3
Water

Learning Objectives

In this chapter, you will learn:

- ➜ Water and the Importance of Hydrogen Bonds
- ➜ pH

Overview

Living organisms contain more water than any other compound. The environment of most living organisms is dominated by water. Understanding water and its properties is key for the study of life on Earth. This chapter will review water's unique properties and how these properties affect living organisms.

Water and the Importance of Hydrogen Bonds

Water is a polar molecule. Its polarity allows it to form hydrogen bonds. These hydrogen bonds give water properties that are essential to life on Earth.

Water contains covalent bonds (shared electrons) between the oxygen and hydrogen atoms. The element oxygen has a high electronegativity (ability to attract electrons), while the element hydrogen has a lower electronegativity. Because of this electronegativity difference, the electrons in the covalent bond between oxygen and hydrogen are unequally shared, with the electrons spending more time around the oxygen atom. This results in a **polar covalent**

bond, with a partial negative charge around the oxygen atom and a partial positive charge around the hydrogen atom, as shown in Figure 3.1.

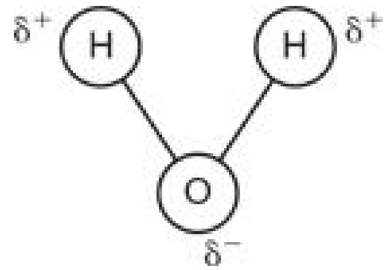


Figure 3.1 Polarity of Water

As a result, the partial negative charge on an oxygen atom in one water molecule is attracted to the partial positive charge on a hydrogen atom in another water molecule, resulting in a hydrogen bond. This causes water molecules to be attracted to one another, as shown in Figure 3.2.

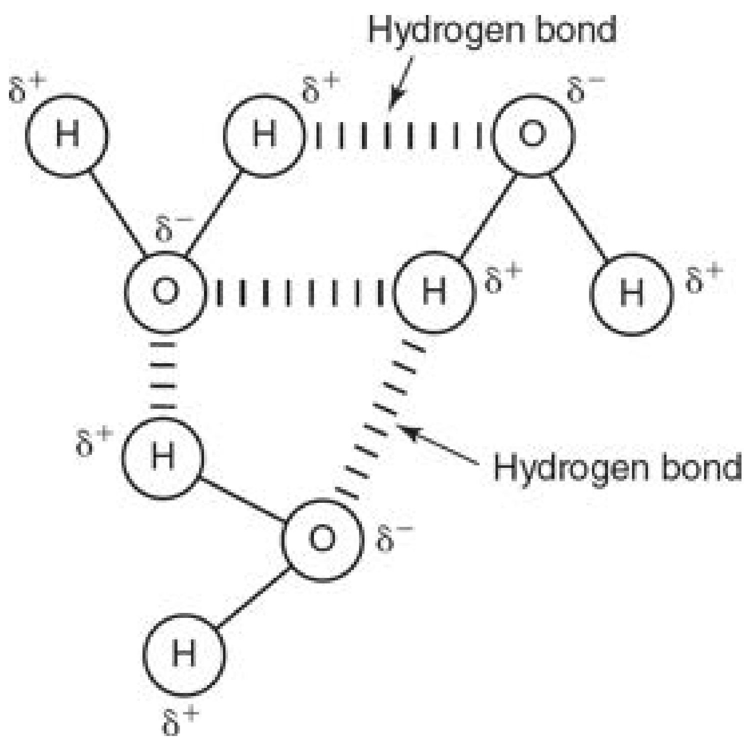


Figure 3.2 Hydrogen Bonds Between Water Molecules

Since water molecules can form hydrogen bonds, they have properties that help sustain life on Earth, including:

- **Exhibiting cohesive and adhesive behavior:** Water molecules are "sticky." They are attracted to other water molecules and to other polar molecules. This is what gives water its unique properties like water's high surface tension and its ability to climb up the xylem in plants through capillary action. (See Figure 3.3.)

