

18

Water Treatment

»» 18.1 The Need for Potable Water

Environmental engineers entering developing communities are often confronted first by the need for potable water. Whether or not the fundamentals of disease transmission are understood, the importance of having a sufficient supply of high-quality and good-tasting water is obvious. Although chemical contamination should be a consideration for drinking water treatment, the majority of water-related health problems in developing countries are related to microbial contamination (WHO 2006). This chapter does, however, cover treatment of arsenic and fluoride, because these chemical constituents are important in many parts of the world.

»» 18.2 Drinking Water Guidelines

According to the World Health Organization (WHO) (2006), *safe drinking water* is water that “does not represent any significant risk to health over a lifetime of consumption, including different sensitivities that may occur between life stages.” The WHO views the risk–benefit approach to be more appropriate for setting individual nations’ standards than setting international standards for drinking water. The *risk–benefit approach* involves analyzing the risks occurring throughout a water supply, including catchment, source, and point of use, and then identifying methods of managing these risks. Instead of publishing international standards, the WHO publishes guidelines for drinking water quality. The most recent guidelines are available online (WHO 2006). Where national standards exist, they should also be met.

The WHO recommends that at minimum, *Escherichia coli* (*E. coli*), thermotolerant (fecal) coliforms, and chlorine residuals (where there is chlorination) be monitored in community water supply systems. This minimum monitoring should be supplemented by monitoring of turbidity and by pH adjustment where the water is chlorinated.

Guidelines that are applicable to many developing world settings are summarized in Table 18-1. Arsenic, nitrate, fluoride, and turbidity can all be measured directly. Microbial water quality is typically measured by analyzing indicator microorganisms, such as *E. coli* or thermotolerant coliforms, or by assessing specific pathogen densities. The presence of *E. coli* in drinking water is conclusive evidence of recent fecal contamination. On the other hand, some viruses and protozoa are more resistant to disinfection,

Erlande Omisca, Maya A. Trotz, and Qiong Zhang contributed to this chapter.

Table 18-1. WHO Guidelines for Common Contaminants

Contaminant	Guideline
Arsenic	0.01 mg/L (P)
Fluoride	1.5 mg/L
Nitrate	50 mg/L
<i>E. coli</i>	0/100 mL ^a
Thermotolerant coliforms	0/100 mL ^a
Turbidity ^b	0.1 NTU
Arsenic	10 µg/L
Fluoride	1.5 mg/L

Note: P = provisional guideline value.

^aIn communities where the water supply fails to meet this guideline, the WHO suggests using a grading scheme based on the percentage of negative samples. See Table 5-2 in the WHO guidelines for an example grading scheme. Total coliforms is not considered an appropriate indicator for fecal contamination because many bacteria of no significance occur naturally, especially in tropical waters.

^bThere is currently no WHO guideline for turbidity, however the guidelines do suggest 0.1 nephelometric turbidity units (NTU) for effective disinfection.

Source: WHO 2006.

so a negative *E. coli* test does not necessarily mean that water is free of pathogens caused by fecal contamination.

18.3 Water Treatment Processes

Water treatment can be accomplished by several different methods, and in conventional treatment, these methods are combined. The methods that are conventionally used in the industrialized world include mechanical separation, coagulation and flocculation, chemical purification, disinfection processes, biological processes, aeration, and membrane technologies. A schematic of the flow of water through a conventional treatment plant is shown in Fig. 18-1. As a last resort, boiling is used to treat disease-carrying water in homes, though it is estimated that hundreds of millions of people use this method. Table 18-2 defines each of these treatment methods and links them to the technologies discussed in this chapter. All of the processes used in conventional treatment systems can be scaled down for point-of-use treatment. The technologies described here may similarly be used in combination to increase effectiveness.

In addition to treatment, water storage at the household is an important component of a safe water supply plan. Proper water storage in the home protects treated water from contamination and can also allow sedimentation of untreated or poorly treated water.

18.4 Point-of-Use Treatment vs. Treatment at the Source

In developed countries, drinking water treatment for communities is often centralized treatment at the source, with distribution to households. Therefore, much emphasis has

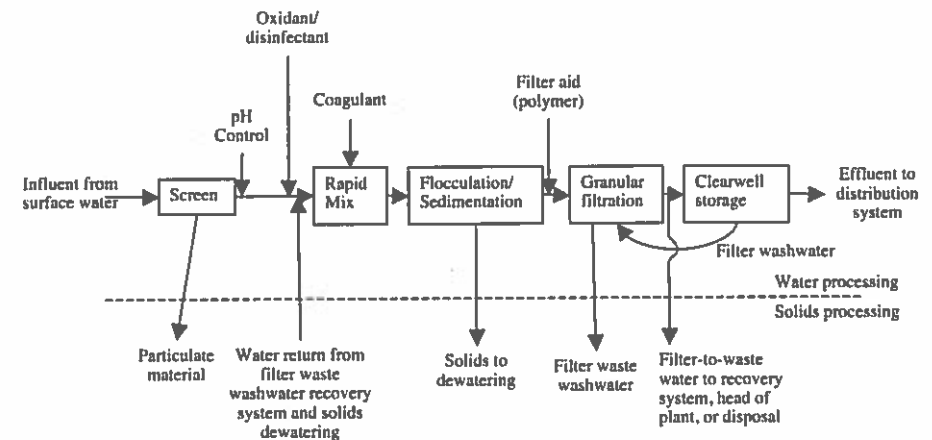


Figure 18-1. Schematic Flow Diagram of Conventional Treatment of Surface Water.

been placed on implementing community-scale drinking water treatment and distribution systems in developing communities. This method may be a viable option for many communities, but in some cases it may be necessary to consider implementing treatment options at the household level for several reasons, among them:

- the requirement for substantial organizational capacity for community-level systems,
- the potential for recontamination during the time between collection of treated water at the source and use in the household, and
- the personal responsibility and pride that may motivate people to maintain a household system more than contribute time or money to the maintenance of a community system.

Point-of-use treatment interventions have been shown to significantly reduce diarrhea morbidity. In fact, a review of water quality interventions found that point-of-use treatment was more effective at reducing diarrhea morbidity than improvement of water quality at the source, shown in Table 18-3 (Clasen et al. 2006). An additional consideration for determining whether to use point-of-use or source interventions would be the objective of the intervention. For example, if reduction of water-washed diseases such as trachoma was the main objective, then improvements at the source and improved access to water (e.g., via distribution) may be a preferred intervention. Community treatment and distribution systems require a great deal of organization. A positive side of this is that it may be an opportunity to bring a community together to build capacity for other development initiatives.

18.5 Pretreatment (Sedimentation, Coagulation, and Flocculation)

Many water treatment processes are affected by turbidity, which is a measure of how cloudy water is. The higher the turbidity, the less light can pass through the water. Turbidity

Table 18-2. Methods Used During Conventional Treatment of Drinking Water

Treatment Method	Definition	Technologies Discussed in This Chapter
Mechanical separation	Removal of large particles through gravity (sedimentation), screening, or adhesion.	Sedimentation Clay pot filtration Slow sand filtration Filtration through cloth Guinea worm straws
Coagulation and flocculation	Coagulation involves adding a coagulant such as alum to water to destabilize suspended, colloidal, and dissolved matter. After coagulation, the destabilized particles and precipitation products aggregate through the process of flocculation. These larger "floc" particles are then removed through mechanical separation. Natural coagulants exist, such as seeds from the <i>Moringa olifera</i> tree.	Alum <i>Moringa olifera</i> seeds
Chemical purification	Softening, removal of iron, and acid neutralization.	
Disinfection processes	Inactivation of microbiological contaminants through the addition of disinfection agents such as free chlorine, combined chlorine, ozone, chlorine dioxide, UV light, or heat.	Chlorine disinfection Solar disinfection Heat
Biological processes	Oxidation of organic matter as it is consumed by organisms, or the death of undesirable organisms from the absence of food or being killed by other organisms.	Slow sand filtration
Aeration	The evaporation of carbonic acid and gases in solution, and supplying oxygen necessary for some chemical disinfection processes and water-purifying organisms.	Not discussed in this chapter, but aeration can be accomplished by nonmechanical methods.
Membrane technology	Physiochemical technique that uses the differences in permeability of water constituents as a separation method.	

Source: Adapted from Crittenden et al. 2005.

can reduce the effectiveness of water treatment in a number of ways. It can clog filters, prevent UV rays from reaching pathogens, and exert excessive oxygen demand during chlorination. For these reasons, many water treatment processes have pretreatment turbidity limits (see Table 18-4). Turbidity can easily be measured with the use of a turbidity tube (see Section 18.9). Treatment techniques that can reduce the turbidity of water before further treatment include settling and decanting, coagulation and flocculation, and roughing filters.

18.5.1 Sedimentation

Gravity is the oldest and most widely used process in water treatment and is effective at removing much of the suspended matter from water. Sedimentation can take place at

Table 18-3. Reduction in Diarrhea for All Age Groups Following Different Interventions to Improve Water Quality

Intervention Type (No. Trials)	Relative Risk (RR) Estimate (Random)	Percentage Reduction (1-RR)	95% CI of Relative Risk Estimates
Source (6)	0.73	27	0.53-1.01
Household total (32)	0.53	47	0.39-0.73
Household filtration (6)	0.37	63	0.28-0.49
Household chlorination (16)	0.63	37	0.52-0.75
Household solar disinfection (2)	0.69	31	0.63-0.74
Household flocculation and disinfection (7)	0.48	52	0.20-1.16
Household improved storage (1)	0.79	21	0.61-1.03

Note: Although all interventions resulted in reduced diarrhea, point-of-use treatment interventions generally had a greater effect. There was significant variation in the relative risk estimates among studies of the same intervention type, which the authors suggest resulted from a variety of conditions that would require further research to understand. Additionally, these studies only considered reduction in diarrhea; results might have been significantly different if water-washed diseases such as trachoma had been considered.

Source: Clasen et al. 2006.

both the community and household level. It can be a stand-alone treatment in situations where other treatment processes are unfeasible, or it can be a part of a larger treatment process, preceded by coagulation and flocculation and followed by filtration and disinfection. For a neighborhood or community, a simple rectangular sedimentation basin provides removal of much of the turbidity in surface water. At the household level, sedimentation can occur in the storage containers, and this process can be maximized by improving storage procedures.

Community Sedimentation Basin Design

In conventional systems, sedimentation often follows coagulation and flocculation and involves water moving through a sedimentation pond or tank, allowing time for particles

Table 18-4. Pretreatment Turbidity Limits for Various Water Treatment Processes

Treatment Type	Pretreatment Turbidity Limit (NTU)
Drinking water (general recommendation)	<5
Ceramic filtration	<15-20
Slow-sand filtration	<20
Chlorination	Ideally <1 Acceptable <5 In emergencies <20 for a very short period
UV disinfection	<30
Disinfection with heat	(No limit)

to settle by gravity. The speed at which the particles move downward—the *settling velocity*—determines the size of the sedimentation pond.

The method used to design a sedimentation tank depends on the treatment objective: removal of particles with a minimum diameter or particle removal efficiency. If the treatment objective is to remove particles of a certain diameter, then calculate the settling velocity to determine the dimensions of the tank.

If particles are assumed to act as discrete particles and settle without the interference of neighboring solids, the settling velocity is determined using Stokes' law:

$$v_s = \frac{g(\rho_p - \rho)d_p^2}{18\mu} \quad (18-1)$$

where v_s is the settling velocity of the particle, g is the acceleration because of gravity 9.81 m/s^2 , ρ_p is the density of the particle (kg/m^3), ρ is the density of water (kg/m^3), d_p is the diameter of the particle (m), and μ is the dynamic viscosity of water (kg/m-s).

