CHAPTER

2

Cycles of Matter

Chapter Concepts

2.1 The Role of Water in Cycles of Matter

- There is a finite amount of water, which is re-used through the hydrologic cycle.
- Water is a universal solvent of polar molecules.
- Water is essential to humans and ecosystems.
- The hydrologic cycle plays a central role in nutrient cycles (biogeochemical cycles).

2.2 Biogeochemical Cycles

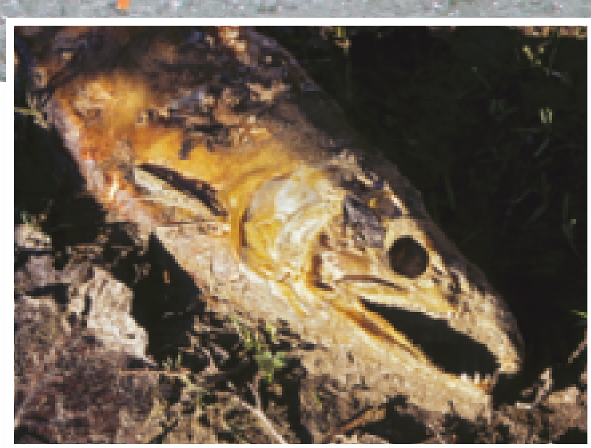
- Carbon, oxygen, sulfur, and nitrogen are found in living organisms and in the land, atmosphere, and water. They are recycled through biotic and abiotic processes.
- Phosphorus is found in living organisms and in the land and water. It is recycled through biotic and abiotic processes.
- Disruptions in one biogeochemical cycle can affect another.

2.3 The Balance of the Matter and Energy Exchange

- Biotic and abiotic processes maintain the balance of matter and energy exchange in the biosphere.
- Natural processes and human activities can affect the transfer of energy and the cycling of matter through the biosphere.

Like all plants, trees of the Pacific Northwest coastal rainforest need nitrogen from the soil to grow. New evidence from the University of British Columbia shows that, unlike most plants, coastal rainforest trees rely on the Pacific Ocean as their source of nitrogen. The urine and feces of bears and scavengers that feast on Pacific salmon are the main source of about 60 million kg of nitrogen-containing salmon tissue that "feeds" the forest soil.

Salmon need healthy forests and streams to reproduce, and forests and bears need abundant salmon. Streams need standing trees to retain soil and provide shade. So healthy streams depend on fish, and the fish depend on the streams. In this chapter, you will explore how the movement of matter in the biosphere connects organisms and ecosystems in a life-sustaining relationship.



As salmon decompose, nutrients such as nitrogen are released to the soil. Tree ring studies show that when salmon are abundant, trees grow up to three times faster than when salmon are scarce.

Launch Lab

Whose Planet?

Salmon stocks are dwindling throughout the Pacific Northwest. Because of the newly discovered close relationship between salmon and the trees, some biologists have urged that forest, wildlife, and fish management must be integrated. This seems reasonable, given that each population—rainforest trees, bears, inland salmon, and ocean-going salmon—affects the health and stability of the others. Some people go further, suggesting that human rights, such as the basic right to exist without interference from others, should be extended to all living things. Other people suggest that natural entities such as streams, oceans, and forests should have legal standing in courts in order to provide some protection from human decisions and actions.

Procedure

1. Consider this proposal by applying your current knowledge and feelings about biosphere connections to one of the following scenarios. Discuss your views and ideas with a partner or in a small group.
   - People wanting to enjoy the quiet and beauty of nature build homes in "wild" areas that are habitat for other species. Should one species (humans) be allowed to "own" the habitat of other species?
   - Loggers working to support their families and communities are often hampered by laws protecting organisms such as endangered owls and old-growth trees. Should these other organisms have rights that encroach on a person's right to make a living?
   - Tourist operators and their clients now have the technology and financial resources to venture almost anywhere in Canada. This includes using helicopters to take mountain bikers and skiers into delicate alpine terrain and taking motor boats through sensitive wetlands. Should people be allowed to go anywhere they wish for whatever purpose?

Analysis

1. In your opinion, should other organisms have the same rights as humans? Should those rights apply only to some organisms? How would you choose?
2. Is it justifiable to extend rights and laws to natural entities such as a mountain? Is it practical? Does that matter? Defend your opinions.