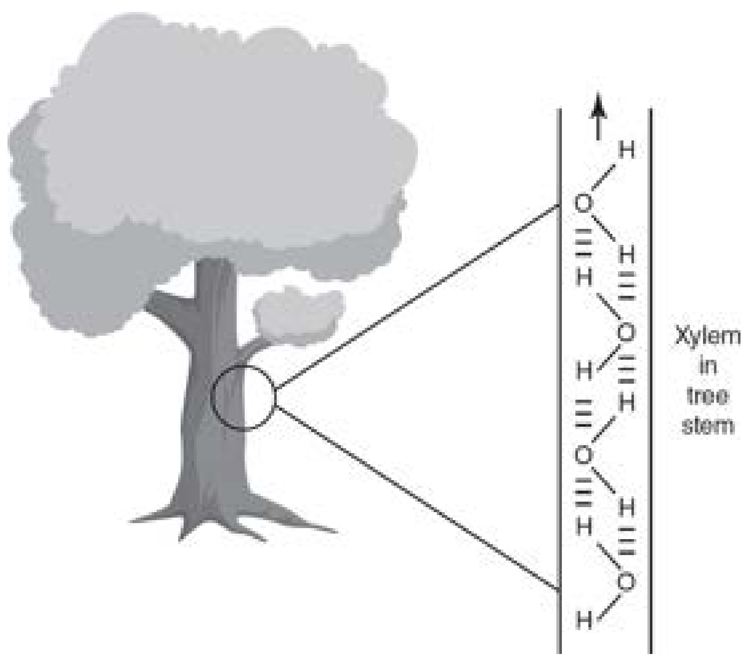


Figure 3.3 Capillary Action

- **Having a high specific heat:** As a result of water's ability to form hydrogen bonds, more energy is required to separate water molecules during phase changes, giving water a high specific heat. When a person sweats, the water in the sweat on the skin absorbs heat from the person's body as the water/sweat evaporates, having a cooling effect on the person's body temperature.
- **Moderating climate:** Since water has a high heat capacity, it can absorb and release large amounts of energy. This stabilizes climates in locations near large bodies of water. (See Figure 3.4.)

Figure 3.4 Effects of a Large Body of Water on Climate

- **Expanding upon freezing:** Since water has the ability to form hydrogen bonds, there is more space between water molecules in the solid state than in the liquid state. As a result, ice has a lower density than that of liquid water, and thus ice floats on liquid water. This has profound consequences for organisms in ponds or lakes that freeze in the winter. The layer of ice on the surface of the lake helps protect the organisms below from temperature extremes in the atmosphere, increasing their chances of surviving the cold winter. If ice were denser than liquid water, the ice would sink, leaving the remaining water in the lake exposed and vulnerable to more freezing and increasing the likelihood that the lake would freeze solid during the winter. This would result in fewer organisms in the lake surviving the winter.
- **Acting as a great solvent for other polar molecules and for ions:** Water has a partially positive end and a partially negative end. Thus, water can readily dissolve ionic compounds (see Figure 3.5) and other polar molecules. This makes water an excellent solvent for many biological molecules.

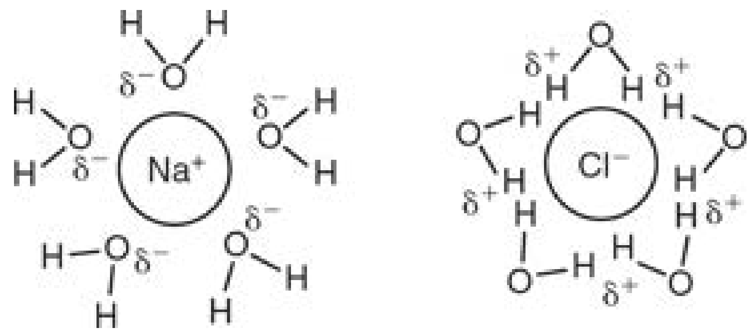


Figure 3.5 Water Interacting with Sodium Chloride

pH

pH (or "power of hydrogen") measures the concentration of H^+ ions in a solution. The formula for pH is the following:

$$\mathrm{pH} = -\log[\mathrm{H}^+]$$

> While you will not be required to calculate pH from $[H^+]$ on the AP Biology exam, you should know the following:
>
> A pH less than 7 is acidic.
>
> A pH greater than 7 is basic.
>
> A pH of 7 is neutral.

Due to the negative sign in the formula for pH, a higher $[H^+]$ leads to a lower pH value and a lower $[H^+]$ leads to a higher pH value. Thus, a solution with a pH of 3 would have a higher $[H^+]$ than that of a solution with a pH of 5. Also, because the pH scale is a logarithmic scale, a pH change of one unit corresponds to a tenfold difference in H^+ concentration. For example, a pH of 3 would have 10 times the H^+ concentration of a pH of 4 and 100 times the concentration of a pH of 5.

