CHAPTER 3

The Big Picture: Systems of Change

The Missouri River at Sioux City is a complex system of water, sediment, animals, and fish, all affected by the city and its processes of runoff and river flood control, as well as upstream human intervention in the flow of the river.

LEARNING OBJECTIVES

In this book we discuss a wide range of phenomena. One thing that links them is that they are all part of complex systems. Systems have well-defined properties. Understanding these properties, common to so much of the environment, smooths our way to achieving an understanding of all aspects of environmental science. Changes in systems may occur naturally or may be induced by people, but a key to understanding these systems is that change in them is natural. After reading this chapter you should understand . . .

- Why solutions to many environmental problems involve the study of systems and rates of change;
- What feedback is, the difference between positive and negative feedback, and how these are important to systems;
- The difference between open and closed systems and between static and dynamic systems, and know which kind is characteristic of the environment and of life;
- What residence time is and how it is calculated;
- The principle of uniformitarianism and how it can be used to anticipate future changes;
- The principle of environmental unity and why it is important in studying environmental problems;
- Some helpful ways to think about systems when trying to solve environmental problems that arise from complex natural systems;
- What a stable system is and how this idea relates to the prescientific idea of a balance of nature.

CASE STUDY

Trying to Control Flooding of the Wild Missouri River

The Missouri River drains one-sixth of the United States (excluding Alaska and Hawaii) and flows for more than 3,200 km (2,000 miles). After the land along the Missouri was settled by Europeans, and after large towns and cities were built on the land near the river, flooding of the Missouri became a major problem. The "wild Missouri" became famous in history and folklore for its great fluctuations, its flows and droughts, and as the epitome of unpredictability in nature. One settler said that the Missouri "makes farming as fascinating as gambling. You never know whether you are going to harvest corn or catfish."[1,2]

Two of the river's great floods were in 1927 and 1993 (Figure 3.1). After the 1927 flood, the federal government commissioned the Army Corps of Engineers to build six major dams on the river (Figure 3.2). (The attempt to control the river's flow also included many other alterations of the river, such as straightening the channel and building levees.) Of the six dams, the three largest were built upstream, and each of their reservoirs was supposed to hold the equivalent of an entire year's average flow. The three smaller, downstream dams were meant to serve as safety valves to control the flow more precisely.

The underlying idea was to view the Missouri as a large plumbing system that needed management. When rainfall was sparse in the huge watershed of the river, the three upstream dams were supposed to be able to augment the flow for up to three years, ensuring a constant and adequate supply of water for irrigation and personal use. In flood years, the six dams were supposed to be able to store the dangerous flow, so that the water could be released slowly, the floods controlled, and the flow once again constant. In addition, levees—narrow ridges of higher ground—were built along the river and into it to protect the settled land along the river from floodwaters not otherwise contained. But these idealistic plans did not stop the Missouri from flooding in 1993 (Figures 3.1 and 3.3).

FIGURE 3.2 The six major dams on the Missouri River. (Based on drawing by Gary Pound from Daniel B. Botkin, *Passage of Discovery: The American Rivers Guide to the Missouri River of Lewis and Clark* [New York: Perigee Books, a division of Penguin-Putnam, 1999].)

FIGURE 3.1 St. Louis, Missouri, during the 1993 flood of the Missouri River. No matter how hard we try to keep this huge river flowing at a fixed rate, neither flooding nor in drought, we always seem to fail. So it is when we try to tame most natural ecological and environmental systems that are naturally dynamic and always changing.

Taking the large view, standing way back from the river, this perception of the Missouri River was akin to thinking about it as one huge lake (Figure 3.4) into which water flowed, then drained downstream and out at its mouth at St. Louis, Missouri, into the Mississippi, which carried the waters to New Orleans, Louisiana, and out into the Gulf of Mexico. The hope was that the Missouri River could be managed the way we manage our bathwater—keeping it at a constant level by always matching the outflow down the drain with inflow from the spigot. This is a perception of the river as a system held in *steady state,* a term we will define shortly.

Before there were permanent settlements along the river—both by American Indians and by Europeans—the Missouri's flooding didn't matter. Nomadic peoples could move away from the river when it flooded during the rainy seasons, and wildlife and vegetation generally benefited from the variations in water flow, as will be explained in later chapters. Only with modern civilization