Equation 18-1 determines the settling velocity for laminar flow (low Reynold's numbers, Re). In turbulent water (high Reynold's numbers), the settling velocity is determined using Newton's law:

$$v_s = \sqrt{\frac{4g(\rho_p - \rho)d_p}{3C_D\rho}} \equiv \sqrt{\frac{4g(sg_p - 1)d_p}{3C_D}} \quad (18-2)$$

where C_D is the unitless drag coefficient and sg_p is the unitless specific gravity of the particle. C_D is calculated using Eq. 18-3 for $Re \leq 1$ or Eq. 18-4 for $1 < Re < 10,000$.

$$C_D = \frac{24}{Re} \text{ for } Re \leq 1 \quad (18-3)$$

$$C_D = \frac{24}{Re} + \frac{3}{\sqrt{Re}} + 0.34 \text{ for } 1 < Re < 10,000 \quad (18-4)$$

The process of calculating the settling velocity is an iterative process. The general procedure for calculating a settling velocity is:

1. Calculate v_s using Stokes' law (Eq. 18-1).
2. Use the v_s calculated from step 1 to determine the Reynold's number.
3. If $Re > 1$, go to step 4. Otherwise, Stokes' law is valid.
4. Calculate C_D using Eq. 18-4 and the Reynold's number from step 2.
5. Calculate v_s from Eq. 18-2 using the drag coefficient from step 4.
6. Recalculate C_D using v_s .
7. Repeat steps 4–6 until C_D converges.

Particle sizes of pollutants and naturally occurring substances are shown in Fig. 18-2, along with treatment processes that correspond to a particular size range. Where

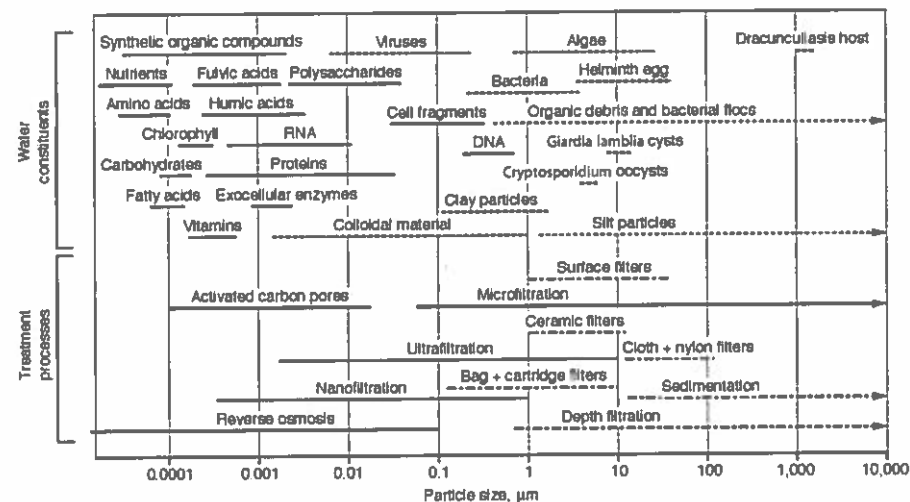


Figure 18-2. Characterization of Particulate Water Quality Constituents Found in Water by Type, Size, and Appropriate Treatment Methods.

Note: Particles that cause health concern in the developing world and appropriate treatment methods are presented by dashed lines. Microbial constituents can be seen in the upper right corner. $1 \mu\text{m}$ is a millionth of a meter and equals $1/25,400$ of an inch.

Source: Adapted from Mihelcic and Zimmerman (2009) with other data obtained from AWWA 1990; Colwell et al. 2003; and Ovanedel-Craver and Smith 2008.

coagulation and flocculation are used for pretreatment, typical settling velocities of floc types are provided in Table 18-5.

A rectangular sedimentation basin is a common treatment method used in community water treatment systems (Fig. 18-3). The design of a sedimentation basin is determined such that the detention time in the basin is sufficient for particles to settle at the calculated settling velocity. Figure 18-4 shows how particles settle as water moves through a rectangular sedimentation basin at fluid velocity, v_f .

In Fig. 18-4, it is clear that particles at the surface will be removed when the hydraulic retention time of fluid in the sedimentation basin is long enough for a particle to settle at its settling velocity, v_s , a distance of h_0 . A particle (particle 2 in Fig. 18-4) that enters at the top of the basin and settles before it flows out of the basin is called a *critical particle*. Its settling velocity is defined as the *critical particle settling velocity* (v_c), which is determined as

$$v_c = \frac{h_0}{\tau} \quad (18-5)$$

where τ is the hydraulic retention time.

Table 18-5. Settling Velocities of Selected Types of Floc

Floc Type	Settling Velocity (m/s)
Small alum floc	2-4.5
Medium-sized alum floc	3-5
Large alum floc	4.0-5.5
Heavy lime softening floc	4.5-6.5
Iron floc	2-4

Source: Adapted from Crittenden et al. 2005.

Because the hydraulic retention time equals the volume (V) of the sedimentation basin divided by the process flow rate, Q , Eq. 18-5 can be written as

$$v_c = \frac{Q}{A} = OR \quad (18-6)$$

where OR is defined as the *overflow rate* ($m^3/m^2 \cdot h$). Note that the OR is the hourly flow rate divided by the surface area of the sedimentation tank. In reality, its units are velocity (m/h). Tanks are designed such that if the settling velocity of individual particles is greater than (or equal to) the OR , then 100% of incoming particles are removed. Typical design criteria for horizontal-flow rectangular sedimentation basins are provided in Table 18-6. Example 18-1 shows how the settling velocity and flow rate are used to design a sedimentation basin that meets the criteria in Table 18-6.

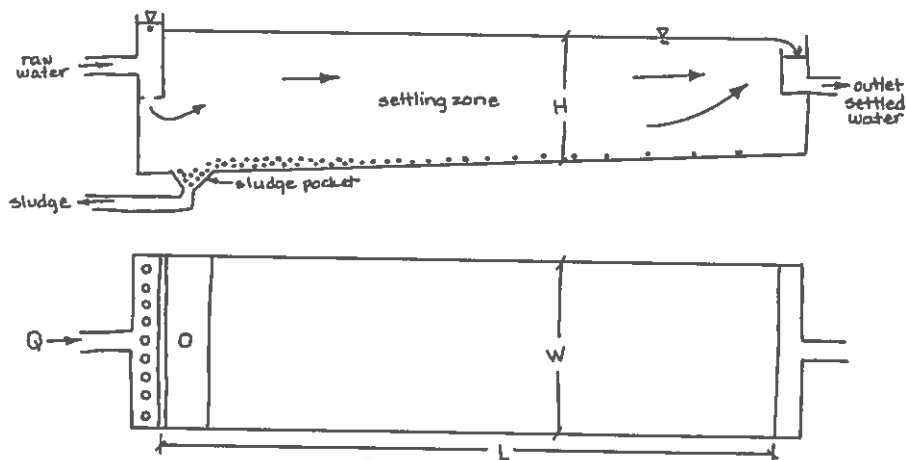


Figure 18-3. Basic Horizontal-Flow Rectangular Sedimentation Basin Design in Cross Section (Top) and Plan View (Bottom).

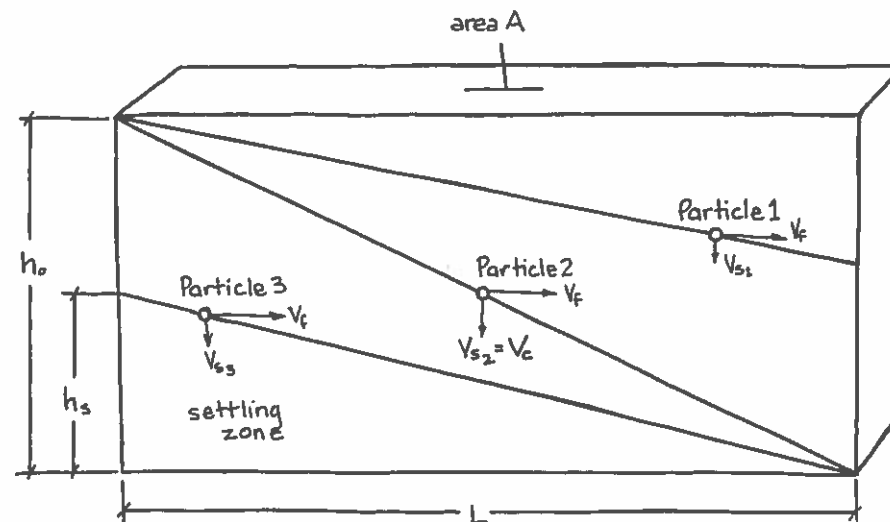


Figure 18-4. Trajectories of Three Discrete Particles Settling in a Rectangular Clarifier.

Note: Particles 2 and 3 will be removed in this particular situation.

Table 18-6. Design Criteria for Horizontal-Flow Rectangular Tanks

Design Parameter	Recommendation
Minimum number of tanks	2
Water depth	3-5 m
Length-to-depth ratio	15:1
Width-to-depth ratio	3:1 to 6:1
Length-to-width ratio	4:1 to 5:1
Surface loading rate (OR)	1.25-2.5 m/h
Horizontal mean-flow velocity at maximum daily flow	0.3-1.1 m/min
Detention time	1.5-4 h
Reynold's number	<20,000
Froude number	> 10^{-5}
Bottom slope for manual sludge removal systems	1:300 m/m

Source: Crittenden et al. 2005.

Example 18-1. Sedimentation Tank Design

A water treatment plant with a maximum daily flow of $3 m^3/s$ (assume this value is 1.5 times the average flow of $2 m^3/s$) is treating surface water. Particle settling velocity was determined to be $2.2 m/h$ at $10^\circ C$. The dynamic viscosity of water at $10^\circ C$ is

0.00131 kg/m³-s, and the density of water at 10 °C is 999.7 kg/m³. Design a horizontal-flow rectangular sedimentation basin based on the maximum flow rate.

Solution

- Determine the number of basins. Two basins would satisfy the minimum requirement for maintenance purposes. However, if one basin were off line, the entire plant flow would be directed through the remaining basin, possibly resulting in overloading of the basin. To minimize the risk of basin overloading, three basins will be selected, and overloading will be checked to verify that three basins are adequate.
- Determine the size of each basin.
 - Select the basin width and depth. The basin width will be governed by the standard size of sludge removal equipment. For example, in the United States, the standard maximum width of the chain-and-flight sludge collector is 6 m, so basin widths in increments of 6 m will be considered, starting at 18 m. Water depths from 3 to 5 m are appropriate, according to Table 18-6. Deeper basins are recommended over shallower basins, so a depth of 4 m will be selected.
 - Determine the basin area. The settling velocity such that the particle is removed in the sludge zone just before the outlet, v_c , is given as 2.2 m/h at 10 °C. (This value is also equal to the overflow rate.) Use Eq. 18-6 to determine the basin surface area:

$$A = \frac{Q}{v_c} = \frac{3 \text{ m}^3/\text{sec}}{(2.2 \text{ m/hr}) \times (1 \text{ hr}/3,600 \text{ s})} = 4,909 \text{ m}^2$$

- Determine the length using the design guidelines in Table 18-6 for length-to-width ratios. For three tanks that are 18 m wide, the tank length and length-to-width ratio can be estimated:

$$L = \frac{4,909 \text{ m}^2}{3 \text{ basins} \times 18 \text{ m}} = 90.9 \text{ m} \quad \frac{L}{W} = \frac{90.9}{18} = \frac{5.0}{1}$$

The length-to-width ratio meets the recommendation of 4:1 to 5:1.

- Check the various design parameters listed in Table 18-6.

- Check the detention times at Q_{\max} and Q_{ave} .

$$\text{Detention time for } Q_{\max} = \frac{(18 \times 90.9 \times 4) \text{ m}^3 \times 3 \text{ basins}}{(3 \text{ m}^3/\text{sec})(3,600 \text{ sec/h})} = 1.8 \text{ h}$$

$$\text{Detention time for } Q_{\text{ave}} = 1.5 \times 1.8 \text{ h} = 2.7 \text{ h}$$

These detention times are within the acceptable range of 1.5 to 4 h.

- Check the length-to-depth ratio:

$$\frac{L}{D} = \frac{90.9}{4} = \frac{22.7}{1}$$

The basin length-to-depth ratio is 22.7:1, which is greater than the recommendation of 15:1.

