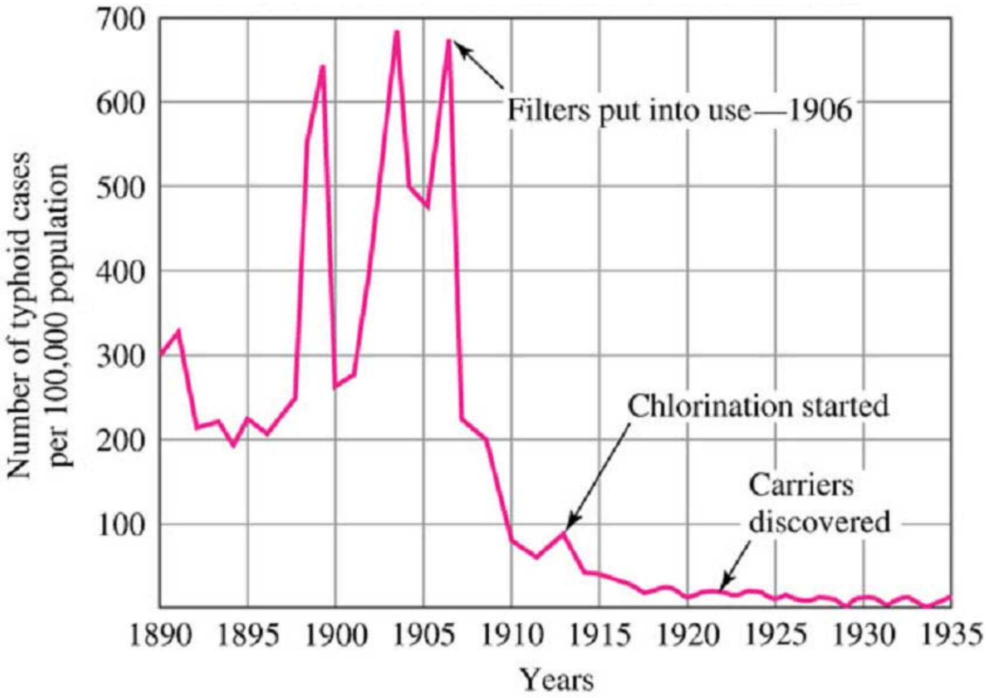
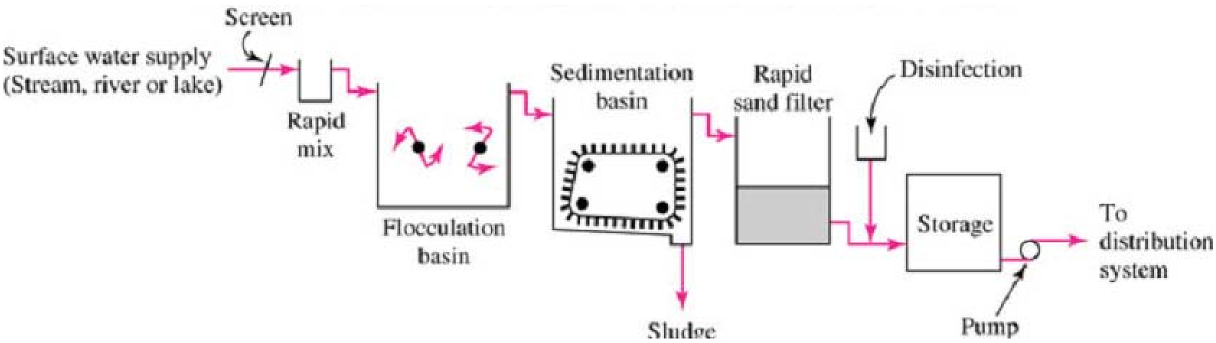
Water Treatment

1. Introduction

- See Fig. 9-1 (p.325): Relationship between drinking water treatment and waterborne diseases



- See Fig. 9-2 (p.329): Flow diagram of a conventional surface water treatment plant



1.1 History

연대 Period	취수원 Source of water-intake	급수 Water Distribu-tion	정수 Water treatment	국내 In Korea
	지표수 Surface water 우물 Well	석재수로 Stone pipe 목관 Wood pipe 연관 Lead pipe	햇빛 Sunlight 목탄 Charcoal 가열 Heating	
1582 1800 1895		Pump 주철관 Cast-iron pipe	완속여과지 Slow sand filter	- 1894. 부산 보수천 집수설비, 자연여과, 배수지 설치 Water intake, filtration, distribution reservoir in Bosucheon in Pusan - 1908. 서울 뚝도 정수장 준공, 125,000 명, 100 L/인,일 TtukDo water treatment plant with 125,000 capita/day, 100L/capita

