Water Treatment – Preparation of water for drinking and municipal distribution

(Nazaroff & Alvarez-Cohen, pages 302 and following; Mihelcic & Zimmerman, Chapter 10)

Consumers in industrialized countries expect safe drinking water, that is:
- Clear
- Colorless
- Odorless
- Free of harmful chemicals
- Free of pathogens.

Natural water, however, rarely exhibits these properties.

Type of impurity	**Specific constituents**	**Typical concentration**
Major inorganic constituents	Usually in ionic form: calcium, chloride, fluoride, iron, manganese, nitrate (NO_3^-), sodium, sulfur	1 – 1000 mg/L
Minor inorganic constituents	Arsenic, cadmium, copper, lead, mercury, nickel, zinc, *etc.*	0.1 – 10 μg/L
Natural organic compounds	Biological detritus (Total Organic carbon = TOC)	0.1 – 20 mg/L
Anthropogenic organic compounds	Synthetic organic chemicals, agricultural, industrial & household chemicals (benzene, vinyl chloride, PCBs, PCE, TCE)	from 1 μg/L to tens of mg/L
Living organisms	Bacteria, algae, viruses	millions/L

(Mihelcic & Zimmerman, Table 10.1)

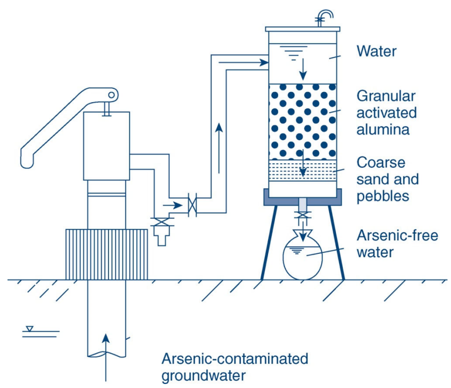
Arsenic

Naturally occurring **arsenic** is widespread, and in many places of the world, arsenic is present in the groundwater. The World Health Organization (WHO) has set a drinking-water guideline for arsenic of 10 μg/L (= 10 ppb_m).

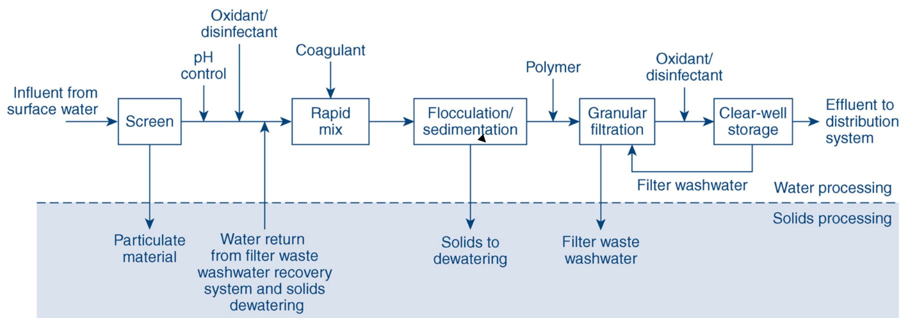
Long-term exposure to arsenic via drinking-water causes cancer of the skin, lungs, urinary bladder, and kidney, as well as other skin changes such as pigmentation changes and thickening (hyperkeratosis).

Increased risks of lung and bladder cancer and of arsenic-associated skin lesions have been observed at drinking-water arsenic concentrations of less than 0.05 mg/L.

Simple technology to remove arsenic from groundwater, which can be implemented in under-developed countries.



(Mihelcic & Zimmerman, Figure 10.2)



Schematic of a typical municipal **drinking-water** treatment system
(Mihelcic & Zimmerman, Figure 10.3a)

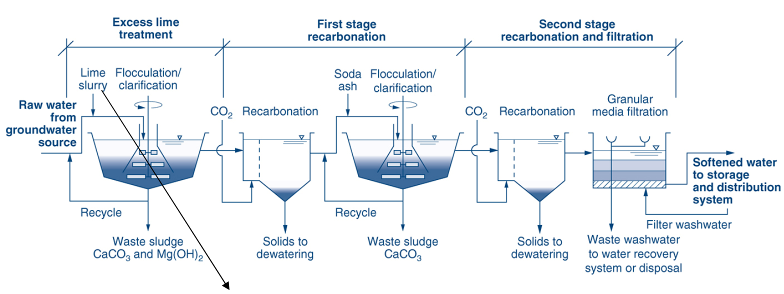
Water Softening = Hardness Removal

(Nazaroff & Alvarez-Cohen, Section 6.D.4)
(Mihelcic & Zimmerman, Section 10.6)

Hardness of water is caused by 2+ ions, primarily Ca^{++} and Mg^{++},
usually associated with the carbonate ions (HCO_3^- and CO_3^{--}) or sulfate ions (SO_4^{--}).
It is a common occurrence with groundwater.