- Check the horizontal-flow velocity. The mean velocity is provided by the expression

$$v_f = \frac{Q}{A} = \frac{(3 \text{ m}^3/\text{sec})(60 \text{ sec}/\text{min})}{18 \text{ m} \times 4 \text{ m} \times 3 \text{ basins}} = 0.833 \text{ m}/\text{min}$$

The mean velocity is greater than 0.3 m/min and less than 1.1 m/min.

- Check the Reynold's and Froude numbers:

$$Re = \frac{\rho v_f R_h}{\mu}$$

$$R_h = \frac{A_x}{P_w} = \frac{4 \text{ m} \times 18 \text{ m}}{18 \text{ m} + 2(4 \text{ m})} = 2.77 \text{ m}$$

$$v_f = \frac{0.833 \text{ m}/\text{min}}{60 \text{ sec}/\text{min}} = 0.014 \text{ m}/\text{sec}$$

$$Re = \frac{(999.7 \text{ kg}/\text{m}^3)(0.014 \text{ m}/\text{sec})(2.77 \text{ m})}{0.00131 \text{ kg}/\text{m} \cdot \text{sec}} = 29,594$$

The Reynold's number of 29,594 is higher than the recommended value of 20,000 for a horizontal sedimentation basin.

$$Fr = \frac{v^2}{gR_h} = \frac{[(0.014)^2 \text{ m}^2/\text{sec}^2]}{(9.81 \text{ m}/\text{sec}^2)(2.77 \text{ m})} = 7.2 \times 10^{-6}$$

The Froude number is lower than the recommended value for sedimentation tanks, so the tank design must be modified.

- Consider the addition of two longitudinal baffles per basin and recompute the Reynold's and Froude numbers.

$$R_h = \frac{A_x}{P_w} = \frac{4 \text{ m} \times 6 \text{ m}}{6 \text{ m} + 2(4 \text{ m})} = 1.71 \text{ m}$$

$$Re = \frac{(997.7 \text{ kg}/\text{m}^3)(0.014 \text{ m}/\text{sec})(1.71 \text{ m})}{0.00131 \text{ kg}/\text{m} \cdot \text{sec}} = 18,162 < 20,000 \text{ OK}$$

$$Fr = \frac{[(0.014)^2 \text{ m}^2/\text{sec}^2]}{(9.81 \text{ m}/\text{sec}^2)(1.71 \text{ m})} = 1.17 \times 10^{-5} > 10^{-5} \text{ OK}$$

If the treatment objective is to remove a percentage of total suspended solids (TSS), then the depth and detention time of the sedimentation tank can be determined using a column settling test, as described in Box 18-1. The column settling test measures the percent removal of TSS for a given sedimentation basin depth and hydraulic detention time. A design basin depth and detention time can be determined by adjusting the depth and hydraulic detention time of the settling test until the required percent removal is achieved.

Sedimentation in Household Storage Containers

Within a few hours, sand, silt, and large microbes settle to the bottom of a typical container used for household drinking water storage. After 1 or 2 days, helminth eggs, some parasites, certain types of algae, and large clay particles also settle out. Sedimentation cannot reliably remove viruses, bacteria, or small clay particles, although some of these are removed if they are attached to larger particles that do settle (Fig. 18-2).

After 1 day of storage, up to 50% of bacteria may die off (Shaw 1999). The transmission of schistosomiasis can also be prevented by storing water for more than 48 h, which is the limit of how long *cercariae* (the intermediate host) can live after leaving the snail and before reaching a human or animal host (Shaw 1999).

After enough time has been allowed for settling, the cleaner water (supernatant) at the top of the container can either be decanted or ladled out, being careful not to disturb the layer of sediment. At least two storage containers are required, one in which the larger particles settle, and one to store the supernatant. The first container should be cleaned after each use for small vessels, and as frequently as necessary for larger cisterns or tanks.

Box 18-1 Simple Column Settling Test to Be Used for Determining Depth and Settling Time of a Sedimentation Basin

1. Measure the total suspended solids (TSS) of the water to be treated.
2. Select a depth and hydraulic detention time for the sedimentation basin.
3. Build a column of any diameter that is equal in height to the depth of the sedimentation basin.
4. Introduce a sample of the water to be treated so that it fills the column to the height of the sedimentation basin. Ensure uniform distribution of particle sizes as you introduce the water.
5. Allow settling to take place over a period of time. This time will be equal to the settling time of the proposed sedimentation basin.
6. Draw off the settled material at the bottom of the column, and mix the remaining water.
7. Measure the TSS of the remaining water in the column. The percent removal of TSS is simply the final TSS over the initial TSS. Adjust the height and settling time of the column test until the desired percent removal is achieved.

Source: Metcalf and Eddy 2003.

A three-pot treatment system (Fig. 18-5) has also been developed to promote sedimentation (Shaw 1999). The three required pots do not include the bucket or other vessel used for collecting water. Pot No. 1 should occasionally be sterilized using boiling water.

Every day, the following steps should be followed:

1. Take water for drinking and cooking from pot No. 3 (far right in Fig. 18-5). This water has already been stored for at least 2 days.
2. Pour water carefully from pot No. 2 to pot No. 3, and wash out pot No. 2 using some water from pot No. 3.
3. Pour water carefully from pot No. 1 to pot No. 2, and wash out pot No. 1 using some water from pot No. 3.
4. After collecting water from the source, pour it from the vessel used for collection into pot No. 1, with the possible use of a cloth to filter the water entering the pot.

Because of its low cost and low level of required skill, sedimentation can be an attractive way to pretreat water by reducing its turbidity, but it should not be relied on as the sole means of pathogen removal.

18.5.2 Coagulation and Flocculation

Because of their small size and charge repulsion, colloidal particles and smaller suspended particles cannot be removed by simple gravity sedimentation. Coagulation and flocculation are used to remove these particulate contaminants. *Coagulation* involves adding a chemical coagulant to water to destabilize suspended, colloidal, and dissolved matter. After coagulation, the destabilized particles and precipitation products aggregate through the process of flocculation. These larger "floc" particles are then removed through gravity settling or mechanical separation. Coagulants include alum, ferric chloride, ferric sulfate, and natural plant materials or synthetic polyelectrolytes. Table 18-5 provides typical settling velocities for selected types of floc.

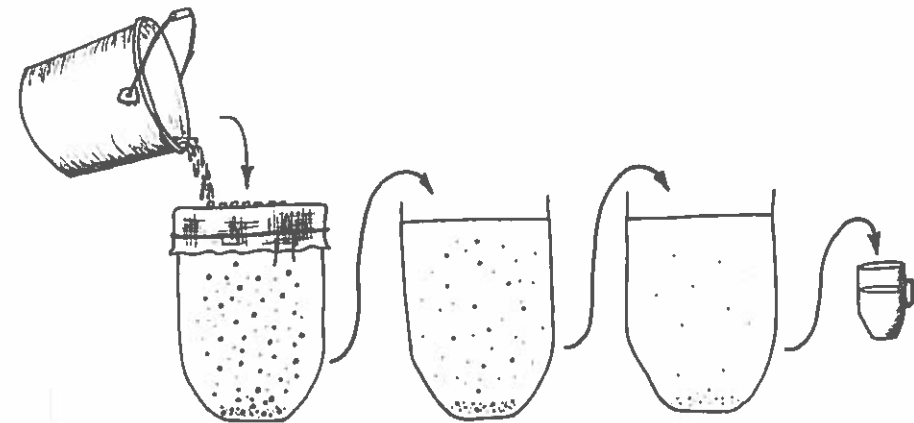


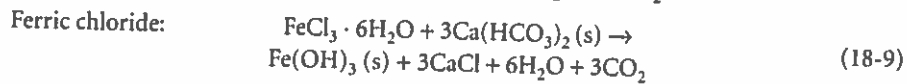
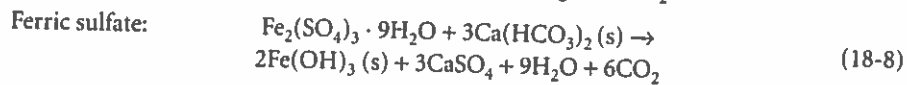
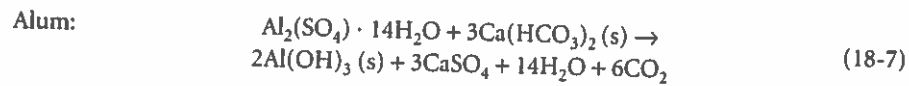
Figure 18-5. A Three-Pot System Used for Household Treatment of Water Using Principles of Sedimentation in All Three Pots and Filtration in the First Pot.

Note: Cover the pots when water is not entering or leaving them.

Alum, Ferric Chloride, and Ferric Sulfate

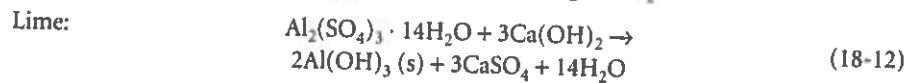
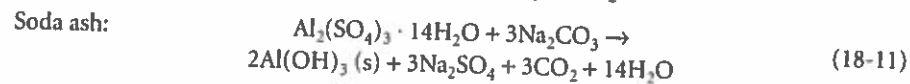
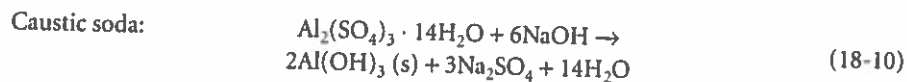
A commonly used coagulant is alum, $Al_2(SO_4)_3 \cdot xH_2O$, where x is usually 14. When added to water, alum dissociates and hydrolytic reactions proceed, producing aquo aluminum ions, mononuclear and polynuclear species, precipitate, and aluminate ions. Depending on the pH of the system, different products will dominate. The goal for coagulation is for the precipitate to dominate. For $Al(OH)_3(s)$ to dominate, the pH should be between about 5.5 and 7.7. This reaction occurs because in this pH range the solubility of $Al(OH)_3$ is near its minimum (so less alum needs to be added to form the precipitate) and the Al species formed have a primarily positively charged composition, which can neutralize the negative charge of most natural colloids.

The overall reactions for addition of alum, ferric sulfate, and ferric chloride, with the metal precipitates as the product, are shown, respectively, in Eqs. 18-7 to 18-9.



Because the interdependence of the characteristics of the coagulant, the concentration and type of particulates, the concentration and characteristics of natural organic matter, water temperature, and water quality is not yet known quantitatively, there is no quantitative prediction of the optimum coagulant combination for a particular sample of water. Instead, a test referred to as jar testing (see Mihelcic and Zimmerman 2009 for explanation) is used at water treatment plants to monitor coagulant addition. Table 18-7 provides typical dosages for alum, ferric sulfate, and ferric chloride that are used to treat typical surface waters.

In Eqs. 18-7 to 18-9, naturally occurring alkalinity (i.e., $Ca(HCO_3)_2(s)$) is consumed in the reaction. If the naturally occurring alkalinity is too low, it may be necessary to add alkalinity in the form of lime ($Ca(OH)_2$), caustic soda ($NaOH$), or soda ash (Na_2CO_3). The stoichiometry of the reactions for alum with caustic soda, soda ash, and lime are provided in Eqs. 18-10 to 18-12, respectively. Caustic soda is often the alkaline of choice because it is relatively easy to handle and it requires a relatively small dosage.



Example 18-2 shows how to determine the amount of alkalinity that will be required using the stoichiometry of these equations.

Table 18-7. Typical Dosages for Coagulants Used in Traditional Water Treatment Processes

Coagulant	Typical Dosage
Alum [$Al_2(SO_4)_3 \cdot 14H_2O$]	10–150 mg/L
Ferric sulfate [$Fe_2(SO_4)_3 \cdot 9H_2O$]	10–250 mg/L
Ferric chloride ($FeCl_3 \cdot 6H_2O$)	5–150 mg/L

Example 18-2. Example Calculation of the Required Amount of Alkalinity for Alum to Completely Precipitate During Coagulation

A dosage of 10 mg/L of alum is added to 1,000 L of water. What is the required dosage of alkalinity (expressed as grams of $CaCO_3$) for the alum to completely precipitate? (10 mg/L of alum in 1,000 L of water equals 10,000 mg alum, or 10 g alum.)

