Lecture 2: Coagulation and Flocculation

This topic appears in almost every exam (usually Q1).

Part 1: Key Definitions (Memorise These)

1. Coagulation vs. Flocculation

- **Coagulation:** The addition of chemicals (coagulants) to **destabilize** colloidal particles (neutralize their negative charge) so they can come together. *Fast mixing process.*

- **Flocculation:** The slow mixing process that encourages destabilized particles to collide and aggregate into larger, heavier clumps ("flocs") that can settle.

2. The 4 Mechanisms of Coagulation (Exam Favorite - 2019 Q1b)
You must be able to list and briefly explain these:

1. **Diffuse Layer Compression:** High ionic strength compresses the electrical double layer around a particle, lowering the repulsive energy barrier.

2. **Charge Neutralisation:** Positively charged coagulant ions (Al^{3+}, Fe^{3+}) adsorb onto negatively charged dirt particles, neutralizing the charge.

3. **Sweep Flocculation:** High coagulant dose forms a metal hydroxide precipitate ($Al(OH)_3$) which physically "sweeps" particles down as it settles. (Preferred method).

4. **Inter-particle Bridging:** Long polymer chains attach to multiple particles, bridging them together like a net.

3. Re-stabilisation (2020 Q1b)

- If you **overdose** the coagulant (add too much positive charge), the particles become positively charged and start repelling each other again. This prevents floc formation.

4. Tapered Flocculation (2019 Q1c)

- Using a series of tanks where the mixing intensity (G) decreases.

- **Why?** High G at the start builds flocs; low G at the end prevents shearing (breaking) the large flocs before they enter the settling tank.

Part 2: Practical & Chemistry

1. Jar Test (2017 Q1b, 2025 Q1b)

- **Purpose:** To determine the optimum **coagulant dose** and **pH**.

- **Graph:** Plot Turbidity (Y-axis) vs. Dose (X-axis). It usually looks like a U-shape (high turbidity at low dose, low turbidity at optimum, high turbidity at overdose due to re-stabilisation).
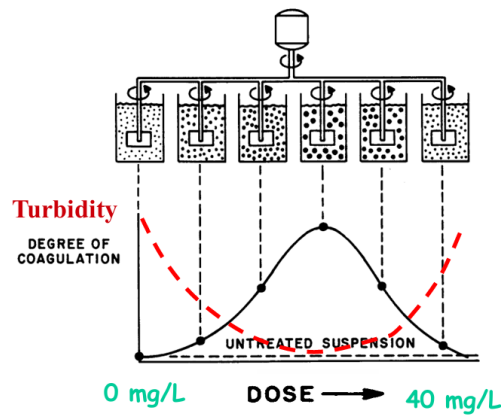
FIGURE 39. Test for Optimum Dosage.

2. Alum & Alkalinity (Chemistry)

- Coagulants (Alum or Ferric) produce H^+ ions (acid).

- They consume the water's **Alkalinity** (buffering capacity).

- **Equation concept:** $Alum + Alkalinity \rightarrow Al(OH)_3 (floc) + CO_2$

- If alkalinity is insufficient, pH drops drastically, stopping the reaction. You must add Lime or Soda Ash to fix this.

- **Exam Tip (2021 Q1b):** If water has high pH/alkalinity, Ferric Chloride is often preferred over Alum as it works over a wider pH range.

Part 3: The "Important" Calculations

This is the most common exam calculation for this topic. It is based on **Problem Set Q2**.

Formula to Memorize:

The Velocity Gradient (G) equation:

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

Where:

- G = Mean velocity gradient (s^{-1}) (Typical range: 20–70 s^{-1})

- P = Power input (Watts) (1 Watt $= 1 \, kg \cdot m^2/s^3$)

- μ = Dynamic viscosity of water (kg/m $\cdot$ s or Pa $\cdot$ s)

- V = Volume of the tank (m^3)

Note: Sometimes you need to calculate Gt (dimensionless), which is simply $G \times$ retention time (in seconds).

IMPORTANT: Problem Set Walkthrough

Here are the solutions to the specific problem set questions provided in your materials.

Problem 1: Alkalinity Calculation

Question: 30 mg/L of alum is added. 3 moles of alkalinity are consumed for 1 mole of alum.

- Molar mass Alum = 600 g/mol.
- Molar mass Alkalinity ($CaCO_3$) = 100 g/mol.
- Initial Alkalinity = 100 mg/L.
- **Calculate remaining alkalinity.**

Step-by-Step Working:

1. **Convert Alum concentration to Moles:**

$$\text{Moles Alum} = \frac{\text{Mass}}{\text{Molar Mass}} = \frac{30 \times 10^{-3} \text{ g/L}}{600 \text{ g/mol}} = 0.00005 \text{ mol/L}$$

2. **Calculate Moles of Alkalinity consumed:**
   Ratio is 1:3 (Alum:Alkalinity).

$$\text{Moles Alk consumed} = 0.00005 \times 3 = 0.00015 \text{ mol/L}$$

3. **Convert consumed Alkalinity back to mg/L:**

$$\text{Mass Alk consumed} = \text{Moles} \times \text{Molar Mass}$$

$$= 0.00015 \text{ mol/L} \times 100 \text{ g/mol} = 0.015 \text{ g/L} = 15 \text{ mg/L}$$

4. **Calculate Final Alkalinity:**

$$\text{Final} = \text{Initial} - \text{Consumed}$$

$$100 \text{ mg/L} - 15 \text{ mg/L} = \mathbf{85 \text{ mg/L as } CaCO_3}$$

(Part b asks what happens if initial alk is only 5 mg/L: The Initial Alkalinity is less than the Alkalinity consumed. The pH would drop; floc wouldn't form. Solution: Add Lime/Soda Ash).

Problem 2: Velocity Gradient (G) Calculation (Very common in Exams)

Question:

- Tank dimensions: 16m wide, 5m deep, 20m long.
- Flow (Q): 80 ML/d (this is extra info not needed for G, but needed for Gt).
- Power (P): 1000 Watts.
- Viscosity (μ): 1.002×10^{-3} kg/m · s.
- **Calculate G and Gt.**

Step-by-Step Working:

1. **Calculate Volume (V):**

$$V = \text{Width} \times \text{Depth} \times \text{Length}$$

$$V = 16 \times 5 \times 20 = 1600 \text{ m}^3$$

2. **Calculate G:**

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

$$G = \sqrt{\frac{1000}{(1.002 \times 10^{-3}) \times 1600}}$$

$$G = \sqrt{\frac{1000}{1.6032}} = \sqrt{623.75}$$

$$\mathbf{G = 25 \ s^{-1}}$$

3. **Calculate Time (t) for Gt:**
   First, convert Flow (Q) to cubic meters per second.

$$Q = 80 \text{ ML/d} = 80{,}000 \text{ m}^3\text{/day}$$

$$Q \text{ in seconds} = \frac{80{,}000}{24 \times 60 \times 60} = 0.926 \text{ m}^3\text{/s}$$

$$t = \frac{V}{Q} = \frac{1600}{0.926} = 1728 \text{ seconds (approx. 29 mins)}$$

4. **Calculate Gt:**

$$Gt = 25 \times 1728 = \mathbf{43{,}200}$$

(This is within the normal range of 10^4 to 10^5).

Exam Variation to Watch For (2020 Q1c, 2023 Q1b)

Sometimes they give you P, μ, and a graph from a jar test to find the optimal G. They ask you to calculate the required **Depth** of the tank.

How to solve:

1. Read the optimal G from the peak of the Jar Test graph provided in the exam question (e.g., $G = 30s^{-1}$).

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

3. Calculate V.

4. Since $V = $ Length $\times$ Width $\times$ Depth, divide your calculated V by the given Length and Width to find the **Depth**.

Lecture 3: Sedimentation (Part 1 - Discrete Settling).

In the exams, this topic is almost always paired with the Coagulation question (Q1). The questions are usually split between **definitions** (types of settling) and **calculations** (Stokes' law and removal efficiency).

Part 1: The 4 Types of Settling (Memorise These)

Past papers (e.g., 2018 Q1d) often ask you to describe these.

1. **Type I: Discrete Settling**
   - Particles settle individually without interacting with neighbors.
   - Properties (size, shape, density) do *not* change during settling.
   - *Example:* Sand or grit removing in a grit chamber.

2. **Type II: Flocculent Settling**
   - Particles collide and stick together (flocculate) as they settle.
   - They get larger and settle faster as they go deeper.
   - *Example:* Alum or iron floc settling after coagulation.

3. **Type III: Hindered (Zone) Settling**
   - High particle concentration. Particles are so close they hinder (block) each other.
   - They settle as a distinct "blanket" or zone, with clear water above.
   - *Example:* Upper layer of sludge thickening.

4. **Type IV: Compression Settling**
   - Very high concentration. Particles physically touch and support each other.
   - Settling only happens by the weight of particles squeezing water out.
   - *Example:* Bottom of a deep sludge tank.

Part 2: Important Concepts

1. Surface Overflow Rate (v_0)
This is the most critical design parameter. It represents the upward velocity of the water.

$$v_0 = \frac{Q}{A}$$

- Q = Flow rate (m^3/d)
- A = Surface Area (m^2)
- v_0 units: m/d or m/h (velocity).

2. The Removal Rule (Ideal Settlement)
If a particle has a settling velocity (v_s):

- If $v_s \geq v_0$: The particle settles fast enough. **100% Removal.**
- If $v_s < v_0$: The particle settles too slow. **Partial Removal.**
   - Percentage removed = $\frac{v_s}{v_0} \times 100$

IMPORTANT: Problem Set Walkthrough

This section covers the calculation of **Settling Velocity (v_s)** using Stokes' Law. This comes up in almost every year (2017, 2020, 2023, 2025).

Formula to Memorize (Stokes' Law)

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

- g = Gravity ($9.81 m/s^2$)
- S = Specific Gravity of particle (density of particle / density of water).
- d = Diameter of particle (**Must be in meters!**)
- ν = Kinematic viscosity of water (m^2/s). *(Note: If given dynamic viscosity μ, remember $\nu = \mu/\rho$).*

Problem 1: Discrete Settling Calculation

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 $\nu = 1.14 \times 10^{-6} m^2/s$).

Step-by-Step Working:

1. **Convert units to SI (Meters and Seconds):**

   o Diameter $d = 0.2$ mm $= 0.2 \times 10^{-3}$ m.

   o Time $t = 10$ minutes $= 600$ seconds.

2. **Calculate Settling Velocity (v_s) using Stokes' Law:**

$$v_s = \frac{9.81 \times (1.2 - 1) \times (0.2 \times 10^{-3})^2}{18 \times (1.14 \times 10^{-6})}$$

$$v_s = \frac{9.81 \times 0.2 \times 4 \times 10^{-8}}{2.052 \times 10^{-5}}$$

$$v_s = \frac{7.848 \times 10^{-8}}{2.052 \times 10^{-5}} = \mathbf{0.00382\ m/s}$$

3. **Check Reynolds Number (Re) (Crucial Exam Step):**

   o Stokes' Law is only valid for Laminar flow ($Re < 1$). You **must** check this to get full marks.

4. $Re = \frac{v_s \cdot d}{\nu}$

$$Re = \frac{0.00382 \times (0.2 \times 10^{-3})}{1.14 \times 10^{-6}} = 0.67$$

   o Since $0.67 < 1$, the flow is laminar. **Stokes' Law is valid.**

5. **Calculate Distance Settled:**

$$\text{Distance} = \text{Velocity} \times \text{Time}$$

$$\text{Distance} = 0.00382 \text{ m/s} \times 600 \text{ s} = \mathbf{2.29\ meters}$$

Problem 2: Why Coagulation Helps (Theory Question)

Question: Explain how Stokes' law shows why coagulation/flocculation is beneficial.

Answer:

- Look at the Stokes' equation: $v_s \propto d^2$ (Velocity is proportional to the **square** of the diameter).
- Coagulation and Flocculation combine small particles into larger flocs, increasing the diameter (d).
- Because of the square relationship, a small increase in diameter leads to a **massive increase in settling velocity**.
  - *Example: If you double the particle size, it settles 4 times faster.*
- Faster settling means you can use a smaller tank or treat more water (higher flow rate).

