Aqueous Solutions and Water Quality

9.4

Water, as you know, is the most abundant substance on Earth's surface. Unfortunately there is more than enough water in some places, but not enough in others. As well, because water is used and re-used, and because it is such a powerful solvent, it is easily polluted.

Canada, with less than 1% of the world's population, has 22% of its fresh water. So, in most regions of our country, the *quality* of water is usually of greater concern than the quantity available. In this section, you will examine factors that affect water quality. You will also study some of the reactions that make polluted water safe and fit to drink.

Acceptable Concentrations of Substances in Drinking Water

The federal government assesses the health risks of specific substances in drinking water. Guidelines for acceptable concentrations of each substance are then established in partnership with provincial and territorial governments. See Table 9.5. These governments require water suppliers to meet the guidelines. Corrective action may be taken when guidelines are violated.

Table 9.5 Acceptable Concentrations of Selected Ions and Compounds in Drinking Water

Ion or compound	Maximum Acceptable Concentration (MAC) (mg/L)	Interim Maximum Acceptable Concentration (mg/L)	Aesthetic Objectives (AO) (mg/L)
aldrin and dieldrin (organic insecticides*)	0.0007		
aluminum		<0.1 or <0.2**	
arsenic		0.025	
benzene (organic component of gasoline)	0.005		
cadmium (component of batteries)	0.005		
chloride			≤250
fluoride	1.5		
iron			≤0.3
lead	0.010		
malathion (organic insecticide)	0.19		
mercury	0.001		
selenium	0.01		
sulfide (as H_2S)			≤0.05
toluene (organic solvent)			≤0.024
uranium	0.1		

*As you will learn in Unit 5, the term "organic" refers to most compounds structured around the element carbon. Toluene belongs to a large class of petroleum-related compounds called hydrocarbons.
** Health-based guidelines have not yet been established. The concentrations that are listed depend on the method of treatment. They are noted as a precautionary measure.

Section Preview/ Specific Expectations

In this section, you will

- **explain** the origins of pollutants in natural waters
- **identify** the allowed concentrations of pollutants in drinking water
- **explain** the origins and consequences of water hardness, and **outline** methods for softening hard water
- **describe** the technology involved in purifying drinking water and treating waste water
- **communicate** your understanding of the following terms: *water treatment, hard water, soft water, ion exchange, waste-water treatment*

CHECKPOINT

You are probably familiar with the water cycle: the natural process that ensures a continual supply of Earth's water. Sketch, from memory, a schematic drawing of the water cycle. Add labels to indicate the states and energy changes involved. Then infer the main solutes and suspended materials in water at each of the following locations:

- the atmosphere
- Earth's surface (at an urban and a rural location)
- below Earth's surface (that is, in ground water)
- a fresh-water lake
- an ocean

For each location, suggest sources of the solutes and materials you inferred.

CHEM FACT

Drinking water guidelines exist for microscopic organisms, such as bacteria and protozoans, as well as for chemicals. These guidelines were compromised in the town of Walkerton, Ontario, in 2000. Seven people died and about 2000 people became ill as a result of exposure to *E. coli* bacteria that were present in the town's water supply. The maximum acceptable concentration for *E. coli* bacteria is zero organisms detectable in 100 mL of drinking water. To achieve this target, chlorine is commonly used to kill *E. coli* and other organisms in drinking water. Despite receiving two warnings from the Ministry of the Environment, the town's water manager chose not to increase the concentration of chlorine in the water supply. As a result of this incident, the Ontario government drafted legislation to enforce strict adherence to water quality guidelines.