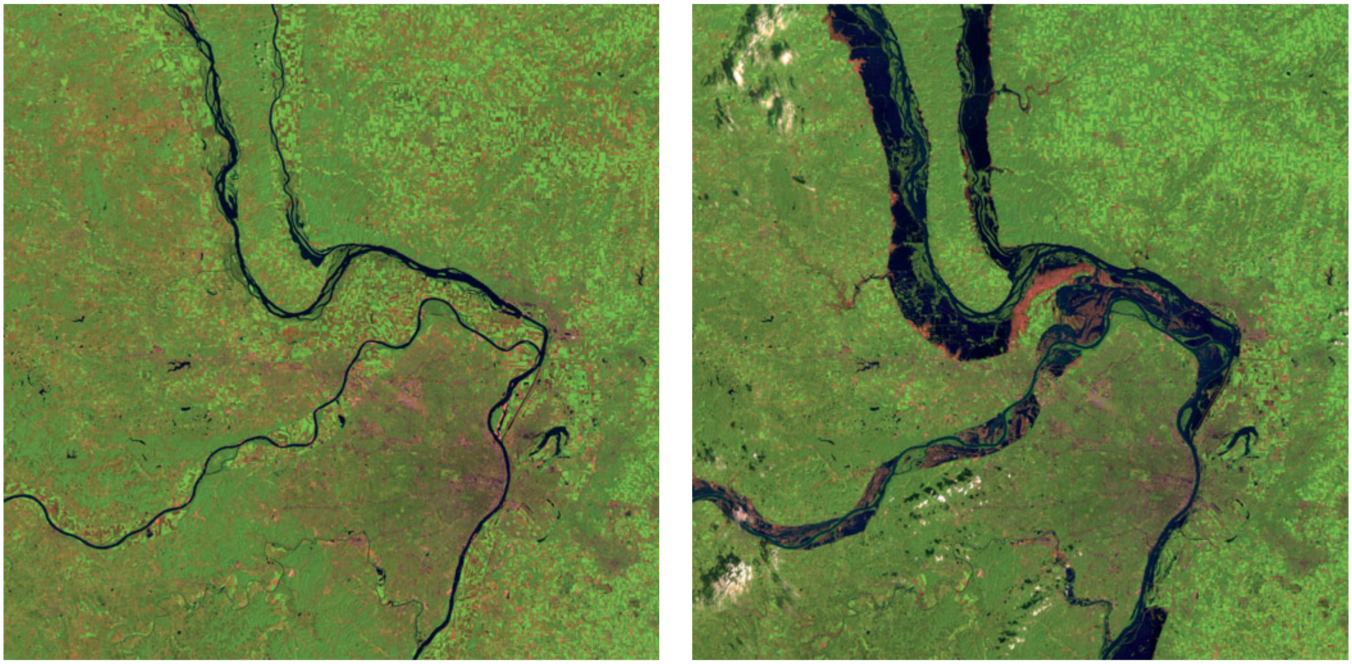
(a)  (b)

FIGURE 3.3 Satellite image of the Missouri River at St. Louis before the flood in 1991 (left) and during the 1993 flood. The dark area is water.

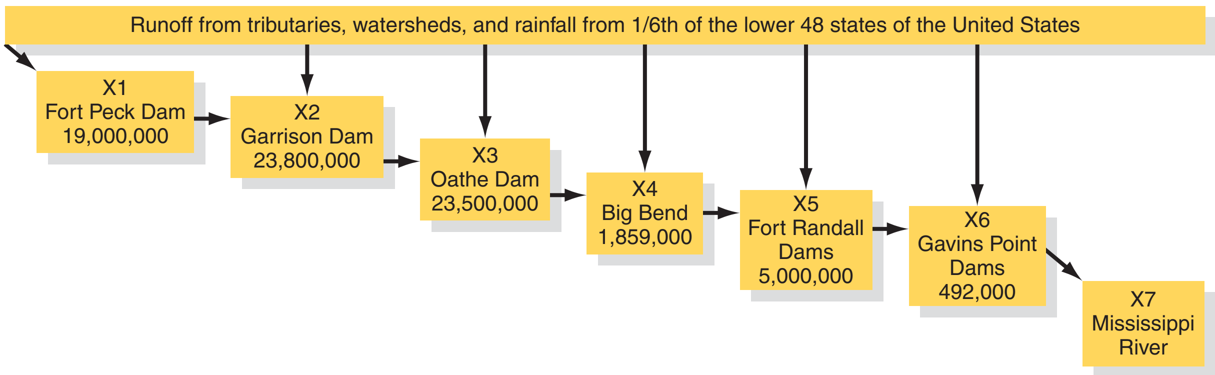


FIGURE 3.4 Imagine the Missouri River as one large lake (composed of the series of dams showed in Figure 3.2) whose water level is controlled. The water level remains constant as water flows into the lake (Fort Peck Dam) at the same rate as water flows out. If more water comes in, more leaves (Gavins Point Dam); if less water comes in, less flows out, and the water level remains at the spillway level. The number inside each box is the dam's maximum storage in acre-feet. The average annual water flow for the Missouri River is 25 million acre-feet (the amount reaching its mouth where it meets the Mississippi at St. Louis, MO)

did it become important to force a huge natural system like the Missouri to flow in steady state.

Unfortunately, people who lived along the Missouri River in 1993 learned that sometimes plans that looked good on paper did not succeed. The Missouri was just too wild and unpredictable—too non-steady-state, to use a systems-analysis term that we will define shortly—for people to control, no matter how great their efforts. The big flood of 1993 breached many levees and affected many lives (Figures 3.1 and 3.3).

