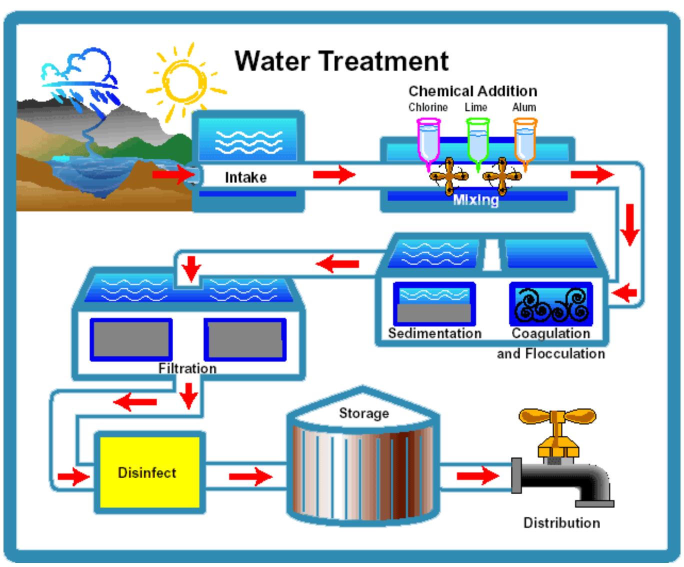
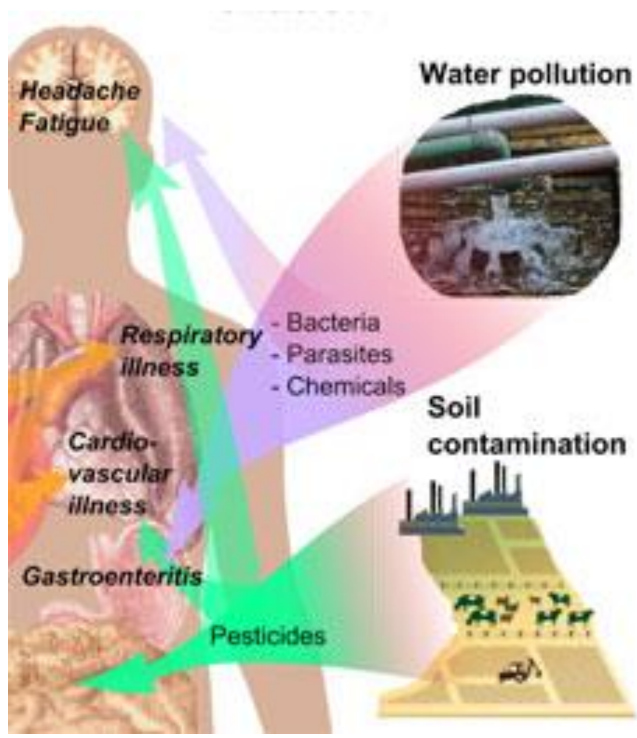
Water Filtration

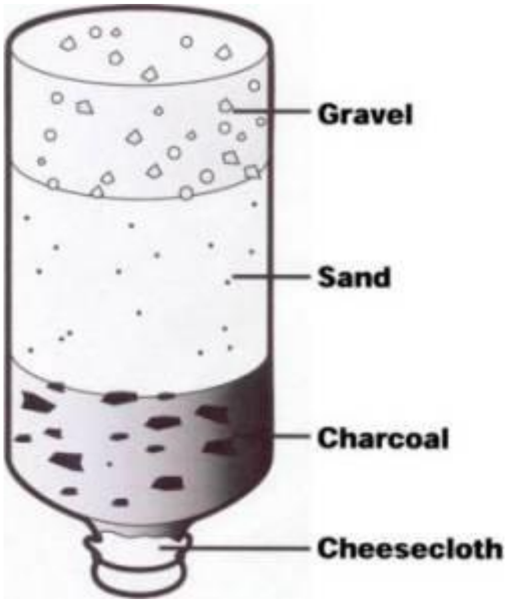
It's a modern-day engineering challenge to remove human-made contaminants from drinking water. After a quick review of the treatment processes that municipal water goes through before it comes from the tap you will learn about the still-present measurable contamination of drinking water due to anthropogenic (human-made) chemicals. Substances such as prescription medication, pesticides and hormones are detected in the drinking water supplies of American and European metropolitan cities. The engineering design process can be used to design solutions for a real-world problem (contaminated water) that could affect health.