The pH of a water-based solution depends on how many of the water molecules are dissociated (separated into H^+ ions and OH^- ions) and the relative numbers of these ions. Pure water will dissociate and produce equal concentrations of H^+ ions and OH^- ions, resulting in a pH of 7. Acids increase the relative concentration of H^+ ions in a solution, and bases increase the relative concentration of OH^- ions in a solution.

Biological systems can be very sensitive to changes in pH. **Buffers** are crucial in maintaining relatively constant pH levels in living cells. Buffers can form acids or bases in response to changing pH levels in a cell. An example of this is the carbonic acid–bicarbonate buffering system in blood plasma. The carbon dioxide that is produced by cellular respiration reacts with water in blood plasma to produce carbonic acid (H_2CO_3). Carbonic acid can dissociate into bicarbonate ions (HCO_3^-) and hydrogen ions, as shown in the following equation:

$$H_2CO_3 \leftrightharpoons HCO_3^- + H^+$$

If the pH of a cell becomes too low (excess H^+), the reaction will shift to the left, allowing the basic bicarbonate ions to neutralize the excess H^+ ions, returning the pH to normal levels. When the pH of a cell becomes too high (excess OH^-), the reaction shifts to the right, adding more H^+ ions to the cell that can neutralize the excess OH^-, which lowers the pH back to normal levels.

Chapter 4 ("Macromolecules") will review how changes in pH can denature proteins, changing their functions. Chapter 7 ("Enzymes") will discuss how most enzymes have a pH at which they function optimally.

Practice Questions

Multiple-Choice

1. In a water molecule, hydrogen atoms are attached to oxygen atoms through which type of bond?

   (A) hydrogen bond
   (B) nonpolar covalent bond
   (C) polar covalent bond
   (D) ionic bond

2. The attraction between the partially positive charge on a hydrogen atom on one water molecule and the partially negative charge on an oxygen atom on another water molecule is called a(n)

   (A) hydrogen bond.
   (B) nonpolar covalent bond.
   (C) polar covalent bond.
   (D) ionic bond.

3. Water's high specific heat is due to

   (A) the lower density of solid ice compared to that of liquid water.
   (B) the amount of energy required to break the covalent bonds within a water molecule.
   (C) the amount of energy required to break the hydrogen bonds between water molecules.
   (D) the low electronegativity of oxygen atoms compared to that of hydrogen atoms.

4. Which of the following solutions has the greatest concentration of H^+?

   (A) stomach acid with a pH of 2
   (B) acetic acid with a pH of 3

(C) coffee with a pH of 5
(D) bleach with a pH of 12

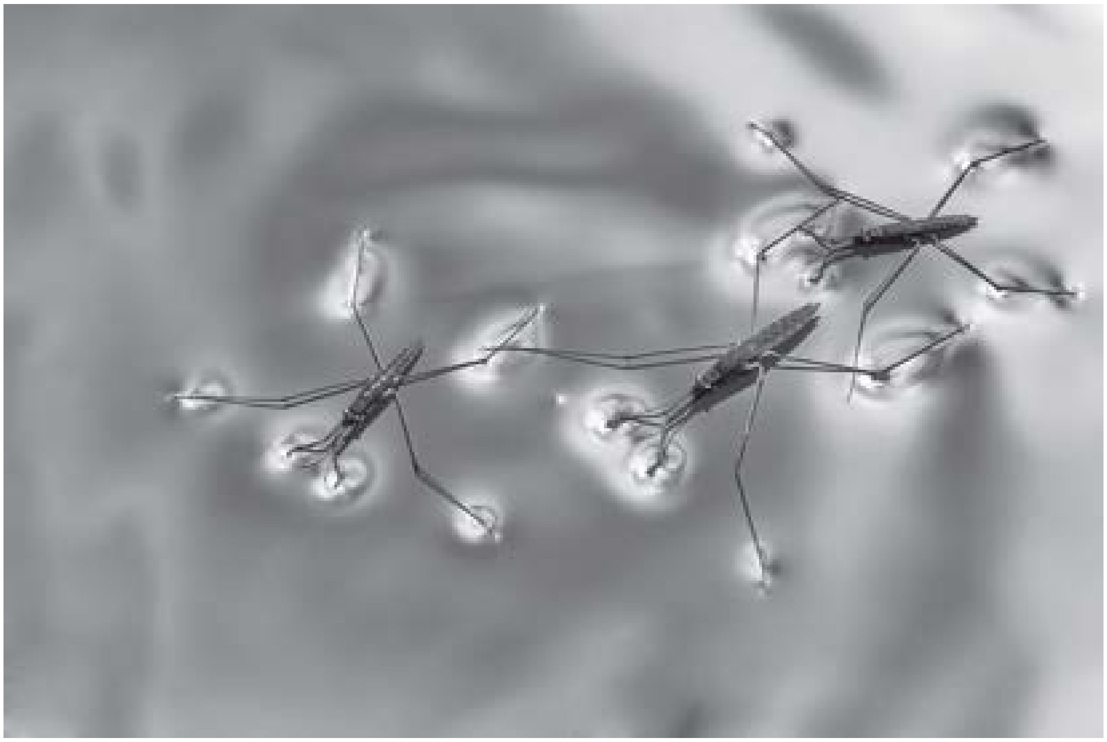
5. Solution A has a pH of 4; solution B has a pH of 7. How do the $[H^+]$ in these solutions compare?