Solution

From Eq. 18-7, 6 moles of alkalinity (HCO_3^-) are consumed for every mole of alum. This reaction occurs because 3 moles of $Ca(HCO_3)_2$ are required and there are 2 moles of HCO_3^- in each mole. The reaction stoichiometry and the molecular weight of different species can be used to determine the amount of alkalinity consumed during the reaction:

$$\begin{aligned} \text{Alkalinity consumed} &= 10 \text{ g } Al_2(SO_4)_3 \cdot 14H_2O \times \left(\frac{1 \text{ mol } Al_2(SO_4)_3 \cdot 14H_2O}{594 \text{ gm } Al_2(SO_4)_3 \cdot 14H_2O} \right) \\ &\times \left(\frac{6 \text{ mole } HCO_3^-}{1 \text{ mole } Al_2(SO_4)_3 \cdot 14H_2O} \right) \times \left(\frac{1 \text{ eqv. alkalinity}}{1 \text{ mole } HCO_3^-} \right) \\ &\times \left(\frac{50 \text{ gm } CaCO_3}{1 \text{ eqv. alkalinity}} \right) \\ &= 5 \text{ gm as } CaCO_3 \end{aligned}$$

Moringa oleifera

The *Moringa oleifera* tree is commonly grown in the tropics. It is also known as the drumstick or horseradish tree. The seeds from these trees can be cultivated and used as a natural coagulant to remove turbidity. In Sudan, the seeds are collected, powdered, placed in a small cloth bag, and tied with a thread. The bag is then swirled in the turbid water to promote coagulation and flocculation, and the flocculated solids are allowed to settle before the water is consumed (Shaw 1999).

Moringa oleifera seeds can be used for coagulation in community water treatment systems with flow $\leq 10 \text{ m}^3/\text{h}$. The steps for obtaining a solution from whole seeds for use in

Box 18-2 Using *Moringa oleifera* Seeds to Treat Water

Preparation of *Moringa oleifera* Solution

1. Allow the seeds to mature and dry naturally to a brown color while still on the tree.
2. Harvest the seed pods. Remove the seeds and shell them.
3. Crush the seeds and sieve with a 0.8-mm mesh. The traditional large mortar and pestle is an appropriate method for crushing the seeds, where there is no mechanical alternative. Seeds and seed powder can be stored dry.
4. Mix the seed powder with clean water to form a paste [2 g (2 teaspoons) of seed powder treats 20 L of water]. As a rule of thumb, the powder from one seed kernel can treat 1 L of very turbid or 2 L of somewhat turbid water. The paste should be freshly prepared for every treatment. Table 18-A provides guidelines for dosage when turbidity is known.

Table 18-A. Dose Requirements for *Moringa oleifera* According to Raw Water Turbidity

Raw Water Turbidity (NTU)	Dose Range (mg/L)
<50	10–50
50–150	30–100
>150	50–200

Source: Shaw 1999.

5. Dilute the paste in 1 cup of water in a sealed bottle, and shake the solution for 5 min to release the chemicals in the powder.
6. Filter the insoluble material using either a fine mesh screen or a muslin cloth. The remaining solution is ready for use.

Treatment of Drinking Water with *Moringa oleifera* Solution

1. Pour the solution into the container of water to be treated.
2. Stir rapidly for 2 min, then stir slowly for 10–15 min.
3. Let the bucket sit for 1–2 h. Do not disturb the bucket. This allows the solid floc to settle.
4. After the floc has settled to the bottom of the container, carefully pour the clean water off the top.

Source: Fuglie 2001.

water treatment are outlined in Box 18-2. Once the *Moringa oleifera* solution is prepared, the instructions in Box 18-2 can be used in the treatment of water.

The seed solution can be prepared using either the shelled whole seeds or the solid residue that remains after the extraction of seed oil. If the solid residue is being used, the press cake is ground to a fine powder and sieved through a 0.8-mm mesh. The solu-

tion is then prepared using steps 4–6 of the solution preparation process for whole seeds described in Box 18-2.

When *Moringa oleifera* seeds are used for treatment of a community water supply, thought should be given to the cultivation of the seeds. According to Shaw (1999), the average mature *Moringa oleifera* tree yields 3 kg of seed kernels per year. Trees should be planted with a spacing of 3 m. Once trees are planted from seeds or cuttings, they grow rapidly, up to 4 m in height. Flowers and fruits are produced after 12 months. In locations with favorable climates, two harvests per year may be possible. As a rule of thumb, expect 3–5 metric tons of seeds per hectare per year. Example 18-3 provides an example calculation for determining the land requirement for treatment of drinking water with *Moringa oleifera* seeds.

Example 18-3. Example Calculation of Land Requirement for Treatment of Drinking Water with *Moringa oleifera* Seeds

Calculate the required land area to treat water with a turbidity of 150 NTU with a process flow rate of 10 m³/h that operates 8 h per day for 1 year:

$$\frac{100 \text{ mg}}{\text{L}} \left(\frac{\text{kg}}{1,000,000 \text{ mg}} \right) \left(\frac{10 \text{ m}^3}{\text{hr}} \right) \left(\frac{1,000 \text{ L}}{\text{m}^3} \right) \left(\frac{8 \text{ hr}}{\text{day}} \right) \left(\frac{365 \text{ days}}{\text{year}} \right) = 2,920 \text{ kg seeds}$$

$$2,920 \text{ kg} \left(\frac{1 \text{ metric ton}}{1,000 \text{ kg}} \right) \left(\frac{1 \text{ hectare}}{3 \text{ metric tons}} \right) = 0.97 \text{ hectare}$$

Thus, approximately 1 hectare of land is required to cultivate *Moringa oleifera* seeds for the treatment process.

Source: From Shaw 1999.

18.6 Filtration

Filtration can be used to remove turbidity from drinking water, as well as for biological disinfection. Several methods of filtration exist that can be used at either a community scale or for point-of-use treatment. Here we focus primarily on point-of-use treatment methods because community-scale treatment design information is more readily available in traditional environmental engineering textbooks.

18.6.1 Filtration through Ceramic Clay Pots

Two types of ceramic clay pot filters exist: the candle type, where water flows from an outer bucket into a partially submerged, smaller receptacle, and the type where the clay filter rests inside a larger bucket and water flows down through the filter into the bucket (Fig. 18-6). Clay pot filters need to be cleaned regularly, both to prevent biofilm accumulation and to

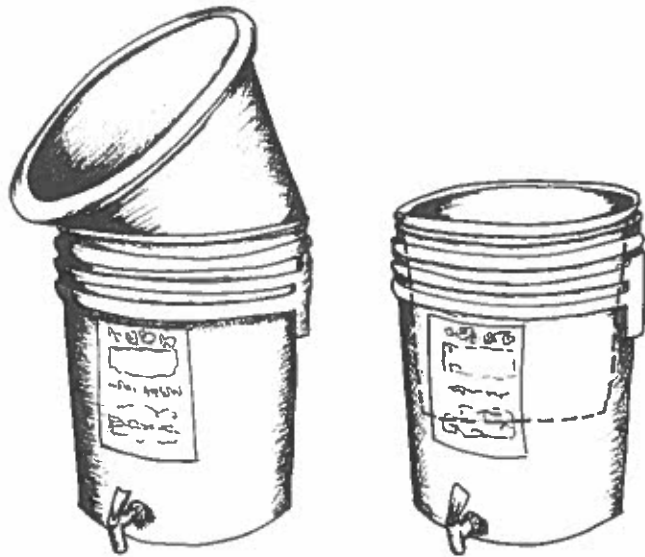


Figure 18-6. Example of a Ceramic Clay Pot Filter Used by Potters for Peace (n.d.).

Note: The water storage container is covered by the clay pot and also has a faucet for withdrawing water.

restore the original flow rate. Even a slight crack in this type of filter makes it unsuitable to remove pathogens and turbidity, so users must be prepared to replace the filter on a regular basis.

The ability of clay filters to remove pathogens varies dramatically with their materials and methods of production. Many clay pot filters produced in developed countries have pore sizes small enough to remove bacteria (Fig. 18-2). A recent study has found that 50% of the pore size diameters range from 0.02 to 15 μm (Ovanedel-Craver and Smith 2008). Clay pot filters can also remove viruses through adsorption. Virus removal decreases over time as these adsorption sites are occupied. Many commercially available filters are also impregnated with silver to help prevent the growth of a biofilm on the surface of the pot. Although the effectiveness of many of the ceramic filters produced in developing countries is uncertain, any of these filters (as long as they are not cracked) likely reduces turbidity and pathogens in water and is recommended over no treatment.

18.6.2 Slow Sand Filtration

In *slow sand filtration*, influent water moves downward through a nonuniform bed of sand, and particles are filtered out in the first few centimeters (called *surface filters* in Fig. 18-2). In addition to this physical process, a biological layer called the *Schmutzdecke* forms an additional filtration layer and biologically degrades some organic matter. Thus, the slow sand filter provides both a filtration process and a biological treatment process.

The slow sand filter consists of three layers: underdrainage, gravel, and sand. Slow sand filters can be designed at a large scale for treatment of water at the source, for example,

integrated with a spring box (see Chapter 15). Similar slow sand filtration technologies can also be implemented at the household level.

For a slow sand filter to function, the sand should have an effective grain size of 0.15–0.30 mm and uniformity coefficient (D_{60}/D_{10}) < 5. The D_{60} is the sieve size that allows 60% of the sand to pass, and D_{10} is the sieve size that allows 10% to pass. The minimum height of the sand layer should be 0.5 m, and the rate of filtration should be no faster than 0.1–0.2 $\text{m}^3/\text{m}^2\text{-h}$ (Visscher et al. 1987). For a filtration rate of 0.1 m/h through a clean filter, the minimum head over the filter is 5 cm, based on the Rose equation for head loss through granular porous medium (Metcalf and Eddy 2003). *Depth filtration* occurs deep in a sand filter. Slow sand filtration is more characteristic of surface filtration where the *Schmutzdecke* layer causes most of the particle removal, with 98% removal of particles of size 1–60 μm reported to be removed (AWWA 1990).

Slow sand filters are ideal where water is drawn from a high-quality source. Turbidity should not exceed 50 NTU, and there should be little or no colloidal clay. If the source water has higher turbidity, pretreatment may be necessary for slow sand filtration to be effective. At the community scale, this step can be accomplished with a sedimentation basin. At the household level, the storage system described in Section 18.5.1 can be used for pretreatment before passing water through the slow sand filter.

Slow Sand Filters for a Community System

Pickford (1991) and Huisman et al. (1981) provide detailed instructions for building a community slow sand filter (Fig. 18-7). The gravel layer should not fill the entire bottom of the filter box, and it should be no closer than 0.6 m to the walls, ensuring that even water that short-circuits the system along the filter walls passes through sand before entering the gravel and underdrainage (Pickford 1991).

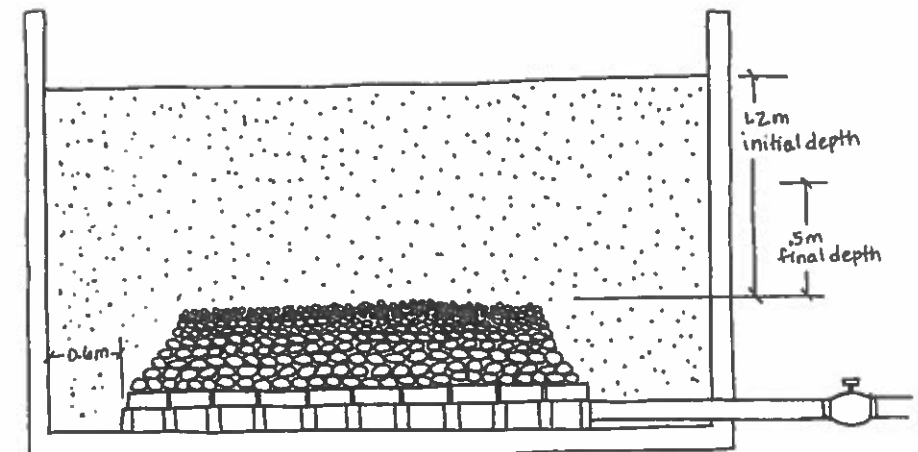


Figure 18-7. Potential Design of a Community Slow Sand Filter.