Sources That Compromise Water Quality

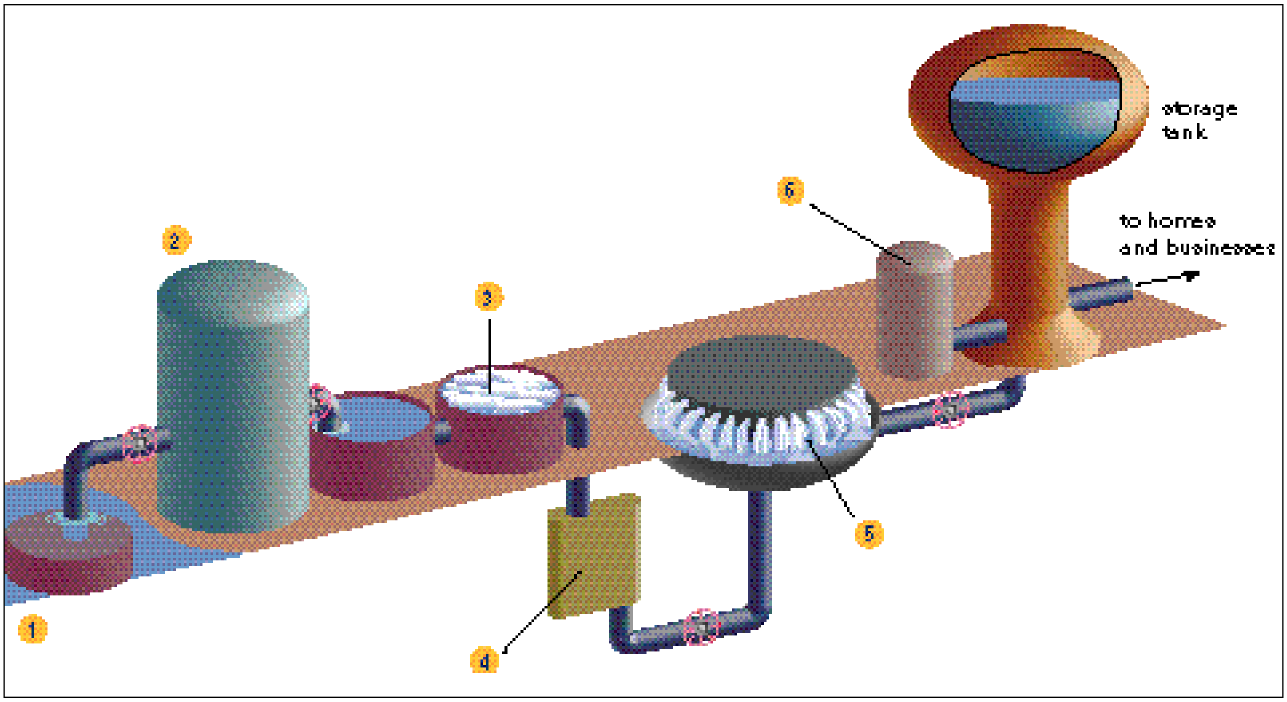
Pure water does not exist in nature. All water naturally contains dissolved substances or ions. For example, rainwater is naturally acidic. This is because water droplets dissolve atmospheric gases, such as carbon dioxide, to form carbonic acid, H_2CO_3. As water filters through soil and rock, it tends to dissolve (leach) certain ions and compounds, such as $Ca^{2+}{}_{(aq)}$, $Mg^{2+}{}_{(aq)}$, $Fe^{2+}{}_{(aq)}$, $Fe^{3+}{}_{(aq)}$, and $SO_4{}^{2-}{}_{(aq)}$. In general, these substances pose little or no threat to plants, animals, or you. In contrast, many of the substances listed in Table 9.5 may pose a threat. They result mainly from human activities, such as manufacturing, food and materials processing, farming, and garbage disposal. The sources of these substances can be classified in the following three broad categories.

- *Point Sources*: A manufacturing or processing plant that discharges untreated or insufficiently treated waste water into a river or lake is a point source of pollution. Point sources include wrecked tankers that leak oil and factories that discharge metallic ions, organic compounds, acids, and bases. Water itself can be a point source of thermal pollution, when thermal power plants discharge warm water into a lake from their cooling towers. Point sources can spread pollution over huge areas.
- *Diffuse Sources*: Pollution that comes from a wide range of sources, not from a single source, is said to come from a diffuse source. (See Figure 9.7.) A heavy downpour can cause run-off from farm fields to enter rivers and lakes. This run-off often carries undesirable pollutants, including fecal matter, pesticides, and fertilizer compounds, such as nitrates and phosphates.
- *Indirect Sources*: Air, water, and soil can become polluted from a variety of indirect sources. Motor vehicles and factory smokestacks release gases that can indirectly cause many different types of pollution. The acidic gases that are produced (sulfur dioxide and nitrogen oxides) dissolve and contribute to the formation of acid rain. The concentrations of ions in ground water are affected by how acidic the water is. For example, aluminum compounds are commonly found in soil. Acidic water increases the leaching of aluminum ions into rivers and lakes.

