SECTION 9.3

Water Quality

Key Terms

- fresh water
- ground water
- surface water
- hard water
- soft water
- maximum allowable concentration (MAC)

fresh water water that is not salty

ground water water that seeps through the ground below the surface

surface water water on the surface of the land

Water is the most abundant substance on Earth's surface. However, naturally available water is never pure because it can dissolve so many substances. Some of the dissolved substances are beneficial to human health, but others are harmful. Many of the harmful substances are pollutants such as pesticides, exhaust gases from vehicles, and by-products of industrial processes.

Over 97 percent, by mass, of Earth's water is in the oceans. Ocean water contains dissolved substances—mainly salts—that make it unsuitable for drinking or irrigation unless it is first treated. So, less than 3 percent of the water on Earth is **fresh water**. Most of this fresh water is in the form of polar ice. A large amount of Earth's **ground water** is not easily accessible because it is in remote locations or too far below Earth's surface. **Surface water**, such as lakes, rivers, and reservoirs, is a tiny fraction of the water on Earth—less than 0.02 percent, as shown in **Figure 9.8**.

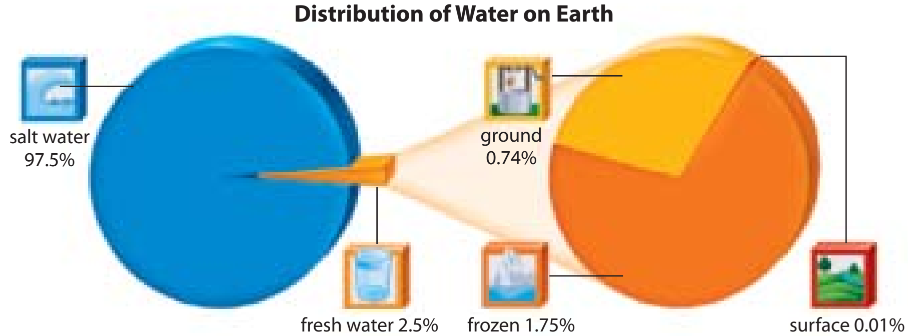

Figure 9.8 Very little of the water on Earth is fresh water, and very little fresh water is available for people to drink.

Interpret *About what percentage of the water on Earth is unavailable for human consumption?*

Canada, which has less than 1 percent of the world's population, has 22 percent of the world's source of fresh water. So, in most regions of Canada, the *quality* of the water is usually of greater concern than the quantity available. Water quality is affected by the substances that have dissolved in it. The sources of these substances can be divided into three broad categories: naturally occurring materials, pollutants, and treatments used to improve the water for human consumption. Many of the ions that are found in water come from more than one of these categories of sources.

Harmful Substances from Natural Sources

The water cycle on Earth circulates water from the land to the sky, and back again. The natural supply of fresh water comes from rain and snow, which contains dissolved gases from the atmosphere. When carbon dioxide gas in the atmosphere dissolves in water, the resulting solution behaves like a dilute solution of carbonic acid:

$$CO_2(g) + H_2O(\ell) \longrightarrow H_2CO_3(aq)$$

As this slightly acidic water filters through soil and rock, it dissolves certain compounds from these materials. Ions that leach into ground water in this way include calcium, magnesium, iron(II), iron (III), carbonate, and sulfate. Most of the ions are largely harmless to plants and animals, and calcium is often beneficial. However, in some parts of the world, ions such as arsenic and fluoride may be present in concentrations that are high enough to be harmful to human health.

Harmful Arsenic Ions in Drinking Water

Arsenic is found naturally in the ground water beneath river deltas, where minerals containing arsenic compounds have been deposited as sediment. In these locations, arsenic is present as ions, such as the arsenate ion, $AsO_4^{3-}(aq)$.

In most of Canada, the concentration of arsenic in ground water is less than 5 ppb, which is considered to be safe. However, in Bangladesh, which is mainly delta land, as many as 35 million people have drinking water that contains more than 50 ppb of arsenic. Long-term exposure to arsenic in drinking water can cause cancer and may be linked to diabetes and other medical problems.