20C			급속여과지 Rapid sand filter 소독 Disinfection	- 2001. 상수도 보급률 87.8%, 361 L/인,일 (공업용수 제외 수치, 인천광역시 428L, 광주광역시 297L). 2001. Water dissemination ratio 87.8%, 361 L per person per day (excluding industrial water, Incheon city 428L, Gwangju city 297L).
현재 Present			색깔 및 냄새 Color and odor 독성물질 Toxic compounds 심해수 이용 Deep seawater 대심도 송수 Deep water pipe	- 취수원 수질 악화 Deterioration of water quality in water source - 물 부족 Shortage of water - 누수 Leakage control - Virus, cryptosporidium, giadia

- Cryptosporidium: 400,000 illinesses, 50-100 deaths, in Milwaukee, WI., 1993
- Cryptosporidium (3-7 μm), Giadia (8-18 μm)

- Portable water (safe) and Palatable water (pleasing)


부산 보수천 상수도 제언 설치(1895) 부산 수정배수지 공사(1928)

Installation of dike in Bosucheon, Busan(1895)

Construction for distribution reservoir in Busan (1928)

상수도관 부설 공사 (부산, 1930 년대)

Water pipe construction (Busan, 1930s)

1.2 Water Quality Standards

미생물에 대한 기준 Microbiological criteria

- Indicator-microorganism (지표미생물): 대장균 E. coli, 일반세균 bacteria
- 물 속의 주요한 수인성 질환 병원체 The main, most notable water-borne disease pathogens in the water: 세균 (e.g., 살모넬라 Salmonella), 바이러스 virus, 원충 protozoa (e.g., cryptosporidium)

건강상 유해영향을 주는 무기물질 Hazardous Inorganic substances that affect health

- 납, 수은, 비소, 카드뮴, 6 가 크롬, 세레늄 등의 중금속 : 축적성 독성물질 Lead, mercury, arsenic, cadmium, hexavalent chromium, heavy metals (such as serenyum): cumulative toxic substances
- 암모니아 (유기질소에서 기인), 질산성 질소, 유독성 시안, 불소 등 Ammonia (due to organic nitrogen), nitrate nitrogen, toxic cyanide, fluoride, etc.

건강상 유해영향을 주는 유기물질 Hazardous Organic substances that affect health

- Solvents : Phenol, Dichloromethane, benzene, toluene, etc.
- 농약류 : 디아지논, 말라티온, 파라티온 등 Pesticides: dia xenon, malathion, parathion, etc.
- DBPs (Dinsinfection byproducts, 소독부산물) : Trihalomethane

심미적인 영향을 주는 물질 Substances that affect the aesthetics

- 직접적인 건강상의 유해물질은 아니지만, 먹는 물로 사용하는 데에 부적절한 영향물질 Although does not affect immediate health or are hazardous materials, has an improper influence for substances containing drinking water
- 탁도, 색도, 맛, 냄새, 경도, 철, 망간, 세제 등 Turbidity, color, taste, smell, hardness, iron, manganese, detergents, etc.

2. Unit Processes

2.1 Coagulation

- to remove turbidity, color, and bacteria
- to turn small particles of color, turbidity, and bacteria into larger flocs, either as precipitates or suspended particles
- Colloidal particles are (1) too small to settle in a reasonable time period, (2) too small to be trapped in the pores of a filter, and (3) stable due to their negative charge.

<u>Mechanisms</u>

- Adsorption and destabilization: extremely fast within 1 second
- Sweep coagulation: 1 to 7 seconds
- Using the Jar test, the predominant mechanism is can be identified.