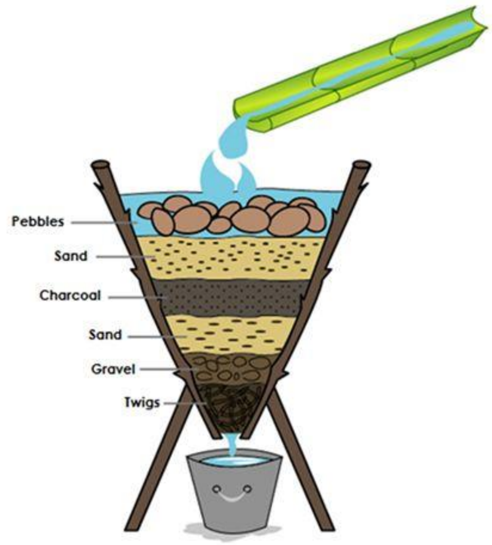
Engineering Connection

The water that comes from our faucets has passed through a complex system designed by many different types of engineers. Civil, chemical, electrical, environmental, geotechnical, hydraulic, structural and architectural engineers all play roles in the design, development and implementation of municipalities' drinking water supplies and delivery systems. Hydraulic engineers design systems that safely filter the water at a rate needed to supply a specific region and population. Chemical engineers precisely determine the amounts and types of chemicals added to source water for coagulation and decontamination to make the water safe to drink and not taste bad. Even so, modern pharmaceutical and agricultural practices persist in contaminating our water supplies.









Treating the Public Water Supply:
What Is In Your Water, and How Is It Made Safe to Drink?

Human Use of Freshwater

Humans' Need for Clean Freshwater

Water is perhaps the most important nutrient in our diets. In fact, a human adult needs to drink approximately 2 liters (8 glasses) of water every day to replenish the water that is lost from the body through the skin, respiratory tract, and urine. But some water sources cannot safely be used to meet our requirement for drinking water. In fact, 99.7% of the Earth's water supply is not usable by humans. This unusable water includes saltwater, ice, and water vapor in the atmosphere. Only freshwater, which is contained in rivers, lakes, and underground sources, can be used for human consumption. Furthermore, many freshwater sources are not suitable for humans to drink. Many serious diseases, such as cholera, are caused by drinking water that contains parasitic microorganisms. Water containing large amounts of industrial waste or agricultural chemicals (*e.g.*, pesticides) can also be toxic and unfit for drinking. Hence, humans have a great need for a reliable source of clean freshwater for drinking.

In addition to the water needed for drinking, humans use much larger amounts of clean freshwater in other applications. These other uses of freshwater include household use (*e.g.*, cooking and cleaning), industry, agriculture (*e.g.*, irrigation), and recreation. Hence, the quality of the freshwater supply is important for virtually every aspect of our lives.

Sources of Freshwater

Where does the water that we use come from? As stated above, saltwater is not suitable for human use. (The high salt concentration makes it unsuitable for most human applications, and removal of the salt is costly.) Water found in the forms of ice and vapor are not readily accessible for human use. This leaves only about 0.3% of the water on the Earth as liquid freshwater.The vast majority (approximately 98.5%) of the Earth's freshwater is contained in underground supplies known as **groundwater.** The remaining freshwater sources, including rivers and lakes, are collectively known as **surface water.** The amount of water that we use from groundwater and surface water varies from region to region. Generally, groundwater is cleaner and requires less treatment, but surface water is easier to obtain.