Advanced Exam Calculation: Integration Method

(Seen in 2018 Q1e, 2019 Q1e, 2020 Q1e, 2024 Q1d)

Sometimes they give you a table of particle size distribution (mass fraction) and ask for the **Total % Removal** for a specific tank overflow rate (v_0).

Step-by-Step:

1. **Calculate** v_s for every particle size in the table using Stokes' Law.
2. **Compare** each v_s to the tank's overflow rate (v_0).
3. **Apply the Logic:**
   - **Group A (Fast particles):** If $v_s > v_0$, these are 100% removed.
   - **Group B (Slow particles):** If $v_s < v_0$, these are partially removed. The fraction removed is $\frac{v_s}{v_0}$.
4. **Sum them up:** Total Removal $=$ (Fraction of Fast Particles) $+ \sum \left(\text{Fraction of Slow Particle} \times \frac{v_{s,slow}}{v_0} \right)$

Note: In the exam, they often provide a graph. You draw a vertical line at v_0. Everything to the right is 100% removed. Everything to the left is integrated (area under the curve).

Lecture 4: Sedimentation (Part 2 - Analysis & Design).

This lecture focuses on **calculating removal efficiency** from experimental data and understanding the **design** of different tank types.

Part 1: Key Definitions & Theory (Memorise These)

1. Surface Overflow Rate (v_0 or SOR)

- This is the "speed limit" of the tank. It represents the upward velocity of the water.

- **Formula:** $v_0 = \frac{Q}{A}$

    - Q = Flow rate (m^3/d)

    - A = Surface Area of the tank (m^2)

- **Physical Meaning:** v_0 is the settling velocity of the slowest particle that is **100% removed**.

### 2. Ideal Horizontal Flow vs. Upflow (Critical Exam Question)
You are often asked to compare these (e.g., 2019 Q1f).

- **Horizontal Flow:** Water flows sideways.

    - Particles with settling velocity $v_s \geq v_0$ are 100% removed.

    - Particles with $v_s < v_0$ are **partially removed** (they settle some distance, and if they hit the bottom before the outlet, they are caught).

- **Upflow Clarifier:** Water flows vertically upwards.

    - Particles with $v_s \geq v_0$ settle down (removed).

    - Particles with $v_s < v_0$ move **upwards** with the water and escape.

    - **Exam Consequence:** Upflow clarifiers are **less efficient** than horizontal ones because they get **zero** removal of slow particles.

3. Tank Sketches (2020 Q1f, 2023 Q1e)
Practice drawing these three:

1. **Rectangular (Horizontal):** Inlet at one end, outlet weir at the other, sludge scraper at bottom.

2. **Radial (Circular):** Inlet in center, water flows out to edge weirs, rotating bridge scraper.

3. **Upflow (Hopper bottom):** Funnel shape. Water enters deep, flows up. Sludge settles in the pointed bottom.
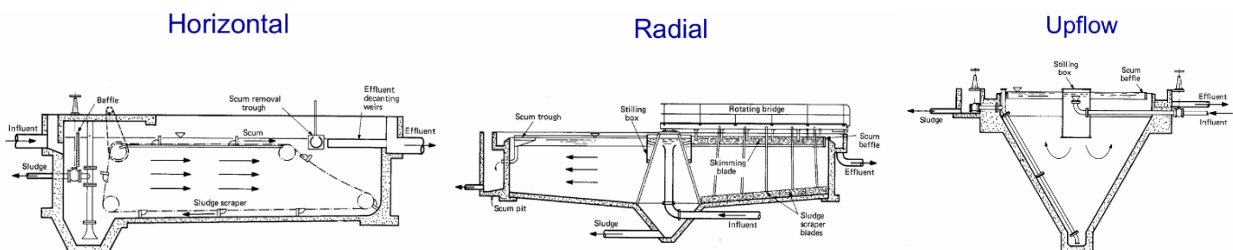
Part 2: The "Big" Calculation (Graphical Integration)

This is the calculation from **Slides 16–22**. It involves using data from a Settling Column Test to predict how well a real tank will perform.

The Logic:
Total Removal (X) = (Fraction of particles fast enough to settle) + (Partial removal of slow particles)

Formula:

$$X = (1 - x_0) + \sum \left(\frac{\Delta x \cdot v_{avg}}{v_0} \right)$$

- $(1 - x_0)$: The fraction of particles that settle faster than the design rate.
- The Summation part: The partial removal of the slower particles.

Problem Set Walkthrough

The Problem:
A settling column (depth 2.0 m) gives the following data.

- **Design Overflow Rate (v_0):** 25 m^3/m$^2 \cdot$ d (which is 25 m/d).
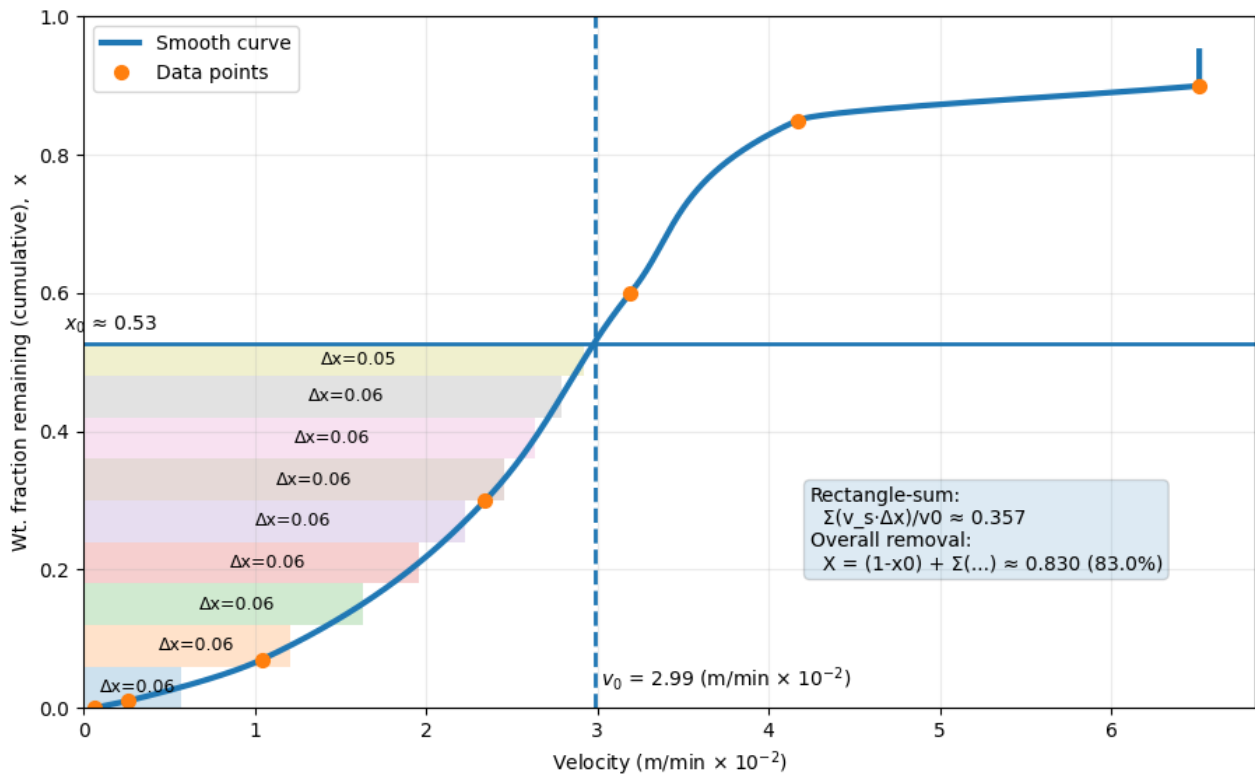- **Goal:** Calculate Total Removal Efficiency.

Data Table (from Slide 17):

Time (min)	Conc (mg/L)	Fraction Remaining (x)	Settling Velocity (v_s)
0	300	1.00	-
60	189	$189/300 = \mathbf{0.63}$	$2.0m/60min = \mathbf{3.3 \times 10^{-2}}$ **m/min**
80	180	$180/300 = \mathbf{0.60}$	$2.0m/80min = \mathbf{2.5 \times 10^{-2}}$ **m/min**
100	168	0.56	2.0×10^{-2}
...	...	...	...

(Note: Velocity is calculated as Depth / Time).

Step-by-Step Solution: Graphical Method for Removal Efficiency

Given

- Surface overflow rate:

$$v_0 = 43 \text{ m/d} = 2.99 \times 10^{-2} \text{ m/min}$$

The graph contains the following labels and annotations:

- y-axis: Wt. fraction remaining (cumulative), x
- x-axis: Velocity (m/min × 10^{-2})
- Legend: Smooth curve; Data points
- $x_0 \approx 0.53$
- $\Delta x = 0.05$
- $\Delta x = 0.06$ (repeated)
- $v_0 = 2.99$ (m/min × 10^{-2})
- Rectangle-sum:
  $\Sigma(v\_s \cdot \Delta x)/v0 \approx 0.357$
  Overall removal:
  $X = (1{-}x0) + \Sigma(...) \approx 0.830$ (83.0%)

Step 1: Plot settling curve

- x-axis: Settling velocity v_s

- y-axis: Cumulative fraction remaining x

- Draw a smooth monotonic curve through data points.

Step 2: Read off cut-off fraction

- Draw a vertical line at v_0

- Intersection with curve gives:

$$x_0 \approx 0.53$$

Step 3: Removal of fast particles

Particles with $v_s \geq v_0$ are fully removed:

$$1 - x_0 = 1 - 0.53 = 0.47$$

Step 4: Partial removal of slow particles

- Area to the left of the curve up to x_0 represents:

$$\int_0^{x_0} \frac{v_s}{v_0}\, dx$$

- Approximate using rectangular strips ($\Delta x \approx 0.06$) as shown on the graph.

- From block summation:

$$\Sigma \left(\frac{v_s \Delta x}{v_0} \right) \approx 0.36$$

Step 5: Total removal efficiency

$$X = (1 - x_0) + \Sigma \left(\frac{v_s \Delta x}{v_0} \right)$$

$$\boxed{X \approx 0.47 + 0.36 = 0.83 \ (83\%)}$$

Part 3: Iso-Removal Curves (The Other Exam Question)

(Seen in 2015 Q1b, 2016 Q1d)

Sometimes, instead of a simple graph, you are given a grid of removal percentages at different depths and times (Iso-removal lines).

How to solve:

1. **Calculate Retention Time:** $t = \frac{\text{Tank Volume}}{\text{Flow Rate}}$.

2. **Find Total Removal:** $R_{total} = r_0 + \Sigma \left(\frac{\text{Depth}_{mean}}{H} \times (r_n - r_{n-1}) \right)$

   - r_0: The removal percentage was achieved at the bottom of the tank at time t.

   - The sum adds up the extra removal from particles that didn't reach the bottom but settled *enough* to be caught (based on the average depth of the iso-removal lines).

Example Strategy (from 2016 Q2d):

- They tell you the detention time is 60 mins.

- Look at the 60 min mark on the graph.

- If the 50% removal line hits the bottom at 60 mins, then $r_0 = 50\%$.

- Then add the partials: $\frac{\text{Avg Depth of 60\% line}}{\text{Total Depth}} \times (60\% - 50\%)$, etc.

Lecture 5: Filtration.

In the exams, this topic usually appears in **Question 1 or 2**. The questions are highly predictable: they almost always ask about **Dual Media** (Theory) and **Headloss** (Calculation).

Part 1: Key Definitions & Theory (Memorise These)

1. Dual Media Filters (The #1 Exam Theory Question)
(Seen in 2018, 2020, 2021, 2023, 2025)
You are often asked: *"Why use Anthracite and Sand?"* or *"Why place Anthracite on top?"*

- **The Problem with Single Media (Sand only):** When backwashed, sand stratifies with the smallest grains at the top. This causes **surface blinding** (clogging at the very top), resulting in short filter runs and wasted space lower down.

