Water Treatment

- It is desired that drinking water be:
  - Safe
  - Clean
  - Clear
  - Free of disagreeable smells and odours
  - Free of pathogens (Over 7000 people a day die due to waterborne diseases that could be prevented with water treatment.)
  - Free of dissolved solids or minerals
  - Conveniently and inexpensively available.
- Sources of drinking water:
  - Ground water
  - Surface water
- The advantages of ground water include:
  - Fewer contaminants (usually)
  - Clarity
- Disadvantages of ground water include:
  - Radon

  - Hardness and alkalinity
  - Finite capacity of aquifers. If an aquifer is depleted, the ground above may subside and become vulnerable to flooding.

- The advantages of surface water include:
  - Availability

- Disadvantages of surface water include:
  - What is upstream?
  - Dissolved organic matter.
  - Biological and chemical oxygen demand.

- Since it was recognized that ground water was better than surface water, the first attempts at water treatment in the 19th century was to "make" ground water.
  - Surface water was trickled through sand.
  - Surface water was used to "reinject" underwater aquifers.
  - This does lead to a decline in the incidence of waterborne diseases such as cholera, typhoid, and amoebic dysentry.

- Modern water treatment consists (typically) of four stages:
    - Settling
    - Aeration
    - Coagulation
    - Disinfection
- Depending on the water supply, one or more of the first three steps may not be necessary.

Settling

- Water brought into a large holding pond an particulate is allowed to settle.
- If the pH is too low, it is adjusted to be greater than 6.5

Aeration

- Aeration has the objective of removing oxidizable substances.
    - These include be both chemical and biological species.
    - Fe^{2+} is removed at this stage to prevent rust stains ($Fe(OH)_3$).

- Upon contact with air Fe^{2+} is quickly oxidized to Fe^{3+}.

$$Fe^{2+} \rightarrow Fe^{3+} + e^-$$

$$4\ H^+ + O_2 + 4\ e^- \rightarrow 2\ H_2O$$

Net reaction: $4\ Fe^2 + +4\ H^+ + O_2 \rightarrow 4\ Fe^3 + 2\ H_2O$

- If pH > 3,then:

$$Fe^{3+} + 3\ OH^- \rightarrow Fe(OH)_3$$

Coagulation (Secondary Settling)

- Coagulation has the objective of removing suspended solids such as:
  - Colloidal minerals
  - Bacteria
  - Pollen
  - Spores

  resulting in water that is clear.

- Since in the settling step, the pH of the water has been adjusted to pH > 6.5.
  - Minimum solubility of Al^3+ occures in the pH range 6.5 to 8.

- Filter alum ($Al_2(SO_4)_3.18H_2O$) is used as a clarifying agent since it forms a gelatinous precipitate that settles slowly, carrying down the suspended solids.
- Alternative settling agents are $Fe(OH)_3$ and activated silica, both of which form gelatinous precipitates.

Disinfection

- Disinfection of drinking water is essential
  - To kill any pathogens that persist through the earlier stages of treatment.
  - To prevent the growth of bacteria in the distribution system (in which water can spend up to a week).
  - To prevent recontamination of the water in the distribution system due to leaks.
- Disinfection agents include:
  - Chlorine
  - Chlorine Dioxide
  - Ozone
  - Ultraviolet radiation

- Chlorine is the only one that leave a residual that can prevent recomtamination.
- Chlorine dissolved in water establishes the following equilibria:

$$Cl_2(g) \rightleftharpoons Cl_2(aq), \quad K_H = 8.0 \times 10^{-3} \text{ mol L}^{-1} \text{ atm}^{-1}$$

$$Cl_2(aq) + H_2O(l) \rightleftharpoons H^+(aq) + Cl^-(aq) + HOCl(aq)$$
$$K_c = 4.5 \times 10^{-4} \text{ mol}^2 \text{ L}^{-2}$$

$$HOCl(aq) \rightleftharpoons H^+(aq) + OCl^-(aq)$$
$$K_c = 3.0 \times 10^{-8} \text{ mol L}^{-1}$$

  - It is HOCl that is effective in killing microorganisms since it can penetrate the cell membrane.
  - Chlorine dose required depends on pH (need to keep pH below 2.5).
  - Desire chlorine residual of about 1 ppm.
- Disadvantages of chlorine include:
  - Taste and odour.
  - Chlorination of organic compounds.
  - Concerns about toxicity.
- Advantages of chlorine include:
  - Inexpensive
  - Residual

- Chlorine dioxide is often considered as an alternative to chlorine.
- Chlorine dioxide has the advantages:
  - Oxidizes organic compounds instead of chlorinating them.
  - Can use a physical plant very similar to that required for chlorine.
  - Possible to easily switch from chlorine temporarily if chlorine is causing problems.
- Disadvantages of chlorine dioxide include:
  - Must be manufactured on site from $NaClO_2$.

$$10\ NaClO_2 + 5\ H_2SO_4 \rightarrow$$
$$8\ ClO_2 + 5\ Na_2SO_4 + 2\ HCl + 4\ H_2O$$

or

$$2\ NaClO_2 + Cl_2 \rightarrow 2\ ClO_2 + 2\ NaCl$$
$$\text{(Must keep pH} < 3.5)$$

  - The first reaction is preferred because it is chlorine free.
  - There is no residual disinfection, therefore the water must be "finished" with chlorine before distribution.

