Municipal wastewater is mostly water (99.9%) with some dissolved materials, BOD, and pathogens.

**TERMINOLOGY:**

primary treatment: use physical processes such as screening and sedimentation

secondary treatment: processes that use microbial oxidation of wastes - BOD removal

advanced or tertiary treatment - remove nitrogen and phosphorus

**ACRONYMS**

TS: Total Solids = TDS + TSS
TDS: Total Dissolved Solids - all cations and anions
TSS: Total Suspended Solids - small particles can be removed with a membrane filter
   Cells, organic macromolecules, inorganic particles, salts, etc.
VSS: Volatile Suspended Solids - solids lost by combustion at 550-600 °C
   Total biomass (viable and inactive) and organic macromolecules
X_a: Total Active Biomass (X_a)
   Viable cells, enzymes, and other catalytic agents

**LAYOUT OF A WASTEWATER TREATMENT PLANT**
TYPICAL WASTEWATER COMPOSITION
(mg/L) for untreated municipal wastewater:

- **BOD**₅ 100 – 300 (Biological Oxygen Demand)
- **COD** 250 – 1000 (Chemical Oxygen Demand)
- **TDS** 200 – 1000 (Total Dissolved Solids)
- **TSS** 100 – 350 (Total Suspended Solids)
- **TKN** 20 – 80 (Total Kjeldahl Nitrogen)
- **TP** 5 – 20 (Total Phosphorus)

PRIMARY TREATMENT

Uses only physical processes plus disinfection.
This is what was done at most places prior to the Clean Water Act (1972).

Typically removes 35% of BOD and 60% of TSS

Remaining BOD can still cause oxygen depletion problems; N, P can result in eutrophication

STEPS IN PRIMARY TREATMENT

1. **Screening** to remove large objects
   use wire mesh or steel bars spaced 3 to 5 cm

2. **Grit Chamber** - take flow into tank.
   Flow velocity slows down, but not too much(<0.3 m/s)
   Settle out only sand and grit and let organic TSS through for biological treatment.
   Grit can be washed and landfilled

3. **Sedimentation chamber**
   or primary settling tank - clarifier
   slows flow even more - much of remaining suspended colloidal material settles
   removes 50 to 65 % of TSS
   25 - 40% of BOD

4. **Disinfection**
   if there will be no further treatment, wastewater is disinfected and released.
SECONDARY OR BIOLOGICAL TREATMENT

Clean Water Act (1972) required all POTW to have at least 85% BOD₅ removal

NDPES standards: Effluent BOD₅ < 30 mg/L, TSS < 30 mg/L

Primary treatment cannot meet these standards
Secondary treatment utilizes microorganisms to oxidize waste and lowering BOD
With properly designed secondary treatment, can remove > 90% BOD₅ and > 90% of SS

Organics + O₂ → Bacteria + CO₂ + H₂O + NH₃

(BOD) (must be provided) (must be removed)

Substrate Removal and Microbial Growth

- A wide variety of substrates and microbes are involved in a complex, dynamic manner when wastewater is being treated.
- The activated sludge process involves aeration and settling in two separate basins.
  - Aeration Basin – bulk contents are known as “mixed liquor (ML)”
  - Settling Basin – settled contents are known as “settled sludge (SS)”
- The Monod equation is empirical and its constants must be developed for each situation (water, process, and reactor).

\[ r_s = \frac{kX_vS}{K + S} = \frac{k'S}{K + S} \quad \ldots \quad v = \frac{\nu_{max}[S]}{K + [S]} \] Michaelis – Menten

\[ r_s = \text{rate of substrate removal, } \text{mg}_{\text{substrate}} \cdot \text{L}^{-1} \cdot \text{t}^{-1} \]
\[ X_v = \text{conc. of volatile suspended solids (biosolids), } \text{mg}_{\text{microbes}} \cdot \text{L}^{-1} \]
\[ k = \text{maximum reaction velocity/rate constant, } \text{mg}_{\text{substrate}} \cdot \text{mg}_{\text{microbes}}^{-1} \cdot \text{t}^{-1} \]
\[ K = \text{half-velocity/rate constant, } \text{mg} \cdot \text{L}^{-1} \]
\[ S = \text{substrate concentration, } \text{mg} \cdot \text{L}^{-1} \]