- **The Solution (Dual Media):**
   - **Layer 1 (Top): Anthracite.** Large particles but *light* density.
   - **Layer 2 (Bottom): Sand.** Small particles but *heavy* density.

- **The Benefit:**
   - **Depth Filtration:** Large dirt is trapped by anthracite (top), small dirt is trapped by sand (bottom). The whole bed depth is used.
   - **Backwash Stability:** Because Anthracite is lighter, it settles *slower* than sand. After backwashing, the Anthracite naturally stays on top of the Sand.

2. Factors Affecting Headloss (h_L)
(Seen in 2019, 2020, 2023, 2025)
You need to know how changing variables affects the resistance to flow (headloss).

- **Increase Headloss:** Higher flow rate (V), Deeper bed (L), Colder water (higher viscosity μ), Angular media (higher shape factor).

- **Decrease Headloss:** Larger grain size (d), Higher porosity (e).
   - *Note on Shape Factor (S or ϕ):* Spheres = low headloss. Angular/Jagged grains = high headloss.

3. Filter Ripening (2017 Q1f)

- Immediately after backwashing, the filter is "too clean" and small particles pass through.

- **Ripening** is the initial period where particles begin to attach to the media; these attached particles act as collectors for other particles, improving efficiency.

- *Action:* Water is "filtered to waste" during ripening until turbidity drops.

4. When to Backwash? (2019 Q2b)
Filters are cleaned based on whichever criteria is met first:

1. **Headloss:** The pressure drop becomes too high (water can't get through).

2. **Breakthrough (Turbidity):** Particles start appearing in the effluent.

3. **Time:** A maximum time limit (e.g., 48 hours) to prevent biological growth/cementing.

Part 2: The "Big" Calculation (Headloss)

This calculation appears frequently (e.g., 2017, 2018, 2025). It uses the **Fair-Hatch Equation** for stratified beds (sieve analysis).

Formula to Memorize

You don't usually need to memorize the big equation (it's often provided or derived from parts), but you **must** know how to use it.

$$h_L = \frac{36k v (1-e)^2 V}{g e^3 \phi^2} \times \sum \left(\frac{P_i}{d_i^2} \right)$$

Variables:

- h_L: Headloss (m)
- k: Kozeny constant (usually 5 or 6)
- v: Kinematic viscosity (m^2/s)
- e: Porosity (dimensionless, e.g., 0.45)
- V: Filtration rate (velocity) (m/s) **<-- Watch out! Usually given in m/h**
- g: Gravity ($9.81 m/s^2$)
- ϕ: Shape factor (dimensionless, e.g., 0.8)
- $\sum \frac{P_i}{d_i^2}$: The sum of the mass fraction divided by the square of the diameter for each sieve size.

IMPORTANT: Problem Set Walkthrough

The Question:
Calculate the headloss through a sand filter.

- Bed depth (L): **0.7 m** (Note: In the Fair-Hatch equation above, the "L" is effectively inside the summation if analyzing the whole bed, but often the equation is written with L outside if calculating total headloss based on a total depth).
- Flow rate (V): **5.0 m/hour**
- Water Temp: 17°C ($v = 1.08 \times 10^{-6}$ m^2/s)
- Porosity (e): **0.45**
- Shape factor (ϕ): **0.82**
- Gravity (g): **9.81**
- Kozeny constant (k): **5** (Assumed standard if not given).

Sieve Data Table:

Sieve Opening (mm)	% Mass Retained
3.36	0
2.38	2
1.68	6
1.19	12

...	...

Step-by-Step Solution:

Step 1: The Sieve Analysis Table
This is the "engine" of the calculation. You must calculate the geometric mean diameter (d_i) for each sieve range and then the specific surface area contribution ($\frac{P_i}{d_i^2}$) for that fraction.

- $d_i = \sqrt{d_{top} \times d_{bottom}}$ (in meters!)
- P_i = Percentage as a fraction (e.g., 2% = 0.02)

Size Range (mm)	P_i (fraction)	Geometric Mean d_i (m)	Term: $\frac{P_i}{d_i^2}$ (m^{-2})
3.36 - 2.38	0.02	$\sqrt{3.36 \times 2.38} \times 10^{-3}$ $= 2.828 \times 10^{-3}$	2,501
2.38 - 1.68	0.06	1.999×10^{-3}	15,006
1.68 - 1.19	0.12	1.414×10^{-3}	60,024
1.19 - 0.84	0.40	0.999×10^{-3}	400,160
0.84 - 0.59	0.20	0.704×10^{-3}	403,551
0.59 - 0.42	0.12	0.497×10^{-3}	484,261
0.42 - 0.297	0.08	0.353×10^{-3}	641,334
0.297 - 0.210	0.00	-	0
SUM	**1.00**		**$\Sigma = 2.0068 \times 10^6$ m^{-2}**

Step 2: The Headloss Formula

$$h_L = 36 \cdot k \cdot v \cdot \frac{(1-e)^2}{e^3} \cdot \frac{V}{g\phi^2} \cdot L \cdot \sum \frac{P_i}{d_i^2}$$

Step 3: Plug and Play

- **Velocity:** $V = 5$ m/h $= \frac{5}{3600} = 0.001389$ m/s
- **Porosity Term:** $\frac{(1-0.45)^2}{0.45^3} = \frac{0.3025}{0.091125} = 3.3196$
- **Constants:** $\frac{36 \times 5 \times (1.08 \times 10^{-6})}{9.81 \times 0.82^2} = \frac{1.944 \times 10^{-4}}{6.596} = 2.947 \times 10^{-5}$

Step 4: Final Calculation

$$h_L = (2.947 \times 10^{-5}) \times (3.3196) \times (0.001389) \times (0.7) \times (2.0068 \times 10^6)$$

$$h_L \approx 0.191 \text{ m}$$

(Note: If you get a result like 200m or 0.0002m, check your unit conversions, especially the diameter in mm vs m).

Part 3: Carmen-Kozeny vs Bernoulli (2022 Q2c)

Sometimes they ask you to show how the headloss equation is a derivation of Bernoulli's equation.

- **Bernoulli:** Energy is conserved. Pressure drop + Elevation change = Headloss. $P_1 + \frac{1}{2}\rho v^2 + \rho g h_1 = P_2 + \frac{1}{2}\rho v^2 + \rho g h_2 + $ Losses

- **Link:** The headloss (h_L) in a filter is physically the pressure drop required to push water through the pores. The Carmen-Kozeny equation basically calculates the friction factor (f) and the hydraulic radius of the pores to define that "Losses" term in Bernoulli.

- **Key Phrase to write:** "The headloss equation recognizes that headloss is a form of pressure drop due to friction in laminar flow."

Lecture 6: Disinfection.

This topic is a guaranteed exam question. It usually appears as **Question 1 or 2** and involves a mix of theory (comparing disinfectants) and calculation (Ct values).

## Part 1: Key Definitions & Theory (Memorise These)

1. Primary vs. Secondary Disinfection

- **Primary Disinfection:** Occurs *in* the treatment plant. High dose to kill/inactivate pathogens (bacteria, viruses, protozoa) present in the source water.

- **Secondary Disinfection:** A residual disinfectant maintained *in the distribution network* (pipes) to prevent regrowth of bacteria and protect against contamination from leaks.

2. Chlorine Chemistry (The pH Effect)
(Exam Favourite: 2019 Q2c, 2020 Q2c)
When Chlorine (Cl_2) dissolves in water, it forms Hypochlorous Acid ($HOCl$) and Hypochlorite Ions (OCl^-).

$$HOCl \leftrightarrow H^+ + OCl^-$$
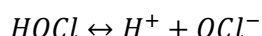
- **HOCl** is a much **stronger** disinfectant than OCl^-.

- **Low pH (< 7.5):** HOCl predominates → **Better/Faster disinfection.**

- **High pH (> 7.5):** OCl^- predominates → **Worse/Slower disinfection.**

  - *Exam Tip:* If the exam asks how to improve chlorine efficiency without adding more chlorine, the answer is often **lower the pH**.

3. Breakpoint Chlorination (Ammonia)
When water contains Ammonia (NH_3), chlorine reacts to form **Chloramines** (Combined Chlorine).

- **Zone A-B:** Chlorine is consumed by reducing agents (Fe, Mn). No residual.

- **Zone B-C:** Chlorine reacts with Ammonia to form Chloramines (Mono/Di). The residual rises, but this is *combined* chlorine (weak disinfectant).

- **Zone C-D:** Adding more chlorine oxidizes the chloramines into nitrogen gas. The residual *drops*.

- **Point D (Breakpoint):** All ammonia is destroyed.

- **Zone D-E:** Adding more chlorine creates **Free Chlorine Residual** ($HOCl + OCl^-$). This is the goal for primary disinfection.

4. Comparison of Disinfectants (2017 Q1i, 2021 Q2c, 2024 Q2a)
You need to know the Pros/Cons of the "Big 3":

Disinfectant	Pros	Cons
Chlorine	Cheap, effective against bacteria/viruses, leaves a **residual** (good for network).	**THMs** (cancer risk) formed with organics, pH dependent, ineffective against *Cryptosporidium*.
Ozone	Very strong oxidant, kills *Cryptosporidium*, improves taste/odour.	Expensive, complex generation onsite, **No residual**, forms Bromate.

UV	Kills *Cryptosporidium* & *Giardia* easily, no chemical by-products (no THMs).	**No residual**, water must be clear (low turbidity/high UVT), lamp fouling.

Part 2: The "Ct" Concept (The Core Calculation)

Regulations require a specific "log removal" (e.g., 3-log = 99.9% removal).
The effectiveness of disinfection depends on:

1. **Concentration (C):** How much disinfectant (mg/L).

2. **Time (t):** How long it is in contact (minutes).

The Golden Rule:

$$Ct_{\text{calculated}} \geq Ct_{\text{required}}$$

- $Ct_{\text{calculated}} = $ Residual Concentration $\times t_{10}$

- t_{10} is the time it takes for 10% of the water to pass through the tank (accounting for short-circuiting).

IMPORTANT: Problem Set Walkthrough

Here are the step-by-step solutions for the problems provided in the slides.

Problem 1: Chlorine Demand Curve

The Data:

Sample	Dose (mg/L)	Residual (mg/L)
1	0.20	0.19
2	0.40	0.37
3	0.60	0.51
4	0.80	0.50
5	1.00	0.40
6	1.20	0.20
7	1.40	0.42
8	1.60	0.65
9	1.80	0.85

Step-by-Step Analysis:

(a) Sketch the curve:

- Plot Dose (X-axis) vs Residual (Y-axis).

- **Observation:** The residual rises up to Dose 0.60 (Peak), then **drops** as dose increases to 1.20 (Dip), then rises linearly after 1.20.

- This "Dip" is the classic sign of chlorine destroying chloramines (ammonia).

(b) What is the breakpoint chlorine dosage?

- The breakpoint is the bottom of the "dip" where the combined chlorine is destroyed and free chlorine begins to form.
- Looking at the table, the lowest residual occurs at **Sample 6**.
- **Answer:** Breakpoint Dosage = **1.20 mg/L**.

(c) What is the chlorine demand at a dosage of 1.0 mg/L?

- Formula: Demand = Dose − Residual
- At Dose 1.00, Residual is 0.40.
- Calculation: $1.00 - 0.40 = 0.60$
- **Answer: 0.60 mg/L**.

(d) Impact of water quality changes (All else equal):

- **(i) pH decreases from 7.5 to 6.5:**
  - Result: **Improve**. Lower pH favours HOCl (stronger) over OCl^- (weaker).
- **(ii) Temperature increases from 10°C to 15°C:**
  - Result: **Improve**. Chemical reactions (kill rate) are faster at higher temperatures.
- **(iii) Organic matter increases:**
  - Result: **Worsen**. Chlorine reacts with organics (demand increases), leaving less residual for disinfection. Also increases THM formation.
- **(iv) Ammonia is added:**
  - Result: **Worsen**. It moves the "breakpoint" to the right. You would need a much higher dose of chlorine to get past the chloramines and achieve a free residual.