Figure 9.7 ***Landfill leachate* is rainwater that has percolated through landfill wastes. It dissolves numerous compounds, many of them toxic. Modern landfills have containment and treatment procedures to prevent this diffuse source of pollution from contaminating ground water.**

Treating Water for Your Home

If you live on a farm or in a remote area, you probably obtain your water directly from a well on your property. If you live in an urban community, you probably obtain your water through a municipal or regional water authority. Before the water is made available to you, it is processed at a **water treatment** plant to remove pollutants. Lake, river, or reservoir water enters the treatment plant, where a number of physical and chemical processes take place. Figure 9.8 summarizes these processes.



1. A coarse screen made of metal bars filters large particles and trash such as bottles and cans.
2. Chlorine is added to kill bacteria and viruses. It also helps to remove dissolved hydrogen sulfide:
3. A process called *flocculation* removes suspended particles such as clay and microorganisms. Lime (CaO) and aluminum sulfate () are added. They react together to form aluminum hydroxide:

   Aluminum hydroxide is a sticky gel that traps the finely suspended particles. Lime is a basic oxide, so it decreases the acidity of the water, and it precipitates some calcium carbonate. The aluminum hydroxide with its trapped particles settles to the bottom of the tank.
4. The water is passed through a bed of graded gravel and sand in a filtering tank.
5. Water is often saturated with oxygen by spraying it into the air, which helps to remove volatile organic compounds and improves the taste and odour.
6. The water receives a second treatment with chlorine to kill bacteria. Ammonia is added to make the chlorine last longer in the piping. Some municipalities add compounds such as sodium fluoride.

Figure 9.8 **The following processes take place at a water treatment plant. These processes must ensure that the water meets all the allowable concentrations.**

CHEM FACT

Why is hard water so hard to lather? Ordinary soap is often sodium stearate, $NaC_{17}H_{35}O_2$. Sodium stearate consists of the sodium salt of a compound that contains many carbon atoms. The calcium ions in hard water displace the sodium ions, and the new salts are insoluble:

$$Ca^{2+}_{(aq)} + 2NaC_{17}H_{35}O_{2(aq)} \rightarrow Ca(C_{17}H_{35}O_2)_{2(s)} + 2Na^{+}_{(aq)}$$

As a result, the effectiveness of the soap is reduced. The insoluble salts form a scum on clothing and a grey slimy deposit in sinks and bathtubs: "bathtub ring."

Hard Water and Soft Water

The water that flows through your faucet has been treated to remove, or limit, a large number of pollutants. It is far from pure, however. For example, it still contains dissolved ions, such as $Ca^{2+}_{(aq)}$, $Mg^{2+}_{(aq)}$, $Fe^{2+}_{(aq)}$, $Fe^{3+}_{(aq)}$, and $SO_4{}^{2-}{}_{(aq)}$. These ions, especially calcium and magnesium, make it difficult to form lather with soap. Water with high concentrations of these ions is called **hard water**, partly because it is "hard" to lather. Water with relatively low concentrations of these ions lathers well. It is called **soft water**.

Ground water is usually harder than surface water in the same region. The extent of the hardness depends on the types of rocks through which the water flows. It also depends on the length of time that the water is in contact with the rocks. The Rocky Mountains, the Canadian Shield, and most of the Maritimes have very insoluble bedrock. Thus, the water in these regions is usually soft. The sedimentary rocks of the Niagara Peninsula and the Prairies are more soluble, resulting in water that ranges from moderately hard to very hard.