Source: Redrawn from Pickford (1991) with permission.

Filter walls can be either vertical or sloping. Walls should be roughened to prevent short-circuiting during treatment. The size of the tank depends on the flow rate and the filtration rate, as provided in Eq. 18-13.

$$A = \frac{Q}{v} \quad (18-13)$$

Here, A is the surface area of the tank, Q is the flow rate, and v is the filtration rate. For slow sand filtration, v should be 0.1–0.2 m³/m²-h. The initial depth should be 1.0–1.2 m (Pickford 1991). Application of Eq. 18-13 is provided for a spring box design in Chapter 15. For larger community systems, the design usually includes at least two units, so that one unit can run while the other is being cleaned.

Slow sand filters require a ripening period of several days for the formation of the *Schmutzdecke*, during which time effluent water quality should improve. Slow sand filters are run until the head loss reaches the available head of the system. At this point, the filter must be cleaned. The filter is cleaned by draining all water and removing the top 1 to 2 cm of sand. The sand is cleaned and stockpiled for reuse. When the minimum depth of sand is reached, the extracted sand is replaced and the process is started over again. After each scraping, the filter should be allowed to ripen, with the ripening time decreasing after several scrapings (Crittenden et al. 2005).

Slow Sand Filters for Point-of-Use Treatment

The slow sand filter in Fig. 18-8 can be constructed easily and functions under intermittent use. It consists of a drum or other large container (one that has not previously contained harmful chemicals), sand, gravel, and small amounts of pipe. If the container is metal, it may be necessary to line it with cement mortar to protect it from rust. Another option is to build the container out of concrete or ferrocement. If there is no faucet, it is important that the outlet pipe reach to 5–10 cm above the surface of the sand to allow 5–10 cm of water over the sand for development of the *Schmutzdecke* layer.

When water is first placed into the filter, allow 3 days for the water to sit before use, and ripen it for biological activity to begin. To use the filter, add the amount of water to be filtered and catch the exiting water from the outlet pipe. Maintenance of the slow sand filter is minimal but important. First, keep the filter covered to prevent contamination. Second, maintain about 5–10 cm of water above the surface of the sand to maintain the *Schmutzdecke*. Never run chemically treated water through the filter (i.e., city water or bleach) because chlorine inhibits the biological activity. When there is a significant change in the speed of filtration, it is time to clean the filter. To do this, remove the sand and gravel and rinse them with clean, nonchlorinated water. Wash the container with clean, nonchlorinated water, and rebuild the filter, again waiting 3 days before use for a new *Schmutzdecke* layer to form.

18.6.3 Filtration Through Cloth, Paper, or Nylon

Locally produced cloth and paper filters generally allow smaller viruses and bacteria to pass through the pore openings and should not be seen as a reliable means of ensuring a

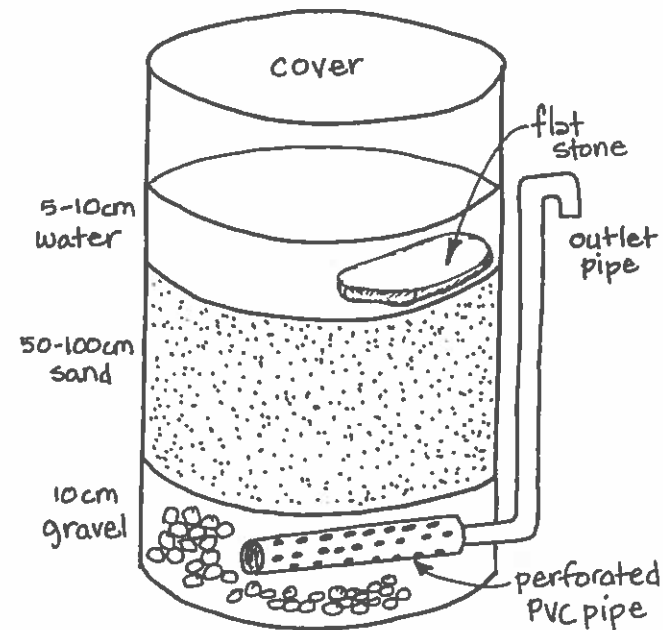


Figure 18-8. Example Design of a Household Slow Sand Filter Used by Peace Corps Cameroon.

safe water supply (Fig. 18-9). However, these filters do have an important role to play. They are reliable at reducing turbidity and eliminating larger pathogens (see Fig. 18-2), and also prevent and reduce the spread of specific diseases (e.g., Guinea worm and cholera). It is important that cloth or paper filters always be used with the same side up. Easy ways to ensure this are to have a logo on one side of the filter, a cloth with different patterns on each side, or two different cloths sewn together. Inexpensive cloth provides a mesh size of 20 μm if folded 4–8 times. This mesh size increases to 100–150 μm in older cloth that has been worn and washed. Nylon filters are available at specific mesh sizes, for example, 150 μm (Colwell et al. 2003). Their advantage is that they retain their stated mesh size.

A study done in Bangladesh showed that cholera could be reduced by half by using old sari cloth folded three times to produce an eight-layer filter (Colwell et al. 2003). A single layer of the cloth was less efficient. The performance of the cloth reduced over time as pore sizes got larger through washing and use. The cloth was decontaminated by being rinsed in the source water and then completely dried in the sun. During monsoon season, the cloths needed to be rinsed with a disinfectant solution, such as bleach.

The transmission of Guinea worm can also be prevented through the use of tightly woven polyester or monofilament nylon cloth filters in conjunction with education and behavior change. The filter should have a 0.15-mm pore size. In comparison, the parasites that cause Guinea worm disease (dracunculiasis) are present in a predatory genus *Cyclops* that is 1–2 mm in size. Personal filters, which are worn around the neck and drunk through like a straw, operate on the same principle (Fig. 18-10). Lifestraw brand personal



Figure 18-9. Filtration Through Overlaid Layers of Fabric Cloth or Nylon Mesh Filters Can Remove Larger Particles.



Figure 18-10. Personal Filters Used to Remove Guinea Worms.

filters remove particles $\geq 15 \mu\text{m}$, remain effective for at least 700 L, and are reported to remove 99.999% of all bacteria (Lifestraw 2008). Similar straw filters have been used in the Carter Center's Guinea worm eradication campaign (Carter Center 2007).

18.7 Disinfection

Disinfection refers to the process of inactivating microbiological contaminants. Several methods of disinfection exist, including free chlorine, ozone, chlorine dioxide, iodine, heat, and UV light.

18.7.1 Chlorine Disinfection

Chlorine disinfection has the advantages that it is simple and that residual disinfection capacity remains after water is treated. Here we discuss methods of disinfection with liquid and powder forms of chlorine. One advantage is that liquid laundry bleach is a readily available source of chlorine in many developing communities. The powder form of chlorine is calcium hypochlorite, and includes chlorinated lime, tropical bleach, bleaching powder, and high-test hypochlorite (HTH). Calcium hypochlorite can be found in 30–70% solutions. Liquid bleach is in the form of sodium hypochlorite and contains between 1 and 18% chlorine.

Chlorination is effective for water with pH below 8.0 and low turbidity. Turbidity should preferably be less than 1–5 NTU, but in emergencies, turbidity less than 20 NTU may be acceptable. When chlorine gas is used to disinfect a water supply, it reacts with water to form hypochlorous acid (HOCl) and hydrochloric acid (HCl), according to the following equation:



Hydrochloric acid is a strong acid and dissociates completely in water to H^+ and Cl^- . Hypochlorous acid dissociates partially, depending on the pH of the water, and forms the base hypochlorite ion.



This reaction is the same chemical reaction that occurs when sodium hypochlorite or calcium hypochlorite is added to water. In this case, the sodium (Na^+) and calcium (Ca^{2+}) ions dissociate, and the chemistry is like adding the base OCl^- to the water.

Hypochlorous acid and hypochlorite ion together are often referred to as free chlorine (free chlorine = $\text{HOCl} + \text{OCl}^-$). Both of these chemical species are active disinfecting agents. However, hypochlorous acid (HOCl) is much more effective than OCl^- for disinfection. The equilibrium constant for the reaction shown in Eq. 18-15 is $10^{-7.5}$. At a pH of 7.5, there are equal amounts of HOCl and OCl^- , and as can be seen from Fig. 18-11, HOCl is the predominant chemical species at a pH level less than 7.5. Chlorination is thus more effective in waters with pH less than 7.5. Fortunately, most natural waters have a pH in the range of 6.5 to 8.5.

Disinfection by chlorine occurs in two ways: *primary disinfection*, which involves the inactivation of bacterial pollution, and *secondary disinfection*, which results from residual chlorine that remains in the treated water. *Chlorine demand* refers to the amount of

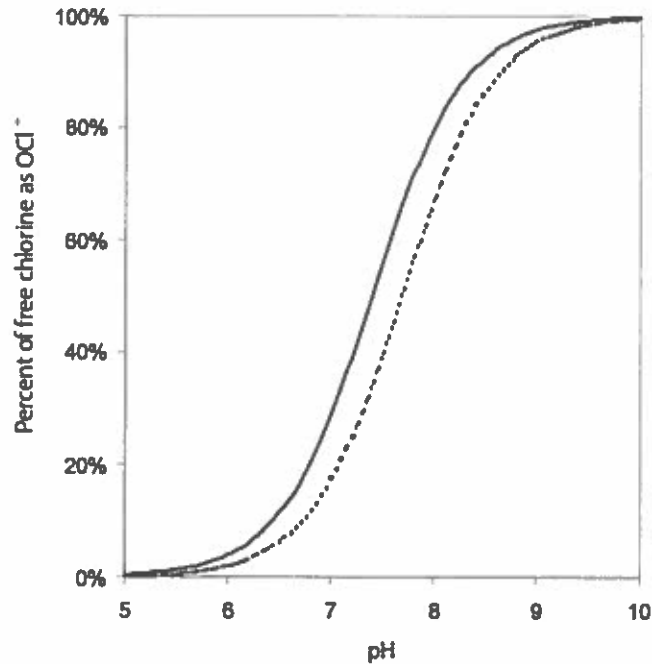


Figure 18-11. Effect of pH on the Fraction of Free Chlorine (HOCl + OCl⁻) Present as the Less-Effective Chemical Species Hypochlorite Ion OCl⁻. Dashed and Solid Lines Provide Effect for Temperatures of Approximately 10–25 °C.

chlorine required for primary disinfection. Once all the bacterial pollutants are destroyed after primary disinfection, excess chlorine remains as *residual chlorine*. This residual chlorine provides capacity to deactivate pathogens resulting from subsequent contamination of treated water, for example, contamination that occurs in pipes between the source and the tap. Disinfection requires a free residual chlorine level of more than 0.5 mg/L for more than 30 min. The WHO guideline for chlorine is 0.5 mg/L which means the WHO considers concentrations below this value (but > 0.5) to be safe. However, this level is well above the taste threshold of 0.6–1 mg/L.

Chlorine Disinfection at the Community Scale

Disinfection of community supplies can be achieved by chlorinating a well or chlorinating water in a storage tank. Hand-dug wells can be chlorinated by lowering a chlorination pot into the well or directly injecting chlorine into the well on a daily basis. Some communities inject chlorine into a well as needed to reduce contamination. However, disinfection will be short-lived with this method if the pathogens are present in the groundwater source.