The attempt to control the flow of the Missouri is just one of many examples of natural ecological and environmental systems that people thought could be engineered, controlled, tamed, and made to do what they wanted. To understand the environment and people's relation to it, it is necessary to take a systems view, and that is the purpose of this chapter. Once you have read this chapter, you will have one of the foundations for the study of all environmental systems. To understand what happens in natural ecosystems, we can't just look for an answer derived from a single factor. We have to look at the entire system and all of the factors that, together, influence what happens to life.

3.1 Basic Systems Concepts

A **system** is a set of components, or parts, that function together as a whole. A single organism, such as your body, is a system, as are a sewage-treatment plant, a city, and a river. On a much different scale, the entire Earth is a system. In a broader sense, a system is any part of the universe you can isolate in thought (in your brain or on your computer) or, indeed, physically, for the purpose of study. Key systems concepts that we will explain are (1) how a system is connected to the rest of the environment; (2) how matter and energy flow between parts of a system; (3) whether a system is static or dynamic—whether it changes over time; (4) average residence time—how long something stays within a system or part of a system; (5) feedback—how the output from a system can affect its inputs; and (6) linear and nonlinear flows.

In its relation to the rest of the environment, a system can be open or closed. In an **open system**, some energy or material (solid, liquid, or gas) moves into or out of the system. The ocean is an open system with regard to water because water moves into the ocean from the atmosphere and out of the ocean into the atmosphere. In a **closed system**, no such transfers take place. For our purposes, a **materially closed system** is one in which no matter moves in and out of the system, although energy and information can move across the system's boundaries. Earth is a materially closed system (for all practical purposes).

Systems respond to **inputs** and have **outputs**. For example, think of your body as a complex system and imagine you are hiking in Yellowstone National Park and see a grizzly bear. The sight of the bear is an input. Your body reacts to that input: The adrenaline level in your blood goes up, your heart rate increases, and the hair on your head and arms may rise. Your response—perhaps to move slowly away from the bear—is an output.

Static and Dynamic Systems

A **static system** has a fixed condition and tends to remain in that exact condition. A **dynamic system** changes, often continually, over time. A birthday balloon attached to a pole is a static system in terms of space—it stays in one place. A hot-air balloon is a simple dynamic system in terms of space—it moves in response to the winds, air density, and controls exerted by a pilot (Figure 3.5a and b). An important kind of static system is one with **classical stability**. Such a system has a constant condition, and if it is disturbed from that condition, it returns to it once the disturbing factor is removed. The pendulum of an old-fashioned grandfather clock is an example of classical stability. If you push it, the pendulum moves back and forth for a while, but then friction gradually dissipates the energy you just gave it and the pendulum comes to rest exactly where it began. This rest point is known as the **equilibrium** (Figure 3.5c).

(a) A static system
(each birthday ballon)

(b) A dynamic system
(each hot-air balloon)

(c) A *stable* static system
(a mechanical grandfather clock's pendulum).

The pendulum's equilibrium is its vertical position

FIGURE 3.5 Static and dynamic systems. (a) *A static system* (each birthday balloon). Balloons are tied down and can't move vertically. **(b)** *A dynamic system* (each hot-air balloon). Hot air generated by a heater fills the balloon with warm air, which is lighter than outside air, so it rises; as air in the balloon cools, the balloon sinks, and winds may move it in any direction. **(c)** *A classical stable static system* (the pendulum on a mechanical grandfather clock). The pendulum's equilibrium is its vertical position. The pendulum will move if you push it or if the clock's mechanism is working. When the source of energy is no longer active (you forgot to wind the clock), the pendulum will come to rest exactly where it started.

We will see that the classic interpretation of populations, species, ecosystems, and Earth's entire biosphere has been to assume that each is a stable, static system. But the more these ecological systems are studied scientifically, the clearer it becomes that these are dynamic systems, always changing *and always requiring change.* An important practical question that keeps arising in many environmental controversies is whether we want to, and should, force ecological systems to be static if and when they are naturally dynamic. You will find this question arising in many of the chapters in this book.

Open Systems

With few exceptions, all real systems that we deal with in the environment are open to the flow of matter, energy, and information. (For all practical purposes, as we noted earlier, Earth as a planet is a materially closed system.) An important distinction for open systems is whether they are steady-state or non-steady-state. In a

steady-state system, the inputs (of anything of interest) are equal to the outputs, so the amount stored within the system is constant. An idealized example of a steady-state system is a dam and lake into which water enters from a river and out of which water flows (Figure 3.4). If the water input equals the water output and evaporation is not considered, the water level in the lake does not change, and so, in regard to water, the lake is in a steady state. (Additional characteristics of systems are discussed in A Closer Look 3.1.)

A CLOSER LOOK 3.1

Simple Systems

A simple way to think about a system is to view it as a series of compartments (also called "reservoirs," and we will use these terms interchangeably), each of which can store a certain amount of something you are interested in, and each of which receives input from other compartments and transfers some of its stored material to other compartments (Figure 3.6a).