SECTION
2.1

The Role of Water in Cycles of Matter

Section Outcomes

In this section, you will
- **explain** water's primary role in the biogeochemical cycles as a result of its chemical and physical properties
- **analyze** data on water consumption and loss in plants and animals
- **evaluate** the use of water by society

Key Terms

biogeochemical cycles
hydrologic cycle
polar
hydrogen bond
cohesion
adhesion

Figure 2.1 Water is constantly being recycled in the hydrologic cycle. As a result, this athlete could be drinking water molecules that were once consumed or respired by a dinosaur.

On a hot day, you might find your skin covered with perspiration. Where did the water in this perspiration come from?

The human body loses and must replace approximately three percent of its total water volume daily. There is a limited amount of water in the biosphere, but water is naturally recycled, which makes it available to living organisms. Part of the water in your body may have come from a distant rainforest. When rain fell on this rainforest, some of it may have gone into the soil, where it was drawn up by a tree's roots and transpired (lost through pores in its leaves, called stomata, that are used for gas exchange) to the atmosphere. Other rain may have fallen on rocks and evaporated back into the atmosphere. The combined transpiration and evaporation from a terrestrial area is called evapotranspiration.

Water is a product of cellular respiration. During cellular respiration, the chemical breakdown of glucose results in the production of water as a byproduct. All the chemical reactions that occur within an organism make up the organism's metabolism. The water that is produced by cellular respiration is therefore known as metabolic water.

The hydrogen and oxygen atoms that make up metabolic water actually come from glucose and atmospheric oxygen gas. Thus, plants, animals, and all other organisms that conduct cellular respiration also release water that makes its way into the atmosphere. Wind currents could have carried some of the water to the Rocky Mountains, where the water molecules would have condensed and fallen as precipitation (rain and snow).

The water molecules might then have joined water molecules from other sources in a river. From there, they might have been drawn into a local water treatment facility and entered the tap water you drank. Your body would have used some of these water molecules in cellular processes and perhaps stored the rest, later secreting them as the perspiration that evaporated and cooled you down (Figure 2.1).

The routes that water and other chemical nutrients take through the biotic and abiotic components of the biosphere are known as **biogeochemical**

