 40 70 93 99 100

Particle size (mm): 0.01 0.02 0.04 0.06 0.07 0.08 0.10

Mass fraction smaller than size (%): 0.00 0.01 0.07 0.30 0.60 0.85 0.90

$v_s \text{ (m/min)} \times 10^{-2}$: 0.07 0.26 1.05 2.37 3.23 4.22 6.59

Step 1: (you will need to find v_o , first, and check Re) Plot the SOR curve. Using data from settling column test, plot the fraction of remaining particles, x on the y-axis against their settling velocity, v_s on the x-axis.

Step 3: Calculate Removal of Fast Particles: This is the fraction of particles with a settling velocity greater than v_o . The formula is simply $(1 - x_0)$.

Step 4: Calculate Partial Removal of Slow particles: This is represented by the area under the curve to the left of the v_o line. Approximate this by summing the area of small rectangular strips under the curve.

*Remember that this area still needs to be divided by v_o , before added with $(1 - x_0)$.

Alternative method: Trapezoidal area method

$$\text{Depth mean} = \frac{v_s \text{ (m/min)} \times 10^{-2}}{v_o} \quad x_0 = \frac{v_s \text{ (m/min)} \times 10^{-2}}{v_o}$$

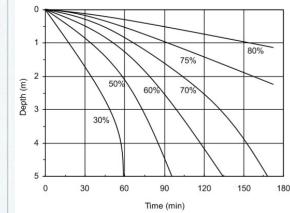
$$x = 1 - x_0 + \frac{v_s \text{ (m/min)} \times 10^{-2}}{v_o}$$

HOW TO CALCULATE TOTAL REMOVAL (ISO-REMOVAL CURVES)

Understanding Iso-Removal Curves

This is an alternative data format showing contour lines of equal removal percentage on a grid of tank depth vs. time.

example of an Iso-Removal Curve:



sometimes in exam it gives in the form of a table:

Iso-removal	Depth (m)
50-60%	2.25
60-70%	1.35
70-75%	0.80
75-80%	0.60

(detention time = 60 min)

this table basically gives the value of all curves at t=60 min

Step 1:
Determine Key Parameters: You will need the tank's total depth (D) and the detention time (t), which is calculated as Tank Volume / Flow Rate. $(A = \frac{V}{t} \Rightarrow t = \frac{V}{A})$

Step 2:
Find the Base Removal (r_n): On the graph, find your detention time (t). The value of the iso-removal curve that intersects the bottom of the tank (depth D) at that time is your r_n . $(\text{e.g.: } t = 60 \text{ min}, D = 2 \text{ m})$

Step 3:
Add Partial Removal Fractions:
For each iso-removal curve above r_n , add a fraction of its removal contribution. This is calculated for each slice between curves (e.g., between the 50% and 60% lines). Formula:

$$R_{\text{total}} = r_n + \sum \left[\frac{\text{Depth mean}}{D} \cdot (r_n - r_{n-1}) \right]$$

In words: Add the base removal (r_n) to the sum of each additional removal percentage (e.g., 60%-50%) multiplied by the ratio of its average depth to the total tank depth.

this section might have been removed from syllabus (not examined ~2016)

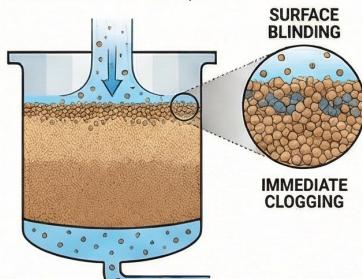
Lecture 5: Filtration

CORE FILTRATION CONCEPTS (EXAM THEORY)

THE DUAL MEDIA ADVANTAGE: WHY ANTHRACITE OVER SAND?

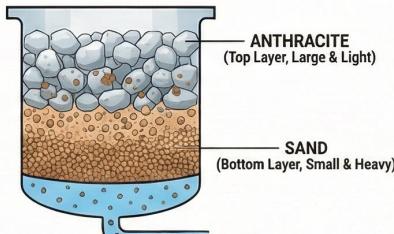
PROBLEM: SINGLE SAND FILTER

After backwashing, small sand grains settle at the top, causing immediate clogging, short filter runs, and inefficient use of the filter bed depth.



SOLUTION: DUAL MEDIA FILTER

A top layer of large, light Anthracite traps coarse particles, while a bottom layer of small, heavy Sand traps fine particles. The density difference ensures the layers automatically re-stratify correctly after every backwash. Allows for TRUE DEPTH FILTRATION.



THE HEADLOSS CALCULATION (A STEP-BY-STEP GUIDE)

THE FAIR-HATCH EQUATION

$$h_L = \frac{36kv(1-e)^2LV}{ge^3\phi^2} \times \sum \left(\frac{P_i}{d_i^2} \right)$$

KEY VARIABLES TO KNOW

- h_L : Headloss (m)
- g : Gravity (9.81 m/s²)
- k : Kozemey constant (~5)
- ϕ : Shape factor (~0.8)
- v : Kinematic viscosity (m²/s)
- P_i : Mass fraction
- e : Porosity (e.g., 0.45)
- d_i : Geometric mean diameter (m)
- V : Filtration Velocity (m/s)

which isn't usually given in m/s, have to convert yourself!

STEP 1: PERFORM THE SIEVE ANALYSIS CALCULATION

Size Range (mm)	P_i (mass %)	Geometric Mean d_i (m)	Term: $P_i/d_i^2 (m^{-2})$
3.36 - 2.38	0.02	2.828 x 10 ⁻³	2,501
2.38 - 1.68	0.06	1.999 x 10 ⁻³	15,006
1.68 - 1.19	0.12	1.414 x 10 ⁻³	60,024
1.19 - 0.84	0.40	0.999 x 10 ⁻³	400,160
0.84 - 0.59	0.20	0.704 x 10 ⁻³	403,551
0.59 - 0.42	0.12	0.497 x 10 ⁻³	484,261
0.42 - 0.297	0.08	0.353 x 10 ⁻³	641,234
0.297 - 0.210	0.00	-	0
SUM	1.00	$\Sigma = 2.0068 \times 10^6$	

Convert sieve data into the summation term.

Engine of the calculation.

Convert diameters to meters.

Size of opening (mm)	% Mass retained
2.38	0
1.68	6
1.19	12
0.84	50
0.59	20
0.42	12
0.297	8
0.210	0

2.38 opening means 3.36-2.38
there is 2% mass

to find geometric mean,
 $d_g = \sqrt[3]{3.36 \times 2.38}$
 $= 2.928 \text{ mm}$
 $= 2.928 \times 10^{-3} \text{ m}$

STEP 2: WATCH YOUR UNITS!