<u>Key properties of a coagulant (응집제)</u>

- Trivalent cation : trivalent cation is the most effective cation.
- Nontoxic
- Insoluble in the neutral pH

  ∴ Al^{3+} and Fe^{3+}

<u>Aluminum</u>

- liquid alum (or dry) : $Al_2(SO_4)_3 14H_2O$(alum)
- $$Al_2(SO_4)_3 \cdot 14H_2O + 6HCO_3^- \rightarrow 2Al(OH)_3(s) + 6CO_2 + 14H_2O + 3SO_4^{2-}$$

  $$Al_2(SO_4)_3 \cdot 14H_2O \rightarrow 2Al(OH)_3(s) + 3H_2SO_4 + 8H_2O$$
- When sufficient alkalinity is not present, the pH may be greatly reduced.
- The aluminum ion does not really exit as Al^{3+} and the final product is more complex than $Al(OH)_3$, for example, $Al_8(OH)_{20}28H_2O]^{4+}$.

Iron

- Dry and liquid forms : $Fe_2(SO_4)_3\ xH_2O$ or $FeCl_3\ xH_2O$
- $FeCl_3 + 3HCO_3^- \rightarrow Fe(OH)_3(s) + 3CO_2 + 3Cl^-$

  $FeCl_3 + 3H_2O \rightarrow Fe(OH)_3(s) + 3HCl$
- Ferric salts generally have a wider pH range for effective coagulation than aluminum.

Coagulant aids

- pH adjusters : sulfuric acid [H_2SO_4], lime [$Ca(OH)_2$], soda [Na_2CO_3], etc.
- Polymers : long-chained carbon compounds of high molecular weight that have many active sites and produce larger flocs (i.e., interparticle bridging).

2.2 Mixing and Flocculation

Rapid Mixing

- The coagulation reaction is completed very fast. Thus, the mixing should be as instantaneous and complete as possible.
- Apparatus: see Fig. 9-5 (p. 334)

Flocculation

- to bring particles into contact so that they will collide, stick together, and grow to a bigger size.
- Apparatus: see Fig. 9-6 (p.335)
-

2.3 Sedimentation

Overview

- Sedimentation basin or Clarifier
- Rectangular or Circular
- Radial flow or Upflow
- Inlet, Settling, Outlet, and Sludge storage (See Fig. 9-14, 15, p.347)

Inlet : to evenly distribute the flow and suspended particles
to reduce the water velocity to the settling zone design velocity
consists of a series of inlet pipes and baffles

Sludge storage : the method of cleaning, the frequency of cleaning, and the quantity of sludge
with bottom slope or sludge hopper, bottom scraper

Settling : $v = \frac{Q}{A_s}$

where v = water velocity, m/s;
Q = water flow, m^3/sec; and
A_s = cross-sectional area, m^2.

Outlet : Weirs (See Fig. 9-15, p.349)to prevent "scouring", i.e., washing out of the floc

Weir overflow rate = [m^3/day,m]

<u>Sedimentation Concept</u>

- Settling velocity and Overflow rate
- For the upflow clarifier, the settling velocity (v_s) > liquid-rise velocity (v_o)

$$v_o = \frac{Volume/Time}{Surface\ Area} = \frac{Depth}{Time} = liquid\ velocity$$

As long as v_s is greater than v_o, the particle will settle downward regardless of the depth.

- For the horizontal clarifier, the removal efficiency is dependent on the overflow rate, v_o (is "overflow rate"),
- In order to remove particles, $v_s > h/t_0$ (see Fig. 3.33, p. 217) and

$$v_s = \frac{h}{t_0} = \frac{h}{V/Q} = \frac{h \times Q}{V} = \frac{h \times Q}{l \times w \times h} = \frac{Q}{l \times w} = \frac{Q}{A_s}$$

$$\frac{Q}{A_s} = v_o \quad \text{(overflow rate)}$$

The removal efficiency is independent of depth.

$$P = 100\frac{v_s}{v_o} \quad \text{(see Fig. 3.34, p.218)}$$

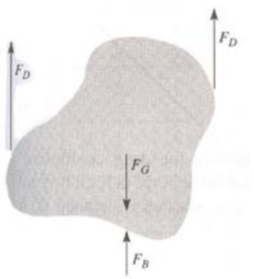
If $v_S > v_O$, P = 100% (not > 100%)

<u>Determination of v_S</u>

$$F_G = \rho_s \cdot g \cdot V_p$$

$$F_B = \rho \cdot g \cdot V_p$$

$$F_D = C_D \cdot A_p \cdot \rho \cdot \frac{v^2}{2}$$



where F_G = gravitational force;

F_B = buoyancy force;

F_D = drag force;

ρ_s = density of a particle;