Problem 2: Ct Calculation (Formula Based)

Given:

- Chlorine Residual (C) = **1.0 mg/L**
- pH = **8.0**
- Temp = **10°C**
- Target: 4-log *Giardia* inactivation.
- Formula provided: $Ct = 0.985 \cdot C^{0.176} \cdot pH^{2.75} \cdot T^{-0.147}$

Step-by-Step Solution:

(a) Calculate Ct under these conditions.

1. Plug values into the formula: $Ct = 0.985 \times (1.0)^{0.176} \times (8.0)^{2.75} \times (10)^{-0.147}$
2. Calculate terms:
   - $(1.0)^{0.176} = 1$
   - $(8.0)^{2.75} \approx 304.4$

- o $(10)^{-0.147} \approx 0.7128$
3. Multiply: $Ct = 0.985 \times 1 \times 304.4 \times 0.7128$ $Ct = 213.7$
4. **Answer: 214 mg·min/L**

(b) Calculate Ct required at 5°C.

- Formula provided: $Ct_2 = Ct_1 \cdot 1.072^{(T_1 - T_2)}$
- $T_1 = 10°C$ (Base condition), $T_2 = 5°C$ (New condition).
- $Ct_1 = 214$
- Calculation: $Ct_2 = 214 \times 1.072^{(10-5)}$ $Ct_2 = 214 \times 1.072^5$ $Ct_2 = 214 \times 1.4157$ $Ct_2 = 302.9$
- **Answer: 303 mg·min/L** (Lower temp requires *more* exposure time).

(c) Calculate Ct for 3-log inactivation at 10°C (Linear assumption).

- The formula in (a) was for 4-log.
- Linear relationship means: $\frac{\text{Required Log}}{\text{Reference Log}} \times$ Reference Ct.
- Calculation: $Ct_{3log} = \frac{3}{4} \times Ct_{4log}$ $Ct_{3log} = 0.75 \times 214$
- **Answer: 160.5 mg·min/L**

(d) Calculate Max Flow Rate (Q).

- **Tank Dimensions:** Length = 10m, Width = 10m, Depth = 6m.
- **Target:** 4-log *Giardia* at 10°C.
- **Residual (C):** 1.0 mg/L (assumed from start of question).
- **Required Ct:** 214 mg·min/L (from part a).
1. **Calculate Tank Volume (V):**

$$V = 10 \times 10 \times 6 = 600 \text{ m}^3$$

2. **Calculate Required Time (t):**

$$Ct = 214 \text{ mg} \cdot \text{min}/L$$

$$t = \frac{Ct}{C} = \frac{214}{1.0} = 214 \text{ minutes}$$

3. **Calculate Flow Rate (Q):**

$$t = \frac{V}{Q} \Rightarrow Q = \frac{V}{t}$$

$$Q = \frac{600 \text{ m}^3}{214 \text{ min}} = 2.80 \text{ m}^3/\text{min}$$

4. **Convert to m^3/day:**

$$Q_{\text{daily}} = 2.80 \times 60 \times 24$$

Answer: 4,032 m³/day

Important Note on Exam Tables vs Formulas

In the actual exam (e.g., 2017 Q1h, 2023 Q2c), they often provide a **Table** of Ct values instead of a formula.

- **If given a table:** Look up the Temp and pH to find the required Ct value directly.
- **Interpolation:** If your specific pH (e.g., 7.3) is between two columns (7.0 and 7.5), you must linearly interpolate between the values.

Lecture 7 (Water Distribution Networks)

This lecture has appeared in **every single exam from 2019 to 2024** as part of **Question 2**.

Here is the "Cheat Sheet" for what you must memorise for this lecture based on the past 5 years of exams.

Part 1: The #1 Most Common Question – DMAs

(Exam: 2019 Q2f, 2020 Q2f, 2021 Q2e)

Question: Explain what a District Metered Area (DMA) is, how it works, and its pros/cons.

1. Definition:
A discrete area of the distribution network (typically 1000–3000 properties) that is permanently hydraulically isolated.

- **Inlet:** Water enters through a single (or few) metered pipes.

- **Boundary:** All other pipes connecting to the rest of the network are permanently closed (boundary valves).

2. The Sketch (You MUST practice drawing this):

- Draw a cloud/shape representing a neighbourhood.

- Draw a pipe entering it with a **Flow Meter symbol** (circle with M).

- Draw pipes leaving it with **Closed Valve symbols** (X).

- Label it "Single Feed DMA".
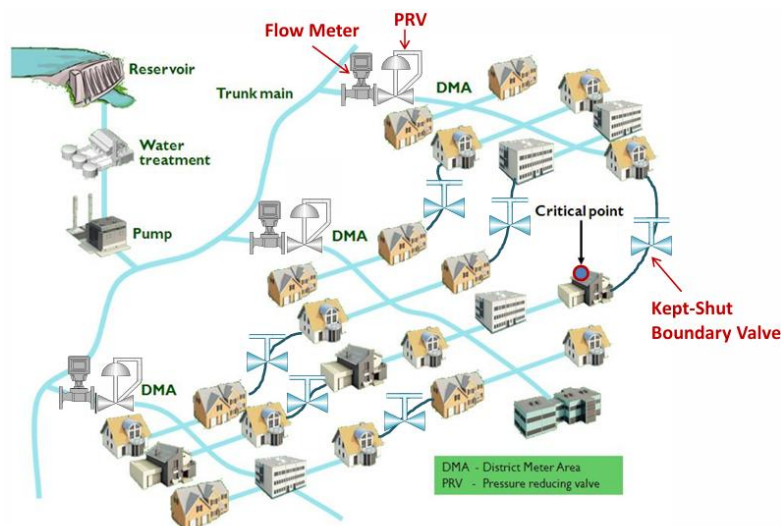
3. Purpose:
To calculate **Net Night Flow** (NNF) to quantify leakage.

$$\text{Leakage} = \text{Total Inflow} - \text{Legitimate Night Consumption}$$

4. Pros vs. Cons (Memorise 2 of each):

- **Pros:**
    - Detects bursts quickly (by monitoring night flow).

- o   Allows targeted pressure management.
- **Cons:**
  - o   **Resilience:** If the single inlet pipe breaks, the whole area loses water.
  - o   **Water Quality:** Closing valves creates "dead ends" where water can stagnate (sedimentation/discolouration).
  - o   Higher energy losses.

Part 2: Minimum Night Flow (MNF)

(Exam: 2020 Q2f)

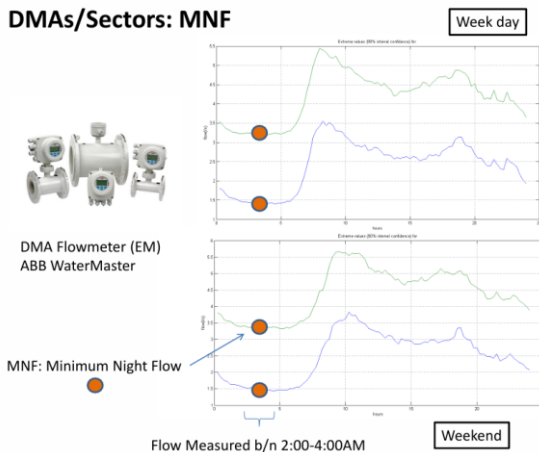**Question:** How is MNF used for leakage management?

Theory:

- Leakage is easiest to detect between **02:00 and 04:00 am**.
- **Why?** Legitimate customer consumption is at its lowest and most stable. Therefore, any significant flow recorded during this time is likely **Leakage**.
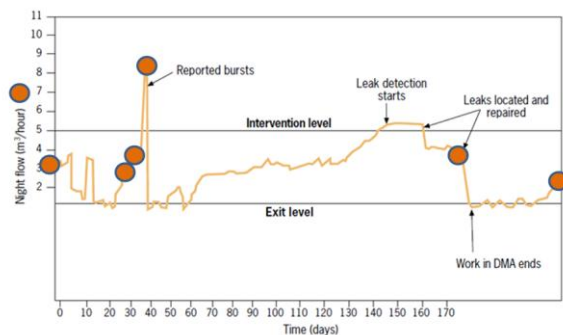
The Diagram to Draw (Slide 93):

- Draw a graph of **Flow (Y-axis)** vs **Time (X-axis)** over 24 hours.
- Show a high peak in the morning (7am) and evening (7pm).
- Show a dip in the middle of the night.
- Draw a horizontal line across the bottom of the graph. Label this **"Background Leakage"**.
- Draw a "spike" in the night flow graph to represent a **"Burst"**.

Part 3: Pressure Management

(Exam: 2020 Q2e, 2023 Q2e)

Question: Explain the benefits of pressure control.

1. The Relationship (FAVOUR equation):
Leakage flow rate (Q_{leak}) is linked to Pressure (P).

$$Q_{leak} \propto P^{N1}$$

- $N1$ is usually > 1 for plastic pipes.
- **Meaning:** If you reduce pressure, you reduce leakage flow rate *significantly*.

2. Benefits of Pressure Control:

1. **Reduces Background Leakage:** Lower pressure pushes less water out of small cracks.
2. **Reduces Burst Frequency:** Pressure transients (water hammer/surges) stress pipes. Keeping pressure stable (calm) prevents pipes from bursting.
3. **Extends Asset Life:** Less stress on the infrastructure.

3. The Diagram (Slide 103):

- Draw a "Sawtooth" graph showing pressure going up and down wildly. Label "Before Management".
- Draw a smooth, lower flat line. Label "After Management".

Pressure Management
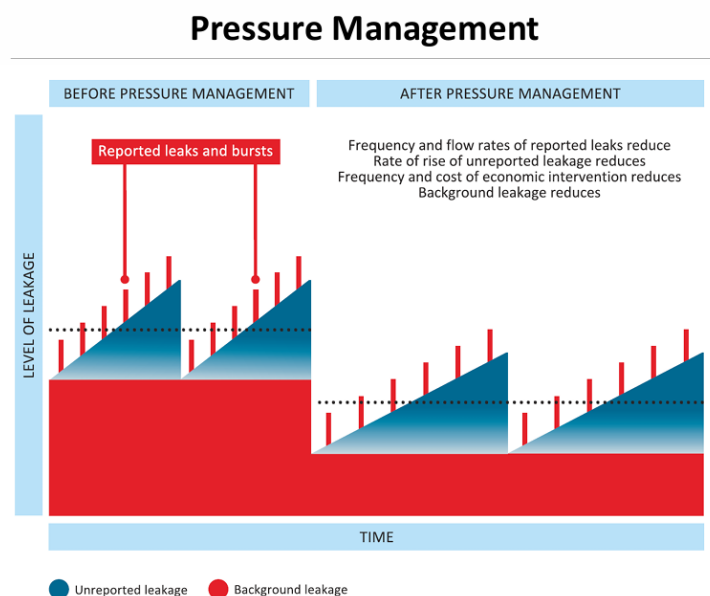
Part 4: TOTEX & Risk (The Modern Question)

(Exam: 2022 Q2f, 2024 Q2d)

Question: How to optimise TOTEX (Total Expenditure) or prioritize pipe renewal?

1. TOTEX Definition:

- TOTEX = CAPEX (Capital Expenditure - building new things) + OPEX (Operational Expenditure - running things).
- The goal is to stop thinking about them separately and look at the *whole life cost*.

2. Risk-Based Renewal:
You don't replace *old* pipes; you replace *risky* pipes.

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

3. The Flowchart (Memorise this sequence):

1. **Data Collection:** Gather data on pipe age, material, soil type, past bursts.

2. **Probability Model:** Use AI/Stats to predict *likelihood* of failure.

3. **Consequence Model:** What happens if it fails? (Flooding a hospital = High consequence. Flooding a field = Low consequence).

4. **Risk Matrix:** Plot Probability vs Consequence.

5. **Decision:** Replace pipes in the "High/High" zone first.

Lecture 8: Stormwater & Wastewater Collection.

In the exam, this is always **Question 2 or 3**. It is a heavy calculation topic. You will almost certainly be asked to calculate **Pipe Capacity (Storm)** or **Sewer Settings (Wastewater)**.