Most common mistake: Velocity.
Convert from m/hour to m/s.

$$5 \text{ m/h} \div 3600 \text{ s/h} = 0.001389 \text{ m/s}$$

STEP 3: PLUG IN VALUES AND SOLVE

FACTORS AFFECTING HEADLOSS (h_L)

THESE INCREASE HEADLOSS ↑

- Higher Flow Rate (V)
- Deeper Bed (L)
- Colder Water (higher viscosity μ)
- Angular/Jagged Media (higher shape factor ϕ)

THESE DECREASE HEADLOSS ↓

- Larger Grain Size (d)
- Higher Porosity (e , more empty space)

WHAT IS FILTER RIPENING?

Initial period post-backwash: "too clean" and particle pass through too easily.
Ripening is the period where particles begin to attach to the media; these particles act as a filter for other particles, improving efficiency.
Water is filtered to waste during ripening

WHEN TO BACKWASH A FILTER?

- Headloss becomes too high (water can't pass through)
- Particle Breakthrough (High Turbidity) (e.g., 48 hours).
- Maximum Time Limit

$$h_L = \frac{36(5)(1.004 \times 10^{-6})(1 - 0.45)^2(0.001389)}{(9.81)(0.45)^2(0.8)^2} \times (2.0068 \times 10^6)$$

Substitute known values, including constants, porosity, velocity, bed depth ($L = 0.7 \text{ m}$), and the summation from the table.

FINAL RESULT

$$0.191 \text{ m}$$

*Tip: If you get a huge or tiny number, double-check your unit conversions, especially for diameter (mm to m).

ADVANCED CONCEPT: CONNECTING EQUATIONS

HEADLOSS (h_L) → BERNoulli's EQUATION

How Headloss Relates to Bernoulli's Equation: The headloss (h_L) in the Carman-Kozeny/Fair-Hatch equation is the "Losses" term in Bernoulli's energy equation. It quantifies the pressure drop caused by friction as water flows through the filter media.

Bernoulli's eqn.:

$$P_1 + \frac{1}{2}\rho u_1^2 + \rho gh_1 = P_2 + \frac{1}{2}\rho u_2^2 + \rho gh_2 + h_L$$

Fair Hatch's eqn.

*THMs can be reduced by:
 - remove precursor better by tweaking coagulations/flocculation
 - switching to an alternative primary disinfectant
 - add air stripping (but not preferred)

CHOOSING YOUR DISINFECTANT: THE BIG 4

Disinfectant	Pros	Cons
Chlorine	<ul style="list-style-type: none"> Cheap effective for bacteria/viruses provides a protective residual 	<ul style="list-style-type: none"> Forms harmful by-products (THMs) pH-dependent ineffective against Cryptosporidium
Chlorine Dioxide	<ul style="list-style-type: none"> Does not react with Ammonia Much stronger than Chlorine. No strong disinfection dependence on pH. Taste and odour control Does not form THMs (unless excess chlorine present) 	<ul style="list-style-type: none"> Generation need to be well controlled to minimise excess free chlorine Must be generated on sites (unstable) Costs more than Chlorine
Ozone	<ul style="list-style-type: none"> Very strong kills Cryptosporidium improves taste and odor does not form halogenated byproducts (e.g. THMs) 	<ul style="list-style-type: none"> Expensive complex to generate leaves NO residual can form Bromate by-product
UV Light	<ul style="list-style-type: none"> Kills Cryptosporidium & Giardia no chemical by-products (no THMs) competitive costs small space requirement 	<ul style="list-style-type: none"> Leaves NO residual requires clear water (low turbidity) lamps can foul no taste control doesn't remove colour

*Multi-barrier philosophy is we can use multiple disinfectant that covers each other weaknesses like UV and Chlorine.

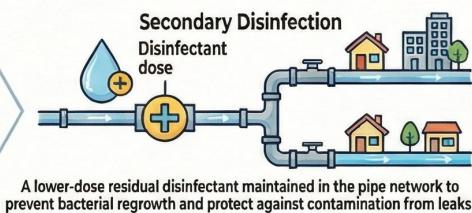
CORE DISINFECTION PRINCIPLES

Primary Disinfection



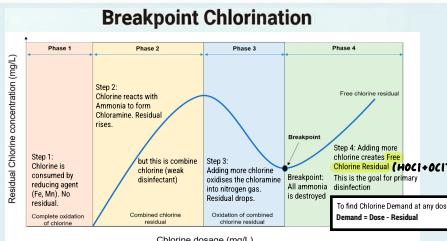
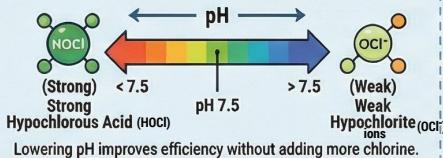
Lecture 6: Disinfection

Secondary Disinfection



THE SCIENCE OF CHLORINE

The pH Effect: Lower pH = Stronger Disinfection



THE "Ct" CONCEPT: THE CORE CALCULATION

The Golden Rule of Disinfection

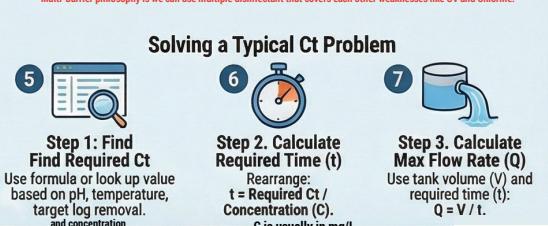
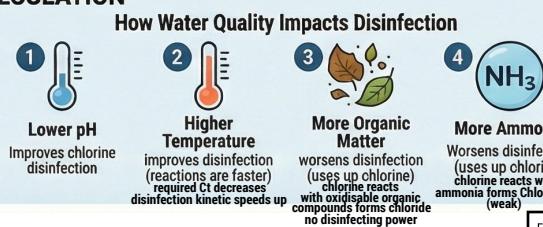
$$Ct \text{ (calculated)} \geq Ct \text{ (required)}$$

*C usually given, find t = V/Q [min] *find from table or equation

What is Ct?

Product of disinfectant Concentration (C, in mg/L) and effective contact time (t, in minutes), measuring overall disinfection power.