- There is some concerned about toxicity of ClO_2.
  - At levels of 50 ppm $NaClO_2$, hemolysis can occur.
  - Finished water has less than 1 ppm ClO_2, which is shortlived.
- Ozone requires a completely different physical infrastructure than chlorine or chlorine dioxide.
  - Usually implemented in new facilities.
  - Economic only on a larger scale.
  - Generated by running a high voltage electrical discharge through air giving about 1
  - Ozone absorbed by water ($K_H = 1.3 \times 10^{-2}$ mol L^{-1} atm^{-1}.)
- Advantages of ozone include:
  - Oxidizes organics
  - Air is the main raw material required.
- Disadvantages include:
  - pH control is necessary.
  - Finishing with chlorine is necessary.

- Ultraviolet radiation with $\lambda < 300$ nm damages pyridine base pairs in DNA sequences.
  - Causes cell death and thus death of microbes.
- Can be generated by mercury arc lamps ($\lambda = 254$ nm) with about 40% efficiency.
- Advantages of UV water treatment include:
  - Contact time is short (< 10 s).
  - No large reservoir required.
  - Low installation cost.
  - Do not need to control or monitor pH or temperature.
  - No toxic residues.
  - Cost competitive with chlorine treatment.
  - Possible to implement on a small or portable scale as an emergency or remote, stand alone system.
- Disadvantages of UV treatment include:
  - Water source must be clear of suspended matter and organic molecules that could absorb the UV.

- If suspended matter or organic molecules are present, then pretreatment with activated charcoal may be required.

- No residual disinfection. The water must be used immediately or be finished with chlorine.

Quality Control in Water Treatment and Distribution

- Before water treatment:

  - What are the potential contaminants in the watershed or aquifer?

  - What dissolved inorganic species are present?

  - What organic chemical species are present, especially those that can survive the treatment process and lead to unacceptable taste or smell?

  - For treatment with chlorine, chlorine dioxide, or ozone: what is the demand of the raw water for the disinfecting agent.

    - For treatment with UV, is the clarity acceptable.
    - Is the quality of the incoming water consistent with the capacity of the treatment facility.
- During water treatment:
    - Are the pH and temperature in the appropriate range for the treatment process?
- After water treatment:
    - Is there an appropriate level of residual chlorine?
    - Are any pathogens present?
    - Are there any undesirable chemicals present that formed during the treatment process or survived the treatment process?
    - Is further treatement (softening, deionization, filtering) required.
    - Are the taste, smell, and appearance acceptable.

Sewage Treatment

- Sewage treatment parallels water treatment.
    - Primary treatment consists of settling and skimming
    - Seconday treatment consists of reducing the biological oxygen demand.
    - Tertiary treatment reduces the concentration of particular contaminants, such as phosphorous.
    - Finishing consists of disinfection.
- Primary sewage treatment
    - Physical separation of solids and immiscibles.
    - Raw sewage enters a lagoon through one or more coarse screens that remove large objects.
    - A grit tank allows for the deposition of grit, sand, etc.
    - The sewage then moves slowly through the clarifier slowly enough for solids to settle.

  - At the same time, greasy material is skimmed off.
  - The result of primary treatment is clear effluent with a very high biological oxygen demand.
  - Solids removed are landfilled.
  - Some facilities use coagulating agents such as alum to aid the settling in the lagoon. This can reduce the BOD to the point that secondary treatment may not be necessary.
- Secondary treatment
  - Reduction of biological oxygen demand by at least 90%.
  - Usually done with either a trickling filter or an activated sludge reactor.
  - A trickling filter is a bed of sand of graduated particle size, ranging from coarse gravel on top to very fine sand on the bottom.
  - The trickling filter is colonized with microbes which reduce the BOD by utilizing the carbon compounds found in the sewage.

- The activated sludge reactor is more compact and can be enclosed in climates too cold for optimum biological activity.
- The reactor is a large tank in which the waste water is aerated to provide sufficient oxygen for the biological removal of BOD.
- Microbial sludge leaving the reactor is reinjected to maintain colonization of microbes.
- Many issues involved in the disposal of sewage sludge.

- Tertiary treatment is usually focused on the removal of phosphorous.
  - Usually achieved by preciptation with lime (a source of Ca^{2+}) or Al^{3+} or Fe^{3+}. The latter two form gelatinous precipitates which can further remove any microorganisms left from secondary treatment.
- Finishing usually involves a heavy dose of chlorine to kill remaining pathogens.
  - There is concern about chlorination of organics.