The most common type of rock to cause hard water is limestone (calcium carbonate). Limestone is usually considered insoluble. The small amount that does dissolve forms low concentrations of important ions.

$$CaCO_{3(s)} + H_2O_{(\ell)} \rightarrow Ca^{2+}_{(aq)} + HCO^{-}{}_{3(aq)} + OH^{-}_{(aq)}$$

When the water contains dissolved acids (often H_2CO_3 from rainwater), the $H^{+}_{(aq)}$ ion increases the concentrations of calcium and hydrogen carbonate ions.

$$CaCO_{3(s)} + H^{+}_{(aq)} \rightarrow Ca^{2+}_{(aq)} + HCO^{3-}{}_{(aq)}$$

Hydrogen carbonate ions can be economically costly. Solutions that contain these ions decompose when heated to form carbonates.

$$2HCO_3{}^{-}{}_{(aq)} \rightarrow H_2O_{(\ell)} + CO_{2(g)} + CO_3{}^{2-}{}_{(aq)}$$

The carbonate ions recombine with calcium ions to form calcium carbonate deposits. These deposits form a coating on heating elements in kettles and boilers, and build up inside hot water pipes. The coating is commonly called boiler scale. (See Figure 9.9.) It not only reduces the flow of water in pipes, but it also increases the cost of heating the water.

A simple way to remove boiler scale from the inside of a kettle or a coffee maker is to add vinegar. Acetic acid in vinegar reacts with calcium (and magnesium) carbonates to form soluble salts. (Remember that all acetates are soluble.)

$$CaCO_{3(s)} + 2CH_3COOH_{(aq)} \rightarrow Ca^{2+}_{(aq)} + 2CH_3COO^{-}_{(aq)} + H_2O_{(\ell)} + CO_{2(g)}$$

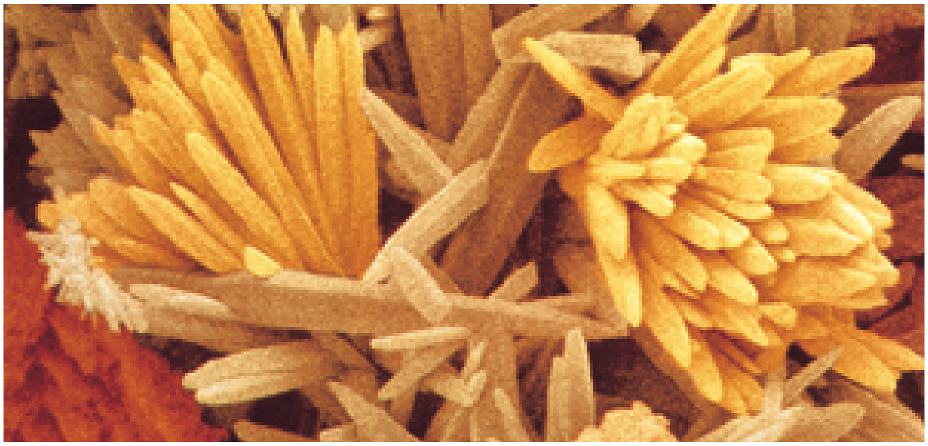


Figure 9.9 This photomicrograph shows the crystalline structure of precipitated boiler scale.

Treating Water at Home

The ions that cause hard water are not a health hazard but they can be a nuisance. They are not always removed at municipal treatment plants. If you wish, you can remove some of these ions (mainly $Ca^{2+}{}_{(aq)}$, $Mg^{2+}{}_{(aq)}$, and $Fe^{2+}{}_{(aq)}$) yourself. For relatively small volumes of water (such as enough to fill a bathtub or a washing machine), you can add sodium carbonate decahydrate, $Na_2CO_3{\cdot}10H_2O$. This compound is commonly called washing soda. It is an inexpensive way to add carbonate ion to the water. The carbonate ions precipitate the unwanted ions.