Part 1: Key Definitions (Memorise These)

1. The WWTP Process Flow Diagram (High Probability Question) (DEFINTELY WILL COME UP IN EXAM)
(Exam: 2019 Q3a, 2020 Q3a, 2023 Q3b, 2024 Q3d)
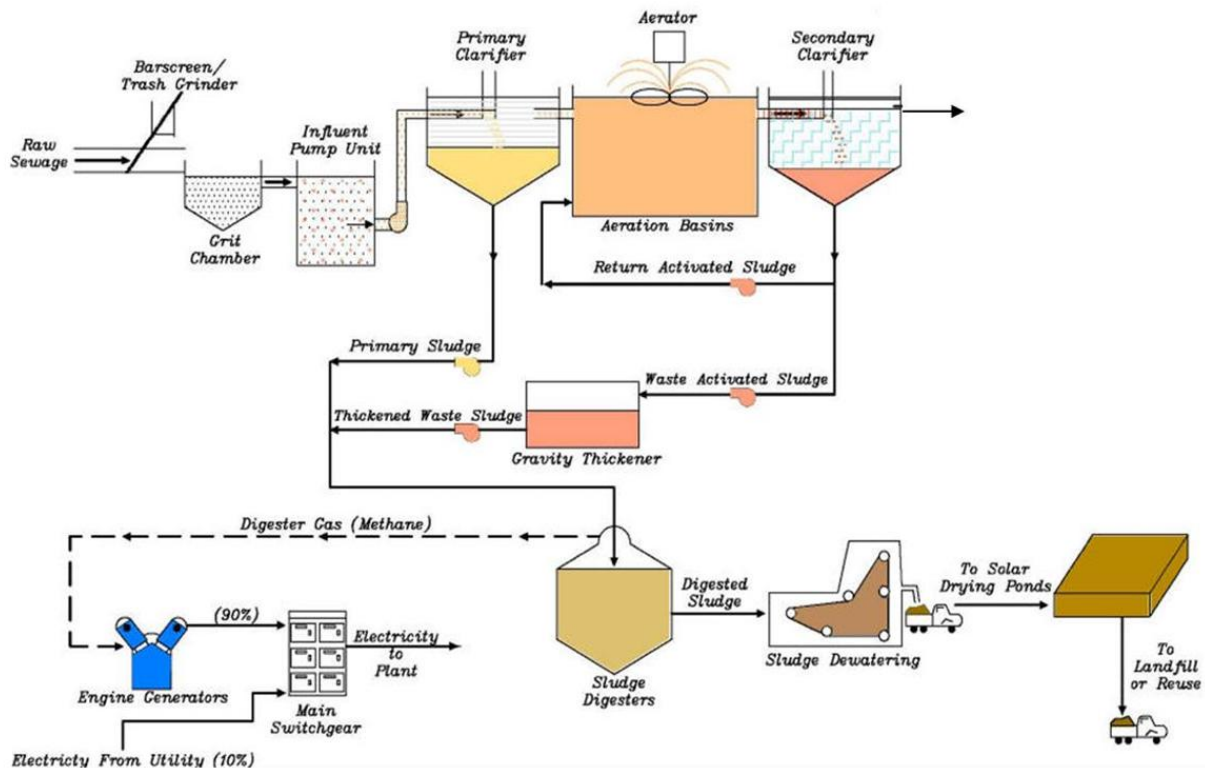
1. **A bar screen** is a mechanical filter for large objects removal, such as rags, plastics etc. (Pretreatment)
2. **A grit chambers** are basins to remove the inorganic particles to prevent damage to the pumps, and to prevent their accumulation in sludge digesters. (Pretreatment)
3. **A primary clarification** objective is suspended solids (SS) removal from wastewater under the sole influence of gravity. Settleable 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)
5. **A secondary clarifier** is to settle microorganisms 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.

2. Dry Weather Flow (DWF)
(Exam Definition: 2015 Q2c, 2017 Q2e)

- **Definition:** 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)

3. Combined Sewer Overflow (CSO)
(Exam Definition: 2017 Q2f, 2022 Q3b)

- **Role 1 (Hydraulic):** To prevent flooding of the treatment plant by diverting excess flow during heavy rain into a river/sea.

- **Role 2 (Environmental):** To retain as much solid/pollutant load as possible in the sewer (going to treatment) and only spill diluted water.

- **First Flush:** The initial surge of stormwater that washes accumulated dirt from roads/pipes. This is very polluted and must be captured (not spilled).

Part 2: Wastewater Calculations (Foul Sewers)

This involves calculating the **Peak Flow** to design the pipe size.

1. Calculate DWF (L/s)

$$DWF = \frac{(P \times G) + I + E}{24 \times 60 \times 60}$$

(Note: Convert everything to Litres/day first, then divide by 86,400 to get L/s).

2. Calculate Peak Flow
(Exam: 2016 Q2c, 2021 Q3d)
You multiply the DWF by a **Peak Factor**. Often you use **Babbitt's Formula**:

$$\text{Peak Factor} = \frac{5}{P^{0.2}}$$

- **CRITICAL WARNING:** In this formula, P **is in thousands**.

- *Example:* If Population is 50,000, use $P = 50$ in the formula.

Part 3: Stormwater Calculations (The Rational Method)

(Exam Favourite: 2016 Q2b, 2019 Q3c)
Used to size pipes for rain.

Formula:

$$Q = 2.78 \cdot C \cdot i \cdot A$$

- Q = Flow (L/s)
- C = Runoff coefficient (0.0 to 1.0, usually ~0.7-0.9 for urban)
- i = Rainfall intensity (mm/hr)
- A = Area ($hectares$)
- 2.78 = Unit conversion constant (memorize this number).

How to find Intensity (i):
You will be given a formula like $i = \frac{750}{D+10}$.

- D **(Duration)** is the **Time of Concentration (t_c).**
- t_c = Time of Entry (t_e) + Time of Flow (t_f).
  - t_e: Time for rain to run off the roof/road into the pipe (usually given, e.g., 5 mins).
  - t_f: Time for water to travel through the pipe (Length/Velocity).

IMPORTANT: Problem Set Walkthrough

There are two main types of calculation problems in this lecture.

Problem 1: Foul Sewer Design (DWF & Babbitt)

Question:
An urban catchment has an area of **500 ha** and population density of **75 people/ha**.

- Water consumption (G) = **160 L/head·d**
- Infiltration (I) = **20 L/head·d**
- Trade Effluent (E) = **10 m^3/ha·d** (applied to **10%** of the catchment area).
- **Calculate Average DWF and Peak Flow.**

Step-by-Step Working:

1. **Calculate Population (P):**

$$P = \text{Area} \times \text{Density} = 500 \times 75 = 37{,}500 \text{ people}$$

2. **Calculate Components (in L/day):**

   - **Domestic ($P \times G$):** $37{,}500 \times 160 = 6{,}000{,}000$ L/d.
   - **Infiltration (I):** $37{,}500 \times 20 = 750{,}000$ L/d.
   - **Industrial (E):**
     - Relevant Area = 10% of 500 = 50 ha.
     - Flow = 50 ha × 10 m³/ha = 500 m³/d.
     - Convert to Litres: $500 \times 1000 = 500{,}000$ L/d.

3. **Calculate Total DWF:**

$$\text{Total} = 6{,}000{,}000 + 750{,}000 + 500{,}000 = 7{,}250{,}000 \text{ L/d}$$

Convert to L/s:

$$DWF = \frac{7{,}250{,}000}{24 \times 60 \times 60} = \mathbf{83.9\ L/s}$$

4. **Calculate Peak Flow (Babbitt's Formula):**

   o P in thousands = 37.5.

5. **Peak Factor** $= \dfrac{5}{37.5^{0.2}} = \dfrac{5}{2.06} = 2.42$

$$\text{Peak Flow} = 83.9 \times 2.42 = \mathbf{203\ L/s}$$

Problem 2: CSO Setting (Formula A)

(Seen in 2022 Q3b)

Question:
Determine the CSO setting (the flow at which the pipe spills to the river).

- Population (P) = 50,000
- Domestic Consumption (G) = 250 L/head·d
- Infiltration (I) = 0
- Industrial (E) = 0
- **Formula A:** Setting $= DWF + 1360P + 2E$ (Litres/day)

Step-by-Step Working:

1. **Calculate DWF:**

$$DWF = 50{,}000 \times 250 = 12{,}500{,}000 \text{ L/day}$$

2. **Apply Formula A:**

$$\text{Setting} = 12{,}500{,}000 + (1360 \times 50{,}000) + (2 \times 0)$$

$$\text{Setting} = 12{,}500{,}000 + 68{,}000{,}000$$

$$\text{Setting} = 80{,}500{,}000 \text{ L/day}$$

3. **Convert to L/s:**

$$\frac{80{,}500{,}000}{86400} = \mathbf{932\ L/s}$$

Problem 3: Storm Sewer Network (Rational Method)

(This is the most complex one, seen in 2019 Q3c. It involves a table, the scenario below is just a mock example of the actual question. In the real question Pipe 1 doesn't flow into Pipe 2).

Scenario: Pipe 1 flows into Pipe 2.

- **Pipe 1:** Length = 240m, Velocity = 1.0 m/s, Area = 1.0 ha, C = 0.7, Time of Entry (t_e) = 5 mins.

- **Pipe 2:** Length = 100m, Velocity = 1.5 m/s, Area = 0.5 ha, $C = 0.7$.
- **Rain Formula:** $i = \frac{750}{D+10}$.

Step-by-Step Working:

Part A: Design Pipe 1

1. **Calculate Time of Flow (t_f):** $t_f = \frac{\text{Length}}{\text{Velocity}} = \frac{240}{1.0} = 240 \text{ s} = 4 \text{ mins}$

2. **Calculate Duration (D):** $D = t_e + t_f = 5 + 4 = 9 \text{ mins}$

3. **Calculate Intensity (i):** $i = \frac{750}{9+10} = 39.5 \text{ mm/hr}$

4. **Calculate Flow (Q):** $Q = 2.78 \times 0.7 \times 39.5 \times 1.0 = \mathbf{76.9 \ L/s}$

Part B: Design Pipe 2 (The Cumulative Effect)
Pipe 2 must handle the water falling on its own area PLUS the water coming from Pipe 1.

1. **Calculate Cumulative Area:** $1.0 + 0.5 = 1.5 \text{ ha}$.

2. **Calculate Longest Time of Concentration (t_c):**
   - Time to get to the *end* of Pipe 1 = 9 mins (calculated above).
   - Time to travel through Pipe 2 = $\frac{100m}{1.5m/s} = 67 \text{ s} = 1.1 \text{ min}$.
   - Total $D = 9 + 1.1 = 10.1 \text{ mins}$.

3. **Calculate New Intensity (i):** $i = \frac{750}{10.1+10} = 37.3 \text{ mm/hr}$

4. **Calculate Total Flow (Q) for Pipe 2:** $Q = 2.78 \times 0.7 \times 37.3 \times 1.5 = \mathbf{108.9 \ L/s}$

Lecture 9: Activated Sludge (AS) & Biological Filtration.

In the exam, this is a **guaranteed Question 2 or 3**.
It is a heavy calculation topic. You will almost certainly have to design an Activated Sludge tank (find Volume or Biomass) or checking Trickling Filter loading rates.

## Part 1: Key Definitions (Memorise These)

1. Activated Sludge vs. Trickling Filters
(Exam: 2015 Q2h, 2016 Q2f, 2019 Q3f)
You must be able to compare these two main biological processes.