Risks and Benefits of Fluoride Ions in Drinking Water

Fluorine is the 17th most abundant element in Earth's crust, and all water supplies contain some fluoride ions. Too many fluoride ions leads to stained teeth, called *dental fluorosis*, shown in **Figure 9.9**. But if the concentration of fluoride ions in drinking water is less than 1 ppm, people benefit from healthier teeth without staining. Fluoride ions form strong ionic bonds. When fluoride ions replace some of the cations that are present in tooth enamel, the enamel becomes more resistant to decay. In regions where the natural concentration of fluoride ions is relatively low, many municipalities add fluoride ions to the water supply to boost the concentration to a level that will help prevent tooth decay.

Figure 9.9 Fluoride ions prevent tooth decay, but too much fluoride can cause brown stains on teeth.

Activity 9.3 Removing Phosphate Ions from Drinking Water

The solubility of phosphate ions, $PO_4^{3-}(aq)$, is similar to the solubility of arsenate ions, $AsO_4^{3-}(aq)$. Phosphate ions can enter ground water as a result of pollution from fertilizers. You will model the precipitation of arsenate ions and phosphate ions using sodium phosphate, $Na_3PO_4(aq)$. Which reaction(s) could be effective for removing arsenate and phosphate ions from drinking water?

Safety Precautions

- Wear chemical safety goggles throughout this activity.
- Wear a lab coat or apron throughout this activity.
- If you spill any calcium hydroxide solution on your skin, wash it off immediately with plenty of cool water.
- When you have completed this activity, wash your hands.

Materials

- 0.1 mol/L sodium phosphate, $Na_3PO_4(aq)$
- 0.1 mol/L aluminum sulfate, $Al_2(SO_4)_3(aq)$, in a dropper bottle
- saturated solution of calcium hydroxide, $Ca(OH)_2(aq)$, in a dropper bottle
- 0.1 mol/L iron(III) sulfate, $Fe_2(SO_4)_3(aq)$, in a dropper bottle
- 4 test tubes with stoppers
- test-tube rack

Procedure

1. Design a table for recording the results of adding three different solutions to a solution of sodium phosphate.
2. Pour a few millilitres of sodium phosphate solution into each of four test tubes. Make sure that the volume of sodium phosphate is about the same in all the test tubes.
3. Add a few drops of aluminum sulfate solution to the first test tube. Cover the test tube with a stopper, and shake the test tube while holding the stopper down. Describe the precipitate that forms. Continue adding aluminum sulfate solution and shaking the test tube until no more precipitate forms. Place the test tube into the test-tube rack for later observation.
4. Repeat step 3 for each of the other two solutions.
5. Shake the fourth test tube, without adding anything to the sodium phosphate solution.
6. Compare the precipitates. Note which precipitates, if any, did not settle at the bottom of the test tube. Also compare the relative total volumes in the test tubes to determine which required the largest volume of reactant to cause complete precipitation.

Questions

1. Based on your observations, which precipitate should be relatively easy to separate by filtration? Explain.
2. Compare the volumes of the reactants you needed to precipitate all the phosphate ions.
3. What can you conclude from your observations of the fourth test tube?
4. Write the net ionic equation for each reaction.
5. What factors would you consider if you were choosing one of the three reactants in this activity to precipitate arsenate ions or phosphate ions from drinking water?

Calcium and Magnesium Ions Can Cause Hard Water

hard water water that contains relatively large concentrations of ions that form insoluble compounds with soap

soft water water that contains relatively small concentrations of ions that form insoluble compounds with soap

Ground water always contains ions dissolved from the surrounding rocks. The rocks shown in **Figure 9.10** are limestone, which is primarily calcium carbonate, $CaCO_3(s)$. Calcium ions enter into solution by reacting with the carbonic acid that is present in rainwater according to the following net ionic equation:

$$CaCO_3(s) + 2H^+(aq) + CO_3^{2-}(aq) \longrightarrow Ca^{2+}(aq) + 2HCO_3^-(aq)$$

If your water supply has a large concentration of calcium ions, you may notice that you have difficulty forming a lather with soap. Soap reacts with dissolved calcium and magnesium ions to form a scum of insoluble substances. Water with high concentrations of dissolved calcium and magnesium ions is called **hard water**. Water with relatively low concentrations of these ions is called **soft water** and lathers readily.