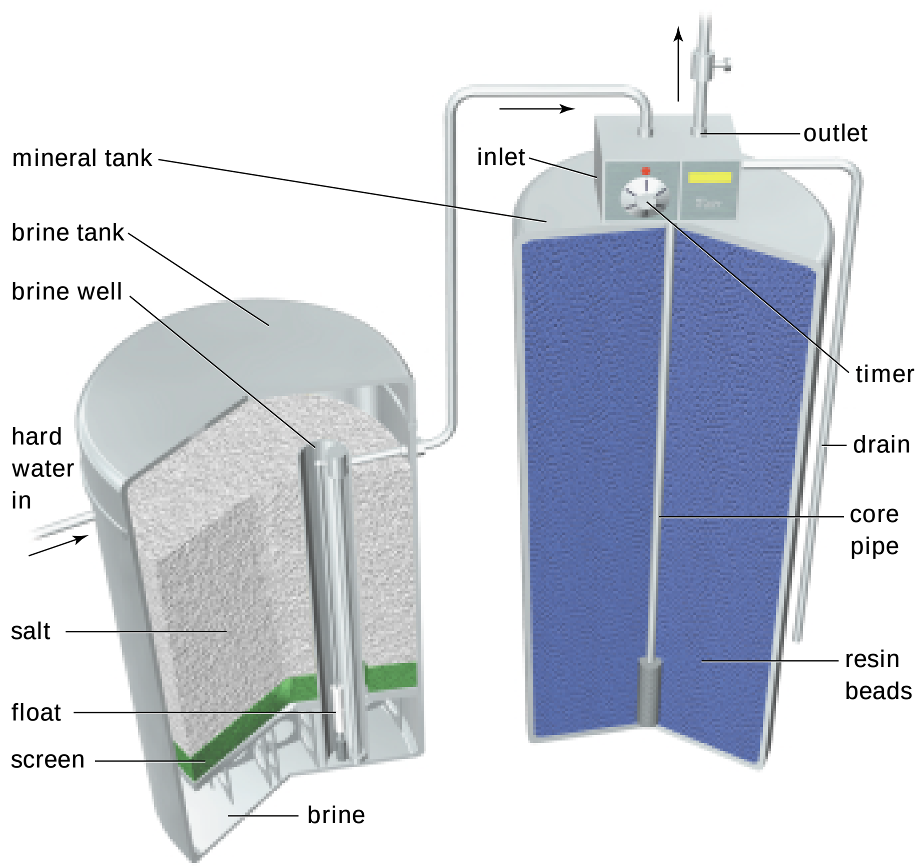
$$Ca^{2+}{}_{(aq)} + CO_3{}^{2-}{}_{(aq)} \rightarrow CaCO_{3(s)}$$

The sodium ions in the washing soda behave as spectator ions, leaving the water soft.

For the large volume of water needed on a daily basis, people often install an **ion exchange** water softener. This apparatus exchanges one kind of ion for another. (See Figure 9.10.) The hard water passes through a column that is packed with beads. The beads are made from an insoluble plastic material and are coated with sodium salts, often NaCl. (The salt-coated beads are referred to as an ion exchange resin.) As the hard water passes through the column, the ions in the water displace the sodium ions on the resin. After most of the sodium ions have been exchanged for calcium ions (and other hardness-causing ions), the resin is regenerated. This is done by passing a very concentrated solution of sodium chloride (brine) through the column. The calcium ions are flushed out of the system, along with excess sodium chloride solution.

Biology LINK

A vivid red dye is produced from a small insect, called the cochineal, that lives in the Peruvian Andes. Two chemists from Simon Fraser University in British Columbia, Dr. Cam Oehlschlager and Dr. Eva Czyzewska, have developed an improved process for extracting the natural red colouring agent from the insects. The ions that cause hard water change the colour of the dye, however. So the first step in the process uses demineralized hot water. After precipitating the dye, it is dried and used for a variety of products. Some of your classmates may be wearing examples of these products right now. Use the library or the Internet to find out what they are.