Water is Not Really Pure H_2O

Why is it necessary to treat freshwater before we drink it or use it for other applications? The answer is that our water supplies are not pure, i.e., these supplies contain other species that may make the water unsuitable for human use. H_2O is certainly the largest and most important component of any water source, but this molecule is hardly the only chemical present in the water supply. It may be surprising to learn that water treatment does not eliminate all of the impurities from water. In fact, the treatment process itself contributes additional impurities to the water. However, the impurities added during the treatment process generally help to make water more suitable for human use.

suspended particles typically have diameters in the range of 1-100 nm); however, the distinction between a suspension and a solution on the basis of particle size is not well-defined. Experimentally, the differenece between the two types of mixtures is seen using the Tyndall effect, in which light is scattered by the suspended particles in a suspension (i.e., the solution appears cloudy), but is not scattered in a homogenous solution. Examples of suspended particles in water samples may include:

- bacteria
- floating debris (*e.g.*, twigs, bits of leaves, and trash)
- sand and dirt

The types and amounts of these species in a given water sample depend on the source of the sample, and what sort of treatment the water has undergone. Some of these dissolved species, such as O_2 gas, are unavoidable and do not detract from our ability to use the water. Other species, such as F^-, are desirable and are often added during the water-treatment process. Many of the species dissolved in water, however, are harmful for humans to drink, or otherwise render the water unsuitable for human use (*e.g.*, Ca^{2+} is responsible for "hard water", which can leave insoluble scum on appliances and industrial boilers). These products must be removed via water-treatment facilities.

Treatment of the Public Water Supply

What, then, must be removed from public water supplies, and what other chemicals are added to the water? How do public water facilities treat our water to make it safe for us to drink and appropriate for other human uses? There are six major steps in the treatment of our water: screening, sedimentation, precipitation, filtration, adsorption, and disinfection. Some of these steps, such as precipitation, involve chemical reactions among the aqueous species dissolved in the water; others, such as screening, involve only separation of particles on the basis of physical characteristics like size. Many of these steps depend on one another. For instance, precipitation generates solids in the water from particles that had been dissolved; these solids must then be removed through sedimentation or filtration. We shall discuss each of the six steps in water treatment below, and then present a schematic showing how the steps work together to produce clean, usable freshwater.

Screening

Surface water (water from lakes and rivers) often has large debris, such as sticks, leaves, fish, and trash, floating in it. These objects can clog the water-treatment system and must be removed before the water enters the treatment plant. Treatment facilities that use surface water have large screens (Figure 4) covering the site of water intake. The debris is too large to pass through the holes in the screens. Thus, as the water enters the plant, the large debris is removed. The screens must be cleaned periodically to remove any objects that have become stuck, so that they do not clog the screen and impede water flow into the plant. (Another problem for water-treatment plants in the Great Lakes and Mississippi Valley is zebra mussels, which can "congregate" at the water intake and clog the screen, eventually sealing it off. Potassium permanganate, $KMnO_4$, can be used to kill these mollusks.)

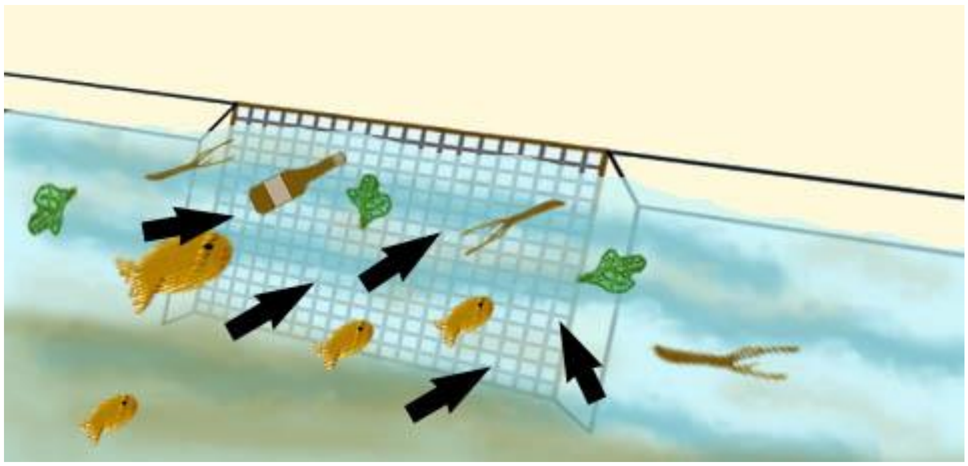


Figure 4

This drawing shows some of the large objects in surface water that are removed as the water passes through a screen into the water-treatment facility. The large black arrows show the direction of water flow through the screen.