Feature	Activated Sludge (AS)	Trickling Filter (TF)
Type	Suspended Growth (bacteria floats in water)	Attached Growth (biofilm grows on rocks/plastic)
Power	High (needs aeration pumps)	Low (gravity flow + natural ventilation)
Skill	Complex operation (needs monitoring)	Simple operation
Space	Small footprint	Large land area required
Issues	Sludge bulking (poor settling)	Flies, odours, clogging

TRICKLING FILTERS
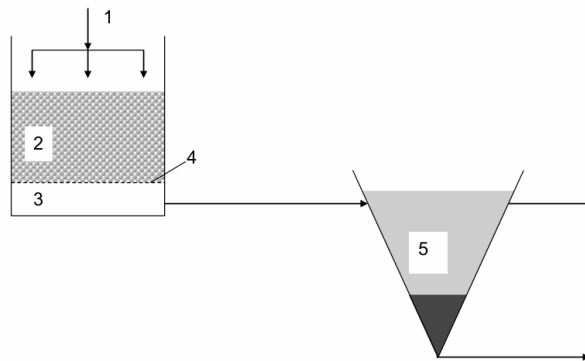
Trickling filters have the following components:
1. a dosing system for applying wastewater
2. a bed of randomly packed solid media
3. an underdrainage system for wastewater collection
4. a ventilation system for supplying oxygen
5. a system for separating the detached biofilm (humus) from treated effluent

2. Sludge Volume Index (SVI)
(Exam: 2017 Q2h, 2021 Q3e)

- **Definition:** The volume (in mL) occupied by 1 gram of sludge after 30 mins settling.
- **Formula:** $SVI = \frac{\text{Settled Volume (mL/L)} \times 1000}{MLSS\,(mg/L)}$

- **Significance:**
  - $50 < SVI < 150$: Good settling.
  - $SVI > 150$: **Sludge Bulking** (Poor settling, often caused by filamentous bacteria).

3. Nitrification vs. Denitrification

- **Nitrification:** Ammonia (NH_3) → Nitrate (NO_3^-). Requires Oxygen (Aerobic).

- **Denitrification:** Nitrate (NO_3^-) → Nitrogen Gas (N_2). Requires **No** Oxygen (Anoxic) and a Carbon source.

Part 2: The "Holy Trinity" of AS Equations

You will use these three equations for almost every calculation.

1. F/M Ratio (Food to Microorganism)
Describes how much food (BOD) is given to the bacteria (MLSS).

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

- Q = Flow rate (m^3/d)

- S_0 = Influent BOD (mg/L or g/m^3)

- V = Tank Volume (m^3)

- X = MLSS (Biomass Concentration) (mg/L or g/m^3)

- *Typical Range*: $0.2 - 0.5 \ kgBOD/kgMLSS \cdot d$

2. Hydraulic Retention Time (θ or HRT)
How long the water stays in the tank.

$$\theta = \frac{V}{Q}$$

3. Sludge Age (θ_c or SRT)
How long the bacteria stay in the system.

$$\theta_c = \frac{\text{Total Biomass}}{\text{Biomass Removed/Day}} = \frac{V \cdot X}{P_x}$$

- P_x = Sludge Production Rate (kg/d). (Also written as $Q_w X_u$).

IMPORTANT: Problem Set Walkthrough

Here are the step-by-step solutions for the two problems in your slides.

Problem 1: Activated Sludge Design

Question:

- Flow (Q) = **5 Ml/d**

- Influent BOD (S_0) = **250 mg/l**

- Target F/M = **0.3 kg BOD / kg MLSS·d**

- Hydraulic Retention Time (θ) = **6 hours**

- Sludge Age (θ_c) = **6 days**
- **Find:** MLSS concentration (X) and Daily Sludge Mass (P_x).

Step-by-Step Working:

Step 1: Unit Conversions (CRITICAL)

- $Q = 5$ Ml/d $= 5,000$ m^3/d.
- $S_0 = 250$ mg/l $= 250$ g/m$^3 = 0.25$ kg/m^3.
- $\theta = 6$ hours $= 6/24 = 0.25$ days.

Step 2: Calculate Tank Volume (V)
Using HRT formula:

$$V = Q \times \theta$$

$$V = 5,000 \times 0.25 = \mathbf{1,250 \ m^3}$$

Step 3: Calculate MLSS (X)
Using the F/M formula:

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

Rearrange to solve for X:

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

$$X = \frac{5,000 \times 0.25}{1,250 \times 0.3}$$

$$X = \frac{1,250 \text{ kg BOD/day}}{375}$$

$$X = 3.333 \text{ kg/m}^3 = \mathbf{3,333 \ mg/L}$$

Step 4: Calculate Daily Sludge Production (P_x)
Using the Sludge Age formula:

$$\theta_c = \frac{V \cdot X}{P_x}$$

Rearrange to solve for P_x:

$$P_x = \frac{V \cdot X}{\theta_c}$$

$$P_x = \frac{1,250 \text{ m}^3 \times 3.333 \text{ kg/m}^3}{6 \text{ days}}$$

$$P_x = \frac{4,166.25 \text{ kg}}{6} = \mathbf{694 \ kg/day}$$

Problem 2: Trickling Filter Loading

Question:

- Settled wastewater flow (Q) = **3.2 Ml/d**

- BOD (S_0) = **200 mg/l**

- Configuration: **Two circular filters**, diameter (d) = **42 m**, depth (D) = **2 m**.

- **Calculate:** Organic Loading Rate (OLR) and Hydraulic Loading Rate (HLR). Check if they are in range.

Step-by-Step Working:

Step 1: Calculate Dimensions

- Radius (r) = 42/2 = 21 m.

- Surface Area of **ONE** filter (A_1) = $\pi r^2 = \pi \times 21^2 = 1385.4 \text{ m}^2$.

- **Total Area (A_{total}):** $2 \times 1385.4 = \mathbf{2770.8 \ m^2}$.

- **Total Volume (V_{total}):** $A_{total} \times \text{depth} = 2770.8 \times 2 = \mathbf{5541.6 \ m^3}$.

Step 2: Unit Conversions

- $Q = 3{,}200 \text{ m}^3/\text{d}$.

- $S_0 = 200 \text{ g/m}^3 = 0.2 \text{ kg/m}^3$.

Step 3: Calculate Organic Loading Rate (OLR)
Formula: Total BOD Load / Total Volume

$$\text{BOD Load} = Q \times S_0 = 3{,}200 \times 0.2 = 640 \text{ kg/d}$$

$$OLR = \frac{640}{5541.6} = \mathbf{0.115 \ kg \ BOD/m^3 \cdot d}$$

Step 4: Calculate Hydraulic Loading Rate (HLR)
Formula: Total Flow / Total Surface Area

$$HLR = \frac{Q}{A_{total}}$$

$$HLR = \frac{3{,}200}{2{,}770.8} = \mathbf{1.15 \ m^3/m^2 \cdot d}$$

Step 5: Check against criteria (Memorise these ranges!)

- Typical OLR range: $0.06 - 0.12$. **Result (0.115) is OK.**

- Typical HLR range: $0.25 - 1.2$. **Result (1.15) is OK.**

Lecture 10: Sewage Sludge Treatment.

In the exam, this usually appears as **Question 2 or 3**.
The questions are evenly split between **Theory** (describing Anaerobic Digestion) and **Calculations** (Sludge Production Mass & Volume).

Part 1: Key Definitions & Theory (Memorise These)

1. Primary vs. Secondary Sludge (Exam: 2015, 2022)
You need to know the difference between the two sources:

- **Primary Sludge:** Comes from the Primary Settlement Tank. It is granular, grey, odorous, and contains **inorganic** solids (grit) and settlable organics. (Higher solid content: ~4-6%).

- **Secondary (Activated) Sludge:** Comes from the Secondary Clarifier. It is light, flocculent, brown, and consists mainly of **biomass** (bacteria). (Lower solid content: ~0.5-2%).

2. Anaerobic Digestion (AD) (The #1 Theory Question)
(Exam: 2016, 2017, 2018, 2020)
You must memorize the **4 Stages** of AD:

1. **Hydrolysis:** Complex organics (fats, proteins) broken down into simple sugars/amino acids.

2. **Acidogenesis:** Simple sugars converted to Volatile Fatty Acids (VFAs).

3. **Acetogenesis:** VFAs converted to Acetic Acid (CH_3COOH), H_2, and CO_2.

4. **Methanogenesis:** Archaea bacteria convert Acetic Acid/Hydrogen into **Methane (CH_4)** and CO_2.

Key Operational Conditions (Memorise):

- **Temp:** Mesophilic (35°C) is most common.

- **Time:** 12-20 days retention time.

- **Biogas Output:** ~60% Methane, ~40% CO_2. Used for energy (CHP engines).

3. Other Treatment Methods (2017 Q2i)
Be able to list 2 advantages/disadvantages of these:

- **Liming:** Adding lime to raise pH > 12. Kills pathogens but increases sludge mass.

- **Composting:** Aerobic process. Good for soil conditioner, but requires space and odour control.

- **Incineration:** Burning. Reduces volume by 90%, generates energy, but high cost and public opposition.

Part 2: Important Calculations

There are two main calculation types for Sludge.

Calculation Type 1: Sludge Production (Mass & Volume)

(Exam: 2015 Q2g, 2022 Q3c)

Formulas to Memorise:

1. **Primary Sludge Mass (M_{ps}):** $M_{ps} = \epsilon \times SS_{in} \times Q$

- ϵ: Removal efficiency of primary tank (e.g., 0.6).
- SS_{in}: Influent Suspended Solids (mg/L or kg/m^3).
- Q: Flow (m^3/d).

2. **Secondary Sludge Mass (M_{ss}):** $M_{ss} = Y_{obs} \times BOD_{removed} \times Q$

- Y_{obs}: Yield coefficient (kg sludge / kg BOD removed).

3. **Sludge Volume (V_{sludge}):** $V_{sludge}(\text{m}^3) = \frac{\text{Mass of Dry Solids (kg)}}{\text{Density of Sludge (kg/m}^3)\times\%\text{Dry Solids}}$

- *Approximation:* Density of wet sludge $\approx$ 1000 kg/m³ (same as water).

IMPORTANT: Problem Set Walkthrough

Here is a typical exam-style problem combining these formulas. (These questions are from past papers but not from problem set. There is no problem set for this chapter)

Question:
A WWTP treats **10,000 m^3/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 Treatment:** Removes 95% of remaining BOD. Yield (Y_{obs}) = **0.4 kg SS / kg BOD**. Secondary sludge is **0.8% DS**.
- **Calculate:** Total Daily Sludge Volume (m^3/d) produced.

Step-by-Step Working:

Step 1: Calculate Primary Sludge Mass

- $Q = 10{,}000$ m³/d.
- $SS_{in} = 300$ mg/L $= 0.3$ kg/m³.
- Removal $\epsilon = 0.6$. $M_{ps} = 0.6 \times 0.3 \times 10{,}000 = \textbf{1,800 kg/day}$

Step 2: Calculate Primary Sludge Volume

- %DS = 5% = 0.05.
- Assume density $\rho \approx 1000$ kg/m³. $V_{ps} = \frac{1{,}800}{1000 \times 0.05} = \frac{1{,}800}{50} = \textbf{36 m}^3\textbf{/day}$

Step 3: Calculate Secondary Sludge Mass

- First, find BOD entering secondary tank.
  - Initial BOD = 250 mg/L.
  - Primary removed 35%, so 65% remains.
  - $BOD_{in\_sec} = 250 \times 0.65 = 162.5$ mg/L.
- Secondary removes 95% of this.
  - $BOD_{removed} = 162.5 \times 0.95 = 154.4$ mg/L $= 0.1544$ kg/m³.
- Calculate Mass using Yield ($Y_{obs} = 0.4$): $M_{ss} = 0.4 \times 0.1544 \times 10{,}000 = \textbf{617.6 kg/day}$

Step 4: Calculate Secondary Sludge Volume

- %DS = 0.8% = 0.008.

- Assume density $\rho \approx 1000 \text{ kg/m}^3$. $V_{ss} = \frac{617.6}{1000 \times 0.008} = \frac{617.6}{8} = \mathbf{77.2 \text{ m}^3/\text{day}}$

Step 5: Total Volume

$$V_{total} = 36 + 77.2 = \mathbf{113.2 \text{ m}^3/\text{day}}$$

Calculation Type 2: Lab Solids Analysis

(Exam: 2018 Q2b, 2023 Q3c)
You are given weights of a dish before/after drying and burning. You must find TS, VS, TSS.

Formulas:

- **Total Solids (TS):** (Mass Dried @ 105°C - Mass Dish) / Sample Volume

- **Volatile Solids (VS):** (Mass Dried @ 105°C - Mass Burnt @ 550°C) / Sample Volume

- *Note: If filtered through paper, it is Suspended Solids (TSS).*

Practice Problem (2018 Data):

- Sample Volume = 100 mL.

- Dish = 81.923 g.