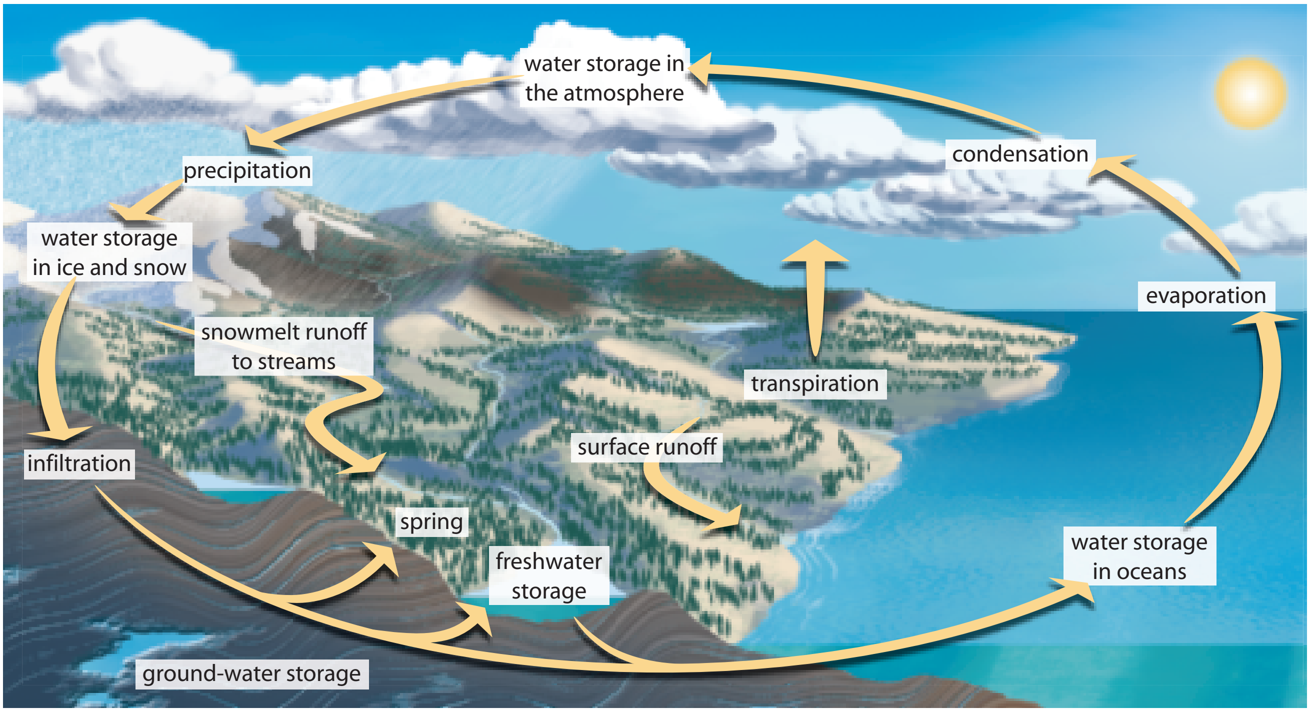


Figure 2.2 As water cycles through the environment, it can transport many other materials along with it.

cycles. You have seen how the water cycle, or **hydrologic cycle**, can connect ecosystems separated by great distances. The hydrologic cycle involves all phases of water (Figure 2.2). More than 97 percent of the water in the biosphere exists in liquid form. This is due, in part, to water's relatively high boiling point compared with the boiling points of other liquids. Water also exists as ice and gas in Earth's atmosphere. The water in the atmosphere results from evaporation, including evapotranspiration. About 86 percent of the global evaporation of water is from the oceans.

Water vapour is a greenhouse gas. It not only traps heat in the atmosphere, but also transfers heat. Where large amounts of sunlight reach Earth, such as in the tropics, the radiant energy heats the ground and causes evaporation. As the water vapour rises, it moves toward the Poles and releases heat as it expands and cools. This process in the atmosphere distributes heat away from the equator.

Heat is also transferred by liquid water. Ocean currents, for example, transfer warm water from hotter to cooler regions. The warm water can heat the air, moderating the temperature over nearby land.

Water has several properties that make it an excellent carrier of dissolved minerals and other materials and an effective medium for transferring energy.

- Water is a universal solvent.
- Water has a relatively high boiling point and melting point.
- Water has special adhesive and cohesive properties.
- Water has a high heat capacity.

The Universal Solvent

As water moves from place to place and changes from one physical state to another, it carries a variety of other substances. Water in the soil, for example, contains nutrients such as nitrogen and phosphorus. Water can also carry toxic compounds, such as methylmercury.

A water molecule consists of two hydrogen atoms that are covalently bonded to one oxygen atom. The hydrogen end of the molecule has a slightly positive charge and the oxygen end has a slightly negative charge, making water a **polar** molecule (Figure 2.3). This polarity allows a water molecule

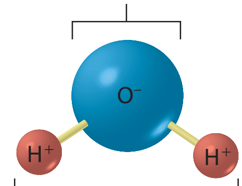


Figure 2.3 The partial positive charges and partial negative charge make this water molecule polar.

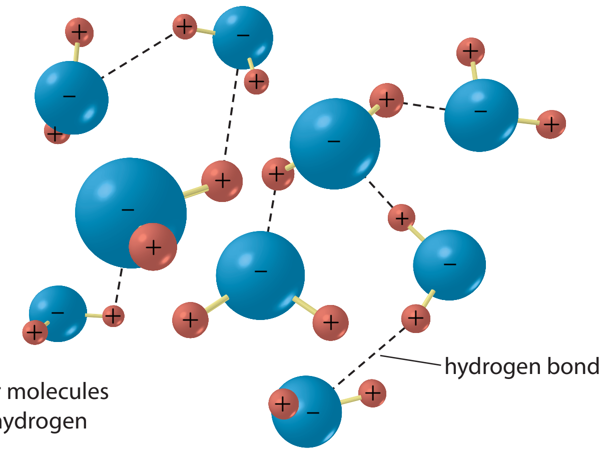


Figure 2.4 Water molecules interact through hydrogen bonding.

to make a weak attraction, called a **hydrogen bond**, between the hydrogen of one molecule and the oxygen of a nearby molecule (Figure 2.4). The structure of water, which includes its polarity and its ability to form hydrogen bonds, enables it to dissolve a wide variety of substances, including molecular compounds such as carbon dioxide and ionic compounds such as sodium chloride (table salt).

Q 1 What makes water a good carrier of ions, such as phosphate (PO_4^{3-})?

Hydrogen Bonding Affects Water in Different Phases

Hydrogen bonding explains why water remains liquid over a large temperature range and why water can continue to dissolve and transport substances over this temperature range.