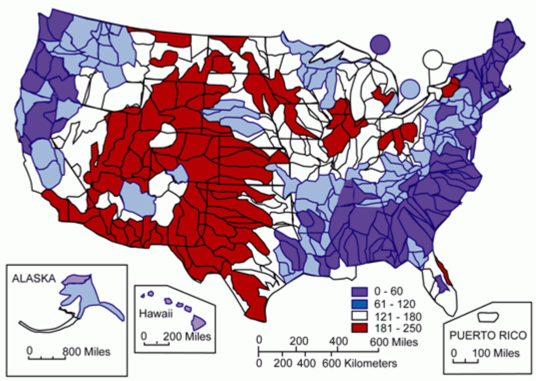
So-called complexation agents can be added to prevent the 2+ ions from precipitating.
Better, hardness can be removed, which softens the water.

Example of process: The lime-soda ash softening process



$$Ca(HCO_3)_2 + Ca(OH)_2 \rightarrow 2\ CaCO_3(solid) + 2\ H_2O$$
$$Mg(HCO_3)_2 + 2\ Ca(OH)_2 \rightarrow 2\ CaCO_3(solid) + Mg(OH)_2(solid) + 2\ H_2O$$

CONCENTRATION OF HARDNESS AS CALCIUM CARBONATE, IN MILLIGRAMS PER LITER



Mean hardness as calcium carbonate at NASQAN water-monitoring sites during 1975 water year.
Colors represent site data representing streamflow from the hydrologic-unit rea.
(Map edited by USEPA, 2005)

Disinfection

(Nazaroff & Alvarez-Cohen, Section 6.D.1)
(Mihelcic & Zimmerman, Section 10.9)

Purpose:

To reduce risk of disease transmission associated with either drinking or waste water.

Objective:

To kill or inactivate microorganisms.

Methods:

Boiling of water	Very effective	Very energy intensive
Irradiation with UV light	Limited efficacy	Cheap and convenient Requires clear water
Chemical disinfection by chlorine or chlorinated compound	Very effective Leaves lasting residuals	Cheap to expensive May create harmful by-products
Chemical disinfection by ozone	Very effective	Quite expensive No residual left

Disinfection by chlorine

The active ingredient that kills microorganisms is hypochlorous acid, HOCl.

HOCl must be made in the water from a chlorinated precursor.
The most common method is the injection of pure chlorine gas, Cl_2.

More expensive but safer than handling chlorine gas is the use of sodium hypochlorite (NaOCl – commonly called bleach) or calcium hypochlorite ($Ca(OCl)_2$), a solid.

U.S. standards for drinking water:

- minimum contact of 45 minutes
- minimum residual chlorine concentration of 1.1 mg/L
  (from initial dose of 2 to 5 mg/L)

U.S. practice for end of wastewater treatment:

- injection of 40 to 60 mg/L.

Chlorine chemistry in pure water

Let us consider the use of chlorine gas as the disinfection method.

First, Cl_2 in gas (from compressed bottle, handled with care!) penetrates the water, following Henry's Law:

$$Cl_{2(gas)} \leftrightarrow Cl_{2(water)} \quad \text{with } K_H = 0.062 \text{ M/atm at } 25^{o}\text{C}$$

Aqueous Cl_2 reacts rapidly with water to form hypochlorous acid:

$$Cl_2 + H_2O \leftrightarrow \boxed{HOCl} + H^+ + Cl^-$$

active ingredient

with constant

$$K = \frac{[\text{HOCl}][\text{H}^+][\text{Cl}^-]}{[\text{Cl}_2]} = 5 \times 10^{-4} \text{ M}^2$$

The preceding two reactions are highly tilted to the right, meaning that chlorine gas most easily goes into hypochlorous acid in the water.

However, hypochlorous acid HOCl is not only consumed in killing microorganisms; it also decays spontaneously into:

$$HOCl \leftrightarrow H^+ + OCl^-$$

with constant

$$K_2 = \frac{[H^+][OCl^-]}{[HOCl]} = 2.6 \times 10^{-8} \text{ M}$$

The hypochlorite ion OCl^- is much less potent as a disinfectant than HOCl.

To keep the above reaction tilted to the left (in favor of HOCl and against OCl^-), the *pH* must be controlled.

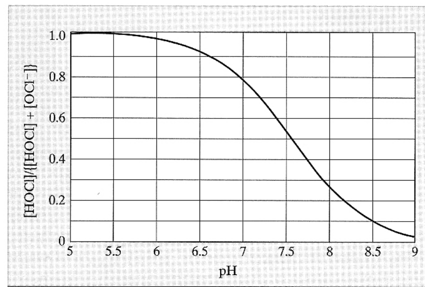


Figure 6.D.1 The fraction of hypochlorous species ($HOCl + OCl^-$) that is present as undissociated hypochlorous acid (HOCl), versus pH.

(From Nazaroff & Alvarez-Cohen, 2001)