- Dish + Wet Sample = (Not needed for TS).

- Dish + Dry Solids (105°C) = 82.015 g.

- Dish + Ash (550°C) = 81.975 g.

Calculation:

1. **Mass of Dry Solids:** $82.015 - 81.923 = 0.092 \text{ g} = 92 \text{ mg}$.

2. **TS Concentration:** $92 \text{ mg}/0.1 \text{ L} = \mathbf{920 \text{ mg/L}}$.

3. **Mass of Volatiles (Lost on ignition):** $82.015 - 81.975 = 0.040 \text{ g} = 40 \text{ mg}$.

4. **VS Concentration:** $40 \text{ mg}/0.1 \text{ L} = \mathbf{400 \text{ mg/L}}$.

5. **Fixed Solids (Ash):** $TS - VS = 920 - 400 = \mathbf{520 \text{ mg/L}}$.

Lecture 11: Sustainability & Water Resources Management (Part A).

This module often appears as **Question 4** in recent exams (e.g., 2022, 2024). It focuses on **Life Cycle Assessment (LCA)** methodology and **Carbon Footprint calculations**.

Part 1: Key Definitions & Theory (Memorise These)

1. Life Cycle Assessment (LCA) - ISO 14040/14044
You must know the **4 Phases** of an LCA (Exam: 2024 Q4 asked for functional units/boundaries):

1. **Goal & Scope:** Defining *why* you are doing it, the **Functional Unit**, and **System Boundaries**.

2. **Inventory Analysis (LCI):** Collecting data on all inputs (energy, materials) and outputs (emissions, waste).

3. **Impact Assessment (LCIA):** Converting the inventory into environmental impacts (e.g., converting Methane into CO_2 equivalents).

4. **Interpretation:** Identifying hotspots, conclusions, and recommendations.

2. Important LCA Terms

- **Functional Unit:** A quantified performance of a product system for use as a reference unit (e.g., "Treatment of 1 m^3 of wastewater").

- **System Boundaries:**
    - **Cradle-to-Grave:** From raw material extraction to disposal.
    - **Cradle-to-Gate:** From extraction to the factory gate (before use).

- **Hotspot:** The stage or process contributing the *most* to the environmental impact (e.g., Electricity consumption is often the hotspot in WWTPs).

3. Indicators

- **Midpoint Indicators:** Focus on specific environmental problems (e.g., **Global Warming Potential** in kg CO_2eq, Eutrophication Potential).

- **Endpoint Indicators:** Aggregated damage to broad areas (e.g., Human Health, Ecosystem Quality).

Part 2: The Calculation – Carbon Footprint (GWP)

This is the standard calculation for this section. It involves converting various emissions and energy uses into a single unit: $kgCO_2$ **equivalents ($kgCO_2e$)**.

Formula to Memorize

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

Common Characterisation Factors (IPCC):

- **Carbon Dioxide (CO_2):** 1

- **Methane (CH_4):** ~27 - 30 (Use value given in exam, typically 28).

- **Nitrous Oxide (N_2O):** ~265 - 298 (Use value given in exam, typically 265).

IMPORTANT: Problem Set Walkthrough

Here is the solution to **Exercise 2 (Slide 80)**. This is very similar to **2024 Q4b**.

The Problem:
A WWTP treats **50,000 m^3/day** of wastewater.
Calculate the **Total Carbon Footprint** ($kgCO_2e/year$) and the **Specific Footprint** ($kgCO_2e/m^3$).

Inventory Data (per year):

- **Direct Emissions:**
    - CO_2 (Direct): 1,200,000 kg
    - CH_4: 8,000 kg
    - N_2O: 1,200 kg
- **Energy Use:**
    - Electricity: 12,000,000 kWh
    - Natural Gas: 500,000 kWh

Factors Provided:

- **GWP Factors:** CO_2 = 1; CH_4 = 27.2; N_2O = 273.
- **Grid Factors:** Electricity = 0.233 kg CO_2e/kWh; Natural Gas = 0.184 kg CO_2e/kWh.

Step-by-Step Solution:

Step 1: Calculate Scope 1 (Direct Emissions)
Convert all direct gas emissions into CO_2 equivalents.

- CO_2: $1,200,000 \times 1 = 1,200,000$ kg CO_2e
  (Note: In real exams, check if they say biogenic CO2 is "neutral" or "ignored". If not specified, include it as per the factors provided).
- CH_4: $8,000 \times 27.2 = 217,600$ kg CO_2e
- N_2O: $1,200 \times 273 = 327,600$ kg CO_2e

Total Scope 1 = $1,200,000 + 217,600 + 327,600 =$ **1,745,200 kg CO$_2$e/year**

Step 2: Calculate Scope 2 (Indirect Energy Emissions)
Multiply energy usage by the grid emission factors.

- **Electricity:** $12,000,000$ kWh $\times 0.233 = 2,796,000$ kg CO_2e
- **Natural Gas:** $500,000$ kWh $\times 0.184 = 92,000$ kg CO_2e

Total Scope 2 = $2,796,000 + 92,000 =$ **2,888,000 kg CO$_2$e/year**

Step 3: Calculate Total Carbon Footprint

$$Total = Scope\ 1 + Scope\ 2$$

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

Step 4: Calculate Specific Footprint (per m^3)

- Functional Unit: 1 m^3 of treated wastewater.

- Total Annual Flow: 50,000 m^3/day × 365 days = 18,250,000 m^3/year.

$$\text{Specific Footprint} = \frac{4{,}633{,}200 \text{ kg } CO_2e}{18{,}250{,}000 \text{ m}^3} = \mathbf{0.254 \text{ kg } CO_2e/m^3}$$

Part 3: Interpretation (The "Why" Question)

Question: Identify the largest contributor and suggest an improvement.

1. **Identify Hotspot:**
    - Look at the totals calculated above.
    - Scope 1 (Direct) ≈ $1.7M$
    - Electricity ≈ $2.8M$
    - **Hotspot: Electricity Consumption** is the largest contributor ($> 60\%$ of total).

2. **Suggest Improvement:**
    - Since electricity is the hotspot, we must reduce it or decarbonise it.
    - *Solution A:* Install **Renewable Energy** on-site (Solar PV, Wind) or switch to a green tariff.
    - *Solution B:* Implement **Energy Efficiency** measures (e.g., replace old pumps, optimise aeration control).
    - *Solution C:* Install **Anaerobic Digestion (AD)** for sludge to generate Biogas → Electricity (CHP).

Lecture 12: Sustainability & Water Resources Management (Part B).

This lecture focuses on the **Circular Economy (CE)** in the water sector.
Based on the **2025 Exam (Question 4)** and **2022 Exam (Question 4)**, this is a **high-probability** topic.
The exam question is usually a "Mass Balance" calculation table followed by questions about Circularity indicators.

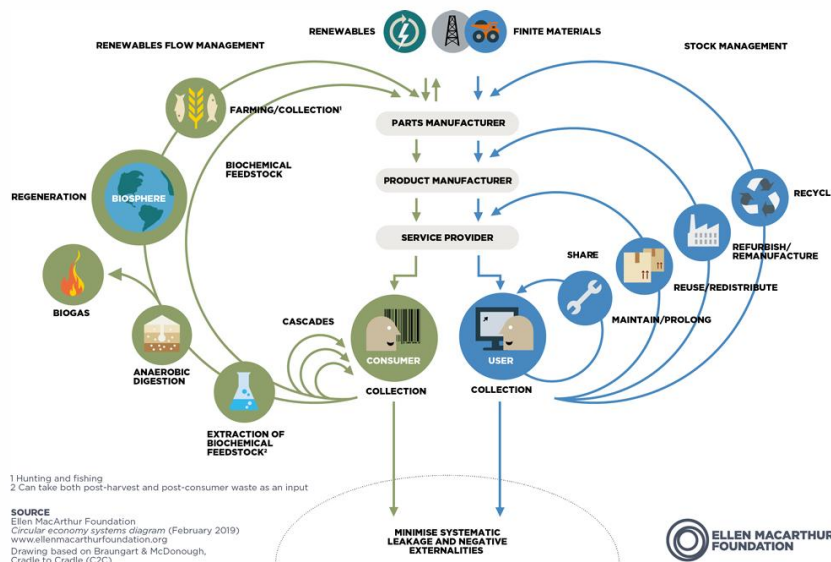## Part 1: Key Definitions & Theory (Memorise These)

1. The Butterfly Diagram (Technical vs. Biological Cycles)
(Exam: 2022 Q4a, 2025 Q4a)
You must know the difference between the two cycles in the Circular Economy:

- **Biological Cycle:** For materials that can biodegrade and return to nature (e.g., food, sludge, biosolids).

  - *Actions:* **Regenerate**, Farm, **Compost**, **Anaerobic Digestion (AD)**, Cascade (use for lower value before returning to soil).

  - *Why not recycle?* Biological matter degrades; you can't "recycle" a sandwich back into a sandwich. You regenerate it into soil/fertiliser.

- **Technical Cycle:** For non-biodegradable materials (e.g., metals, plastics, pumps, pipes).

  - *Actions (Inner loops are better):* **Share/Maintain** (Best) → Reuse/Redistribute → Refurbish/Remanufacture → **Recycle** (Worst of the circular options).

Butterfly Model

2. Resource Recovery Technologies
Know one example of recovery for each main resource in wastewater:

- **Carbon: Biogas** (via Anaerobic Digestion) or **Cellulose** (via fine sieves).

- **Phosphorus: Struvite** precipitation (fertiliser).

- **Nitrogen: Ammonia stripping**.

- **Water:** Membrane filtration (UF/RO) for reuse.

Part 2: The "Big" Calculation – Mass Balance

(Exam: 2025 Q4c - worth 5 marks)
You will be given a table of **Inflows** and **Outflows** (Effluent, Gas, Solid Waste) and asked to calculate the missing values (usually the **Biosolids** content) using the principle of Mass Balance.

The Golden Rule:

$$\text{Mass}_{IN} = \text{Mass}_{OUT}$$

$$\text{Mass}_{IN} = \text{Effluent} + \text{Gas Emissions} + \text{Biogas} + \text{Biosolids}$$

Part 3: Circularity Indicators (Recovery Rate)

(Exam: 2025 Q4d)
After the mass balance, you are asked to calculate the **Recovery Rate**.

Formula:

$$\text{Recovery Rate (\%)} = \frac{\text{Mass Recovered as Product}}{\text{Mass Input}} \times 100$$

What counts as "Recovered"?

- **Biogas:** Yes (Energy).

- **Biosolids: ONLY** if used as fertilizer/soil conditioner. If landfilled/incinerated without recovery, it is **waste** (0% recovery).

- **Effluent: ONLY** if reused (water reuse). If discharged to sea, it is 0% recovery.

Exam Tip: Be careful with the "Biosolids" definition. In the 2024 exam, they specifically asked you to calculate rates *after* a technology upgrade (Cellulose recovery), so you had to add the cellulose stream to the recovered pile.

Problem Set Walkthrough

A WWTP treats **12,000 m^3/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				Outlet			
Wastewater Inlet	Water	12,000	m³/d	Wastewater Effluent	Water	11,990	m³/d
	Nitrogen	1.0	t/d		Nitrogen	0.05	t/d
	Phosphorus	0.15	t/d		Phosphorus	0.01	t/d
	Carbon (COD)	2.5 (7.1)	t/d (t/d)		Carbon	0.05	t/d
				Grit, Screenings, FOG (solid waste)	Water	1.0	m³/d
					Carbon	0.35	t/d
				Gas Emissions	Carbon (CO₂)	0.4	t/d
					Carbon (CH₄)		t/d
					Nitrogen (N2)	0.65	t/d
					Nitrogen (N2O)		t/d
				Biogas	Carbon (CO2)		t/d
					Carbon (CH4)		t/d
				Biosolids	Water		m³/d
					Nitrogen		t/d
					Phosphorus		t/d
					Carbon		t/d

Step 1: Calculate Fugitive Gas Emissions

Calculate the mass of Carbon and Nitrogen lost to the atmosphere as leaks.