The general equation is

$$I = O \pm \Delta S$$

where I is input into a compartment; O is output, and ΔS is change in storage. This equation defines a budget for what is being considered. For example, if your checking account has $1,000 in it (no interest rate) and you earn $500 per month at the bookstore, input is $500 per month. If you spend $500 per month, the amount in your account will be $1,000 at the end of the month (no change in storage). If you spend less than $500 per month, your account will grow ($+\Delta S$). If you spend more than $500 per month, the amount of money in your account will decrease ($-\Delta S$).

An environmental water engineer could use this kind of systems diagram (Figure 3.6a) to plan the size of the various dams to be built on the Missouri River, taking into account the desired total storage among the dams (Figure 3.4) and the role of each dam in managing the river's flow (refer back to the opening case study and also see Figure 3.7). In Figure 3.7, the amount stored in a dam's reservoir is listed as Xn, where X is the amount of water stored and n is the number of the compartment. (In this case the dams are numbered in order from upstream to downstream.) Water flows from the environment—tributaries, watersheds, and direct rainfall—into each of the reservoirs, and each is connected to the adjacent reservoirs by the river. Finally, all of the Missouri's water flows into the Mississippi, which carries it to the Gulf of Mexico.

For this water-flow system, we can make a complete flow diagram. This kind of diagramming helps us to think about and do a scientific analysis of many environmental problems, so you will find such diagrams throughout this book.

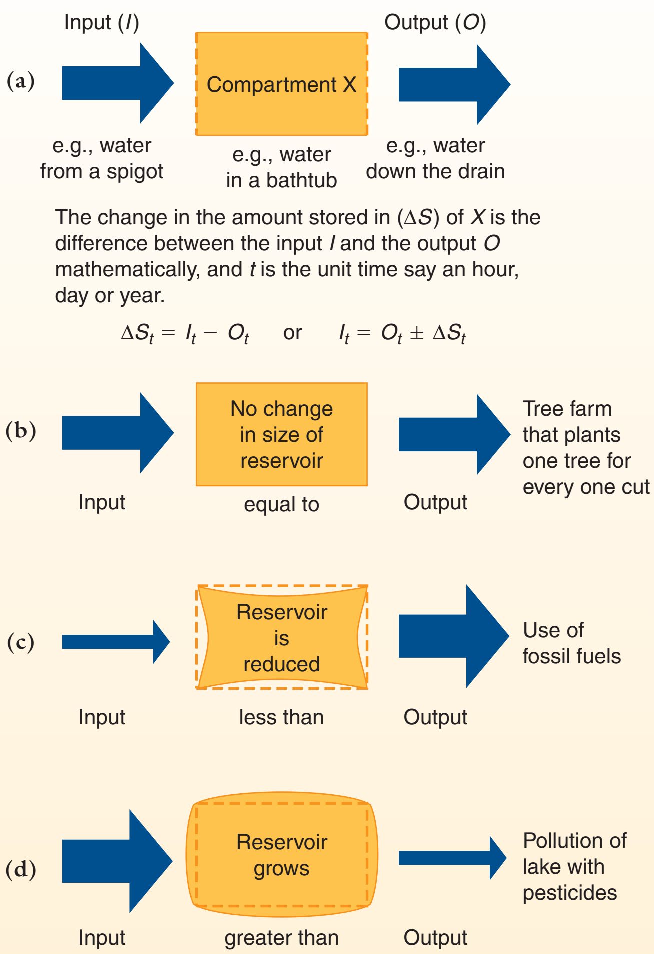


FIGURE 3.6 **(a)** General equation for ways in which a compartment of some material can change. (*Source*: Modified from P.R. Ehrlich, A.H. Ehrlich, and J.P. Holvren, *Ecoscience: Population, Resources, Environment*, 3rd ed. [San Francisco: W.H. Freeman, 1977].) Row **(b)** represents steady-state conditions; rows **(c)** and **(d)** are examples of negative and positive changes in storage.