ρ = density of fluid;

g = acceleration due to gravity;

V_p = volume of the particle;

C_D = drag coefficient;

A_p = cross sectional area of the particle; and

v_s = velocity of the particle;

The driving force for acceleration of the particle is,

$$F_G - F_B = (\rho_s - \rho) \cdot g \cdot V_p$$

When the drag force is equal to the driving force, the particle velocity reaches a constant value called the terminal settling velocity (v_s).

$$(\rho_s - \rho) \cdot g \cdot V_p = C_D \cdot A_p \cdot \rho \cdot \frac{v^2}{2}$$

For a spherical particles with a diameter = d

$$v_s = \left[\frac{4 \cdot g \cdot (\rho_s - \rho) \cdot d}{3 \cdot C_D \cdot \rho} \right]^{1/2}$$

C_D vs. Reynolds number (by Thomas Camp, see Fig. 3.36, p.223)

$$R = \frac{d \cdot v_s}{\nu} = \frac{d \cdot \rho \cdot v_s}{\mu}$$

$$C_D = \frac{24}{R} \quad (R < 0.5)$$

Stokes' law (Terminal settling velocity for a sphere under laminar flow condition)

$$v_s = \frac{g \cdot (\rho_s - \rho) \cdot d^2}{18 \cdot \mu}$$

<u>Sludge Blanket</u>

- Mixing, flocculation, and clarification can be conducted in a single reactor. "Sludge blanket"– an upflow solid-contact basin.

2.4 Filtration

- to separate suspended (or colloidal impurities) from water
- media : sand, coal (anthracite), dual media (coal-lighter than sand + sand), or mixed media (coal, sand, and granite)
- Loading rate

$$v_a = \frac{Q}{A_s}$$

where v_a = loading rate (or face velocity), $m^3/day,m^2$;
Q = flow rate onto filter surface, m^3/day; and
A_s = surface area of filter, m^2.

Slow sand filter(완속여과) (< $10m^3/day,m^2$) – top layer (e.g., 75mm) is scraped off, cleaned, and replaced.

Rapid sand filter(급속여과) (Fig. 9-17, p.353, > $100m^3/day,m^2$)

High-rate sand filter – upto $800m^3/day,m^2$

Backwashing (역세척)

2.5 Disinfection

- Disinfection (소독) vs. Sterilization (멸균)
- Targets : Bacteria, Virus, and Ametic cysts

- Disinfectants

(1) destroy pathogens that may be introduced within a practical period of time;
(2) meet possible fluctuations;
(3) at reasonable cost, safe, easy to store, transport, handle, and apply;
(4) determined easily, quickly, and (preferably) automatically;
(5) persist against possible recontamination
(6) neither toxic to humans and domestic animals nor unpalatable;

<u>Disinfection Kinetics</u>

Chick's law (a first order reaction)

$$-\frac{dN}{dt} = k \cdot N$$

<u>Disinfecting Action</u>

- CT : Product of C and T
- CT values (mg/L.min) (see Table 3.20, p.244 : 3-log reduction of Giardia is

required.)

$$CT = 0.9847 \cdot C^{0.1758} \cdot pH^{2.7519} \cdot temp^{-0.1467}$$

Chlorine Reactions in Water

- Chlorine gas (Cl_2), Sodium hypochlorite (NaOCl), and Calcium hypochlorite ($Ca(OCl)_2$)
- Chlorine gas

  $Cl(g) + H_2O \rightarrow HOCl + H^+ + Cl^-$ (within a very few milliseconds)

  $HOCl \rightarrow H^+ + OCl^-$ (pK = 7.537 at 25^{o}C)
- Sodium hypochlorite

  $NaOCl \rightarrow Na^+ + OCl^-$
- Cacium hypochlorite

  $Ca(OCl)_2 \rightarrow Ca^{2+} + 2 \cdot OCl^-$
- "free available chlorine" : chlorine existing in the form of HOCl and/or OCl^-.
- Optimum pH = 6.5 - 7.5

Chlorine/Ammonia Reactions

- Chloramines : retain the oxidizing power of the chlorine

  $NH_3 + HOCl \rightarrow NH_2Cl + H_2O$ (monochloramine)

  $NH_2Cl + HOCl \rightarrow NHCl_2 + H_2O$ (dichloramine)

  $NHCl_2 + HOCl \rightarrow NCl_3 + H_2O$ (trichloramine)
- High Cl_2:NH_3, low temperatures, and low pH, favor dichloramine formation.
- Combined available chlorine (결합염소): chlorine in chemical combination with ammonia or organic nitrogen compounds
- Combined available chlorine is a less effective disinfectant than free available chlorine (유리염소). However, it does not produce odor and taste, is reduced more slowly and persists for a long time in the distribution system (Chloramine disinfection).

