DRINKING WATER TREATMENT AND DISTRIBUTION

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An adequate supply of clean water, sanitation and hygiene are the most important preconditions for sustaining human life, for maintaining ecological systems that support all life and for achieving sustainable development.

Population with no access to sanitation\(^1\) in % of the total population, 2004

- **Red**: more than 50%
- **Orange**: from 31 to 50%
- **Light Blue**: from 5 to 30%
- **Dark Blue**: Less than 5%
- **Gray**: Data not available

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1. According to the definition of WHO and Unicef: Population having no access to a waste water or solid waste treatment infrastructure, well maintained toilets or linked to a septic tank.

Sources: World Health Organization (WHO) and Unicef, *Meeting the MDG drinking water and sanitation target*, 2006.
Safe water is essential for life.

Sadly, **1.2 billion** people around the world lack access to safe drinking water, and **twice that many** lack adequate sanitation.

As a result, the WHO estimates that **3.4 million** people, mostly children, die every year from water-related diseases (WHO 2002).

**Diarrheal disease**, a result of lack of adequate water and sanitation services, in 10 years, have killed more children than all the people lost to armed conflict since World War II (United Nations 2002).

Many of these diseases can be prevented with appropriate water treatment and proper sanitation and hygiene practices.
Increasing access to safe water can improve more than public health.

In Africa, women and girls spend as much as 3 hours a day fetching water, an expenditure of calories greater than one-third their daily food intake (United Nations 2002).

The task of keeping the home supplied with drinking water is often so laborious and time consuming that it can constitute the most significant single obstacle standing in the way of a child’s education.

In addition, a reliable supply of water is necessary for almost all economic development.
The United Nations has recognized the critical link between **safe water** and **sustainable development**.

At the 2002 World Summit on Sustainable Development (WSSD) in Johannesburg, South Africa, the UN reaffirmed its goal to reduce by one-half the proportion of people without access to safe water by 2015.

The WSSD also adopted a comparable goal for improving access to basic sanitation.
Despite remarkable global progress to improve access to drinking water facilities

- There are currently **884 million** people with limited access to improved water resources
- Additional **2.5 billion** people with limited access to sanitation
- Further stress is placed on the deteriorating water and sanitation infrastructure by Socio-economic and environmental factors, such as: poverty, accelerated population growth, rapid urbanization, hydrological variability and climate change

- UN & WHO, 2012
Potential **sources of drinking water** include: rivers, streams, lakes, and underground aquifers.

Water obtained from **surface sources** and groundwater under the influence of surface waters (e.g., nearby rivers) must be **filtered** and **disinfected**.

**Groundwater** needs either **no treatment** or **only disinfection** before use as drinking water. Soil acts as a filter to remove pathogenic MOS.
- **Slow sand filtration** was the only means employed for purifying public water supplies, at first.

- Development of **germ theory of disease** in the 1870s moved things more quickly.

- **Koch** demonstrated that chlorine could kill bacteria in 1881. **Chlorination** of public water supply was used for the first time in **1905**, following the **outbreak of typhoid fever** in London.

- Regular use of disinfection in the U.S. began in Chicago in **1908**.

- Application of modern water treatment processes has a major impact on water-transmitted diseases (**Fig. 22.1**).
FIGURE 22.1 Impact of water filtration and chlorination on typhoid fever death rate in Albany, New York. (From Logsdon and Lippy, 1982.)
Exhibit 4-10: Percent of population with treated water versus typhoid deaths in the United States, 1880-1980

Water Treatment Processes

- Provides barriers or lines of defense between consumers and water-borne diseases.

- These barriers, when implemented as a succession of treatment processes, are known as **treatment process train** (Fig. 1).

- These include:
- **Chlorination (Fig. 1a):** disinfection by chlorine

- **Filtration (Fig. 1b):** chlorination followed by filtration through a sand or coal, to remove particulate matter from the water and reduces turbidity

- **In-line filtration (Fig. 1c):** coagulation prior to filtration.
**Direct filtration (Fig. 1d):** disinfection is enhanced by adding chlorine (or an alternative disinfectant at both the beginning and end of the process train.