(A) Solution A has 3 times the $[H^+]$ concentration of solution B.
(B) Solution A has 30 times the $[H^+]$ concentration of solution B.
(C) Solution A has 1,000 times the $[H^+]$ concentration of solution B.
(D) Solution A has 3,000 times the $[H^+]$ concentration of solution B.

6. Coastal areas near large bodies of water tend to have more stable climates than inland areas at the same latitude. Which of the following is the property of water that best explains this difference in climate?

(A) high surface tension
(B) high specific heat
(C) capillary action
(D) density of ice

7. Small, lightweight insects can walk on the surface of water, as seen in the following figure:



Which of the following is the property of water that best explains this phenomenon?

(A) high surface tension
(B) high specific heat
(C) capillary action
(D) density of ice

8. Arctic seals and walruses rely on ice floes for survival. Which of the following best explains why these ice floes exist?

(A) high surface tension
(B) high specific heat
(C) capillary action
(D) density of ice

9. Redwood trees, which are over 200 feet tall, can move water upward from their roots to other parts of the tree, despite the downward pull of gravity. Which of the following properties of water best explains this?

(A) high surface tension
(B) high specific heat
(C) capillary action
(D) density of ice

10. In hot weather, humans can cool their body temperature by sweating. Which of the following properties of water makes this possible?

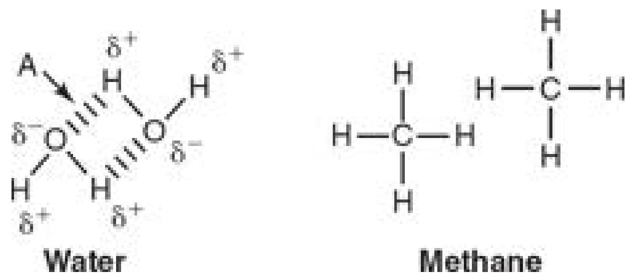
(A) high surface tension
(B) high specific heat
(C) capillary action
(D) density of ice

Short Free-Response

11. On hot summer days, misters will sometimes be used to cool participants at outdoor events.

(a) **Describe** the property of water that allows misters to have an effective cooling effect.
(b) **Explain** why the evaporation of water makes the participants in these events more comfortable.
(c) Instead of water, nonpolar oil is spread on the skin. **Predict** whether this would have a less effective cooling effect, a more effective cooling effect, or the exact same cooling effect as water on the skin.
(d) Using what you know about the comparative properties of water and nonpolar substances, **justify** your prediction from part (c).

12. Refer to the following figure, which depicts water and methane.



(a) **Describe** the type of bond indicated by arrow A.

(b) **Explain** why the bond indicated by arrow A forms between water molecules.

(c) Would an ionic salt dissolve more readily in water or methane? **Explain** your reasoning.

(d) Plants in arid climates often need to conserve water loss due to evaporation through the leaves of the plant. Some plant species have a waxy, nonpolar cuticle on the outer surface of their leaves. A student claims that this waxy cuticle reduces water loss from the leaves. **Support the student's claim** with reasoning.