1. **Methane (CH_4):**

   o Total Mass $CH_4 = 0.0075 \times 7.1$ (COD load) $= 0.05325$ t/d.

   o **Carbon Fraction in CH_4:** $12/(12 + 4) = 0.75$.

   o **Carbon Mass:** $0.05325 \times 0.75 = \mathbf{0.040\ t/d}$.

2. **Nitrous Oxide (N_2O):**

   o Total Mass $N_2O = 0.02 \times 1.0$ (N load) $= 0.02$ t/d.

   o **Nitrogen Fraction in N_2O:** $(2 \times 14)/((2 \times 14) + 16) = 28/44 = 0.636$.

   o **Nitrogen Mass:** $0.02 \times 0.636 = \mathbf{0.0127\ t/d}$.

Step 2: Calculate Biogas Composition

Calculate the mass of Carbon recovered in the Biogas stream.

1. **Methane (CH_4):**

   o Volume = $1,565 \times 0.65 = 1,017.25$ m³.

   o Mass = $1,017.25 \times 0.66$ (density) $= 671.4$ kg $= 0.671$ t/d.

   o **Carbon Mass:** $0.671 \times 0.75 = \mathbf{0.503\ t/d}$.

2. **Carbon Dioxide (CO_2):**

   o Volume = $1,565 \times 0.35 = 547.75$ m³.

   o Mass = 547.75×1.98 (density) $= 1,084.5$ kg $= 1.085$ t/d.

   o **Carbon Fraction in CO_2:** $12/(12 + 32) = 12/44 = 0.273$.

   o **Carbon Mass:** $1.085 \times 0.273 = \mathbf{0.296\ t/d}$.

Step 3: Biosolids Mass Balance (The "Fill the Gap" Step)

Use the principle: Input = Sum(Outputs).
We are solving for the unknown Biosolids value.

1. **Water Balance:**

$$\text{Biosolids}_{water} = \text{In} - (\text{Effluent} + \text{Solid Waste})$$

$$\text{Biosolids}_{water} = 12{,}000 - (11{,}990 + 1.0) = \mathbf{9\ m^3/d}$$

2. **Nitrogen Balance:**

$$\text{Biosolids}_N = \text{In} - (\text{Effluent} + \text{Gas } N_2 + \text{Fugitive } N_2O)$$

$$\text{Biosolids}_N = 1.0 - (0.05 + 0.65 + 0.0127)$$

$$\text{Biosolids}_N = 1.0 - 0.7127 = \mathbf{0.287\ t/d}$$

3. **Phosphorus Balance:**

$$\text{Biosolids}_P = \text{In} - (\text{Effluent})$$

$$\text{Biosolids}_P = 0.15 - 0.01 = \mathbf{0.14\ t/d}$$

4. **Carbon Balance:**

$$\text{Biosolids}_C = \text{In} - (\text{Effluent} + \text{Solid Waste} + \text{Gas } CO_2 + \text{Fugitive } CH_4 + \text{Biogas } C)$$

$$\text{Biogas } C = 0.503(CH_4) + 0.296(CO_2) = 0.799\ \text{t/d}$$

$$\text{Biosolids}_C = 2.5 - (0.05 + 0.35 + 0.4 + 0.040 + 0.799)$$

$$\text{Biosolids}_C = 2.5 - 1.639 = \mathbf{0.861\ t/d}$$

Step 4: Calculate Recovery Rates

Treat Biogas and Biosolids as "Recovered Products". Treat Effluent and Emissions as "Losses".

1. **Water Recovery:**

$$\frac{\text{Biosolids Water}}{\text{Total Input}} = \frac{9}{12{,}000} = \mathbf{0.075\%}$$

(Note: This assumes effluent is discharged to sea, not reused).

2. **Carbon Recovery:**

$$\text{Recovered} = \text{Biosolids C} + \text{Biogas C} = 0.861 + 0.799 = 1.66\ \text{t/d}$$

$$\text{Rate} = \frac{1.66}{2.5} = \mathbf{66.4\%}$$

3. **Nitrogen Recovery:**

$$\text{Recovered} = \text{Biosolids N} = 0.287\ \text{t/d}$$

$$\text{Rate} = \frac{0.287}{1.0} = \mathbf{28.7\%}$$

4. **Phosphorus Recovery:**

$$\text{Recovered} = \text{Biosolids P} = 0.14 \text{ t/d}$$

$$\text{Rate} = \frac{0.14}{0.15} = \mathbf{93.3}\%$$

Step 5: Interpretation & Improvement Strategy

This is the final part of the exam question (usually worth 2-4 marks).

Question: Which resource has the greatest potential for improvement, and what technology could be used?

1. **Identify the Weakness:**

   o   Compare the rates: P (93%), C (66%), N (29%), Water (0.075%).

   o   **Water** is the clear priority for improvement (it is currently treated as waste).

2. **Suggest Technology:**

   o   To turn the effluent (currently "waste") into a "product", we need **Tertiary Treatment**.

   o   **Configuration:** Add **Ultrafiltration (UF)** and **Reverse Osmosis (RO)** followed by UV disinfection.

3. **Suggest Use Case:**

   o   This treated water can be used for **non-potable applications**: Irrigation (agriculture/parks), Industrial process water, or Toilet flushing.

Lecture 13: Solid Waste & Resource Management.

While there isn't a *separate* problem sheet, **this topic was the standard "Question 3" in exams from 2015 to 2018**. The lecturer (Dr. Costas Velis) includes "Check-point Questions" (Q1–Q17) directly inside the slides.

The **Calculation** for this module is almost always the same: **Waste Projections & Infrastructure Planning** (How many plants do we need?).

Here is your exam guide.

## Part 1: Key Definitions (Memorise These)

1. The Waste Hierarchy (Slide 74)
(Exam: 2015, 2016, 2018)
You must be able to list these in order (Top to Bottom):

1. **Prevention/Reduction:** Best option. Using less material.

2. **Reuse:** Using item again for same purpose without reprocessing.

3. **Recycling:** Reprocessing into new materials/products.

4. **Recovery (Other):** Energy from Waste (Incineration), Anaerobic Digestion.

5. **Disposal:** Landfill (Worst option).
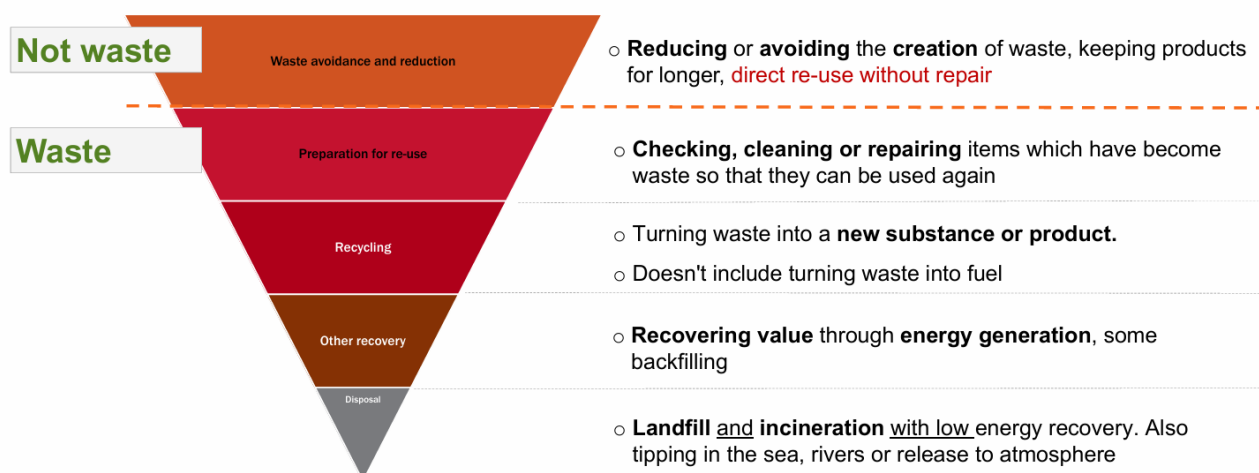
2. Waste Definitions (Slide 16 & Past Papers)

- **MSW (Municipal Solid Waste):** Household waste + similar commercial/institutional waste collected by the municipality.

- **End-of-Waste Status:** When waste undergoes a recovery operation and becomes a product (no longer waste).

- **SRF (Solid Recovered Fuel):** Fuel produced by shredding and dehydrating solid waste (used in cement kilns).

3. Plastic Pollution (New Focus)

- **Leakage:** Waste that escapes the management system (uncollected + dumpsites).
- **Macro vs Micro:** Macroplastics (>5mm) degrade into Microplastics (<5mm).

Part 2: The Main Calculation (Infrastructure Planning)

This calculation appears in **Slide 80** ("How many plants...") and almost every past paper from 2015-2018.

The Logic:

1. Calculate **Future Waste Generation** using compound growth.
2. Calculate the **Target Mass** (e.g., how much *must* be diverted from landfill).
3. Calculate **Number of Plants** needed to treat that mass.
4. Calculate **Energy Output**.

Formulae to Memorize

1. **Future Waste Generation (W_{future}):**

$$W_{future} = W_{current} \times (1 + r)^n$$

   - W: Waste amount (tonnes per annum, tpa).
   - r: Growth rate (decimal, e.g., 1% = 0.01).
   - n: Number of years.

2. **Number of Plants:**

$$N = \frac{\text{Total Waste to be Treated (tpa)}}{\text{Capacity of One Plant (tpa)}}$$

IMPORTANT: Problem Set Walkthrough

The Question:
A city generates **15,000,000 tonnes per annum (tpa)** of MSW in 2015.

- Annual waste growth rate: **1%**.
- We are planning for the year **2025** (10 years later).
- **Target:** We must divert **60%** of the total 2025 waste to **Energy from Waste (EfW)** plants.
- **Plant Capacity:** Each EfW plant can process **400,000 tpa**.
- **Energy Output:** Each plant generates **25 MW** of electricity.
- **Calculate:**
    a. Total waste in 2025.
    b. Number of EfW plants required.
    c. Total Electricity generated.

Step-by-Step Working:

Step 1: Calculate Future Waste Generation (2025)

- $W_{2015} = 15,000,000$

- $r = 0.01$
- $n = 10 W_{2025} = 15{,}000{,}000 \times (1 + 0.01)^{10} W_{2025} = 15{,}000{,}000 \times 1.1046 W_{2025} = \mathbf{16{,}569{,}000 \ tpa}$

Step 2: Calculate Target Waste Amount
We need to treat 60% of this total.

$$\text{Target Load} = 16{,}569{,}000 \times 0.60 = \mathbf{9{,}941{,}400 \ tpa}$$

Step 3: Calculate Number of Plants

$$N = \frac{\text{Target Load}}{\text{Plant Capacity}}$$

$$N = \frac{9{,}941{,}400}{400{,}000} = 24.85$$

Crucial Engineering Step: You cannot build 0.85 of a plant. **Always round UP** to handle the load.

$$N = \mathbf{25} \ \text{Plants}$$

Step 4: Calculate Total Energy

$$\text{Total Energy} = \text{Number of Plants} \times \text{Energy per Plant}$$

$$\text{Total Energy} = 25 \times 25 \ \text{MW} = \mathbf{625 \ MW}$$

Part 3: The Recycling Rate Calculation

(Exam: 2016 Q3d)
You may be asked to calculate the recycling rate or obligation.

Concept:
Recycling Rate is notoriously difficult to define.

- **Collection Rate:** Mass collected / Total Waste (High number, inaccurate because of contamination).
- **True Recycling Rate:** Mass actually reprocessed into new product / Total Waste.

Example Calculation:

- A city collects **100 tonnes** of plastic for recycling.
- The sorting plant (MRF) has a **20% reject rate** (contamination/wrong plastics).
- The reprocessing plant has a **10% process loss**.
- **Calculate the Net Recycling Rate.**

1. **After Sorting:** $100 \ t \times (1 - 0.20) = 80 \ t$.
2. **After Reprocessing:** $80 \ t \times (1 - 0.10) = 72 \ t$.
3. **Net Rate:** If 100t was the total waste generated: Rate $= 72/100 = \mathbf{72\%}$ *(Note: If measured at collection, it would have falsely looked like 100%).*