Sedimentation

Other suspended (insoluble) particles, such as sand and dirt, are small enough to pass easily through the screens. These particles must be removed from the water by another process known as **sedimentation** (Figure 5). When water is allowed to sit, heavy suspended particles (*e.g.*, sand) will settle to the bottom over time because they are denser than water. The water, now free of the suspended impurities, can be collected from the top without disturbing the layer of sediment at the bottom (which is eventually discarded).

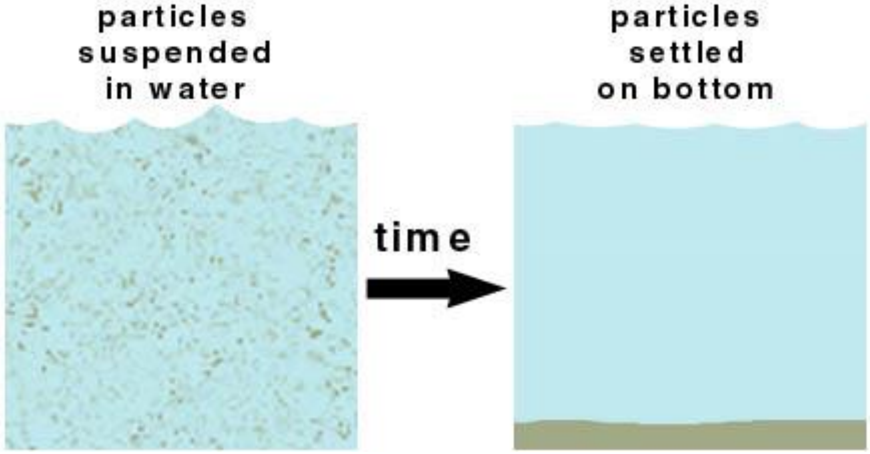


Figure 5

Particles that are insoluble in water may be suspended in the water, particularly if the water is turbulent (stirred up). If the particles are heavy enough, they will settle to the bottom when the water is allowed to sit still over time.

Sometimes the insoluble particles are too small to settle out quickly enough to use sedimentation alone. Two processes, known as **flocculation** and **coagulation**, are used to create larger particles that will settle quickly to the bottom. In flocculation, small particles with non-rigid surfaces are made to agglomerate by mixing the water (and thus bringing the particles into contact with one another so that the surfaces can become stuck together). When the agglomeration of the particles gets large enough, the aggregate can settle in still water by sedimentation. Other suspended particles do not agglomerate well by flocculation. To remove these particles from the water, coagulation must be used. Coagulation is the process of gathering particles into a cluster or clot, often achieved by the addition of special chemicals known as **coagulants.** The most common coagulant used in water-treatment facilities is **aluminum sulfate** (alum, $Al_2(SO_4)_3$). Other Al and Fe salts, including poly-aluminum chloride, ferric chloride, and ferric sulfate, may be used as well. These salts react with ions naturally found in the water to produce a solid precipitate (Equation 2). As this precipitate forms, other particles are caught in the solid, forming a mass that will settle to the bottom via sedimentation (Figure 6).

$$Al^{3+}_{(aq)} + SO_4^{2-}{}_{(aq)} + Ca^{2+}_{(aq)} + 3HCO_3^{-}{}_{(aq)} \longrightarrow Al(OH)_{3(s)} + Ca(SO_4)_{(s)} + 3CO_{2(g)} \qquad \textbf{(2)}$$