**Conventional treatment (Fig. 1e):** consists of disinfection, coagulation, flocculation, sedimentation, filtration, and disinfection – **Common treatment process train for surface water supplies.**
Coagulation

- Involves the addition of **chemicals** to facilitate the removal of dissolved and suspended solids by **sedimentation** and **filtration**.

- Most **common primary coagulants** are:
  
  - **Hydrolyzing metal salts**, notably; **Alum** \([\text{Al}_2(\text{SO}_4)_3 \cdot 14\text{H}_2\text{O}]\), **ferric sulfate** \([\text{Fe}_2(\text{SO}_4)_3]\) and **ferric chloride** \((\text{FeCl}_3)\).
  
  - **Additional chemicals** - Charged organic molecules (polyelectrolytes) such as polyacrylamides, dimethyldiallyl ammonium chloride, polyamines, and starch.
These chemicals ensure the **aggregation of the suspended solids** during flocculation.

Coagulation can also remove **dissolved organic** and **inorganic compounds**.

Hydrolyzing metal salts may react with the organic matter to form a **precipitate** or form **aluminum or ferric hydroxide floc particles** on which organic molecules adsorb.

**Adsorption** and **precipitation** also remove inorganic substances.
**Flocculation**

- Purely *physical process* in which treated water is gently stirred to increase *inter-particle collisions*, thus promoting *formation of large particles*.

- After adequate flocculation, most of the aggregates settle out during the **1 to 2 hours** of *sedimentation*.

- MOS are trapped on or adsorbed to the suspended particles and removed during sedimentation.
Sedimentation & Filtration

- Physical process involving the *gravitational settling of suspended particles* that are denser than water.

- The resulting effluent is subjected to *filtration* to separate out solids that are still suspended in water.

- **Rapid filtration** is commonly used in the U.S.

- Typical *rapid filters* consist of 50-70 cm of sand and/or *anthracite* having a diameter 0.5 and 1.0 mm.

- Particles are removed as water is filtered through the medium at rates of 4-24/min/10 dm².

- Buildup of suspended matter on the filter is prevented by **backwashing the filters** regularly.
Schematic diagram of a rapid filter
Slow sand filtration

- It operates at **low filtration rates without the use of coagulation.**

- Slow sand filters contain;
  - a **layer of sand** (60-120 cm) supported by a **gravel layer** (30-50 cm deep).
  - The **hydraulic loading rate** is between **0.04 and 0.4 m/hr**.
  - A biologically active layer, **schmutzdecke**, develops during the operation of a slow sand filter.

- This leads to head loss across the filter, requiring removing or scraping the top layer of sand.
Slow sand filters
Pathogen removal by slow sand filters is influenced by:

- Temperature;
- sand grain size
- filter depth;
- flow rate
- well-developed biofilm layer
Taken together, coagulation, flocculation, sedimentation, and filtration, effectively remove many contaminants (Tables 22.2 and 22.3).

They also reduce turbidity, yielding water of good clarity and enhance disinfection efficiency.

Filtration is important in the removal of *Giardia lamblia* and *Cryptosporidium* (protozoan parasites).

The cysts and oocysts of these organisms are very resistant to inactivation by disinfectants.
### TABLE 22.2 Coagulation, Sedimentation, Filtration: Typical Removal Efficiencies and Effluent Quality

<table>
<thead>
<tr>
<th>Organisms</th>
<th>Coagulation and sedimentation (% removal)</th>
<th>Rapid filtration (% removal)</th>
<th>Slow sand filtration (% removal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total coliforms</td>
<td>74–97</td>
<td>50–98</td>
<td>&gt;99.999</td>
</tr>
<tr>
<td>Fecal coliforms</td>
<td>76–83</td>
<td>50–98</td>
<td>&gt;99.999</td>
</tr>
<tr>
<td>Enteric viruses</td>
<td>88–95</td>
<td>10–99</td>
<td>&gt;99.999</td>
</tr>
<tr>
<td>Giardia</td>
<td>58–99</td>
<td>97–99.9</td>
<td>&gt;99</td>
</tr>
<tr>
<td>Cryptosporidium</td>
<td>90</td>
<td>99–99</td>
<td>99</td>
</tr>
</tbody>
</table>