Substrate Removal and Microbial Growth

1. Chemical Oxygen Demand (COD): Chemically oxidizable organic matter (natural + synthetics)
2. Biochemical Oxygen Demand (BOD): Biologically oxidizable organic matter
   a. cBOD: carbonaceous BOD (aka BOD₅)
   b. nBOD: nitrogenous BOD (extended oxidation)
3. Total Organic Carbon (TOC)
4. Thermally oxidizable organic matter (as carbon) ~ VSS
Three Treatment Process Designs
1. trickling filter
2. activated sludge
3. oxidation ponds

A. TRICKLING FILTERS and RBCs

- Used since 1893. Waste is applied with a rotary sprayer arm, and trickles down through filter medium
- To provide high concentration of microorganisms, filter medium is corrugated plastic or porous rocks.
- Air circulates in spaces and filter medium is covered by layer of slime - bacteria, fungi, algae (biofilm process)
- Waste diffuses into slime, where it is oxidized
- Bottom of filter has collection system, water is passed out to a secondary settling tank
- Treated wastewater may be recycled to wet the slime in the system and to dilute high-strength wastes and preclude oxygen flux limitation
Rotating Biological Contactors (RBCs)

- Similar to trickling filter (i.e., also a biofilm process)
- Rather than pass water over the media and slime, pass the media through the water
- RBCs consist of of 3.6-m plastic disks, mounted on a rotating shaft. Bacteria form biofilm on disk surface
- Bottom 40% of disk is submerges in wastewater so the microorganisms pass through water - oxidize wastes, then pass through air to get the oxygen that they need.
- RBCs easier to use under varying flow conditions that TFs
- The main advantage of both TF’s and RBC’s is that they are simple and relatively inexpensive to operate.
- Their main disadvantage is the lack of flexibility for operational control to respond to changes in wastewater characteristics and/or flow.
B. ACTIVATED SLUDGE

- Invented in 1914 (England)
- Most popular and most efficient Biological Treatment Process
- More versatile (e.g., less temperature sensitivity) and cheaper to build than Trickling Filter

![Diagram of Activated Sludge Process]

a) Aeration Tank:
- Where bacteria grow and BOD is destroyed and/or converted to new bacteria.
- Residence time is 4-8 hours.

b) Aeration System:
- Supplies O2 and mixing to keep bacteria in suspension
  - For diffused aeration, need 20 to 30 m³ air /1,000 m³ tank/minute
  - For mechanical aeration, need 15 to 30 Kw per 1,000 m³ tank

c) Settling Tank:
- Removes suspended solids (bacteria) and clarifies effluent
- Thickens and reduces volume of waste sludge
- Proper operation is critical to efficiency of overall process
- (easy to get bacteria to eat BOD, more difficult to ensure efficient settling)

d) Wasting of Settled Sludge:
- Controls cells residence time and biomass concentration
- Want food to microorganisms ratio, F/M = 0.2 lbBOD₅/lb biomass/day

e) Recycle:
- Returns activated bacteria to eat more waste (keep bacteria you grow in the system)
Design of aeration tanks:

1. Completely stirred reactor
   - reactor concentration = effluent concentration
   - high rate or low rate extended aeration
   - expensive to maintain equilibrium O₂ concentration

2. Plug flow
   - concentration gradient from inlet to outlet
   - oxygen demand is high at the inlet, low at the outlet
   - difficult to maintain aerobic conditions throughout