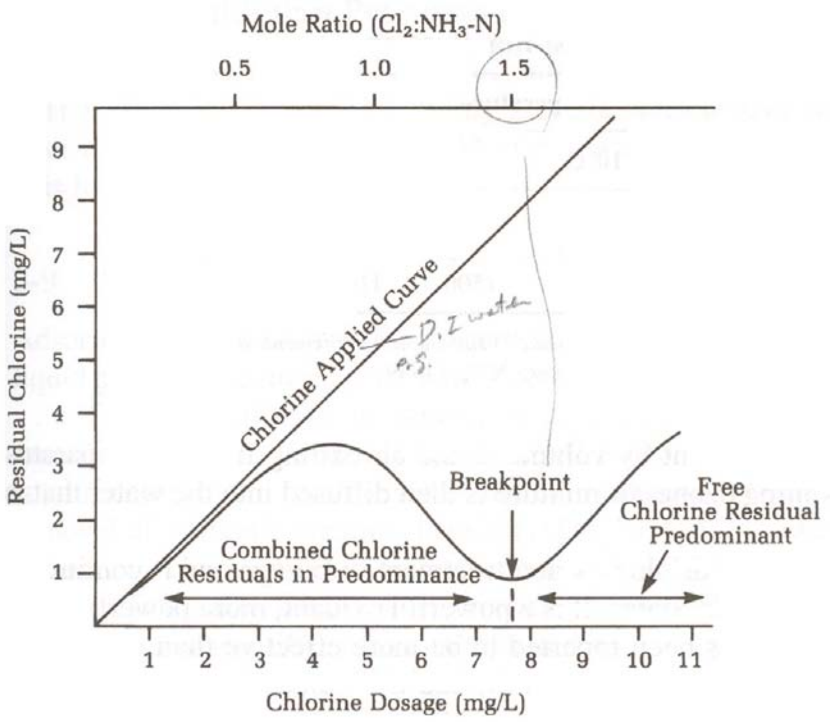
<u>Breakpoint chlorination</u>, See Fig. 3.44 (p.247)

- 심하게 오염된 원수에 대해, NH_3 와 취미의 원인이 되는 유기물을 분해하는 데에 필요한 염소요구량 이상의 염소를 주입하는 처리법 (파괴점염소처리법) When raw water is heavily polluted by NH_3 and organic substances, there is a higher demand of chlorine to treat them. Thus, a method of injecting more chlorine is necessary (chlorine treatment breaking point).

- $3 \cdot Cl_2 + 2 \cdot NH_3 \rightarrow N_2 \uparrow + 6 \cdot HCl$ ($Cl_2:NH_3$ = 1.5:1.0, breakpoint)

  or $3Cl_2 + 2NH_4^+ \rightarrow N_2\uparrow + 6HCl + 2H^+$

  then after, $Cl_2 + H_2O \rightarrow HOCl + H^+ + Cl^-$ (free available chlorine)



<u>Other Disinfectants</u>

- Chlorine dioxide(ClO_2): not forming THMs, however, health concerns, taste and odors, high cost, less residual effect, etc.
- Ozone(O_3): not forming THMs, however, less residual effect, decaying back to oxygen, etc.

- Ultraviolet radiation(UV): good to bacteria and viruses, however, no residual protection, very expensive, etc.

3. Additional Treatments

Adsorption

- GAC(Granular Activated Carbon)

AOP (Advanced Oxidation Processes)

- Hydroxyl radicals(OH•): Highly reactive nonselective oxidants
- Ozone, Hydrogen peroxide (H_2O_2), and UV

4. Water Treatment Plant Waste Management

The logical sludge management

(1) Minimizing sludge generation (using polymers, optimum dosing, direct filtration, etc.)
(2) Chemical recovery of precipitates;
(3) Sludge treatment to reduce volume;
(4) Ultimate disposal in an environmentally safe manner.