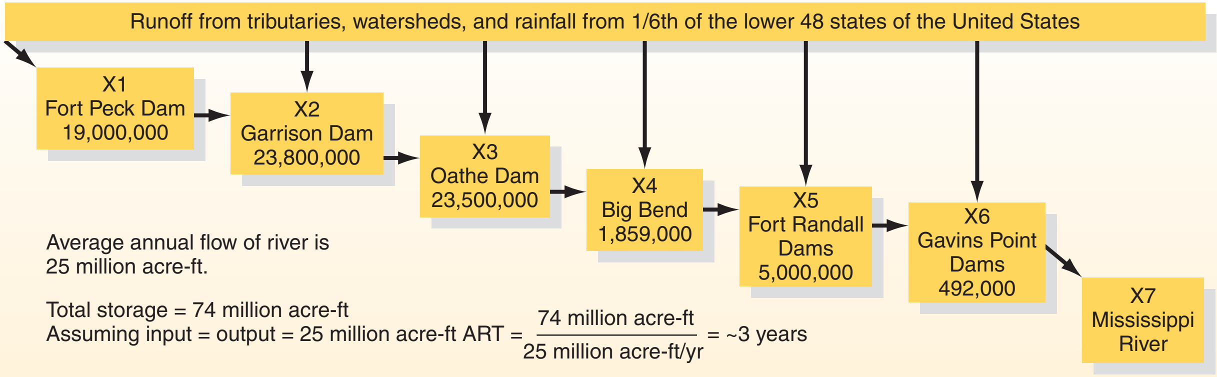


FIGURE 3.7 The Missouri River and its dams viewed as a systems flow chart. The number inside each box is the dam's maximum storage in acre-feet, where one acre-foot is the volume of water that would cover one acre to a depth of 1 foot (1,233 m^3). The average annual water flow for the Missouri River is 25 million acre-feet (the amount reaching its mouth where it meets the Mississippi at St. Louis, Missouri).

Often we want real systems in the environment to be in steady state, and we try to manage many of them so they will be. This has been the case with the Missouri River, the subject of this chapter's opening case study. As with that river, attempts to force natural ecological and environmental systems into a steady state often fail. In fact, such attempts commonly make things worse instead of better, as we will see in many chapters in this book.

The Balance of Nature: Is a Steady State Natural?

An idea frequently used and defended in the study of our natural environment is that natural systems, left undisturbed by people, tend toward some sort of steady state. The technical term for this is **dynamic equilibrium**, but it is more familiarly referred to as the **balance of nature** (see Figure 3.8). Certainly, negative feedback operates in many natural systems and may tend to hold a system at equilibrium. Nevertheless, we need to ask how often the equilibrium model really applies.[3]

FIGURE 3.8 The balance of nature. This painting, *Morning in the Tropics* by Frederic Edwin Church, illustrates the idea of the balance of nature and a dynamic steady state, with everything stationary and still, unchanging.

If we examine natural ecological systems or **ecosystems** (simply defined here as communities of organisms and their nonliving environment in which nutrients and other chemicals cycle and energy flows) in detail and over a variety of time frames, it is evident that a steady state is seldom attained or maintained for very long. Rather, systems are characterized not only by human-induced disturbances but also by natural disturbances (sometimes large-scale ones called natural disasters, such as floods and wildfires). Thus, changes over time can be expected. In fact, studies of such diverse systems as forests, rivers, and coral reefs suggest that disturbances due to natural events, such as storms, floods, and fires, are necessary for the maintenance of those systems, as we will see in later chapters. The environmental lesson is that systems change naturally. If we are going to manage systems for the betterment of the environment, we need to gain a better understanding of how they change.[3,4]

Residence Time

By using rates of change or input-output analysis of systems, we can derive an **average residence time**—how long, on average, a unit of something of interest to us will remain in a reservoir. This is obviously important, as in the case of how much water can be stored for how long in one of the reservoirs on the Missouri River. To compute the average residence time (assuming input is equal to output), we divide the total volume of stored water in the series of dams (Figures 3.4 and 3.7) by the average rate of transfer through the system (Figure 3.7) For example, suppose a university has 10,000 students, and each year 2,500 freshmen start and 2,500 seniors graduate. The average residence time for students is 10,000 divided by 2,500, or four years.

Average residence time has important implications for environmental systems. A system such as a small lake with an inlet and an outlet and a high transfer rate of water has a short residence time for water. On the one hand, from our point of view, that makes the lake especially vulnerable to change because change can happen quickly. On the other hand, any pollutants soon leave the lake.

In large systems with a slow rate of transfer of water, such as oceans, water has a long residence time, and such systems are thus much less vulnerable to quick change. However, once polluted, large systems with slow transfer rates are difficult to clean up. (See Working It Out 3.1.)

WORKING IT OUT 3.1 Average Residence Time (ART)

The average residence time (ART) is the ratio of the size of a reservoir of some material—say, the amount of water in a reservoir—to the rate of its transfer through the reservoir. The equation is

$$ART = S/F$$

where S is the size of the reservoir and F is the rate of transfer.

For example, we can calculate the average residence time for water in the Gavins Point Dam (see Figure 3.7), the farthest downstream of all the dams on the Missouri River, by realizing that the average flow into and out of the dam is about 25 million acre-feet (31 km^3) a year, and that the dam stores about 492,000 acre-feet (0.6 km^3). This suggests that the average residence time in the dam is only about seven days:

$$ART = S/F = 0.6\ km^3\ per\ year\ (31\ km^3\ per\ year)$$

$$S/F = 0.019/year\ (about\ 7\ days)$$

If the total flow were to go through Garrison Dam, the largest of the dams, the residence time would be 347 days, almost a year.