Figure 9.10 Many of the rocks in southern Ontario are limestone, which makes most of the water in this region hard.

Figure 9.11 The lime scale in this water pipe was caused by hard water.

Another sign of hard water is calcium carbonate deposits (often called lime scale) that build up inside water pipes, kettles, and humidifiers, as shown in **Figure 9.11**. You can use ordinary white vinegar to remove lime scale from the inside of a kettle or humidifier. Vinegar is an aqueous solution of acetic acid, $CH_3COOH(aq)$. Acetic acid reacts with the calcium and magnesium carbonates in the scale to form soluble compounds. (Remember that all acetates are soluble.) The following equation shows the reaction between calcium carbonate and acetic acid:

$$CaCO_3(s) + 2CH_3COOH(aq) \longrightarrow Ca(CH_3COO)_2(aq) + H_2O(\ell) + CO_2(g)$$

Learning Check

13. Is the water in your home hard or soft? What observations support your opinion?

14. What ions are you likely to find in greater concentrations in hard water than in soft water?

15. Why does the hardness of water differ from place to place throughout the world?

16. In Bangladesh, water from relatively shallow wells is likely to contain a greater concentration of arsenic than surface water or water from deep wells. Suggest a reason for this difference.

17. Why is a chemical treatment that precipitates phosphate ions from an aqueous solution likely to remove arsenate ions from ground water?

18. What are the signs of dental fluorosis? If you were a dentist and saw these signs in a patient, what advice would you offer?

Harmful Water Pollutants from Human Activities

Human activities, such as manufacturing, farming, transportation, and garbage disposal, can lead to the pollution of water systems. Sources of pollutants are often classified as either point source or non-point source:

- A *point source* of pollution has a single source with a specific location, as shown in **Figure 9.12 (A)**. Examples include a wrecked tanker that is leaking oil or a pulp mill that discharges effluent into a river.
- A *non-point source* of pollution does not come from a single, easily defined location. A non-point source may involve substances spread over large areas, such as pesticides and fertilizers from farmland or golf courses, as shown in **Figure 9.12 (B)**. A non-point source can also be a combination of thousands or even millions of small point sources, such as the exhaust from cars or the mercury from compact fluorescent lamps (CFLs).

The cumulative effect of many small point sources of pollution on Ontario's lakes and ground water is a major problem. In 2009, Ontario introduced the Cosmetic Pesticide Act to protect the environment from harmful lawn and garden pesticides. Yet, pollutants including lead, mercury, nitrates, and phosphates remain a problem in Canada and around the world.

Figure 9.12 (A) Point source of pollution: Waste water from a factory can quickly pollute a body of water. **(B)** Non-point source of pollution: Run-off from farms can carry fertilizer and pesticides into nearby waterways.

Effects and Sources of Lead Pollution

Exposure to lead can cause a variety of medical problems, including abdominal pain, kidney failure, nerve damage, and brain disorders. Babies and children are particularly susceptible. Lead in fresh water rarely comes from natural sources. Much of the lead in municipal drinking water comes from old water pipes. Until the 1950s, lead pipe was commonly used for the underground connection from a water main to a home because lead lasts longer than iron when buried in the ground. At that time, the potential health effects of the small amount of lead that leaches from a lead pipe were not known. Many municipalities now have programs to replace underground lead pipes.

Lead is released into the environment by some industrial processes, especially ore smelting, the manufacture and recycling of car batteries, and the production of some types of plastic. Over the last 30 years, the concentrations of lead measured in the air and the oceans have dropped dramatically—more than 75 percent in some tests. This decrease is largely the result of a worldwide effort to phase out the use of leaded gasoline. In 1990, Canada banned the use of leaded gasoline in on-road vehicles.