$C = C_{\text{effluent}}$ (i.e. disinfection concentration leaving tank)
 $t = t_{10}$ (i.e. 10th percentile shortest contact time)
 (tracer test: this is how we find t_{10})

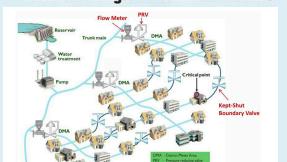


*NOTE: If specific pH (e.g. 7.3) is between two columns (7.0 and 7.5), you must linearly interpolate between the values to find Ct from the table.

Lecture 7: Water Distribution Network

1. District Metered Areas (DMAs): The Most Common Question

How a "Single Feed DMA" Works



Main Purpose: Quantifying Leakage

DMAs are used to calculate the Net Night Flow (NNF), which helps isolate and measure water loss in a specific zone.

Leakage = Total inflow - Legitimate night consumption

Pros vs. Cons of DMAs

- | | |
|--|--|
| Pros <ul style="list-style-type: none"> Detects bursts quickly by monitoring night flow. Allows for targeted pressure management. | Cons <ul style="list-style-type: none"> If the inlet pipe fails, the entire area loses its water supply. Water Quality Risk: Closed valves create 'dead ends', leading to water stagnation and sedimentation. |
|--|--|



3. Pressure Management: Reducing Stress on the System

The FAVOUR Equation: Linking Leakage to Pressure

The relationship is defined as:

$$Q_{\text{leak}} \propto P^{N_1}$$

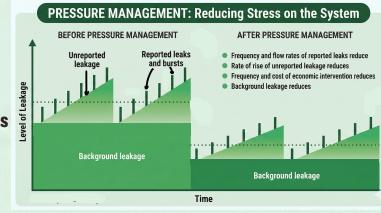
where N_1 is usually greater than 1, meaning a small pressure drop causes a large leakage reduction.

Lower Pressure = Lower Leakage & Fewer Bursts

Reducing and stabilizing pressure has multiple direct benefits for the network's health and efficiency.

Top 3 Benefits of Pressure Control

- Reduces background leakage.
- Lowers burst frequency by preventing surges (water hammer). Keeping pressure stable (calm)
- Extends the life of pipes and assets.

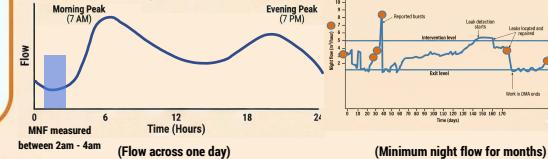


2. Minimum Night Flow (MNF): Finding Hidden Leaks

The Golden Hours for Leak Detection are 2 AM - 4 AM

During this period, legitimate customer water consumption is at its lowest and most stable, making flow from leaks much easier to identify.

Visualizing Flow Over 24 Hours



4. TOTEX & Risk: The Modern Approach to Pipe Renewal

What is TOTEX?

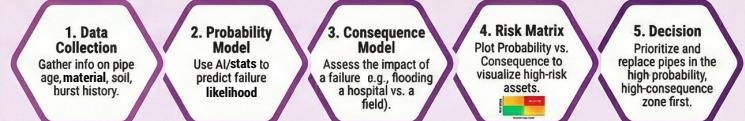
(building new things)
 Total Expenditure (TOTEX) = Capital Expenditure (CAPEX) + Operational Expenditure (OPEX). This holistic view considers the whole-life cost of an asset.

Strategy Shift: Replace Risky Pipes, Not Old Pipes

Modern asset management prioritizes pipes based on their risk profile rather than simply their age.

$$\text{The Risk Calculation:} \\ \text{Risk} = \text{Probability of Failure} \times \text{Consequence of Failure}$$

5-Step Risk-Based Renewal Process



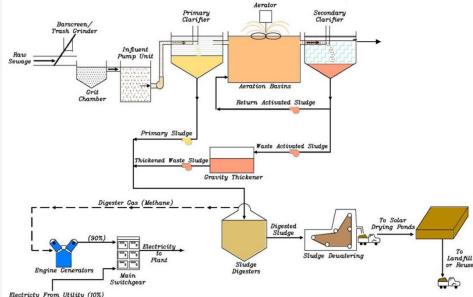
How to enhance TOTEX efficiency on an aging water supply infrastructure:
 1. Implement pressure management techniques for the main supply network & distribution system.
 2. Optimize pump scheduling (the operation of pumps to reduce energy costs).

Lecture 8: Stormwater and Wastewater Collection

A visual summary of key definitions, formulas, and step-by-step calculation methods for high-probability exam questions.

The Wastewater Treatment Plant (WWTP) Process Flow

A High-Probability Exam Question
Memorize the stages and their functions.



1. A bar screen is a mechanical filter for large objects removal, such as rags, plastics etc. (Pre-treatment)
2. Grit chambers are basins to remove the inorganic particles to prevent damage to the pumps, and to prevent their accumulation in storage digesters. (Pre-treatment)
3. Primary clarification objective: suspended solids (SS) removal from wastewater under gravity. Removal of particulate, suspended solids and floatable materials elimination is intended. (Primary Treatment)
4. An aeration tank uses microbes to remove soluble matter convert it to biomass and stabilise compounds. (Secondary Treatment) **Activated Sludge**
5. A grit chamber is used to collect inorganic materials so that the supernatant meets an effluent discharge standard. (Secondary Treatment)
6. A gravity thickener is to reduce water content in the secondary sludge. (Sludge Treatment)
7. An anaerobic digester is to convert organic biomass into biogas (mainly methane and CO₂) for energy recovery. (Sludge Treatment)
8. A sludge dewatering system is to separate sludge into liquid ("the centre") and solid components for waste minimization. (Sludge Treatment)
9. (There is no tertiary treatment here e.g. filtration / nutrient removal (N, P) / disinfection / polishing.)

1. Primary Treatment: The objective is to remove large solids and suspended particles through sedimentation, producing sludge.
2. Secondary Treatment: The goal is to biologically degrade dissolved and suspended organic matter using microorganisms, further reducing the organic load.
3. Tertiary Treatment: This stage aims to remove any remaining impurities, including nutrients, and to disinfect the effluent before it is discharged into the environment.

Core Concepts & Definitions



Dry Weather Flow (DWF)
The average daily flow in a sewer during seven consecutive days without rain.