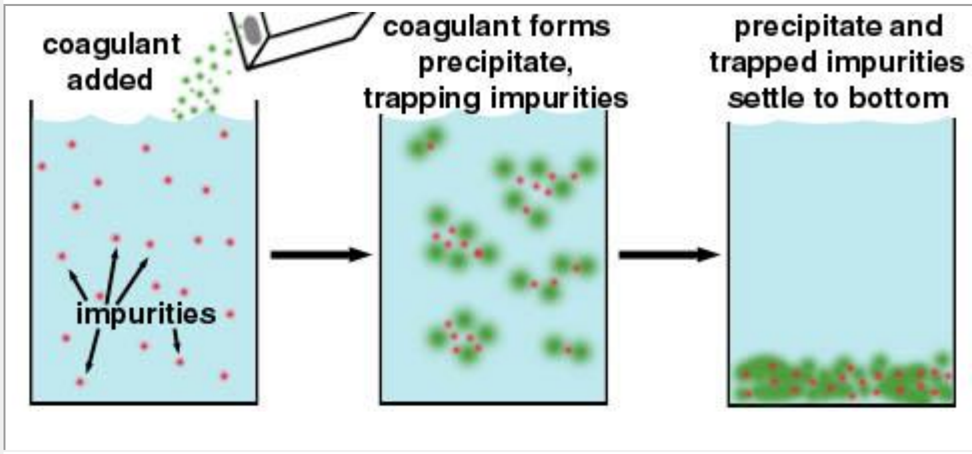


Figure 6

When coagulants such as $Al_2(SO_4)_3$ are added to the water supply, they form solid precipitates (green), as shown in Equation 2, above. These precipitates catch other impurities (red) in the water, forming a solid mass containing the precipitate formed by coagulation and the trapped impurities. This mass will settle to the bottom by sedimentation, and the water (with the trapped impurities now removed) can be drained off of the top.

Filtration

Often, the particles generated by the precipitation reactions described above are too small to settle efficiently by sedimentation. One strategy that is frequently employed to remove these solids is **gravity filtration** (Figure 7).In this process, water containing solid impurities (*e.g.*, precipitates from water softening) is passed through a porous medium, typically layers of sand and gravel. The force of gravity is used to push the water through the medium. The small water molecules pass through the holes between sand and gravel pieces. However, the solids (from precipitation) get stuck in the holes, and are thus retained in the porous medium. The water that passes through the bottom of the filter no longer contains those solid impurities.

Gravity filters at water-treatment plants have a pipe feeding into the under drain, the bottom layer where the clean water is collected. By adding water to the filter through this pipe, clean water can be forced upward through the filter to remove the solids that have collected in the filter. This process is used to clean the filter.

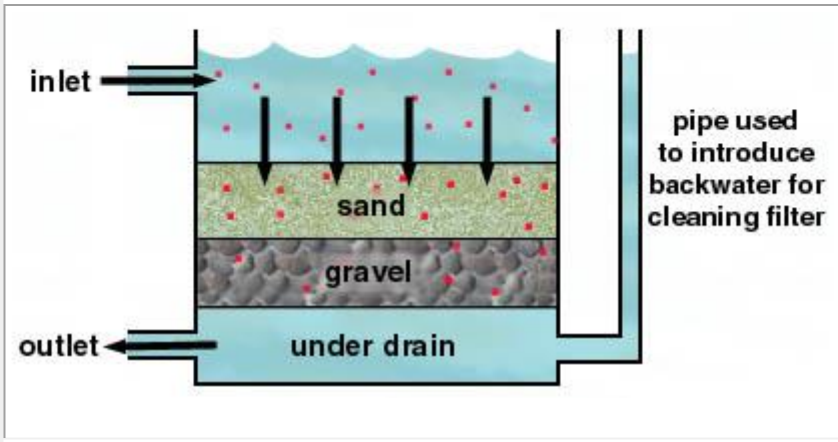


Figure 7

Water containing solid impurities (red) enters the filter through an inlet at the top and is forced by gravity through layers of sand and gravel. The solids get trapped between the sand and gravel pieces. The water that emerges into the under drain at the bottom of the filter is cleaned of these solids and exits the filter through an outlet at the bottom.

Addition of Other Chemicals to the Water Supply

Certainly a principal objective of the water-treatment process is to remove substances from water that are harmful, or that otherwise make the water unsuitable for human use. However, another important component of the process is the addition of chemicals that make the water better for human use. For example, fluoride (F^-) is routinely added to public water supplies to protect the teeth of those who drink the water. Cities that add appropriate amounts of fluoride to their drinking-water supplies have successfully reduced the incidence of cavities among the children who inhabit those cities.

Schematic of a Water-Treatment Plant

The processes of screening, sedimentation, precipitation, filtration, adsorption, and disinfection work together to remove the unwanted substances from our water supply, making it safe to drink and appropriate for other uses. Addition of other chemicals, such as fluoride, further enhance the quality of the water for drinking. Figure 9, below, depicts a flowchart showing how these processes work together. Once the water is treated, it is sent to storage chambers and then distributed to household consumers, businesses, and industries.