Effects and Sources of Mercury Pollution

Mercury and most mercury compounds are highly toxic. They affect the central nervous system, producing symptoms such as tremors, irritability, insomnia, numbness, and tunnel vision. Mercury can also damage the liver and kidneys. Some mercury exposure does come from natural sources. For example, volcanoes may be responsible for about half of the mercury in the atmosphere. However, much of the mercury deposited in the Great Lakes comes from emissions from coal-fired power plants. Other major sources of mercury emissions include gold mines, cement plants, and smelters for non-ferrous metals.

Effects and Sources of Nitrate and Phosphate Pollution

Livestock waste and nitrogen-based fertilizers are the greatest sources of nitrate ion, $NO_3^-(aq)$, pollution in Canada. Nitrate fertilizer is applied to farmland to increase crop yields, but the soluble fertilizer easily finds its way into lakes and rivers. There, it increases the growth of plants and algae, as shown in **Figure 9.13**. Phosphate ions, $PO_4^{3-}(aq)$, also promote excessive growth of aquatic plants. When bacteria decompose the remains of these plants, dissolved oxygen is removed from the water. The decreased oxygen supply puts stress on fish, especially in the summer when warmer water naturally contains less dissolved oxygen. In the 1960s, Lake Erie experienced many *algal blooms*: rapid growths of large quantities of algae. **Figure 9.14** shows how algal blooms happen and how they affect an aquatic wetland.

Figure 9.13 Nitrate and phosphate pollution can cause excessive plant growth in lakes and rivers.

A high concentration of nitrate ions in drinking water is harmful to babies who are less than three months old. Bacteria in a baby's digestive system convert nitrate ions to nitrite ions, $NO_2^-(aq)$. When the nitrite ions enter the bloodstream, they bond to hemoglobin, leaving less hemoglobin available to carry oxygen in the bloodstream. The baby's tissues can become starved for oxygen, causing the lips and fingertips to become blue. This condition is called *blue-baby syndrome*. Older babies are less susceptible to this condition since they have more acid in their stomach. Stomach acid inhibits the bacteria that convert nitrate ions to nitrite ions.

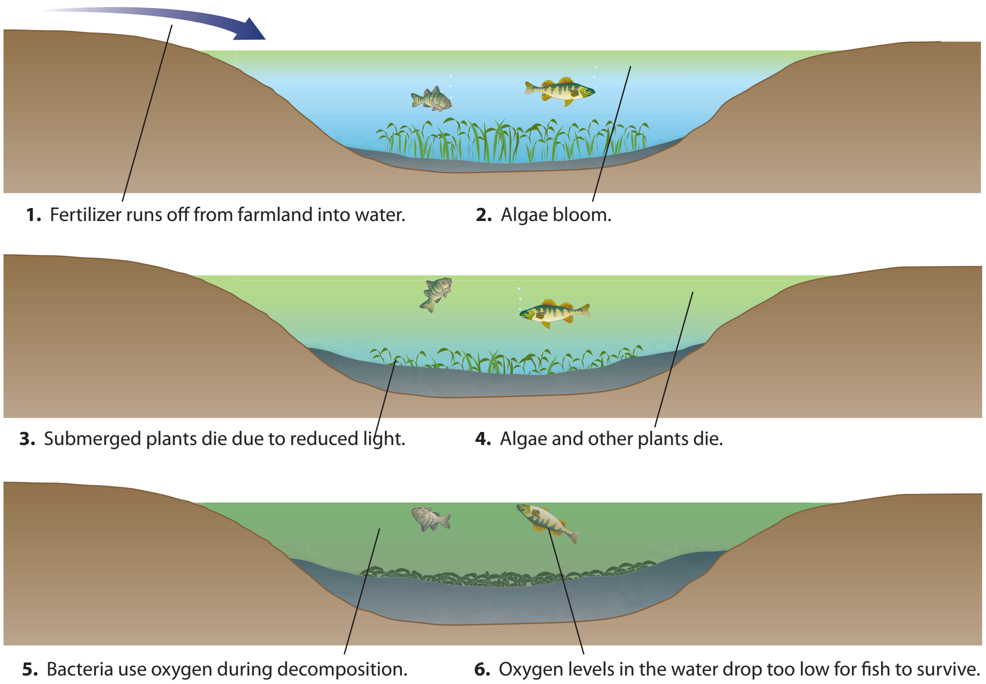

Figure 9.14 Although algal blooms appear to help plant growth at first, the overall environmental effect is negative because of the loss of both plant and animal life.