Chlorination pots use bleaching powder or chlorinated lime. An example design of a chlorination pot is shown in Fig. 18-12. The chlorination pot can be made locally out of an earthen pot, ferrocement, or a plastic jug. Holes of 6- to 8-mm diameter are drilled into the bottom of the pot, and the pot is filled part way with pebbles and pea gravel

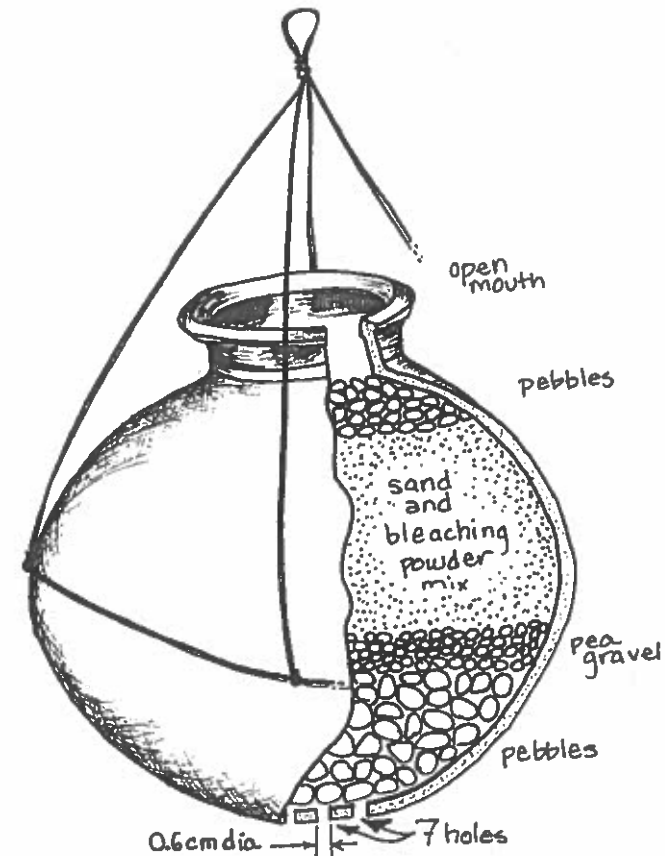


Figure 18-12. Chlorination Pot Using Bleaching Powder for Hand-Dug Wells.

Source: Redrawn with permission of Cairncross and Feachem (1983).

of 20–40-mm diameter. Above the pea gravel, a 1:2 bleaching powder:sand mixture is placed, and the pot is filled to the neck with more pebbles.

According to Huisman et al. (1981), 1.5 kg of bleaching powder in such a system should provide one week's worth of chlorination for a well from which water is drawn at a rate of 1,000–1,200 L/day. Variations of this design exist, and adjustments should be made so that the free chlorine residual concentration remains between 0.5 and 1 mg/L (or less if the users complain of taste).

Pressed calcium hypochlorite tablets have also been used successfully for chlorination of hand-dug wells (Libessart and Hammache 2000; Garandau et al. 2006). This process involves using a press to make a 70-g press cake and placing it in the center of a durable plastic bag filled with 2 L of sand.

Chlorinators are sometimes added on top of a water storage tank to drip a bleach solution into the water, as was discussed in Chapter 14. For a batch treatment of water stored in a tank, a 1% chlorine stock solution can be added, with the dose calculated based

on the volume of the tank to be disinfected. To make the 1% stock solution, mix the quantity shown in Table 18-8 for the appropriate chemical source with water to a total of 1 L.

Once the 1% stock solution is made, it is necessary to determine the dosage for disinfection of the water to be treated because the water will have biological and chemical constituents that react with the chlorine. Box 18-3 provides instructions for determining the dosage of 1% stock solution to drinking water. If measurement of residual chlorine level is infeasible, an approximate dose of 10 drops of 1% solution per quart or liter may be used, where 1/8 teaspoon is roughly equivalent to 8 drops (EPA 2006).

The chlorine residual should be measured daily, if possible. At a community scale, this task of dosing and monitoring the free residual chlorine level should be carried out by an individual trained for this task.

More advanced methods of chlorination include the drip chlorinator, solution feed devices, and proportioning devices for pumped supplies (Huisman et al. 1981; White 1999).

Chlorination at the Household Level

A 1% chlorine stock solution can also be used at the household level, with the appropriate dosage being calculated as demonstrated in Box 18-3. The small doses required for household treatment require that an appropriate measuring device be found. Plastic water bottle caps may be one possible measuring tool that people can find relatively easily.

18.7.2 Safety Considerations for Chlorine Disinfection

One disadvantage of chlorine disinfection is the dangers inherent in handling chemicals. Chlorine gas, which is given off by all concentrated compounds, may burn the eyes and skin and can start fires or explosions. A trained person should therefore handle concentrated forms of chlorine with care. Additionally, reaction of chlorine with natural organic matter in water and the presence of bromide ion (Br^-) results in the formation of disinfection by-products, such as chloroform and trihalomethanes. The health effects of disinfection by-products are not fully known, however. These by-products, as well as the residual chlorine in treated drinking water, cause concern for some water users. Additionally, the taste and odor of treated water with residual chlorine may actually discourage users from drinking the water, resulting in beneficiaries finding other, more contaminated, untreated sources of water.

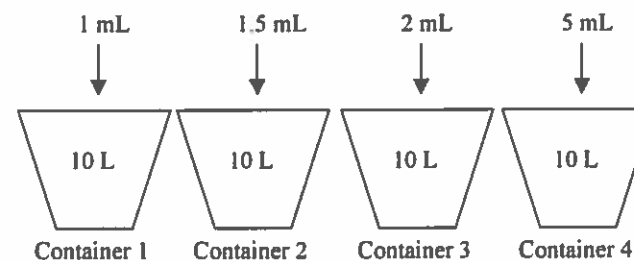
Table 18-8. Amounts of Various Chlorine Sources for Preparation of a 1% Stock Solution in 1 L of Water

Chlorine Source	Percentage Available Chlorine	Quantity Required	Approximate Measures
Bleaching powder	35	30 g	2 heaping tablespoons
Stabilized or tropical	25	40 g	3 heaping tablespoons
High-test hypochlorite	70	14 mL	1 tablespoon
Liquid laundry bleach	5	200 mL	1 teacup or 6-oz milk tin
Liquid laundry bleach	7	145 mL	10 tablespoons
Javelle water	1	Already a 1% stock solution	

Source: Wisner and Adams 2002.

Box 18-3. Determination of Chlorine Dosage Using a 1% Stock Solution

1. Place 10 L of the water to be treated in each of four nonmetallic containers.
2. Add the following doses of 1% chlorine to each container:



3. Wait for 30 min, and then measure the residual free chlorine concentration. This can be done using a comparator or test strip.
4. The container with a residual chlorine concentration of 0.4–0.5 mg/L has the appropriate dosage.
5. Calculate the dosage required for the quantity of water to be treated:

$$\text{Volume to be treated} \times \frac{\text{dose added to test container (mL)}}{10\text{L}}$$

For example, if the dosage test reveals that container 2 contains a residual chlorine concentration between 0.4 and 0.5 mg/L, and a tank with a volume of water of 1,000 L is to be treated, the dosage is calculated to be

$$\text{Dosage} = 1,000\text{L} \times \frac{1.5\text{mL}}{10\text{L}} = 1,500\text{mL} = 1.5\text{L}$$

Source: Wisner and Adams 2002.

18.7.3 Disinfection with Heat

Heat can also be used to disinfect water. There are two basic approaches to this: boiling and pasteurization. Both work, regardless of the turbidity of the water. Neither method offers residual protection, so take measures to prevent recontamination. Storing water in the same container (with a lid) in which it is boiled or pasteurized helps to reduce opportunities for recontamination. Also, consume water on the same day it is boiled or pasteurized.

Boiling is capable of destroying all types of water-borne pathogens. Bring water to a rolling boil to ensure that all pathogens have been destroyed. Although this is an

extremely effective way to disinfect water, it has several disadvantages. The main disadvantage is that fuel is required to boil the water. This fuel can require significant time to gather and can also place additional stress on a region that is already experiencing deforestation. Additionally, using wood for fuel increases exposure to the environmental risk factor indoor smoke from burning of solid fuels. Also, water requires time to cool after it is boiled. Boiled water can have an unpleasant, "flat" taste, which can be improved by shaking the storage container to allow more air to enter the water.

Boiling is often recommended to treat water but is actually overkill because water does not need to reach 100 °C to be disinfected. However, bringing water to a rolling boil provides a built-in indicator that a sufficiently high temperature has been reached. If alternative indicators are available, water only needs to be treated to pasteurization temperatures. For example, *water pasteurization indicators* (WAPIs) are small devices filled with wax that melts at a certain temperature, which can tell users when water can be considered safe to use. Several recommendations exist as to the temperature that must be reached and the length of time that water must stay at that temperature. A conservative recommendation is that water should stay at 70 °C for 10–15 min (Laurent 2005). Figure 18-13 shows that at lower temperatures, water must be heated for longer periods of time. Water can be heated over a fire or by using a solar cooker as well (see www.solarcooking.org).

18.7.4 Solar UV Disinfection

Lower wavelengths of light disinfect water by inactivating the DNA of bacteria, viruses, and other pathogens (Gadgil and Shown 1995). In addition to the effects of direct absorption of the radiation by the bacteria, light radiation also produces reactive forms of oxygen that kill microorganisms. Ultraviolet light is most effective and is divided into three ranges: UV-A (315–400 nm), UV-B (280–315 nm), and UV-C (100–280 nm) (Gadgil and Shown 1995). The most lethal wavelength for destruction of pathogens is between 200 and 300 nm, so UV-C light is the best germicidal wavelength (Crittenden et al. 2005). A mercury lamp, similar to a fluorescent lamp, provides light of wavelengths around 254 nm, an appropriate range for destruction of germs, and this method is commonly used in drinking water treatment in developed countries.

In the case where electricity is expensive or unavailable, the next-best option may be to use solar radiation. Although the smallest wavelengths of radiation do not reach the earth, wavelengths in the UV-A range (also called the near-ultraviolet region) do reach the surface of the earth and have disinfection potential. Additionally, if the water temperature reaches 45 °C, synergy between UV radiation and temperature occurs, improving treatment. In fact, if the temperature exceeds 50 °C, the treatment process is three times faster (EAWAG 2002).

Solar disinfection (SODIS) is a simple treatment method that takes advantage of the bacterial destruction potential of sunlight. Treatment involves placing clear bottles of water to be treated in direct sunlight for a determined amount of time.

SODIS is mainly limited by the initial water quality and availability of clear and clean plastic bottles. In tropical regions, where daylight is consistent throughout the year,

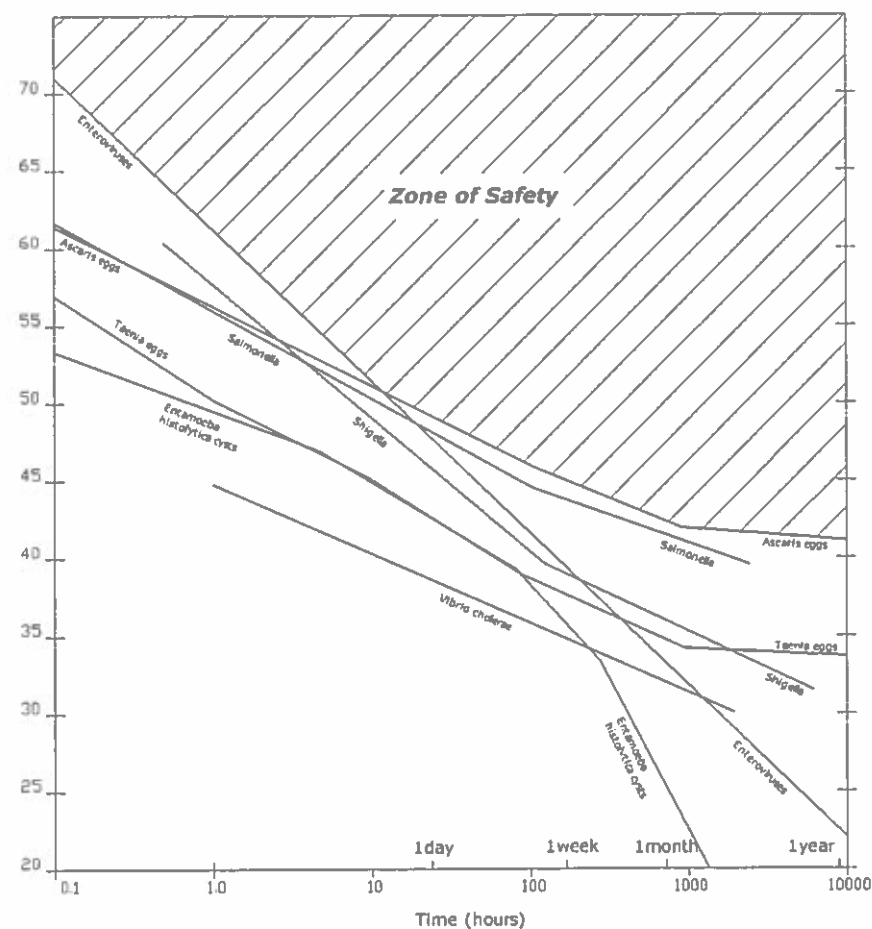


Figure 18-13. Required Temperatures for Complete Inactivation of Pathogens.