Formula:

$$DWF = PG + I + E$$

P = Population
G = Domestic consumption per person (L/head/day)
I = Infiltration (groundwater leaking into pipes)
E = Trade Effluent (industrial waste)



Combined Sewer Overflow (CSO)
A safety valve in older sewer systems that combines rainwater and sewage in one pipe

CSO Role 1: Hydraulic Protection

Prevent flooding at the WWTP by diverting excess flow during heavy rain into rivers/seas



CSO Role 2: Environmental Protection

Design to retain as much solid/pollutant as possible (first flush) and only spill diluted water

What is the "First Flush"?
The highly polluted initial surge of stormwater that washes accumulated dirt from surfaces and must be captured for treatment

CSO setting: (i.e. Retained flow Q_o)

traditional setting: Q = 6xDWF

formula A setting: Q = DWF + 1360P + 2E

other excess flow get spilled into a CSO storage, to which can hold a certain amount of volume before spilling into the river/seas

The Two Key Calculation Methods

Method 1: Foul Sewer Design (Wastewater)

Used to calculate the peak wastewater flow to size the sewer pipe correctly.

Step 1: Calculate Average DWF
Use the formula $DWF = (P \times G) + I + E$ convert the final value from L/day to L/s by dividing by $24 \times 60 \times 60$ (86,400)

Step 3: Calculate Peak Flow
Multiply the DWF by a Peak Factor, often calculated using Babbitt's Formula
$$\text{Peak Factor} = 5 + (P^{0.2})$$
 sometimes a, b, g, α, β given:
$$\text{Peak Factor} = 5 + \frac{\alpha}{\beta}$$

Babbitt's Formula Alert!
In this formula, the Population P must be in thousands. For 50,000 people, use $P=50$.

Method 2: Storm Sewer Design (The Rational Method)

A common method used to calculate the peak stormwater runoff

Step 1: Apply the Rational Formula

$$Q = 2.78 \cdot C \cdot i \cdot A$$
 where Q is flow (L/s)

Rational Formula Variables

C = Runoff coefficient (0.0 to 0.1, 0.7 to 0.9 for urban)
i = Rainfall intensity (mm/hr)
A = Area (hectares)

Step 2: Find Rainfall Intensity (I)
I is found using a given formula
$$I = \frac{a}{D+b}$$

$$I = \frac{\text{rainfall intensity (mm/hr)}}{D + \text{duration (hrs)}}$$

Step 3: Find Duration (D)
Duration is the same as the Time of Concentration (t_c), calculated as
$$t_c = \frac{L}{V}$$

$$t_c = \frac{\text{length of the reach (m)}}{\text{flow rate (m/s)}}$$

Worked Exam Problems

Problem 1: Foul Sewer Peak Flow Calculation

Problem: For a population of 37,500, calculate the DWF and then the Peak Flow.
*Sometimes I will be given as a % of P_G

Solution:

1. Calculate DWF: Sum domestic, infiltration, and industrial flows. $DWF = (P \times G) + I + E$
Total = 7,250,000 L/day.
2. Convert DWF: $7,250,000 / 86,400 = 83.9 \text{ L/s}$.
3. Find Peak Factor: $P = 37.5$ (in thousands).
 $\text{Factor} = 5 / (P^{0.2}) - 3.42$
4. Calculate Peak Flow: $83.9 \text{ L/s} \times 2.42 = 203 \text{ L/s}$.

(Problem 1 is about how big sewage flow is)

Problem 2: CSO Setting Calculation

Problem: Determine the flow at which a CSO spills using Formula A for a population of 50,000.

Solution:

1. Calculate DWF: 80,000 people = $250 \text{ L/head/day} = 12,500,000 \text{ L/day}$.
2. Apply Formula A:
Setting = $DWF + 1360P + 2E$
 $= 12,500,000 + (1360 \times 50,000) + (2 \times 0)$
 $= 80,500,000 \text{ L/day}$
3. Convert to L/s: $80,500,000 / 86,400 = 932 \text{ L/s}$.

(Problem 2 is about how much combined flow is retained before the excess is spilled)

Problem 3: Storm Sewer Network (Rational Method)

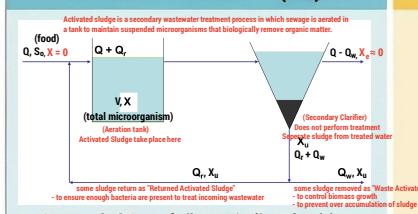
Pipe number	Length (m)	Contributing area (ha)	Time of concentration (sec)	Flow (l/sec)	Rainfall intensity (mm/min)	Open capacity, Q (l/sec)
1	240	0.8	8.5	40.3	180	186.1
2	180	0.6	5.5	6.5	75.8	75.8
3	120	0.4	4.0	4.0	40.0	40.0
4	180	1.0	4	9.8	39.5	172.7
5	120	0.6	3.5	3.5	27.5	27.5
6	120	0.6	1	11	35.7	35.7

(Problem 3 is about how big stormwater flow is)

Lecture 9: Activated Sludge and Biological Filtration

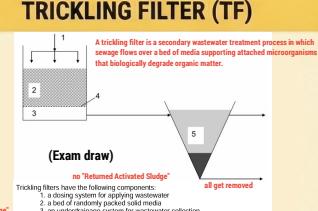
Two Core Processes: A Head-to-Head Comparison

ACTIVATED SLUDGE (AS)



- Suspended Growth (bacteria float freely)
- High Power (aeration pumps)
- Complex Operation (requires monitoring)
- Small Footprint (compact)
- Common Issues: Sludge Bulking (poor settling)

TRICKLING FILTER (TF)



- Attached Growth (biofilm on media)
- Low Power (gravity, natural ventilation)
- Simple Operation
- Large Footprint (significant space)
- Common Issues: Flies, odors, filter clogging

Key Performance Indicators & Definitions

SLUDGE VOLUME INDEX (SVI)

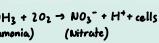
Measures volume (ml) of 1 gram of sludge after 30 min settling. Indicates settling quality.

$$SVI = \frac{Settled Volume (ml)}{MLSS (mg/L)} \times 1000$$

50-150 mL/g: Good Settling
>150 mL/g: Sludge Bulking (poor settling)

$$X_o = \frac{1}{SVI}$$

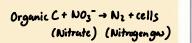
NITRIFICATION



(Ammonia) (Nitrate) (Aerobic)

Requires Oxygen. (Aerobic)

DENITRIFICATION



(Organic) (Nitrogen) (Anoxic)

Requires no oxygen (Anoxic)

Needs carbon source.