Long Free-Response

13. Aquatic animals produce carbon dioxide as a product of cellular respiration. Carbon dioxide combines with water to form carbonic acid (H_2CO_3), which releases hydrogen ions (H^+) into solution. Four test tubes (containing 10 mL of water each and different numbers of aquatic snails) are prepared. pH levels were measured in each tube at the beginning of the experiment and after 20 minutes. The results are shown in the following table.

Tube	Number of Aquatic Snails in Tube	Initial pH	pH After 20 Minutes
A	0	7.0	7.0
B	1	7.0	6.0
C	2	7.0	5.0
D	3	7.0	4.0

(a) **Explain** why tubes B, C, and D all had lower pH levels after 20 minutes.

(b) **Identify** the independent variable and the dependent variable in this experiment.

(c) **Analyze** the data, and **predict** which tube (B, C, or D) contained 100 times as many H^+ ions as that of tube A after 20 minutes.

(d) Aquatic plants, such as *Elodea*, perform cellular respiration, but they also perform photosynthesis. Photosynthesis removes carbon dioxide from the water, reducing the amount of carbonic acid. **Predict** the effect of adding *Elodea* to all four tubes at the start of the experiment. **Justify** your prediction.

Answer Explanations

Multiple-Choice

1. **(C)** Oxygen atoms and hydrogen atoms are joined in covalent bonds within a water molecule. Because oxygen has a higher electronegativity than hydrogen does, the electrons in this bond are unequally shared, and this results in a polar covalent bond. Choice (A) is incorrect because hydrogen bonds occur between different water molecules, not within a given water molecule. Choice (B) is incorrect because nonpolar covalent bonds form between atoms with similar electronegativities. Choice (D) is incorrect because the electrons in the bonds within a water molecule are shared; they are not transferred as is the case in an ionic bond.

2. **(A)** Hydrogen bonds occur between the hydrogen atom of one water molecule and the oxygen atom of another water molecule. Choices (B) and (C) are incorrect because both describe *intra*molecular bonds, not *inter*molecular bonds between different molecules. Choice (D) is incorrect because there is no transfer of electrons between water molecules.

3. **(C)** Because of the attraction between water molecules that is the result of hydrogen bonds, more energy is required to separate water molecules. Choice (A) is incorrect because although solid ice does have a lower density than that of liquid water, this does not affect water's specific heat. Choice (B) is incorrect because specific heat does not depend on the energy needed to break the *intra*molecular covalent bonds *within* a water molecule; rather, specific heat depends on the energy needed to break the *inter*molecular bonds *between* molecules. Choice (D) is incorrect because oxygen atoms have a higher electronegativity than that of hydrogen atoms.

4. **(A)** Of the choices presented, a stomach acid with a pH of 2 has the greatest concentration of H^+. All the other answer choices have a higher pH value than that of choice (A) and therefore a lower $[H^+]$.

5. **(C)** pH is a logarithmic scale, so a difference of three pH units would result in a difference of 10^3 times the $[H^+]$ concentration. Choice (A) is incorrect because pH is not a linear scale. Choice (B) is incorrect because 10^3 is not 30 times. Choice (D) is incorrect because 10^3 is not 3,000 times.

6. **(B)** Water's ability to form hydrogen bonds allows it to absorb and release large amounts of heat, giving water a higher specific heat than that of many other liquids. Locations near large bodies of water have more stable climates because the nearby bodies of water can absorb atmospheric heat during the day and then release it at night, leading to more stable climates. Choice (A) is incorrect because surface tension only affects the surface of the body of water and does not affect climate. Choice (C) is incorrect because capillary action describes water's ability to climb up narrow tubes. While ice may cool limited areas, the density of ice does not explain why coastal areas have more stable climates than inland areas, so choice (D) is incorrect.

7. **(A)** Surface tension describes the attraction of molecules to each other on the surface of a liquid. Since water has strong hydrogen bonds, it has a higher surface tension that is sufficient enough to support the mass of very lightweight insects on its surface. Choice (B) is incorrect because specific heat is not involved in supporting the mass of an insect on the surface of water. Choice (C) is incorrect because capillary action describes water's ability to climb up narrow tubes. While the density of ice is less than the density of liquid water, this does not explain why lightweight insects can walk on the surface of water, so choice (D) is incorrect.

8. **(D)** Ice has a lower density than that of liquid water, which allows ice floes to float on the ocean surface. Choice (A) is incorrect because surface tension describes the attraction between molecules of water at the surface of a liquid. Specific heat does not contribute to the creation of ice floes, so choice (B) is incorrect. Choice (C) is incorrect because capillary action describes water's ability to climb up narrow tubes.