3. Step aeration
   - allows for more uniform mixing and is easier to maintain in operation

Other designs include pure oxygen, Krauss process (separate nitrification reactor)
Activated sludge uses less space that tricking filters, but has higher operating costs due to pumps and blowers

Membrane Bioreactors: low-pressure microfiltration or ultrafiltration membranes immersed in the aeration tank eliminate the need for a separate secondary clarifier
Advantages:
   - Smaller footprint
   - Better effluent quality
   - Operates at high solids concentration (8-12,000 mg/L vs. 2-3,000 mg/L for activated sludge)
   - High residence time (~ 15 days) to allow for nitrification
   - Does not depend on the sludge settling characteristics

Disadvantages:
   - Expensive to build and operate – high energy consumption
   - Membrane fouling and failure
**Sludge Treatment**
- sludge is 97% water, and disposal costs are related to volume ⇒ want to remove as much water as possible
- sludge volume is up to 2% of original wastewater volume, fed to digesters

**Purposes of digestion:**
- Stabilize Organic Solids
- Reduce Mass and Volume of Sludge
- Kill pathogens
- Condition for Further Processing

**Aerobic digestion**
- Aerobic bacteria utilize organics for growth
- Simpler organics from metabolism and bacterial endogenous decay
- Same flow diagram as activated sludge
- Discontinue aeration to allow settling and decanting
- Oxygen transfer is critical
- At long solids retention time, can get nitrification, so watch out for pH drop

**Anaerobic digestion** (no oxygen) involves 3 steps:
- hydrolysis and fermentation of complex wastes
- breakdown into simpler organic acids (e.g., acetate)
- methane formation from breakdown of acetate

Two-stage anaerobic digester: analogous to activated sludge

1st stage: well-mixed, detention time 10 to 15 days, heated
2nd stage: stratified, methane gas collected (energy), supernatant returned to treatment plant upstream

Digested sludge is dewatered in drying bed, vacuum filter, or centrifuge, and then landfilled or used as soil conditioner.
C. OXIDATION PONDS

• Suspended growth earthen basins

\[
\text{Air} \quad Q^o, S^o \quad \cdots \quad V, S, X \quad Q^o, X, S
\]

• \(O_2\) supplied by wind + algae (aerated lagoon has aerators)
• No recycle \(\Rightarrow\) SRT = HRT
• Good BOD removal (partly by settling) & coliform kill
• Small communities (<10,000) + industries (poultry, refineries)
• Shallow \(\Rightarrow\) large area requirement (A<10 acres to minimize short-circuiting)

<table>
<thead>
<tr>
<th>Advantages*</th>
<th>Disadvantages*</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Cheaper (construction + operation)</td>
<td>• Land use (large surface area)</td>
</tr>
<tr>
<td>• Can treat high strength waste (&gt; 5,000 mg-BOD5/l)</td>
<td>• High TSS in effluent</td>
</tr>
<tr>
<td>• High heat transfer (hot waste)</td>
<td>• High heat transfer (winter, slow)</td>
</tr>
<tr>
<td>• Simple operation (no recycle)</td>
<td>• No recycle (\Rightarrow) no independent control of SRT</td>
</tr>
<tr>
<td></td>
<td>• Uncontrolled odor</td>
</tr>
</tbody>
</table>

Will pond be aerobic or anaerobic?

depends on depth (controls light penetration, turbulence)
BOD of wastes
some ponds have both conditions
called facultative ponds
upper level aerobic, lower level anaerobic
Ponds with mechanical aeration are called *aerated lagoons*. Mechanical aeration allows for deeper aerobic zone.

Ponds require a lot of land to provide sufficient residence time, about 1 acre for every hundred people.

Unlikely to be used alone because of EPA BOD & TSS regulations.

Often, ponds used after secondary treatment - called polishing ponds.

Constructed wetlands – engineered swamps or marshes used for stormwater or wastewater treatment, land reclamation, and wildlife habitat.