The Activated Sludge "Holy Trinity": Essential Formulas

1. F/M RATIO

(Food-to-Microorganism)

Daily food (BOD) supplied to microorganisms (MLSS). Typical range: 0.2 - 0.5 kg BOD/kg MLSS-d.

$$F/M = \frac{Q \cdot S_0}{V \cdot X}$$

BOD after primary!

$$S_0 = \text{Influent BOD (mg/L or g/m}^3\text{)}$$

$$V = \text{Tank Volume (m}^3\text{)}$$

$$X = \text{MLSS (mg/L or g/m}^3\text{)}$$

if no sludge return:
$$Q_X = (Q - Q_R)X_R + Q_R X_o$$

$$Q_X = Q - Q_R X_R + Q_R X_o$$

mass in = mass out

$$\frac{Q_X}{Q} = \frac{X_R}{X} + \frac{X_o}{X}$$

$$Q_X = Q \cdot X_o / (X_R + X_o)$$

if no sludge return:
$$Q_X = Q - Q_R X_R$$

$$Q_X = Q - Q_R X_R$$

mass in = mass out

$$\frac{Q_X}{Q} = 1 - Q_R X_R / Q$$

$$Q_X = Q \cdot (1 - Q_R X_R / Q)$$

if no sludge return:
$$Q_X = Q - Q_R X_R$$

$$Q_X = Q - Q_R X_R$$

mass in = mass out

$$\frac{Q_X}{Q} = 1 - Q_R X_R / Q$$

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mass in = mass out

$$\frac{Q_X}{Q} = 1 - Q_R X_R / Q$$

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if no sludge return:
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mass in = mass out

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$$Q_X = Q \cdot (1 - Q_R X_R / Q)$$

if no sludge return:
$$Q_X = Q - Q_R X_R$$

$$Q_X = Q - Q_R X_R$$

mass in = mass out

$$\frac{Q_X}{Q} = 1 - Q_R X_R / Q$$

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Lecture 10: Sewage Sludge Treatment

Key Concepts & Theory

Primary vs. Secondary Sludge

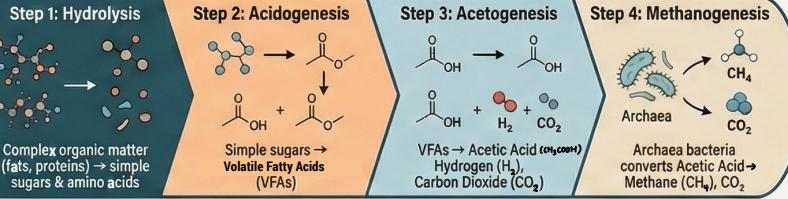


Primary Sludge
(From Primary Settlement)
Granular, grey, odorous,
higher solid content (~4-6%)
Contains inorganic solids (grit)
and settleable organics.
(generated by gravity)



Secondary Sludge
(From Secondary Clarifier)
Light, flocculent, brown,
mostly biomass, lower
solid content (~0.5-2%)
(generated by converting BOD to activated biomass)

The 4 Stages of Anaerobic Digestion (AD) THESE VISUALS ARE INACCURATE



Biogas

Calculation 1: Sludge Production Walkthrough (How much sludge is produced?)

Key Formulas: Mass & Volume

$$\text{Primary Mass } (\text{M}_{ps}) = \frac{\text{BOD removed in primary}}{\text{BOD removed in secondary}} \times \text{SS}_{influent} \times Q$$

$$\text{Secondary Mass } (\text{M}_{ss}) = Y_{obs} \times \text{BOD removed} \times Q$$

$$\text{Sludge Volume } (V_{sludge}) = \frac{\text{Mass of Dry Solids}}{\text{density of Sludge}} \times \% \text{ Dry solids}$$

Example Problem: Daily Sludge Volume

A WWTP treats 10,000 m³/d of wastewater.

Influent SS = 300 mg/L

Influent BOD = 250 mg/L

Primary Tank: Removes 60% of SS and 35% of BOD.

Primary sludge is 5% Dry Solids (DS)

Secondary tank: Removes 95% of remaining BOD.

Final K_{ds} = 0.44 kg DS / kg BOD. Secondary sludge is 0.8% DS.

Calculate Total Daily Sludge Volume (m³/d) produced.

$$e: \text{Removal efficiency of primary tank. } \\ \text{SS}_{influent} = \text{Influent Suspended Solids (mg/L or kg/m}^3\text{). } \\ Q: \text{Flow (m}^3/\text{d). } \\ Y_{obs}: \text{Yield coefficient (kg sludge / kg BOD removed). } \\ \text{BOD}_{removed}: \text{Amount of BOD removed in secondary treatment}$$

$$\text{Step 1: Calculate Primary Sludge Mass } (\text{M}_{ps}) \\ 0.6 \times (0.3 \text{ kg/m}^3) \times (10,000 \text{ m}^3/\text{d}) \\ = 1,800 \text{ kg/day}$$

$$\text{Step 2: Calculate Primary Sludge Volume } (V_{ps}) \\ \frac{1,800}{1000 \times 0.008} = 36 \text{ m}^3/\text{day}$$

$$\text{Step 3: Calculate BOD removed in secondary treatment} \\ \text{Initial BOD (250 mg/L)} \\ - 1,800 \text{ kg/day removes 35% BOD after primary (250} \times 0.65 = 162.5 \text{ mg/L)} \\ - secondary treatment removes another 95% BOD removed in secondary treatment \\ = 0.95 \times 162.5 = 154.4 \text{ mg/L} = 0.1544 \text{ kg/m}^3$$

$$\text{Step 3: Calculate Secondary Sludge Mass } (\text{M}_{ss}) \\ 0.4 \times (0.1544 \text{ kg/m}^3) \times (10,000 \text{ m}^3/\text{d}) \\ = 617.6 \text{ kg/day}$$

$$\text{Step 4: Calculate Secondary Sludge Volume } (V_{ss}) \\ \frac{617.6}{1000 \times 0.008} = 77.2 \text{ m}^3/\text{day}$$

$$\text{Step 5: Calculate Total Daily Volume} \\ 36 \text{ m}^3/\text{day} + 77.2 \text{ m}^3/\text{day} \\ = 113.2 \text{ m}^3/\text{day}$$

Calculation 2: Lab Solids Analysis Walkthrough

Key Formulas: Lab Analysis

$$\text{Total Solids (TS)} = \frac{\text{Mass Dried @ 105°C} - \text{Mass Dish}}{\text{Sample Volume}}$$

$$\text{Volatile Solids (VS)} = \frac{\text{Mass Dried @ 105°C} - \text{Mass Burnt @ 500°C}}{\text{Sample Volume}}$$