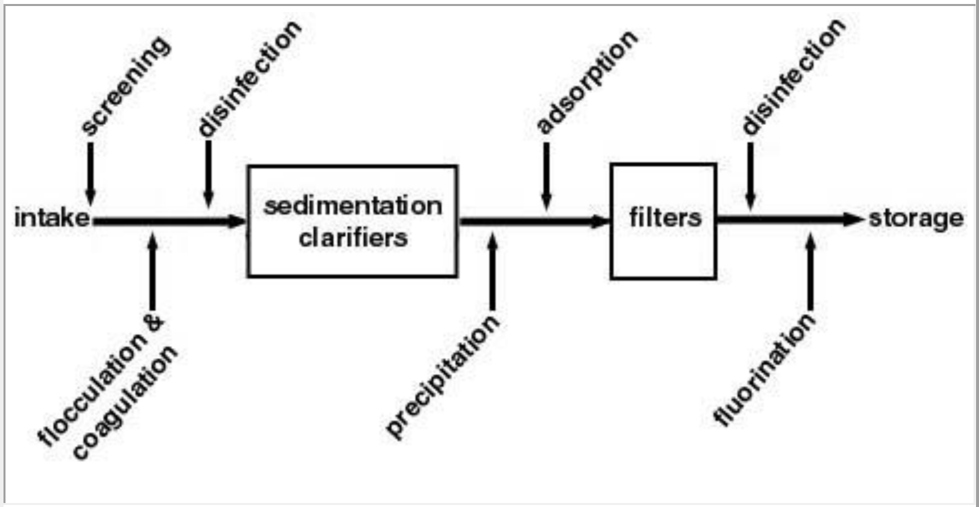


Figure 9

This flowchart shows the path that water takes from the intake of the water treatment plant (from the freshwater source) to the storage tank, from which it is pumped to homes, businesses, and industries. The specific steps and their sequence may vary somewhat from one treatment plant to another.

Questions on the Schematic of a Water-Treatment Plant

- Figure 9, "Filtration in the water-treatment process," shows that adsorption typically occurs before filtration. Briefly, explain why this order of events is important.
- How would the staff at a water-treatment plant know when the filter needs to be cleaned?

Point-of-Use Water Treatment

In most communities, the water that reaches our homes, businesses, and industries is clean and free from impurities that detract from the water's suitability for human use. However, water-treatment facilities in some communities do not adequately treat the water to make it safe to drink and appropriate for other uses. And even when the public water supply is considered good by most people, some users have special requirements that necessitate further treatment of the water. In these situations, special **point-of-use** treatment procedures are employed. Point-of-use water treatment includes any treatment of the water that occurs at the location where the water is to be used (*e.g.*, in the home or at an industrial site, as opposed to in a community plant from which the water will be distributed to many locations). Two of the most common types of point-of-use treatment are water softening and adsorption filtration.

Point-of-Use Adsorption Filters

Many of the contaminants that make our drinking water unsafe or unpleasant to drink, such as lead (which may be leached into the water from lead pipes) or organic molecules producing offensive odors and tastes, can be removed by adsorption-filtration devices installed at the tap. These devices have filters containing powdered activated carbon, which adsorbs the offending contaminants in the water. The PAC (with the unwanted contaminants attached) is strained out of the water exiting the device (for consumption) by the filter. Periodically, the filter must be replaced so that it does not become clogged and ineffective.

Questions on Point-of-Use Water Treatment

- Eventually, an ion-exchange water-softening device becomes ineffective, because all of the Na^+ ions have been replaced by Ca^{2+} and Mg^{2+} ions. Briefly, describe a way that you could "refresh" the device (i.e., flush out the Ca^{2+} and Mg^{2+} ions and replenish the Na^+ ions) using a common kitchen product.

- Can an ion-exchange water-softening device be used to remove organic contaminants? Briefly explain your answer.

Completing the Cycle: What Happens to Water After We Use It?

Once water has been used, it must somehow re-enter the freshwater supply. Some of the water is evaporated (*e.g.*, if it is used to generate steam for industry, or if we drink the water and then sweat). The evaporated water eventually collects in clouds and returns to the earth via precipitation. However, most of the water that we use remains in the liquid state, and is returned to the freshwater supply directly (as runoff) or via wastewater treatment facilities.