Electronic Learning Partner

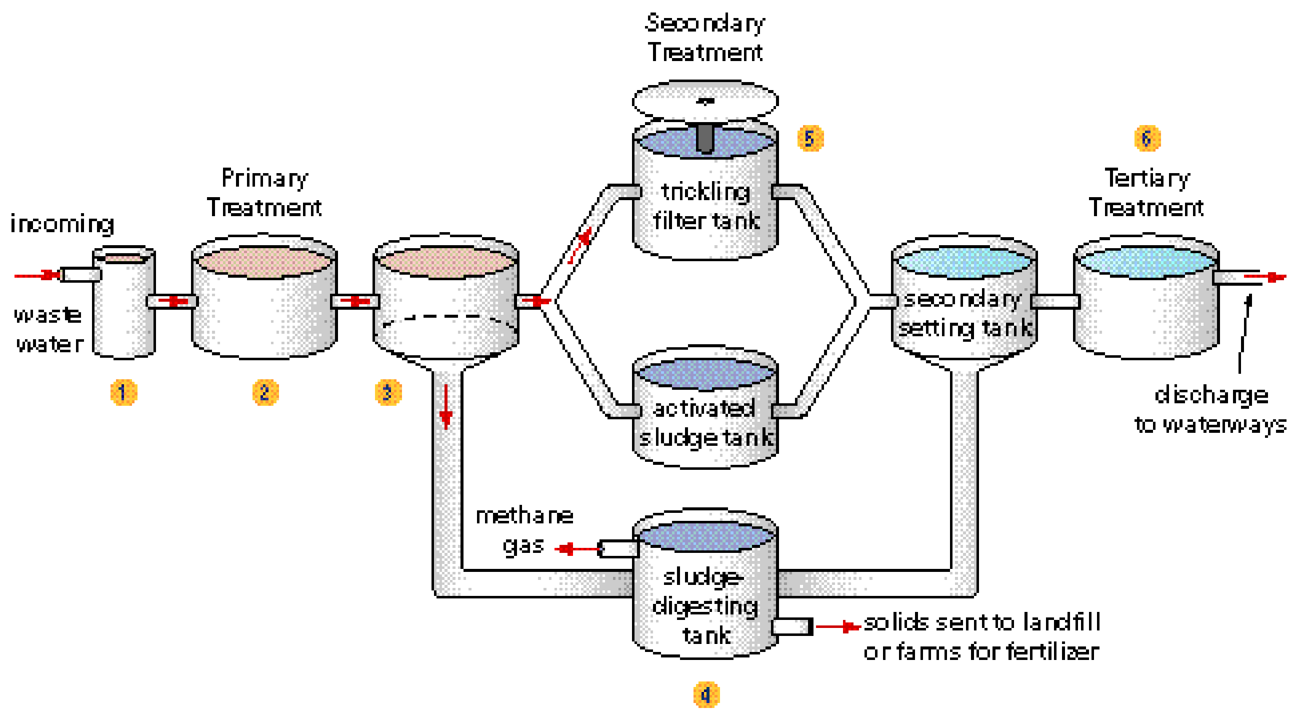
Your Chemistry 11 Electronic Learning Partner has a movie detailing several methods for purifying water.

Figure 9.10 **An ion exchange water softener adds significant amounts of sodium to the water. Thus, it may not be the best choice for drinking water. This is especially true for people on sodium-restricted diets.**

Waste-Water Treatment

The treatment of waste water (sewage) is often divided into three types: primary, secondary, and tertiary treatment. (See Figure 9.11.)

- Primary treatment mainly involves removing solids from waste water physically, using filters and settling tanks.
- Secondary treatment involves using bacteria to chemically decompose dissolved and suspended organic compounds.
- Tertiary treatment involves chemical treatments to remove the majority of remaining ions and disease-causing micro-organisms.



Primary Treatment

1 Screens remove larger solids.

2 As waste water slowly passes through a grit tank, smaller particles (such as gravel, sand, and food wastes) settle out.

3 In a sedimentation tank, finer-sized particles settle out slowly to form sludge.

4 Sludge, oils, and grease from the sedimentation tank move to a sludge-digesting tank. There they are chemically decomposed ("digested") by anaerobic bacteria.

Secondary Treatment

5 Bacterial decomposition of dissolved organic matter takes place in trickling filter tanks and activated sludge tanks.

Tertiary Treatment

6 The resulting waste water may be returned to waterways or used by industries or for irrigation. Processes such as precipitation and filtration remove most remaining pollutants. Treatment with chlorine or ozone kills most of the disease-causing micro-organisms. The resulting water is safe for most purposes, but not for drinking.

Figure 9.11 The main steps involved in the treatment of waste water: Municipalities may use one, two, or all three treatment methods, depending on their needs and finances.

ThoughtLab Testing Hard Water and Soft Water

Water is hard if it contains high concentrations of calcium and magnesium ions, and . If these ions are present in lower concentrations, the water is considered to be soft. Distilled water has few ions of any kind, and no or . Sodium oxalate, , is a compound that causes to precipitate as calcium oxalate, , and to precipitate as magnesium oxalate, .