An individual hydrogen bond is relatively weak. As a result, hydrogen bonds between water molecules form, break, and re-form frequently. Many hydrogen bonds together are quite strong, however. A large amount of energy is needed to break the many hydrogen bonds in a volume of water. Only when its hydrogen bonds are broken can water start to boil and undergo a phase change from a liquid to a gas. Therefore, water has a relatively high boiling point (100 °C) when compared with other liquids that do not have hydrogen bonding. Similarly, frozen water (ice) has a relatively high melting point (0 °C), compared with substances that do not have hydrogen bonds.

Hydrogen bonding also explains the density of liquid water. Unlike the solid and liquid phases of most other substances, frozen water is less dense than liquid water. When water freezes, it expands because hydrogen bonds hold the water molecules in an open crystal structure (Figure 2.5). When ice melts at 0 °C, its solid, crystalline structure begins to break down. The loosened molecules pack more closely together and fill in spaces in the collapsing solid structure. This increases the density of water, until water reaches its greatest density (1 kg/L) at 4 °C. As the temperature continues to rise, water becomes less dense because of thermal expansion.

Water's density characteristics have key consequences for life and the cycling of nutrients. In the spring, as water is melting, it becomes more dense as it warms until it reaches 4 °C. The denser water sinks below the less dense and cooler water, leaving the cooler water at the top to warm and subsequently sink. Similarly, as winter approaches and the water temperature cools towards 4 °C, the cooler water becomes more dense and sinks below the warmer water. When the warmer water cools, it sinks until it reaches its maximum density at 4 °C.

As water sinks and rises, nutrients and dissolved oxygen are cycled with it. Water that percolates into spaces in rocks expands when it freezes, weathering the rocks to help create sand and soil and unlocking nutrients in the process. Because ice is less dense and therefore floats on water, it insulates the deep water in a lake during the winter, preventing the water from freezing and providing a refuge for aquatic life.

Hydrogen bonding causes **cohesion**, the attraction of water molecules to each other. Cohesion is responsible for surface tension, the reason why many insects can walk on water (Figure 2.6). Surface

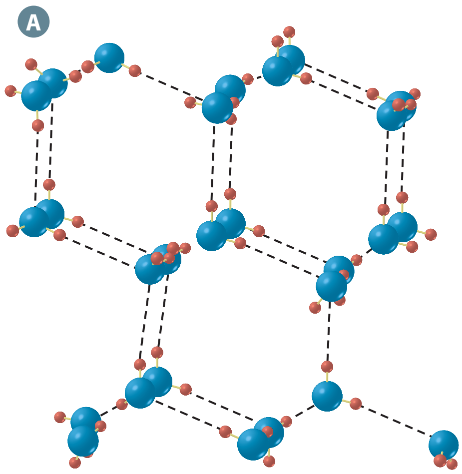


Figure 2.5 **(A)** Hydrogen bonds prevent the water molecules in ice from getting as close to each other as they do in liquid water. **(B)** Ice floats on water because ice has a lower density than water.

tension also keeps organic debris on the water surface, where it provides nutrients for aquatic organisms.

Adhesion is the attraction of water molecules to molecules of other substances, such as the inner surface of a glass tube or the cell wall of a tree's xylem (water-conducting tissue). Adhesion provides an upward force on water and counteracts the pull of gravity. The water molecules in xylem are also cohesively attracted. So, when transpiration removes water molecules from the xylem, the remaining water in the xylem is pulled up to replace these lost molecules. Together cohesion and adhesion explain how, in transpiration, water can travel from the roots of a tree up to its leaves against the force of gravity.

Q 2 Explain the role of hydrogen bonding in

a) transporting nutrients over a large temperature range

b) nutrient cycling in lakes

c) transpiration

Water Stores Heat

Because of hydrogen bonding, water has a very high heat capacity compared with other substances. *Heat capacity* is a measure of the amount of heat a substance can absorb or release for a given change in temperature. Substances with a high heat capacity, such as water, require the transfer of large amounts of energy to effect small changes in temperature. Thus, water heats up more slowly than almost any other compound and holds its temperature longer when the input of energy stops. This property enables organisms, which have a high concentration of water in their tissues, to maintain a fairly constant internal temperature. At an ecosystem level, water's high heat capacity means that bodies of water such as oceans and lakes have a moderation effect on the air temperatures of nearby land. At a global level, water's heat capacity and its ability to hold heat make it possible for surface currents to distribute heat from warm equatorial regions to higher latitudes.