Wastewater from municipalities (i.e., household and business use), industries, and agriculture typically follow different pathways in their return to the freshwater supply, although municipal and industrial wastewater may sometimes be combined. Wastewater from all of these sources may contain contaminants that are harmful both to humans and to the environment. Hence, water-treatment facilities (sewage facilities) must be employed to remove these harmful products before the water is returned to the freshwater supply in the environment.

Muncipal wastewater may contain bacteria-harboring fecal material, as well as small amounts of grease, suspended solids, and chemicals from household use. The water passes through a wastewater-treatment facility before it is then disposed of into rivers, lakes, or estuaries, where any remaining contaminants will be diluted. Other methods of disposal, including irrigation and evaporation, are used more rarely. The wastewater-treatment facilities use many of the same techniques described above for treating water to deliver to consumers. The degree to which the water must be treated before it is returned to the environment depends on the quality of the wastewater, as well as how the water into which the wastewater is disposed will be used. For instance, wastewater that is emptied into lakes that are used for recreational swimming and fishing must be treated particularly carefully.

Industries typically do not actually consume much water (the water is used for applications, such as cooling and processing, that do not significantly diminish the amount of water), so the amount of industrial wastewater is generally very large. Industrial wastewater may contain many contaminants, such as toxic metals, organic chemicals, and radioactive materials. Before it can be returned to the water supply, this wastewater must be carefully evaluated and treated, using many of the same techniques for water treatment described above. Then, the industrial wastewater, like municipal wastewater, is released into rivers, lakes, or estuaries.

Agricultural wastewater often contains soil sediment, as well as potentially harmful materials such as pesticides, fertilizers (which may cause an overgrowth of algae), and animal wastes (which may harbor disease-causing organisms). Unfortunately, the wastewater from agriculture often drains directly into streams, rivers, and lakes. Hence, a great deal of concern has arisen about the types of pesticides and fertilizers that are used.

Additional Links:

- The St. Louis Water Company's web site gives information about the analysis and treatment procedures that are used for our local water supply.
- This site, from the Doulton Water Filters company, contains a wealth of information about contaminants in the water and how the contaminants are removed. Check out their "Six Chapter Training Guide to Water and its Problems" in particular.
- This tutorial developed at Washington University in St. Louis discusses the chemistry behind acid rain, an important contributor to contamination in the water supply.
- Another tutorial from Washington University in St. Louis provides more a detailed explanation of water hardness, and the strategies for dealing with this problem.
- Collier County, Florida Water Department also has an extensive web site.

References:

Greenwood, N.N. and Earnshaw, A. In *Chemistry of the Elements*, Pergamon Press, 1984, p. 1269.

Letterman, D., ed. *Water Quality and Treatment, 5th Edition.* American Waterworks Association. New York: McGraw-Hill.1999

Oxtoby, D.W. and Nachtrieb, N.H. *Principles of Modern Chemistry*, 3rd ed., Fort Worth: Saunders College Publishing, 1996, p. 140-144.

Persistence of Vision Ray Tracer (POV-Ray). URL: *http://www.povray.org*.

PowderCell for Windows. Kraus, W. and Nolye, G.; *Bundesanstalt f�r Materialforschung und -pr�fung (BAM).*
URL: *http://www.bam.de/de/service/publikationen/powder_cell.htm*.

Tebbutt, T.H.Y. *BASIC Water and Wastewater Treatment*, London: Butterworths, 1990.

Viessman, W. and Hammer, M.J. *Water Supply and Pollution Control*, 6th ed., Menlo Park, CA: Addison-Wesley, 1998.

"Where is Earth's Water Located?" *Water Science for Schools.* United States Geological Survey, 1999. URL: *http://ga.water.usgs.gov/edu/earthwherewater.html.*

Acknowledgements:

The authors thank Dewey Holten, Michelle Gilbertson, Jody Proctor and Carolyn Herman for many helpful suggestions in the writing of this tutorial.

The development of this tutorial was supported by a grant from the Howard Hughes Medical Institute, through the Undergraduate Biological Sciences Education program, Grant HHMI# 71199-502008 to Washington University.

This page was updated 9/5/08