Procedure

1. A student added 1 mL of hard water to one test tube, 1 mL of soft water to another, and 1 mL of distilled water to a third. The hard water sample contained and . The soft water contained lower concentrations of these ions.
2. Into each test tube, the student put two drops of 0.1 mol/L sodium oxalate solution. Then the student mixed the contents.

Analysis

1. Infer what the student observed in each test tube. Write a net ionic equation if you predict that a precipitate formed. Write "NR" if you think that no reaction occurred.
2. Imagine that you have the three water samples the student used, but no sodium oxalate solution. How else could you test the validity of your predictions?
3. With your teacher's permission, test your predictions. **CAUTION** Sodium oxalate is poisonous. Wear an apron and safety goggles. Handle all the solutions carefully.

Canadians in Chemistry

Dr. Jiangning Wu: Cleaning the World's Water

Around the world, researchers are working to reduce the pollutants in our lakes, rivers, and ground water. Both industry and agriculture too often produce waste water that contains everything from animal droppings and excess fertilizer to artificial colours and other chemicals. Yet, without industry and agriculture, we would not have many of the modern comforts we expect and enjoy.

Jiangning Wu was born and raised in Nanjing, China. She came to Canada to complete her studies in chemical engineering at the University of Windsor. After earning her doctorate in 1992, she turned her attention to the use of enzymes for purifying waste water.

Enzymes are naturally occurring substances that speed up chemical reactions without being used up or changed by the reactions. They are basic to living organisms. Thus it is no surprise that they are well-suited to removing organic pollutants from waste water. For instance, an enzyme that is found in horseradish helps to accelerate the oxidation of soluble organic pollutants known as phenols. The resulting compounds are less soluble and more easily removed from the waste water.

In 1993, Dr. Wu found that, with a single additive, the same enzyme was able to remove phenols from waste water. Her strategy worked even for the low concentrations of phenols typical of industrial waste water. Moreover, significantly lower concentrations of the enzyme were needed! Dr. Wu's discovery brought researchers one step closer to a commercial process, which would mean cleaner waters and less stress on the environment.

Dr. Wu is a professor in the School of Chemical Engineering at Ryerson Polytechnical University in Toronto. She is currently investigating the use of ozone for waste-water treatment and food preservation.

Section Wrap-up

In this section, you applied your understanding of aqueous solutions to explore the chemistry of water quality. Some of the chemicals you considered belong to a group of compounds that are called acids and bases. In the next chapter, you will investigate the properties and chemical behaviour of these important compounds.

CHEM FACT

Chlorine was first used to disinfect water in Britain in 1904, after a typhoid epidemic. (Typhoid is a water-borne, contagious illness that is caused by a species of *Salmonella* bacteria.) Strict limits are necessary because chlorine is ineffective when its concentration is less than 0.1 mg/L. It gives water an unpleasant taste at concentrations above 1.0 mg/L. Chlorine has a disadvantage, however. It can react with other chemicals in the water to form poisonous compounds, such as chloroform, $CHCl_3$. These chemicals may remain in solution even after the entire treatment process.

Section Review

1. **K/U** In what ways can water in the environment become polluted? Give at least two examples for each.
2. **K/U** Which chemical in Table 9.5 has the lowest acceptable concentration? Which chemical has the highest acceptable concentration? Rearrange the chemicals in the table so they are organized by concentration, from lowest to highest, rather than alphabetically by name.
3. **MC** What is the source of the water you use at home? Based on your experience with this water, which ions do you think it contains? Explain your answer.
4. **C** Use a graphic organizer to outline the main steps involved in treating drinking water and waste water.
5. **MC** An alternative to ion exchange water softening is a process called *reverse osmosis*. Use your knowledge of osmosis to infer, in general terms, how this method might work. Consult print or electronic resources to modify or expand on your ideas. Then use suitable software to communicate your findings as a graphic organizer or a virtual slide presentation.
6. **MC** One component of the waste water that enters a waste water plant for treatment is urea, $(NH_2)_2CO$.
   - **(a)** Use reference materials to find out how urea is chemically changed to nitrate ions. (There are several steps.)
   - **(b)** Write chemical equations to represent the steps involved in this process.
   - **(c)** What happens to aqueous nitrates when they are discharged to waterways in the environment?