Source: Redrawn with permission of Cairncross and Feachem (1983).

light should not pose a problem. Even on 100% cloudy days, the method works with a longer exposure time. Regions between 15° N/S and 35° N/S are considered to be most favorable for solar disinfection because they generally have semiarid climates with little cloud cover. However, the region between the equator and 15° N/S is also favorable (EAWAG 2002). SODIS can be used for microbially contaminated water that has low turbidity (<30 NTU) and is free of chemical contamination (EAWAG 2002).

Because the most effective germicidal wavelengths are below the visible light range (<400 nm), clear glass or plastic bottles are the best option for solar disinfection. Clear containers transmit light in the near-ultraviolet range, as well as in the visible range. Another important factor is the material of the bottle. Glass and plastic are the only real

options. The advantages to glass are that it is more resistant to scratching (which reduces light penetration), it has no photoproducts, and it is heat resistant.

Obvious disadvantages to glass are its ability to break, higher costs, and weight. Also, ordinary glass will not transmit UV-radiation if it is thicker than 2 mm. Pyrex, Corex, Vycor, and quartz glasses transmit UV-radiation significantly more than window glass. These types of glass are more costly than ordinary window glass. Plastic bottles are lightweight and less breakable, although less heat resistant (EAWAG 2002). Because they are also generally less expensive, plastic bottles seem to be the best option.

Plastic drinking bottles are either made of polyethylene terephthalate (PET) or polyvinyl chloride (PVC). Although both kinds of plastics contain additives like UV stabilizers, PET bottles contain fewer and so are chemically more stable (EAWAG 2002). In many places, plastic bottles are used for distributing commercial bottled water and are thus readily available for reuse, either sold as used bottles in markets or collected from individuals who consume bottled water.

The procedure for solar disinfection is as follows:

1. Use SODIS for water with no chemical contamination and with turbidity less than 30 NTU. Pretreat the water by filtration or sedimentation to remove turbidity.
2. Wash a 1–2-L PET bottle well the first time the bottle is used. Use four bottles per person, allowing two bottles to be used for consumption and two bottles to be used for treatment.
3. Fill the bottle 75% full of water to be treated, cover it, and shake it for 20 s to aerate the water and increase the dissolved oxygen. Higher oxygen content results in more efficient disinfection because disinfection results from oxygen free radicals and hydrogen peroxides that are produced by the sunlight in water. EAWAG recommends, however, that aeration only take place at the beginning of the SODIS process because continuous shaking throughout exposure reduces efficiency.
4. Fill the bottle fully and replace the cover.
5. Place it in the sun for at least 6 h. Table 18-9 provides the required exposure times for three meteorological conditions. To reduce the risk of breaking or contamination of the bottles, place them out of reach of children and off the ground. One good place to place the bottles is on corrugated metal roofs, in between the grooves.
6. The water is ready for consumption after the appropriate exposure time.
7. Replace old or scratched bottles.

Table 18-9. Required Exposure Time for Solar Disinfection (SODIS) Treatment of Water

Conditions	Required Exposure Time
Sunny to 50% cloudy	6 h
50% to 100% cloudy	2 full days
Continuous rainfall	SODIS is not suitable
Water temperature at or above 50 °C	1 h

Source: EAWAG 2002.

18.8 Storage

Water storage is a critical issue (Box 18-4). Water that is clean at the source is often contaminated by the time it is consumed because of poor storage practices. Risk factors contributing to higher contamination include containers with wide openings; water being touched by hand, cups, or dippers that can be contaminated by fecal matter; high storage temperatures; increased storage times; high levels of airborne particles (dust storms); and inadequate hand washing (Sobsey 2002).

Box 18-4 How Safe Is Household Storage?

The drinking water guidelines established by the World Health Organization (WHO), state that the water source should not contain any microbiological agents that are pathogenic to humans (WHO 2006). However, these drinking water guidelines are based on water quality at the point of delivery, not through the point of actual consumption (Wright 2004).

Microbiological contamination of drinking water during collection and storage in the home has been examined by several researchers (VanDerslice and Briscoe 1995; Clasen and Bastable 2003). Agard et al. (2002) examined the microbial quality of water sources supplied to the San Fernando community in southern Trinidad and found that out of the 104 drinking water samples obtained from households, 80.8% tested positive for total coliforms, 53.8% tested positive for thermotolerant coliforms, and 67.3% tested positive for *E. coli*. Out of the 81 water samples collected from the Water and Sewerage Authority distribution point, 46.9% tested positive for total coliforms, 16% tested positive for thermotolerant coliforms, and 33.3% tested positive for *E. coli*. As the level of residual chlorine decreased, there was a statistically significant increase in the prevalence of total coliforms in water from 0.0% in treated reservoir to 80.0% in household drinking water. Agard et al. concluded that the level of household water contamination presented a public health concern to residents.

Brick and Primrose (2004) examined the effects of household storage on water quality in a southern town in India. The study showed that two-thirds of the water sources became increasingly contaminated within nine days of current household storage practices, in spite of receiving safe drinking water from municipal plants. However, the use of brass storage containers significantly decreased contamination of water. Trevett et al. (2004) evaluated the drinking water quality in three rural Honduran communities that used either a protected hand-dug well or bore hole supply. Water quality was examined in 43 households with observations made of household collection and storage practices over a two-year period. There was frequent and substantial water quality deterioration between the points of supply and consumption. Additionally, it was concluded that none of the storage factors examined made any significant difference to the stored water quality and that the contamination could have occurred at several points.

Based on what is reported in the literature, it is thus necessary to take every possible precaution to prevent contamination of water during collection, transport, and household storage.

►►► Box 18-5 How Safe Are Plastic Containers and Tubing?

When designing a water distribution, treatment, or storage system, engineers often are faced with the need to weigh the need for biological treatment of pathogens against potential health outcomes from chemical exposure. For example, some plastic bottles contain the chemical bisphenol A (BPA). BPA is known to be a hormone disrupting chemical in animal studies and has been associated with reproductive abnormalities, precancerous changes in the breast and prostate, and obesity and insulin resistance (NRDC 2008). In the United States, where plastics have been used for decades for storing consumable liquids, more than 93% of the population has some form of BPA in their bodies (CDC 2008).

The Natural Resources Defense Council (NRDC 2008) has recommended that plastics numbered as 1 (PETE), 2 (HDPE), 4 (LDPE), and 5 (PP) are safe and that plastics numbered 7 (other, usually polycarbonate), 3 (PVC or V), and 6 (polystyrene) should be avoided. The NRDC (2008) also recommends that infants in particular should not be given drinks from polycarbonate bottles or cups.

Water that is stored in the home should always be covered. Ideally, the storage container should also have a spout through which water can exit. Otherwise, a dipper can contaminate the water every time it is used. If a spout is not possible, the dipper should be hung from a hook in a clean place (not set on a surface) and it should have a handle, so that no hands (or surfaces that come in contact with hands) ever enter the water (Box 18-5).

Optimal storage containers (Fig. 18-14) have the following characteristics:

- 10–25-L capacity,
- one or more handles,

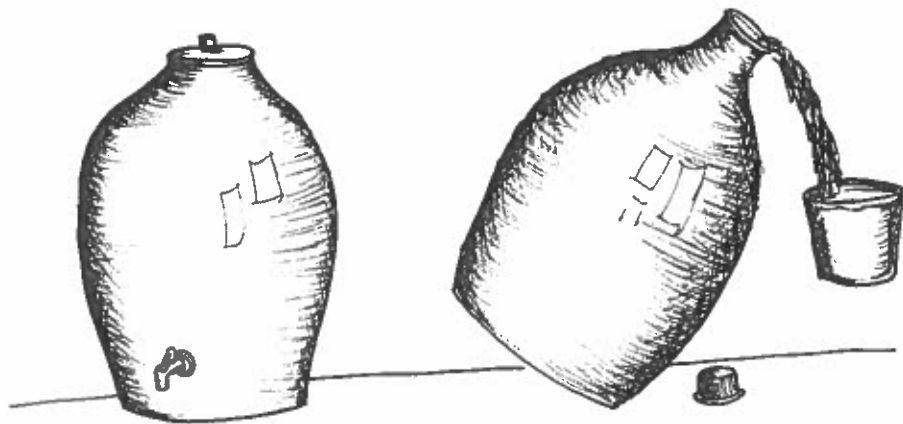


Figure 18-14. Examples of Good Water Storage.

Note: The left container has a lid, narrow neck to prevent dipping cups into it, and a spigot for drawing water. Although the right container does not have a spigot, it is easily poured, and the narrow neck prevents contamination by cups used to draw water. The containers would be easier to use if they had handles.

- flat bottoms,
- construction of light-weight, oxidation-resistant plastic (e.g., polyethylene or polypropylene),
- a 6–9-cm screw cap (big enough to allow cleaning but small enough that it discourages using hands or dippers to access the water),
- a durable and easily closed spigot or spout to dispense water, and
- pictorial and written instructions permanently attached to the container (Sobsey 2002).

Storage containers also need to be compatible with the water treatment methods being used by the household.

►►► 18.9 Measuring Turbidity with a Turbidity Tube

Turbidity is easily measured in the field by a turbidity tube, which is simple to construct (Myre and Shaw 2006). The procedure for measuring turbidity is depicted in Fig. 18-15. Pour water into the tube until the black-and-white quartered pattern located at the bottom of the tube can no longer be seen. The height of the column of water when the pattern disappears corresponds to the turbidity of the water, as shown in Table 18-10. A shadow should be cast on the tube while measurements are being taken, for example by standing between the sun and the tube.

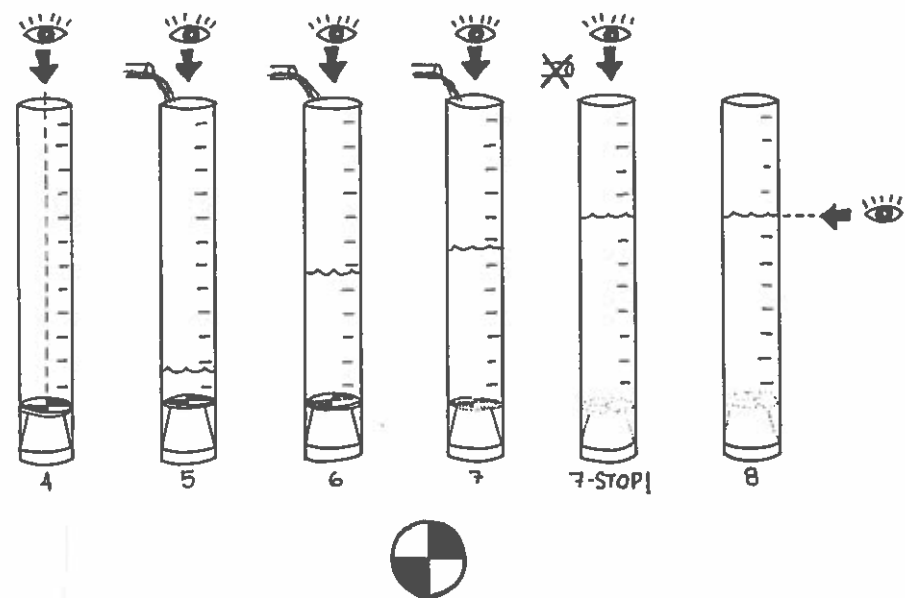


Figure 18-15. Measuring Turbidity with a Turbidity Tube.

Note: If a water sample is more turbid, the quartered disk located at the bottom will disappear with a smaller volume of water added to the tube.