Figure 2.6 Surface tension prevents the legs of this water strider (*Gerris remigis*) from penetrating the surface of the water.

Water World

Living organisms depend on the hydrologic cycle and are an essential part of it. By mass, water comprises more than 50 percent of all plant and animal tissue. The adult human body is composed of about 70 percent water, and a radish is composed of 95 percent water. Dormant forms of life, such as fungal spores, bacterial spores, and plant seeds contain much smaller percentages of water.

For actively metabolizing organisms, water consumption, retention, and loss are part of the daily routine. Animals obtain water directly by eating, drinking, and absorbing water through the surface of their skin. Animals also obtain water through cellular respiration. They lose water through breathing and sweating,

Thought Lab 2.1 Water Gains and Losses

Target Skills

Analyzing data on water consumption and loss in a human and a small animal

Stating conclusions based on the analysis of data

Animals must strictly balance water gains and losses to live. The Ord's kangaroo rat (*Dipodomys ordii*) is a small, nocturnal (active at night) rodent that is found in southern Alberta and Saskatchewan, the United States, and Mexico. Like other kangaroo rats, the Ord's kangaroo rat lives in sand dunes and semi-arid (fairly dry) grasslands where there are few to no sources of surface water, such as ponds and streams. Although it rarely drinks water, the Ord's kangaroo rat is able to obtain most of the water it needs by metabolizing the food it eats. As well, it is very efficient at conserving water.

Procedure

1. A water budget quantifies the amount of water an organism gains and loses through various activities. The data table below compares the daily water budget for a human and an Ord's kangaroo rat.
2. Calculate the percentage of the total water gain from (a) metabolic water and (b) absorbed water for a human and an Ord's kangaroo rat.
3. Calculate the percentage of the total water loss from (a) urine and (b) evaporation for each organism.

Analysis

1. What are the similarities between the two water budgets?
2. What is the relative importance of metabolic water for the Ord's kangaroo rat, compared with a human?
3. **a)** In what part of the water budget is an Ord's kangaroo rat more efficient at conserving water than a human?
   b) Suggest one physiological strategy that the kangaroo rat uses to conserve water.
4. Compare the percentages of total water lost through evaporation for a human and an Ord's kangaroo rat. How might the Ord's kangaroo rat's nocturnal behaviour be related to its water budget?
5. The cellular respiration of different foods produces different amounts of water:
   - 1.0 g of glucose (carbohydrate) results in 0.6 g of water.
   - 1.0 g of fat results in 1.07 g of water.
   - 1.0 g of protein produces 0.4 g of water.

   a) Assume that grain is two percent fat, 62 percent carbohydrate, 11 percent protein, and 10.4 percent free water. For how many days could the kangaroo rat's water needs be met by 1 kg of grain?
   b) Assume that a cooked beef steak is seven percent fat, 27 percent protein, and 65.6 percent free water. For how many days could a human's water needs be met by 1 kg of beef?

Water Budgets for a Human and an Ord's Kangaroo Rat

Water budget for a human			
Water gains (mL)		**Water losses (mL)**	
metabolic water	190	urine	900
absorbed (drinking)	1045	feces	200
absorbed (eating)	665	evaporation (including 350 mL from breathing)	800
Total water gain	1900	Total water loss	1900

Water budget for an Ord's kangaroo rat			
Water gains (mL)		**Water losses (mL)**	
metabolic water	54.0	urine	13.5
absorbed water total	6.0	feces	2.6
		evaporation (including breathing)	43.9
Total water gain	60.0	Total water loss	60.0

Source: Bodil Schmidt-Nielsen and Knut Schmidt-Nielsen. 1951. A complete account of the water metabolism in kangaroo rats and an experimental verification. *Journal of Cellular and Comparative Physiology* Volume 38, Issue 2, Pages 165–181.

and in urine and feces. Plants obtain water through their roots but lose vast amounts by transpiration.

Q3 What is metabolic water?

Q4 How do organisms gain water?

Q5 How do organisms lose water?

Water—An Essential Service

People, like other organisms, depend on their environment for food, water, and clean air to breathe. Natural features, such as an underground river that is tapped for drinking water, are sometimes called ecosystem services to reflect the fact that these features provide for human needs. Fresh water provides an essential ecosystem service.