Step 1: Calculate Total Solids (TS) Concentration

$$\text{Mass of Dry Solids} = 82.015 \text{ g} - 81.923 \text{ g} = 0.092 \text{ g (92 mg)} \\ TS = \frac{92 \text{ mg}}{0.1 \text{ L}} = 920 \text{ mg/L}$$

Step 2: Calculate Volatile Solids (VS) Concentration

$$\text{Mass of Volatiles (lost on ignition)} = 82.015 \text{ g} - 81.975 \text{ g} = 0.040 \text{ g (40 mg)} \\ VS = \frac{40 \text{ mg}}{0.1 \text{ L}} = 400 \text{ mg/L}$$

Step 3: Calculate Fixed Solids (Ash)

$$75 - VS = 920 \text{ mg/L} - 400 \text{ mg/L} = 520 \text{ mg/L}$$

(covered in chapter 1)

Lecture 11: Sustainability and Water Resource Management Part A

1. The Life Cycle Assessment (LCA) Framework



Life Cycle Assessment (LCA)

A methodology (ISO 14040/14044) for assessing the environmental impacts associated with all stages of a product's life.

Phase 1: Goal & Scope

Define the purpose, the functional unit (e.g., "Treatment of 1 m³ of wastewater"), and the system boundaries.

Phase 2: Inventory Analysis (LCI)

Collect data on all inputs (energy, materials) and outputs (emissions, waste) for the system.

Phase 3: Impact Assessment (LCA)

Convert the inventory data into potential environmental impacts, such as converting methane to CO_2 equivalents.

Phase 4: Interpretation

Identify significant issues ("hotspots"), draw conclusions, and make recommendations for improvement.



Functional Unit: The reference unit for comparison (e.g., Treatment of 1 m³ of wastewater).

System Boundaries: Defines the scope, from "Cradle-to-Graze" or "Cradle-to-Gate".

Hotspot: The stage or process with the largest environmental impact.

2. The Calculation: Carbon Footprint Formula



Carbon Footprint (Global Warming Potential - GWP)

A measure of the total greenhouse gas emissions caused by an activity, expressed as a single unit: kg CO_2 equivalents (kg CO_2e).

$$\text{Total GWP} = \sum (\text{Mass of Emission} \times \text{Characterisation Factor})$$

This formula converts different greenhouse gases into a common unit based on their global warming potential relative to CO_2 .

Greenhouse Gas	IPCC Characterisation Factor
CO_2	1
Methane (CH_4)	~28
Nitrous Oxide (N_2O)	~265

3. Walkthrough: Calculating a WWTP's Carbon Footprint



EXAMPLE SCENARIO: A WWTP treats 50,000 m³/day of wastewater. We will calculate its total annual carbon footprint and specific footprint per cubic meter of water treated.



Step 1: Calculate Scope 1 (Direct Emissions)

Convert all direct gas emissions from the plant into CO_2 equivalents.

$$\text{CO}_2: 1,200,000 \text{ kg} \times 1 = 1,200,000 \text{ kg } \text{CO}_2\text{e}$$

$$\text{CH}_4: 8,000 \text{ kg} \times 27.2 = 217,600 \text{ kg } \text{CO}_2\text{e}$$

$$\text{N}_2\text{O}: 1,200 \text{ kg} \times 273 = 327,600 \text{ kg } \text{CO}_2\text{e}$$

$$\text{Total Scope 1} = 1,745,200 \text{ kg } \text{CO}_2\text{e/year}$$



Step 2: Calculate Scope 2 (Indirect Energy Emissions)

Multiply energy consumption by grid emission factors to find the associated carbon footprint.

$$\text{Electricity: } 12,000,000 \text{ kWh} \times 0.233 = 2,796,000 \text{ kg } \text{CO}_2\text{e}$$

$$\text{Natural Gas: } 500,000 \text{ kWh} \times 0.184 = 92,000 \text{ kg } \text{CO}_2\text{e}$$

$$\text{Total Scope 2} = 2,888,000 \text{ kg } \text{CO}_2\text{e/year}$$



Step 3: Calculate Total Carbon Footprint

Add Scope 1 and Scope 2 emissions together for the final annual total.

$$1,745,200 + 2,888,000 = 4,633,200 \text{ kg } \text{CO}_2\text{e/year}$$



Step 4: Calculate Specific Footprint

Divide the total footprint by the annual volume of treated water to get the footprint per functional unit (1 m³).

$$\text{Total Annual Flow} = 50,000 \text{ m}^3/\text{day} \times 365 \text{ days}$$

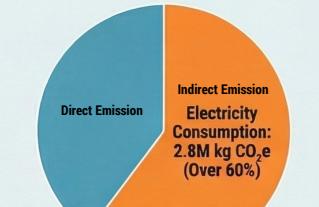
$$= 18,250,000 \text{ m}^3/\text{year}$$

$$4,633,200 \text{ kg } \text{CO}_2\text{e} \div 18,250,000 \text{ m}^3 = 0.254 \text{ kg } \text{CO}_2\text{e}/\text{m}^3$$

$$0.254 \text{ kg } \text{CO}_2\text{e}/\text{m}^3$$

4. Interpretation: Identify the Hotspot & Suggest Improvements

Hotspot Identified: Electricity Consumption



Solution A: Decarbonise Power
Install on-site renewable energy like solar panels or switch to a green electricity tariff from the provider.

Solution B: Improve Energy Efficiency
Implement measures like replacing old, inefficient pumps and optimising the aeration control systems.

Solution C: Generate Your Own Energy
Install an Anaerobic Digester to convert sludge into biogas, which can be used to generate electricity and heat (CHP).

Lecture 12: Sustainability and Water Resource Management Part B

THE CORE THEORY:
TWO CYCLES OF THE CIRCULAR ECONOMY

BIOLOGICAL CYCLE:
Material that can biodegrade and safely return to earth.

TECHNICAL CYCLE:
Product can be used rather than consumed. Focus on how each step allow material to remain in use.

KEY RESOURCE RECOVERY TECHNOLOGIES

- Carbon:** Biogas (via Anaerobic Digestion)
- Phosphorus:** Struvite Precipitation (creates fertilizer)
- Nitrogen:** Ammonia Stripping
- Water:** Membrane Filtration (for water reuse)

Problem Walkthrough: Closing Mass Balance

A WWTP treats 12,000 m³/d. You are given inlet loads, some outlet data, emission factors, and biogas data. You need to close the mass balance (complete the table) and calculate recovery rates. Which resource has the greatest potential for improvement, and what technology could be used?