The ART for a chemical element or compound is important in evaluating many environmental problems. For example, knowing the ART of a pollutant in the air, water, or soil gives us a more quantitative understanding of that pollutant, allows us to evaluate the extent to which the pollutant acts in time and space, and helps us to develop strategies to reduce or eliminate the pollutant.

Figure 3.9 shows a map of Big Lake, a hypothetical reservoir impounded by a dam. Three rivers feed a combined 10 m^3/sec (2,640 gal/sec) of water into the lake, and the outlet structure releases an equal 10 m^3/sec. In this simplified example, we will assume that evaporation of water from the lake is negligible. A water pollutant, MTBE (methyl tertiary—butyl ether), is also present in the lake. MTBE is added to gasoline to help reduce emissions of carbon monoxide. MTBE readily dissolves in water and so travels with it. It is toxic; in small concentrations of 20–40 μg/l (thousandths of grams per liter) in water, it smells like turpentine and is nauseating to some people. Concern over MTBE in California led to a decision to stop adding it to gasoline. The sources of MTBE in "Big Lake" are urban runoff from Bear City gasoline stations, gasoline spills on land or in the lake, and gasoline engines used by boats on the lake.

We can ask several questions concerning the water and MTBE in Big Lake.

1. What is the ART of water in the lake?
2. What is the amount of MTBE in the lake, the rate (amount per time) at which MTBE is being put into the lake, and the ART of MTBE in the lake? Because the water and MTBE move together, their

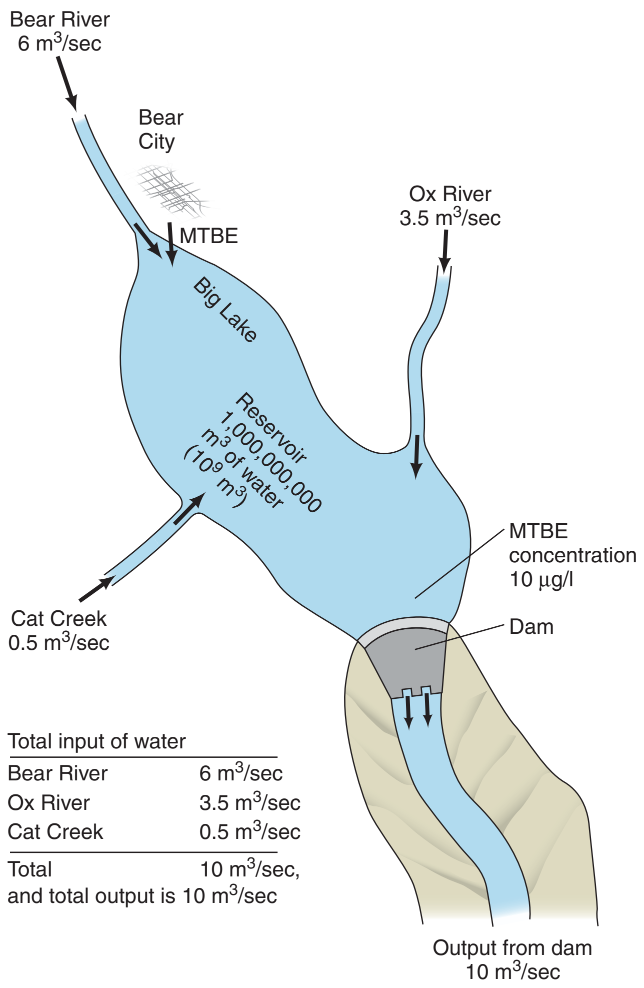


FIGURE 3.9 Idealized diagram of a lake system with MTBE contamination.

ARTs should be the same. We can test this.

ART of Water in Big Lake

For these calculations, use multiplication factors and conversions in Appendixes B and C at the end of this book.

$$ART_{water} = \frac{S}{F} = ART_{water} = \frac{1{,}000{,}000{,}000\,m^3}{10\,m^3/sec}$$

$$or\ \frac{10^9\ m^3}{10\,m^3/sec}$$

The units m^3 cancel out and

$$ART = 100{,}000{,}000\ sec\ or\ 10^8\ sec$$

Convert 10^8 sec to years:

$$\frac{seconds}{year} = \frac{60\ sec}{1\ minute} \times \frac{60\ minutes}{1\ hour} \times \frac{24\ hours}{1\ day} \times \frac{365\ days}{1\ year}$$

Canceling units and multiplying, there are 31,536,000 sec/year, which is

$$3.1536 \times 10^7\ sec/year$$

Then the ART for Big Lake is

$$\frac{100{,}000{,}000\,sec}{31{,}536{,}000\,sec/yr}\ or\ \frac{10^8\ sec}{3.1536 \times 10^7\ sec/yr}$$

Therefore the ART for water in Big Lake is 3.17/years.

ART of MTBE in Big Lake

The concentration of MTBE in water near the dam is measured as 10 μg/l. Then the total amount of MTBE in the lake (size of reservoir or pool of MTBE) is the product of volume of water in the lake and concentration of MTBE:

$$10^9\ m^3 \times \frac{10^3\,1}{m^3} \times \frac{10\,\mu g}{1} = 10^{13}\,\mu g\ or\ 10^7\ g$$

which is 10^4 kg, or 10 metric tons, of MTBE.