The two largest natural disasters in Canada were droughts in the prairie provinces. North America experienced two regional- to continental-scale droughts in the twentieth century, during the 1930s and the 1980s. The impact of the drought in the 1980s was less severe, however, due to improved farming practices since the 1930s. There is evidence from Moon Lake, North Dakota, United States, that extreme droughts were more frequent before about 1200 C.E. These droughts had greater intensity and duration (from decades to a century) than the drought in the 1930s.

Alberta has experienced droughts many times in the past and will continue to do so in the future. If global temperatures rise, the rate of evaporation of water from land, lakes, and plants may increase, potentially making Alberta even drier. Currently, Alberta has rich supplies of freshwater from rivers, lakes, wetlands, and underground sources. Population growth, however, combined with agricultural and industrial use, has increased the demand for water in the province.

Water quality is another issue that affects the amount of water that is available for drinking, washing, and other uses. Water that cannot be cleaned of toxic chemicals and pathogens is no longer useful. If it is released into the environment, it can cause great harm to ecosystems. Water is considered to be a renewable resource, but only if it is used wisely. How do human activities affect water quality in your community? Examine this question further in Investigation 2.A on page 41.

Water and Ecosystems

A 4000 m^2 cornfield can transpire 16 000 L of water in a day. When water is scarce, plants respond by closing their stomata, which reduces transpiration. When the stomata are closed, however, plants cannot take in carbon dioxide. As a result, photosynthetic activity in plants drops if there is insufficient water.

To test the effect of a drought on an entire forest, researchers working in the Amazon shielded a group of more than 500 trees (the trial group) from rain using plastic panels (Figure 2.7). A group of uncovered trees was used as a control. Throughout the five-year drought simulation, scientists checked for changes

Figure 2.7 In 1998, the Woods Hole Research Center of the United States began testing the effects of a simulated drought on trees in an Amazon rainforest. The researchers used plastic panels to prevent rainwater from reaching the forest floor. After five years in drought conditions, many of the larger, older, trees died.

BiologyFile

Web Link
University of Alberta ecology professor, Dr. David Schindler, has received numerous awards and honours for his untiring work in the study of water, aquatic ecosystems, and the effects of pollutants and overindulgent human use on both. In what ways has Dr. Schindler been recognized by the Canadian and international community, and for what reasons?

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in the trees. At the end of the simulation, the roots of many of the covered trees had grown deeper into the soil, where they could access water. As well, the rate of growth of the tree trunks had slowed. Many of the largest trees, which were hundreds of years old, had died.

The experimental results led the researchers to pose a number of questions, which scientists continue to examine. For example, if there was a severe drought in the tropics, would the rain forests take in significantly less carbon dioxide for photosynthesis? If the rain forests absorbed less carbon dioxide, which is a greenhouse gas, how might this affect the global climate? How would limited plant growth affect biogeochemical cycles other than the hydrologic cycle?

The hydrologic cycle is linked to all the other cycles of matter. Therefore, a change in the hydrologic cycle will affect the other cycles of matter. How can such changes affect ecosystems? You will investigate possible answers to this question in the next section.

Section 2.1 Summary

- There is a limited (finite) amount of water in the biosphere. It is re-used, however, in the hydrological cycle and exists as a solid, a liquid, and a gas in the environment.
- Water is able to dissolve a wide variety of substances. Hydrogen bonding plays a key role in determining the properties and uses of water, such as its ability to dissolve and transport materials.
- Water provides an essential service for humans and ecosystems. Drought and poor water quality can affect water availability and impact humans and the environment.
- The hydrologic cycle plays a central role in nutrient cycles (biogeochemical cycles).

Section 2.1 Review

1. a) Use graphics or word processing software to illustrate the hydrologic cycle. ICT

b) Use this cycle to make an operational definition of the term "biogeochemical cycle."

2. Explain the role that water vapour plays in maintaining global temperatures.

3. a) Use graphics or other software to draw a model of a water molecule. Label your diagram. ICT

b) Use graphics or other software to draw a model of water molecules interacting though hydrogen bonding. Label your diagram. ICT

4. Describe the relationship between the structure of the water molecule and the fact that many call water a "universal solvent."

5. Explain how the cohesion of water molecules allows the insect shown opposite to walk on the surface of liquid water.

6. State three reasons why water is important to life.

7. Explain how animals cope with the constant loss of water.

8. Identify five major uses of water in Alberta.

Question 5 Water strider (*Gerris remigis*)

9. Define the term "water quality." Explain why it is important for:

a) society

b) ecosystems