	Inlet	Wastewater	Outlet
Water	10,000	9,990	9,975
Nitrogen	0	0	0
Phosphorus	0.95	0.95	0.95
Carbon (CO ₂)	2.6	2.6	2.6
Total	10,000	9,990	9,975

Gas Streamflow, Dissolved, and Emissions

Gas Stream	Flow (m ³ /d)	Dissolved (kg/m ³)	Emissions (kg/d)
Gas 1 (CH ₄)	0.51315	0.001	0.001
Gas 2 (N ₂ O)	0.065	0.001	0.001
Gas 3 (NO _x)	0.01	0.001	0.001
Gas 4 (CO ₂)	0.4	0.001	0.001
Gas 5 (O ₂)	0.001	0.001	0.001
Gas 6 (H ₂)	0.001	0.001	0.001
Gas 7 (N ₂)	0.001	0.001	0.001
Gas 8 (Ar)	0.001	0.001	0.001
Gas 9 (He)	0.001	0.001	0.001
Gas 10 (Ne)	0.001	0.001	0.001
Gas 11 (Kr)	0.001	0.001	0.001
Gas 12 (Xe)	0.001	0.001	0.001
Gas 13 (R ₁₃)	0.001	0.001	0.001
Gas 14 (CH ₄)	0.001	0.001	0.001
Gas 15 (N ₂ O)	0.001	0.001	0.001
Gas 16 (NO _x)	0.001	0.001	0.001
Gas 17 (CO ₂)	0.001	0.001	0.001
Gas 18 (O ₂)	0.001	0.001	0.001
Gas 19 (H ₂)	0.001	0.001	0.001
Gas 20 (N ₂)	0.001	0.001	0.001
Gas 21 (Ar)	0.001	0.001	0.001
Gas 22 (He)	0.001	0.001	0.001
Gas 23 (Ne)	0.001	0.001	0.001
Gas 24 (Kr)	0.001	0.001	0.001
Gas 25 (Xe)	0.001	0.001	0.001
Gas 26 (R ₁₃)	0.001	0.001	0.001
Gas 27 (CH ₄)	0.001	0.001	0.001
Gas 28 (N ₂ O)	0.001	0.001	0.001
Gas 29 (NO _x)	0.001	0.001	0.001
Gas 30 (CO ₂)	0.001	0.001	0.001
Gas 31 (O ₂)	0.001	0.001	0.001
Gas 32 (H ₂)	0.001	0.001	0.001
Gas 33 (N ₂)	0.001	0.001	0.001
Gas 34 (Ar)	0.001	0.001	0.001
Gas 35 (He)	0.001	0.001	0.001
Gas 36 (Ne)	0.001	0.001	0.001
Gas 37 (Kr)	0.001	0.001	0.001
Gas 38 (Xe)	0.001	0.001	0.001
Gas 39 (R ₁₃)	0.001	0.001	0.001
Gas 40 (CH ₄)	0.001	0.001	0.001
Gas 41 (N ₂ O)	0.001	0.001	0.001
Gas 42 (NO _x)	0.001	0.001	0.001
Gas 43 (CO ₂)	0.001	0.001	0.001
Gas 44 (O ₂)	0.001	0.001	0.001
Gas 45 (H ₂)	0.001	0.001	0.001
Gas 46 (N ₂)	0.001	0.001	0.001
Gas 47 (Ar)	0.001	0.001	0.001
Gas 48 (He)	0.001	0.001	0.001
Gas 49 (Ne)	0.001	0.001	0.001
Gas 50 (Kr)	0.001	0.001	0.001
Gas 51 (Xe)	0.001	0.001	0.001
Gas 52 (R ₁₃)	0.001	0.001	0.001
Gas 53 (CH ₄)	0.001	0.001	0.001
Gas 54 (N ₂ O)	0.001	0.001	0.001
Gas 55 (NO _x)	0.001	0.001	0.001
Gas 56 (CO ₂)	0.001	0.001	0.001
Gas 57 (O ₂)	0.001	0.001	0.001
Gas 58 (H ₂)	0.001	0.001	0.001
Gas 59 (N ₂)	0.001	0.001	0.001
Gas 60 (Ar)	0.001	0.001	0.001
Gas 61 (He)	0.001	0.001	0.001
Gas 62 (Ne)	0.001	0.001	0.001
Gas 63 (Kr)	0.001	0.001	0.001
Gas 64 (Xe)	0.001	0.001	0.001
Gas 65 (R ₁₃)	0.001	0.001	0.001
Gas 66 (CH ₄)	0.001	0.001	0.001
Gas 67 (N ₂ O)	0.001	0.001	0.001
Gas 68 (NO _x)	0.001	0.001	0.001
Gas 69 (CO ₂)	0.001	0.001	0.001
Gas 70 (O ₂)	0.001	0.001	0.001
Gas 71 (H ₂)	0.001	0.001	0.001
Gas 72 (N ₂)	0.001	0.001	0.001
Gas 73 (Ar)	0.001	0.001	0.001
Gas 74 (He)	0.001	0.001	0.001
Gas 75 (Ne)	0.001	0.001	0.001
Gas 76 (Kr)	0.001	0.001	0.001
Gas 77 (Xe)	0.001	0.001	0.001
Gas 78 (R ₁₃)	0.001	0.001	0.001
Gas 79 (CH ₄)	0.001	0.001	0.001
Gas 80 (N ₂ O)	0.001	0.001	0.001
Gas 81 (NO _x)	0.001	0.001	0.001
Gas 82 (CO ₂)	0.001	0.001	0.001
Gas 83 (O ₂)	0.001	0.001	0.001
Gas 84 (H ₂)	0.001	0.001	0.001
Gas 85 (N ₂)	0.001	0.001	0.001
Gas 86 (Ar)	0.001	0.001	0.001
Gas 87 (He)	0.001	0.001	0.001
Gas 88 (Ne)	0.001	0.001	0.001
Gas 89 (Kr)	0.001	0.001	0.001
Gas 90 (Xe)	0.001	0.001	0.001
Gas 91 (R ₁₃)	0.001	0.001	0.001
Gas 92 (CH ₄)	0.001	0.001	0.001
Gas 93 (N ₂ O)	0.001	0.001	0.001
Gas 94 (NO _x)	0.001	0.001	0.001
Gas 95 (CO ₂)	0.001	0.001	0.001
Gas 96 (O ₂)	0.001	0.001	0.001
Gas 97 (H ₂)	0.001	0.001	0.001