The output of water from Big Lake is 10 m^3/sec, and this contains 10 μg/l of MTBE; the transfer rate of MTBE (g/sec) is

$$MTBE/sec = \frac{10\,m^3}{sec} \times \frac{10^3\,1}{m^3} \times \frac{10\,\mu g}{1} \times \frac{10^6}{\mu g}$$
$$= 0.1\,g/sec$$

Because we assume that input and output of MTBE are equal, the input is also 0.1 *g/sec*.

$$ART_{MTBE} = \frac{S}{F} = \frac{10^7\,g}{0.1\,g/sec} = 10^8\ sec\text{, or } 3.17\ years$$

Thus, as we suspected, the ARTs of the water and MTBE are the same. This is because MTBE is dissolved in the water. If it attached to the sediment in the lake, the ART of the MTBE would be much longer. Chemicals with large reservoirs or small rates of transfer tend to have long ARTs. In this exercise we have calculated the ART of water in Big Lake as well as the input, total amount, and ART of MTBE.

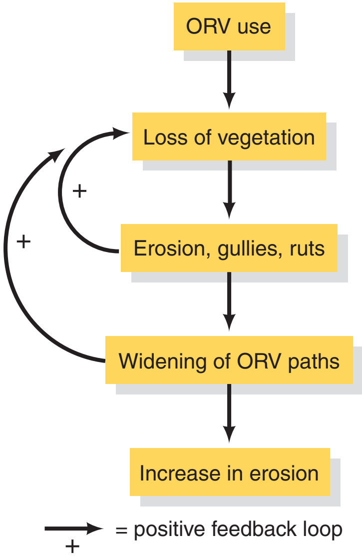
Feedback

Feedback occurs when the output of a system (or a compartment in a system) affects its input. Changes in the output "feed back" on the input. There are two kinds of feedback: negative and positive. A good example of feedback is human temperature regulation. If you go out in the sun and get hot, the increase in temperature affects your sensory perceptions (input). If you stay in the sun, your body responds physiologically: Your pores open, and you are cooled by evaporating water (you sweat). The cooling is output, and it is also input to your sensory perceptions. You may respond behaviorally as well: Because you feel hot (input), you walk into the shade (output) and your temperature returns to normal. In this example, an increase in temperature is followed by a response that leads to a decrease in temperature. This is an example of negative feedback, in which an increase in output now leads to a later *decrease* in output. **Negative feedback** is self-regulating, or stabilizing. It is the way that steady-state systems can remain in a constant condition.

Positive feedback occurs when an increase in output leads to a further *increase* in output. A fire starting in a forest provides an example of positive feedback. The wood may be slightly damp at the beginning and so may not burn readily. Once a fire starts, wood near the flame dries out and begins to burn, which in turn dries out a greater quantity of wood and leads to a larger fire. The larger the fire, the faster more wood becomes dry and the more rapidly the fire grows. Positive feedback, sometimes called a "vicious cycle," is destabilizing.

Environmental damage can be especially serious when people's use of the environment leads to positive feedback. For example, off-road vehicles—including bicycles—may cause positive feedback to soil erosion (Figure 3.10).


(a)



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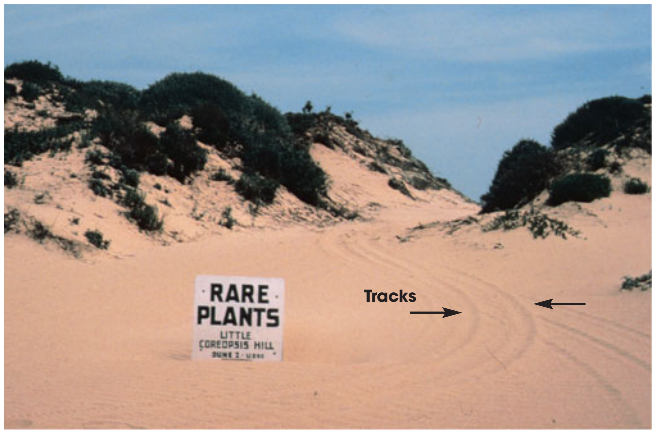


(c)

FIGURE 3.10 How off-road vehicles **(a)** create positive feedback on soil erosion **(b)** and **(c)**.

The vehicles' churning tires are designed to grip the earth, but they also erode the soil and uproot plants. Without vegetation, the soil erodes faster, exposing even more soil (positive feedback). As more soil is exposed, rainwater more easily carves out ruts and gullies (more positive feedback). Drivers of off-road vehicles then avoid the ruts and gullies by driving on adjacent sections that are not as eroded, thus widening paths and further increasing erosion (more positive feedback). The gullies themselves increase erosion because they concentrate runoff and have steep side slopes. Once formed, gullies tend to get longer, wider, and deeper, causing additional erosion (even more positive feedback). Eventually, an area of intensive off-road vehicle use may become a wasteland of eroded paths and gullies. Positive feedback has made the situation increasingly worse.