How Airborne Pollution Contributes to Water Pollution

Motor vehicles, refineries, and many factories release carbon dioxide, sulfur dioxide, and nitrogen oxide gases. These non-metallic oxides dissolve in rainwater and contribute to the formation of acid rain. The greater the acidity, the greater the amounts of various compounds dissolved from soil and rocks by the rainwater. For example, aluminum is the most abundant metal in Earth's crust. Acidified rainwater leaches more aluminum ions into ground water and surface water. The dissolved aluminum ions can harm fish, since these ions impede the extraction of oxygen from water in the gills.

Leachates from Plastics

Drinking water may contain dissolved substances from unexpected sources. For example, polycarbonates are hard, clear plastics that are commonly used to make water bottles and other containers, like the containers shown in **Figure 9.15**. Polycarbonates are made using a chemical called bisphenol A, often abbreviated as BPA. A polycarbonate bottle can leach BPA into the water it contains. BPA is known to trigger biological changes like those caused by estrogen, the female sex hormone. Recent research suggests that BPA exposure is linked to breast cancer and heart disease, and may be a factor in several other serious disorders.

Canada was the first country to ban BPA from baby bottles and to restrict its use for lining infant formula cans. However, BPA is still used for making a variety of products, including kitchen containers, and for lining food and beverage cans. Unless processed in a properly contained landfill or recycling centre, discarded plastic containers can leach BPA and other pollutants into the environment.

Figure 9.15 Bisphenol A can leach from polycarbonate containers, such as these water cooler jugs.

maximum allowable concentration (MAC) a drinking water standard for a substance that is known or suspected to affect health when above a certain concentration

Drinking Water Standards

Ideally, drinking water should be clear and colourless, and it should not have an unpleasant taste or odour. More critically, drinking water must not contain disease-causing organisms or unsafe concentrations of compounds that could affect health. The absence of detectable micro-organisms, such as *E. coli* and coliform bacteria, is one example of a standard for drinking water quality. Ontario has standards for drinking water quality that specify the **maximum allowable concentration (MAC)** of many substances and micro-organisms that are known to affect human health. For example, drinking water must contain no *E. coli* bacteria and no more than five coliform bacteria per 100 mL.

In Canada, the federal, provincial, and territorial governments co-operate to produce guidelines for drinking water. These guidelines are the basis for the provincial and territorial standards. The guidelines and standards are often adjusted in response to new research about possible hazards. When insufficient data are available to establish a MAC with reasonable certainty, an *interim* maximum acceptable concentration (IMAC) is stated. The guidelines for drinking water also include aesthetic objectives (AOs), which suggest limits for substances that affect the taste, odour, or colour of drinking water but are not health hazards. **Table 9.3** lists some of the standards for chemicals in drinking water.

Suggested Investigation

Plan Your Own Investigation 9-C, Testing Drinking Water

Table 9.3 Maximum Concentrations of Selected Ions and Compounds in Ontario's Drinking Water