Table 18-10. Conversion of Length to Turbidity When Using a Turbidity Tube

Centimeters	NTU
6.7	240
7.3	200
8.9	150
11.5	100
17.9	50
20.4	40
25.5	30
33.1	21
35.6	19
38.2	17
40.7	15
43.3	14
45.8	13
48.3	12
50.9	11
53.4	10
85.4	5

Source: UW Extension 2003.

18.10 Arsenic

18.10.1 Arsenic Occurrence and Chemistry

The occurrence of arsenic in groundwater in many parts of the world is significant enough to require removal. Exposure to high levels of arsenic rarely causes acute poisoning, but long-term exposure can result in skin diseases that can eventually lead to urinary bladder and lung cancer, damage to internal organs, gangrene in the legs, and hypertension. When developing a source of groundwater in regions where arsenic is known to exist, it is important to know whether treatment is necessary.

Arsenic poisoning may be difficult to diagnose in cases where internal organs are affected first. However, visible symptoms exist, such as darkening of the skin, hardening of the palms of the hands and the soles of the feet, or skin depigmentation. Naturally occurring arsenic in drinking water supplies has been found throughout the world (Table 18-11), but the problem is most serious in Bangladesh and West Bengal, India, where millions of wells were installed in the 1970s and 1980s to provide what was thought to be safe drinking water.

Arsenic occurs in both particulate and soluble forms. Particulate arsenic can be removed by a 0.45- μm filter (Petrusevski et al. 2007). Soluble arsenic is more difficult to remove and requires an understanding of the chemistry of soluble arsenic to plan treatment methods. Treatment of arsenic in drinking water is the subject of current research and technology development (Amy et al. 2005; SenGupta 2005; Petrusevski et al. 2007).

Table 18-11. Countries Where Arsenic Has Been Reported in Groundwater

Continent	Countries
Asia	Bangladesh, Cambodia, China (including Taiwan and Inner Mongolia), India, Iran, Japan, Myanmar, Nepal, Pakistan, Thailand, Vietnam
Americas	Argentina, Chile, Dominica, El Salvador, Honduras, Mexico, Nicaragua, Peru, United States
Europe	Austria, Croatia, Finland, France, Germany, Greece, Hungary, Italy, Romania, Russia, Serbia, United Kingdom
Africa	Ghana, South Africa, Zimbabwe
Pacific	Australia, New Zealand

Source: Petrusevski et al. 2007.

In natural waters, soluble arsenic occurs primarily in the oxidized pentavalent form [As(V)] (which occurs mostly in surface water) and the more toxic trivalent form [As(III)] (most often found in groundwater). Table 18-12 shows the many forms of soluble arsenic found in groundwater and surface water.

Table 18-13 lists treatment processes used to remove arsenic from water. Conventional treatment technologies involve processes that are heavily dependent on surface charge, and therefore speciation. As Table 18-12 shows, As(V) occurs primarily as an anion in natural surface waters, and therefore, removal of As(V) is easier than removal of As(III). Most arsenic removal technologies involve chemically oxidizing As(III) to As(V), followed by conventional adsorption and coprecipitation.

Table 18-12. The Forms of Soluble Arsenic Found in Groundwater and Surface Water

Valency	Speciation	Form	Primary Occurrence	pH at Which Ionic Forms Dominate
Arsenite [As(III)]	H_4AsO_3^+	Reduced	Groundwater, assuming anaerobic conditions ^a	pH > 9
	H_3AsO_3			
	H_2AsO_3^-			
	HAsO_3^{2-}			
	AsO_3^{3-}			
Arsenate [As(V)]	H_3AsO_4	Oxidized	Surface water	pH > 3
	H_2AsO_4^-			
	HAsO_4^{2-}			
	AsO_4^{3-}			

Note: Treatment technologies require that ionic species dominate. Because As(V) is ionic at natural pH, it is easier to remove than As(III).

^aThe generalization that As(III) is most often dominant in groundwater is less universal than the rule that As(V) dominates surface water. As(V) has been found in groundwater.

Source: Petrusevski et al. 2007.

Table 18-13. Proven Processes Used to Remove Arsenic That Can Be Feasible for Developing Communities

Process	Technologies
Precipitation	Coagulation and flocculation Coagulation-assisted microfiltration Enhanced coagulation Lime softening Enhanced lime softening
Adsorption	Activated alumina Activated carbon Iron and manganese oxide based or coated filter media
Ion exchange	Anion exchange
Membrane filtration	Nanofiltration Reverse osmosis Electrodialysis

Note: Other technologies exist but would either be too costly or are still in the development stage.

Source: Petrusevski et al. 2007.

18.10.2 Arsenic Treatment

In the absence of treatment, arsenic-contaminated wells can simply be painted with a distinguishing color. Arsenic removal in developing communities uses conventional precipitation and adsorption processes. A typical precipitation process to remove arsenic in groundwater would involve aeration, followed by coagulation and flocculation with aluminum or iron salts, followed by sedimentation and rapid sand filtration. If As(III) is known to be a significant portion of the arsenic in the water, a chemical preoxidation through chlorination or ozonation may be required. However, this process increases treatment costs and may result in oxidation by-products (Petrusevski et al. 2007). After treatment, the liquid waste should be treated as toxic. Adsorption processes have in the past used activated alumina; more recently, iron-based adsorbents are being used. A typical iron-based adsorption process involves a series of adsorptive filters and has no requirement for chemical addition (Petrusevski et al. 2007). Iron oxide coated sand can also be used as an arsenic adsorbent.

Table 18-14 lists some common systems that have been used with limited success at the household level. Figure 18-16 shows a treatment unit that uses granular activated alumina. The exhausted activated alumina is disposed of below the ground in a concrete-lined vault.

18.11 Fluoride

Fluoride in drinking water can have negative or positive effects on human health, depending on concentration. Industrialized drinking water treatment often includes addition of fluoride because concentrations of approximately 1 mg/L are associated with reduced

Table 18-14. Common Processes for Point-of-Use Arsenic Removal and Examples of Systems That Use Them

Process	System	WaterAid (2001a, b) Test Result
Passive sedimentation	Passive sedimentation	Failed
Passive sedimentation and adsorption	Ardasha filter	Failed
Adsorptive filtration	Alcan enhanced activated alumina	Passed
	BUET activated alumina filter	Passed
	Apyron arsenic treatment unit	Not tested
	Read-F arsenic removal unit	Not tested
	Wellhead arsenic removal systems developed by Dr. Arup K. SenGupta and others at Lehigh University	Not tested by WaterAid (2001), but proven successful by Sarkar et al. (2005)
	UNESCO-IHE family filter (iron oxide coated sand)	Not tested by WaterAid (2001), but proven successful by Khan (2004)
Coagulation	DPHE-Danida bucket treatment unit technology system	Passed under certain conditions
	Garnet filter	Passed under certain conditions
	Stevens Institute	Passed
Ion exchange	Tetrahedron	Passed
Coagulation and adsorption	Sono 3-Kalshi filter	Passed

Note: Nine of these systems were tested by WaterAid for successful removal to below the Bangladeshi standard of 50 µg/L.

Sources: Khan (2004); Sarkar et al. (2005); and Petrusevski et al. (2007) with data from WaterAid (2001a,b).

incidence of dental cavities. Excessive levels of fluoride are associated with a number of negative health effects, including dental fluorosis (staining of teeth and erosion of enamel) and skeletal fluorosis (resulting in osteosclerosis, ligamentous and tendinous calcification, and extreme bone deformity).

Fluoride exists in natural waters primarily as the fluoride ion (F⁻) or as a complex with aluminum, beryllium, or ferric iron (Crittenden et al. 2005). Because fluoride ions have the same charge and almost the same radius as hydroxide ions, they form mineral complexes with many cations (Fawell et al. 2006). Fluoride is therefore found abundantly in the Earth's crust, occurring in a variety of minerals. When calcium is present, fluorite is common (CaF₂), which has low solubility. Therefore, higher concentrations of fluoride in solution occur in calcium-poor aquifers where fluoride-bearing minerals are common.

Water is not the only exposure pathway for humans to fluoride. Fluoride can also be found in air, dental products, and foods and beverages other than water. Therefore, if dental or skeletal fluorosis exists, it may not necessarily mean that fluoride removal from

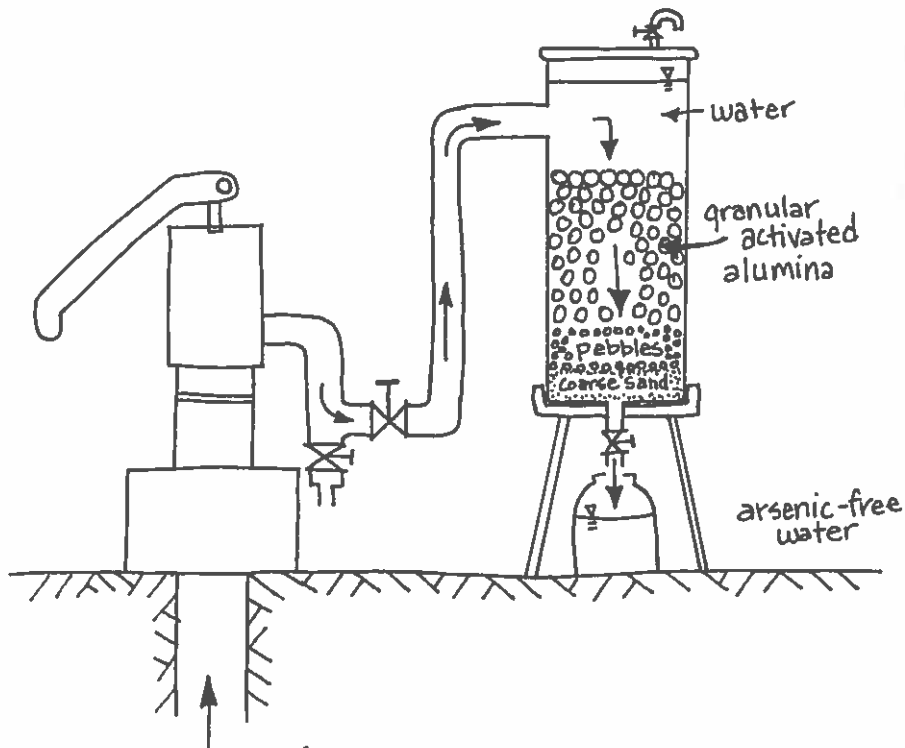


Figure 18-16. Community Treatment System to Treat Arsenic-Contaminated Water Supplies.

Note: This unit is installed at hand-pumped wells and can be regenerated with caustic soda every 4 months.

Source: Courtesy of Dr. Arup SenGupta and others at Lehigh University.

water is required. The WHO guideline for fluoride in drinking water is 1.5 mg/L. However, local conditions should be evaluated to determine whether fluorosis is a problem and if there are other sources of fluoride exposure that can be reduced or eliminated.

In the past, fluoride removal initiatives have met with limited success. Therefore, the WHO recommends that, whenever possible, an alternative source of water be used or blended with the fluoride-containing source (Fawell et al. 2006). Where this is not possible, several treatment processes can be used: sorption, coprecipitation, ion exchange, and contact precipitation (Table 18-15). Even where centralized water distribution systems exist, point-of-use treatment is often preferable because removal is only necessary for water used for drinking or cooking. Minimizing the amount of water to be treated by not treating water for other uses will also minimize the amount of toxic sludge produced by treatment.

Table 18-15. Processes Used for Removal of Fluoride in Drinking Water

Process	Technologies
Sorption	Bone charcoal Activated alumina Clay
Coprecipitation	Coagulation and flocculation (Nalgonda technique) Polyaluminum chloride Lime
Contact precipitation	Calcium and phosphate compounds
Ion exchange	Clay or other naturally occurring mineral

Source: Fawell et al. 2006.

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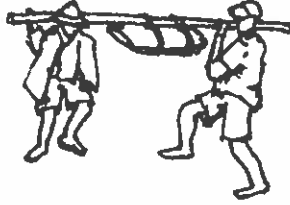
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Field Guide to Environmental Engineering for Development Workers

Water, Sanitation, and Indoor Air

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