Good for removing solids, metals, pathogens, etc.

*Figure 19.3* Subsurface flow wetlands system. After USEPA (1988).
TERTIARY (ADVANCED) WASTEWATER TREATMENT

- Primary and secondary systems reduce BOD and TSS
- May still have left undesirable P, N or metals concentrations
- Why? NH₃ toxic to fish, NBOD, methemoglobinemia (NO₃⁻), eutrophication

Ammonia stripping
- physico-chemical process
- nitrogen starts as part of organic molecule of wastes
- as waste is decomposed, org-N \rightarrow \text{ammonia}
- NH₃ - gas, not very soluble in water
- NH₄⁺ - highly soluble in water

Recall, \( \text{NH}_4^+ + \text{OH}^- \Leftrightarrow \text{NH}_3 \uparrow + \text{H}_2\text{O} \), \( \text{pKa} = 9.4 \)

If we increase pH (i.e., OH⁻) more NH₃ will form
From the equilibrium constant, find we need the pH > 10
Use quick lime (CaO) to raise the pH
Problems:
- scaling: CaO + dissolved CO₂ \rightarrow CaCO₃↓
- air pollution
- temperature dependence (NH₃ more soluble in cold water)

Microbiological control of N

1. Aerobic nitrification: *Nitrosomonas* and *Nitrobacter* convert ammonia to nitrite to nitrate (NO₃⁻)
   \( \text{NH}_4^+ + 2\text{O}_2 \rightarrow \text{NO}_3^- + 2\text{H}^+ + \text{H}_2\text{O} \)
   - nitrification is autotrophic, sensitive to disturbances, and produces acidity
   - nitrifiers grow slowly, need high retention time, low BOD
   - nitrifiers are sensitive to xenobiotics & dissolved oxygen

2. Anaerobic denitrification: denitrifiers take NO₃⁻ to N₂↑
   \( 2\text{NO}_3^- + \text{organic matter} \rightarrow \text{N}_2\uparrow + \text{CO}_2 + \text{H}_2\text{O} \)
   - may have to add organics to the system (recycled wastewater, acetate, methanol)
   - denitrification is heterotrophic, produces alkalinity (DO, 0.3 mg/L)
   - anammox is attractive option but complex to maintain
Phosphorus Removal

Remember P is a limiting nutrient - to prevent eutrophication and algal growth must also remove P

frequent form of P: orthophosphate $\text{H}_2\text{PO}_4^-$, $\text{HPO}_4^{2-}$, $\text{PO}_4^{3-}$

phosphate does not form an insoluble gas like ammonia but can create a precipitate or insoluble solid by adding alum- $\text{Al}_2(\text{SO}_4)_3$ or lime $\text{Ca(OH)}_2$

1. Physicochemical precipitation
   a. Alum
      \[ \text{Al}_2(\text{SO}_4)_3 + 2 \text{PO}_4^{3-} \rightarrow 2 \text{AlPO}_4 \text{ (solid)} + 3\text{SO}_4^{2-} \]

   If you are using an activated sludge treatment add Alum to the aeration tank and let the phosphate-containing solid settle out in the settling basin

   b. Lime
      \[ 5 \text{Ca(OH)}_2 + 3 \text{HPO}_4^{2-} \rightarrow \text{Ca}_5\text{OH(PO}_4)_3 \text{ (solid)} + 2 \text{H}_2\text{O} + 6 \text{OH}^- \]

   product is calcium hydroxyphosphate

2. Biological P removal (luxury uptake)
   - *Acinetobacter, Arthrobacter, Aeromonas, Pseudomonas, Nocardia*, etc. store P inside the cells, under alterations between feast and famine regimes
   - P uptake occurs under aerobic conditions
   - P is released under anaerobic conditions or low pH
   - Initial anaerobic phase produces short chain acids which enable storage of polyphosphates as a phosphorous store and for energy generation.
   - P removed with settled sludge