Ions or Compounds (Common Sources)	Maximum Allowable Concentration (mg/L)	Interim Maximum Allowable Concentration (mg/L)	Aesthetic Objective (mg/L)
arsenic, As^{3+}(aq), and As^{5+}(aq) (some types of soil and rock; mining activities)		0.025	
cadmium, Cd^{2+}(aq) (some types of batteries)	0.005		
iron, Fe^{2+}(aq) and Fe^{3+} (some types of rock; iron water mains)			0.3
lead, Pb^{2+}(aq) (lead-alloy solder; lead water pipes; old house paint*)	0.01		
mercury, Hg_2^{2+}(aq) and Hg^{2+}(aq) (fluorescent lamps; some batteries; some types of fish, such as tuna)	0.001		
chloride, Cl^-(aq) (water treatment)			250
fluoride, F^-(aq) (some rocks; water treatment)	1.5		
nitrate, NO_3^-(aq), and nitrite, NO_2^-(aq) (fertilizer; animal waste)	10.0		
Alachlor (herbicide)		0.005	
Benzene (component of gasoline)	0.005		
Dioxin and furan (burning of waste, especially plastics)		0.000 000 015	

*Lead is no longer permitted in water-supply piping, and lead in new house paint must not exceed 0.06 percent (m/m). **Source:** Ontario Ministry of the Environment

Section 9.3 REVIEW

Section Summary

- Only a tiny fraction of the water on Earth is readily available fresh water.
- Drinking water is obtained from surface water and ground water, and always contains dissolved substances from the environment.
- The dissolved substances in fresh water can include naturally occurring materials, pollutants, and chemicals added for water treatments.
- Drinking water standards specify the maximum allowable concentrations of substances that are known to affect human health.

Review Questions

1. K/U The substances that are dissolved in fresh water can be divided into three broad categories. List these categories, and give an example of a substance and a source for each.
2. K/U Describe two ways that you could test for hard water.
3. A List two point sources of pollution and two non-point sources of pollution that may affect your local water supply.
4. K/U How might sediment deposited by a river affect the quality of local ground water?
5. K/U List four household substances that can pollute the ground water if disposed of improperly.
6. A Describe a process that could be used to remove arsenic from drinking and irrigation water. Suggest reasons why this process is not used on a large scale in Bangladesh.
7. T/I Road salt is applied on ice-covered roads to improve driving conditions. When the ice melts, it dissolves the road salt. Is the run-off that contains the dissolved road salt a point source of pollution? Explain your reasoning.
8. T/I Why should the well water on a farm be tested regularly? Which contaminants would be of most concern?
9. C Which ions or compounds in **Table 9.3** have the lowest acceptable concentration? Draft a letter to the editor of your local newspaper, explaining the source of these ions or compounds. In your letter, describe what people can do to ensure that this type of pollution does not occur.
10. T/I Use **Table 9.3** to decide which of the following are unacceptable in a sample of drinking water. Which of the following should be of most concern? Explain your reasoning.
    - iron ions, 0.35 mg/L
    - chloride ions, 200 ppm
    - benzene, 0.000 007 g/L
11. K/U Excessive plant growth in a body of water is called an *algal bloom*.
    a. What substances cause algal blooms?
    b. List two sources of this type of pollution.
    c. Why might fish in a water system with this type of pollution be at risk, especially on a hot summer day?
12. C Volatile organic compounds (VOCs) include gasoline fumes and vapours from solvents. The table below lists the main sources of VOC emissions in Canada. Use the data in the table to construct a pie chart.

Sources of VOC Emissions in Canada*

Source	Percentage (%)
Combustion of fossil fuels for transportation	44
Production and distribution of petroleum and natural gas	26
Commercial and consumer products (e.g., solvents, paints)	12
Combustion of wood for home heating	8
Other sources	10

*Does not include sources such as agricultural animals and forest fires. **Source:** Environment Canada

13. A Crawford Lake is a small lake on the Niagara Escarpment in southern Ontario. This lake is unusually deep for its size. The rock cap of the escarpment is limestone, which contains both calcium carbonate, $CaCO_3(s)$, and magnesium carbonate, $Mg(CO_3)_2(s)$.
    a. Is the water in Crawford Lake more likely to be hard or soft? Explain your reasoning.
    b. Below a depth of 15 m, the water in Crawford Lake contains very little dissolved oxygen. Suggest why the shape of the lake causes this lack of oxygen.
14. A Herbicides can increase crop yields by preventing the growth of weeds. Discuss the risks and benefits of using a herbicide that is slow to break down into less potent chemicals.