9. **(C)** Capillary action describes water's ability to climb up narrow tubes. The trunks of redwood trees contain many narrow tubes made of xylem cells, which allow water to travel from the roots to the rest of the tree. Choice (A) is incorrect because surface tension describes the attraction between molecules of water at the surface of a liquid. Specific heat is not involved in capillary action, so choice (B) is incorrect. Choice (D) is incorrect because the density of ice has nothing to do with water's ability to move upward from the roots to the rest of the tree.

10. **(B)** Due to water's high specific heat, more energy is required to evaporate water molecules than other liquids. Sweat on the skin absorbs heat from the body as it evaporates, lowering body temperature. Choice (A) is incorrect because surface tension describes the attraction between molecules of water at the surface of a liquid. Choice (C) is incorrect because capillary action describes water's ability to climb up narrow tubes. Choice (D) is incorrect since ice is not involved in sweating.

Short Free-Response

11. (a) Water forms hydrogen bonds between water molecules, so water requires more energy to evaporate than molecules that do not form hydrogen bonds.

    (b) Energy is required to break the hydrogen bonds between water molecules before those molecules can evaporate. As the hydrogen bonds are broken, heat energy is absorbed from the participant's body, which has a cooling effect.

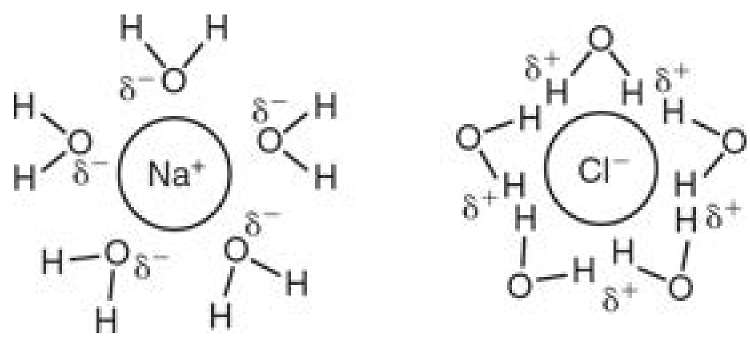
    (c) A nonpolar molecule would have a less effective cooling effect.

    (d) Nonpolar molecules do not form hydrogen bonds between them, so they would require less energy to evaporate and therefore have a less effective cooling effect.

12. (a) Arrow A indicates a hydrogen bond between water molecules.

(b) Oxygen has a much greater electronegativity than hydrogen does. So the electrons in the covalent bond between oxygen and hydrogen in a water molecule are not shared equally and form a polar covalent bond. This gives the oxygen atom a partially negative charge and the hydrogen atom a partially positive charge.

(c) An ionic salt would dissolve more readily in water because the polar water molecules could form hydration shells around the ions, as shown in the following figure.



Since methane is nonpolar, it could not form hydration shells around the ions.

(d) Polar water molecules cannot cross a waxy, nonpolar cuticle layer, so less water can evaporate from leaves surrounded by a waxy, nonpolar cuticle.

Long Free-Response

13. (a) The aquatic snails in tubes B, C, and D all produced carbon dioxide. The carbon dioxide combined with the water in the tubes to form carbonic acid, which released H^+ ions into the solution and lowered the pH. The more H^+ ions there are, the lower the pH is.

(b) The independent variable in this experiment is the number of aquatic snails in each tube. The dependent variable is the pH.

(c) The equation for pH ($pH = -\log[H^+]$) is a logarithmic scale, which means each pH change of 1 unit will increase the number of H^+ ions by a factor of 10. A decrease of 2 pH units would indicate a 100-fold increase in H^+ concentration. Since tube A has a pH of 7.0 after 20 minutes, it makes sense to predict that tube C, with a pH of 5.0, would have 100 times the H^+ concentration as that found in tube A.

(d) In tube A, the pH will increase after 20 minutes. The *Elodea* in tube A will remove carbon dioxide by the process of photosynthesis and therefore increase the pH. In tubes B, C, and D, which contain aquatic animals as well as *Elodea*, the pH will still decrease after 20 minutes since the animals are performing cellular respiration. However, since the *Elodea* will absorb some of the carbon dioxide produced, the decrease in pH will not be as large as it was when the tubes only contained aquatic snails.