### TABLE 22.3 Removal of Virus by Coagulation–Settling–Sand Filtration

<table>
<thead>
<tr>
<th>Virus</th>
<th>Viral assays, total PFU/200 l (percentage removed)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Input</td>
</tr>
<tr>
<td>Poliovirus</td>
<td>$5.2 \times 10^7$</td>
</tr>
<tr>
<td>Rotavirus</td>
<td>$9.3 \times 10^7$</td>
</tr>
<tr>
<td>Hepatitis A virus</td>
<td>$4.9 \times 10^{10}$</td>
</tr>
</tbody>
</table>

Adapted from Rao et al. (1988).
Viruses and bacteria can pass through the filtration process because of their small sizes.

Disinfection therefore remains the ultimate barrier to the microorganisms.

Removal of viruses by filtration and coagulation depends on their attachment to particles (adsorption).
This is dependent on the **surface charge** of the virus, which is related to the **isoelectric point** (pH at which the virus has no charge) – **strain & type dependent**

Different types of viruses are removed with different efficiencies by coagulation and filtration due to **variations in their surface properties**.

The list of various **disinfectants** and **oxidants** used in the disinfection process is shown in **Table 22.4**.
Methods of Disinfection

Drinking water systems serving a population > 10,000

- Chlorination  70%
- Chloramination  25%
- Chlorine dioxide  5%
- Ozonation  1%

Drinking water systems serving a population < 10,000

- Chlorination  >95%
A typical water treatment plant
IOWA Municipal Water Treatment Plant
Umgeni Water Treatment Plant

Umgeni Water is a state-owned business enterprise, established in 1974 to supply potable water in bulk to municipalities within its operational area. The primary function of Umgeni Water - to treat raw water and distribute it in a drinkable form through its infrastructure - has been legislated under the Water Services Act of 1956, which was subsequently amended in 1997. Umgeni Water has six municipal customers: eThekwini and Msunduzi Metropolitan Municipalities; and Ugu, Ilembe, Sisonke and uMgungundlovu District Municipalities.
In the Financial Year 2007 - 2008 the municipal customers of Umgeni Water collectively purchased 403 million kilolitres of treated water. The water supplied ultimately reached an estimated 4,8 million consumers.

The infrastructure Umgeni Water owns comprises:

- About 514 kilometres of pipelines
- Three dams
- Nine water works
- Two wastewater works
- Administration buildings: Head Office in Pietermaritzburg and Regional Offices in Mkondeni (Pietermaritzburg); Pineside (Durban) and Umhlali (North Coast)
- Water treatment plants: Midmar (Howick); DV Harris (Pietermaritzburg) and Durban (Durban Heights; Wiggins; Amanzimtoti and Hazelmere)
Water Distribution Systems

- After treatment of drinking water, it must be distributed to the final consumers.

- The presence of dissolved organic compounds in water can cause problems, such as:
  - taste and odors
  - enhanced chlorine demand
  - bacterial colonization of water distribution systems.
Microbial biofilms have potential for protection of pathogens from the action of residual disinfectant in the water and the re-growth of indicator bacteria.

Other problems caused by biofilms in distribution systems include:
- Frictional resistance of fluids
- Photoreduction of $\text{H}_2\text{S}$ because of anaerobic conditions
- Taste and odor problems
- Resistance to disinfection
- Regrowth of coliform bacteria
- Growth of pathogenic bacteria
- Colored water (red, black) from activity of iron- and manganese- oxidizing bacteria
Biofilms may appear as a **patchy mass** in some pipe sections or as **uniform layers**.

They may consist of a monolayer of cells in a microcolony or can be as thick as 10 to 40 mm, as in **algal mats** at the bottom of a reservoir.

The biofilms provide a variety of **microenvironments for growth**, including aerobic and anaerobic zones.

Biofilm MOS are held together by an extracellular polymeric matrix called a **glycocalyx**.
The glycocalyx is composed of glucans, uronic acids, glycoproteins, and mannans.