Gas 98 (N ₂)	0.001	0.001	0.001
Gas 99 (Ar)	0.001	0.001	0.001
Gas 100 (He)	0.001	0.001	0.001
Gas 101 (Ne)	0.001	0.001	0.001
Gas 102 (Kr)	0.001	0.001	0.001
Gas 103 (Xe)	0.001	0.001	0.001
Gas 104 (R ₁₃)	0.001	0.001	0.001
Gas 105 (CH ₄)	0.001	0.001	0.001
Gas 106 (N ₂ O)	0.001	0.001	0.001
Gas 107 (NO _x)	0.001	0.001	0.001
Gas 108 (CO ₂)	0.001	0.001	0.001
Gas 109 (O ₂)	0.001	0.001	0.001
Gas 110 (H ₂)	0.001	0.001	0.001
Gas 111 (N ₂)	0.001	0.001	0.001
Gas 112 (Ar)	0.001	0.001	0.001
Gas 113 (He)	0.001	0.001	0.001
Gas 114 (Ne)	0.001	0.001	0.001
Gas 115 (Kr)	0.001	0.001	0.001
Gas 116 (Xe)	0.001	0.001	0.001
Gas 117 (R ₁₃)	0.001	0.001	0.001
Gas 118 (CH ₄)	0.001	0.001	0.001
Gas 119 (N ₂ O)	0.001	0.001	0.001
Gas 120 (NO _x)	0.001	0.001	0.001
Gas 121 (CO ₂)	0.001	0.001	0.001
Gas 122 (O ₂)	0.001	0.001	0.001
Gas 123 (H ₂)	0.001	0.001	0.001
Gas 124 (N ₂)	0.001	0.001	0.001
Gas 125 (Ar)	0.001	0.001	0.001
Gas 126 (He)	0.001	0.001	0.001
Gas 127 (Ne)	0.001	0.001	0.001
Gas 128 (Kr)	0.001	0.001	0.001
Gas 129 (Xe)	0.001	0.001	0.001
Gas 130 (R ₁₃)	0.001	0.001	0.001
Gas 131 (CH ₄)	0.001	0.001	0.001
Gas 132 (N ₂ O)	0.001	0.001	0.001
Gas 133 (NO _x)	0.001	0.001	0.001
Gas 134 (CO ₂)	0.001	0.001	0.001
Gas 135 (O ₂)	0.001	0.001	0.001
Gas 136 (H ₂)	0.001	0.001	0.001
Gas 137 (N ₂)	0.001	0.001	0.001
Gas 138 (Ar)	0.001	0.001	0.001
Gas 139 (He)	0.001	0.001	0.001
Gas 140 (Ne)	0.001	0.001	0.001
Gas 141 (Kr)	0.001	0.001	0.001
Gas 142 (Xe)	0.001	0.001	0.001
Gas 143 (R ₁₃)	0.001	0.001	0.001
Gas 144 (CH ₄)	0.001	0.001	0.001
Gas 145 (N ₂ O)	0.001	0.001	0.001
Gas 146 (NO _x)	0.001	0.001	0.001
Gas 147 (CO ₂)	0.001	0.001	0.001
Gas 148 (O ₂)	0.001	0.001	0.001
Gas 149 (H ₂)	0.001	0.001	0.001
Gas 150 (N ₂)	0.001	0.001	0.001
Gas 151 (Ar)	0.001	0.001	0.001
Gas 152 (He)	0.001	0.001	0.001
Gas 153 (Ne)	0.001	0.001	0.001
Gas 154 (Kr)	0.001	0.001	0.001
Gas 155 (Xe)	0.001	0.001	0.001
Gas 156 (R ₁₃)	0.001	0.001	0.001
Gas 157 (CH ₄)	0.001	0.001	0.001
Gas 158 (N ₂ O)	0.001	0.001	0.001
Gas 159 (NO _x)	0.001	0.001	0.001
Gas 160 (CO ₂)	0.001	0.001	0.001
Gas 161 (O ₂)	0.001	0.001	0.001
Gas 162 (H ₂)	0.001	0.001	0.001
Gas 163 (N ₂)	0.001	0.001	0.001
Gas 164 (Ar)	0.001	0.001	0.001
Gas 165 (He)	0.001	0.001	0.001
Gas 166 (Ne)	0.001	0.001	0.001
Gas 167 (Kr)	0.001	0.001	0.001
Gas 168 (Xe)	0.001	0.001	0.001
Gas 169 (R ₁₃)	0.001	0.001	0.001
Gas 170 (CH ₄)	0.001	0.001	0.001
Gas 171 (N ₂ O)	0.001	0.001	0.001
Gas 172 (NO _x)	0.001	0.001	0.001
Gas 173 (CO ₂)	0.001	0.001	0.001
Gas 174 (O ₂)	0.001	0.001	0.001
Gas 175 (H ₂)	0.001	0.001	0.001
Gas 176 (N ₂)	0.001	0.001	0.001
Gas 177 (Ar)	0.001	0.001	0.001
Gas 178 (He)	0.001	0.001	0.001
Gas 179 (Ne)	0.001	0.001	0.001
Gas 180 (Kr)	0.001	0.001	0.001
Gas 181 (Xe)	0.001	0.001	0.001
Gas 182 (R ₁₃)	0.001	0.001	0.001
Gas 183 (CH ₄)	0.001	0.001	0.001
Gas 184 (N ₂ O)	0.001	0.001	0.001
Gas 185 (NO _x)	0.001	0.001	0.001
Gas 186 (CO ₂)	0.001	0.001	0.001
Gas 187 (O ₂)	0.001	0.001	0.001
Gas 188 (H ₂)	0.001	0.001	0.001
Gas 189 (N ₂)	0.001	0.001	0.001
Gas 190 (Ar)	0.001	0.001	0.001
Gas 191 (He)	0.001	0.001	0.001
Gas 192 (Ne)	0.001	0.001	0.001
Gas 193 (Kr)	0.001	0.001	0.001
Gas 194 (Xe)	0.001	0.001	0.001
Gas 195 (R ₁₃)	0.001	0.001	0.001
Gas 196 (CH ₄)	0.001	0.001	0.001
Gas 197 (N ₂ O)	0.001	0.001	0.001
Gas 198 (NO _x)	0.001	0.001	0.001
Gas 199 (CO ₂)	0.001	0	