The glycocalyx helps protects MOS from predation and adverse conditions (e.g. disinfectants).

The occurrence of even low levels of organic matter in the distribution system allows the growth of biofilm MOS.
The growth of biofilm MOS is controlled by the following factors:

- Temperature
- Water hardness (Determined by mineral content of water)
- pH
- Redox potential
- Dissolved carbon
- Residual disinfectant
- *E. coli* is **2400 times more resistant** to chlorine when attached to surfaces than as free cells in water, leading to high survival rates within the distribution systems.

- Biofilms in distribution systems are **difficult to inactivate**.

- Water-based pathogens such as *Legionella* are known to occur in distribution systems and colonize the plumbing, faucet fixtures, and taps in homes.
Assimilable Organic Carbon

- **AOC** is the amount of biodegradable organic matter available to microorganisms.

- Growth of bacteria in distribution systems is influenced by:
  - concentration of biodegradable organic matter
  - water temperature
  - nature of the pipes
  - concentration of residual disinfectant
  - detention time within the distribution system
Bacteria like *P. aeruginosa* and *P. fluorescens* can grow in tap water at relatively low conc. (μg/l) of low-molecular-weight organic substrates – e.g. lactate, acetate, succinate, and amino acids.

**Assimilable organic carbon (AOC)** in tap water has been estimated as between **0.1** and **9%** of the total organic carbon (Table 22.6).

### TABLE 22.6 Concentrations of Assimilable Organic Carbon (AOC) in Various Water Samples

<table>
<thead>
<tr>
<th>Source of water</th>
<th>Dissolved organic carbon (DOC), mg C/l&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Assimilable organic carbon (AOC), mg C/l</th>
</tr>
</thead>
<tbody>
<tr>
<td>River Lek</td>
<td>6.8</td>
<td>0.062–0.085</td>
</tr>
<tr>
<td>River Meuse</td>
<td>4.7</td>
<td>0.118–0.128</td>
</tr>
<tr>
<td>Brabantse Diesbosch</td>
<td>4.0</td>
<td>0.08–0.103</td>
</tr>
<tr>
<td>Lake Yssel, after open storage</td>
<td>5.6</td>
<td>0.48–0.53</td>
</tr>
<tr>
<td>River Lek, after bank filtration</td>
<td>1.6</td>
<td>0.7–1.2</td>
</tr>
<tr>
<td>Aerobic groundwater</td>
<td>0.3</td>
<td>&lt;0.15</td>
</tr>
</tbody>
</table>

<sup>a</sup> DOC, dissolved organic carbon; C/l, carbon/liter.

Adapted from van der Kooij *et al.* (1982).
When **ozone** is used as disinfectants, complex organic molecules are broken down, making it more available to MOS, and thus increasing the AOC (**Fig. 22.5**).

Rapid regrowth of HPC usually occurs after ozonation of tap water.

**FIGURE 22.5** Relationship between mean coliform densities and total assimilable organic carbon (AOC) levels. (From LeChevallier et al., 1992.)
Coliform Growth Response (CGR) test is used to indicate the growth potential of coliforms.

- uses *Enterobacter cloacae* as the bioassay organism

- changes in viable densities of this organism in the test water over a 5-day period at 20°C are used to develop an index of nutrients available to support coliform biofilm regrowth.
CGR is calculated by log transformation of the ratio of the colony density achieved at the end of the incubation period to the initial cell concentration

\[ \text{CGR} = \log \left( \frac{N_5}{N_0} \right) \]

- \( N_5 = \text{number of cfu/ml at day 5} \) and
- \( N_0 = \text{number of cfu/ml at day 0} \)

A value of 1-log or greater is interpreted that the sample is supportive of coliform growth.
Calculated values between 0.51 and 0.99 are considered moderately growth supportive.

Those less than 0.5 are regarded as not supportive of coliform growth.

CGR test responds only to the concentrations of assimilable organic materials that support growth of coliforms characteristics of regrowth in biofilms.

The biodegradable dissolved organic carbon (BDOC) is given by the following formula:

\[ \text{BDOC (mg/l)} = \text{initial DOC} - \text{final DOC} \]