Some systems have both positive and negative feedbacks, as can occur, for example, for the human population in large cities (Figure 3.11). Positive feedback on the population size may occur when people perceive greater opportunities in cities and move there hoping for a higher standard of living. As more people move to cities, opportunities may increase, leading to even more migration to cities. Negative feedback can then occur when crowding increases air and water pollution, disease, crime, and discomfort. These negatives encourage some people to migrate from the cities to rural areas, reducing the city's population.

Practicing your critical-thinking skills, you may ask, "Is negative feedback generally desirable, and is positive feedback generally undesirable?" Reflecting on this question, we can see that although negative feedback is self-regulating, it may in some instances not be

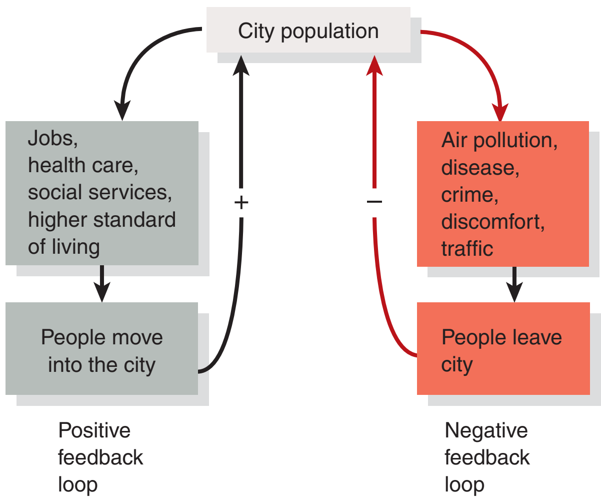


FIGURE 3.11 Potential positive and negative feedback loops for changes of human population in large cities. The left side of the figure shows that as jobs increase and health care and the standard of living improve, migration and the city population increase. Conversely, the right side of the figure shows that increased air pollution, disease, crime, discomfort, and traffic tend to reduce the city population. (*Source:* Modified from M. Maruyama, the second cybernetics: Deviation-amplifying mutual causal processes, *American Scientist* 51 [1963]:164–670. Reprinted by permission of *American Scientist* magazine of Sigma Xi, The Scientific Research Society.)

desirable. The period over which the positive or negative feedback occurs is the important factor. For example, suppose we are interested in restoring wolves to Yellowstone National Park. We will expect positive feedback in the wolf population for a time as the number of wolves grows. (The more wolves, the greater their population growth, through exponential growth.) Positive feedback, for a time, is desirable because it produces a change we want.

We can see that whether we view positive or negative feedback as desirable depends on the system and potential changes. Nevertheless, some of the major environmental problems we face today result from positive feedback mechanisms. These include resource use and growth of the human population.

3.2 System Responses: Some Important Kinds of Flows[4]

Within systems, there are certain kinds of flows that we come across over and over in environmental science. (Note that **flow** is an amount transferred; we also refer to the **flux**, which is the rate of transfer per unit time.) Because these are so common, we will explain a few of them here.

Linear and Nonlinear Flows

An important distinction among environmental and ecological systems is whether they are characterized by linear or nonlinear processes. Put most simply, in a **linear process**, if you add the same amount of anything to a compartment in a system, the change will always be the same, no matter how much you have added before and no matter what else has changed about the system and its environment. If you harvest one apple and weigh it, then you can estimate how much 10 or 100 or 1,000 or more of the apples will weigh—adding another apple to a scale does not change the amount by which the scale shows an increase. One apple's effect on a scale is the same, no matter how many apples were on the scale before. This is a linear effect.

Many important processes are **nonlinear**, which means that the effect of adding a specific amount of something changes depending on how much has been added before. If you are very thirsty, one glass of water makes you feel good and is good for your health. Two glasses may also be helpful. But what about 100 glasses? Drinking more and more glasses of water leads quickly to diminishing returns and eventually to water's becoming a poison.

Lag Time

Many responses to environmental inputs (including human population change; pollution of land, water, and air; and use of resources) are nonlinear and may involve delays, which we need to recognize if we are to understand and solve environmental problems. For example, when you add fertilizer to help a tree grow, it takes time for it to enter the soil and be used by the tree.

Lag time is the delay between a cause and the appearance of its effect. (This is also referred to as the time between a stimulus and the appearance of a response.) If the lag time is long, especially compared to human lifetimes (or attention spans or our ability to continue measuring and monitoring), we can fail to recognize the change and know what is the cause and what is the effect. We can also come to believe that a possible cause is not having a detrimental effect, when in reality the effect is only delayed. For example, logging on steep slopes can increase the likelihood and rate of erosion, but in comparatively dry environments this may not become apparent until there is heavy rain, which might not occur until a number of years afterward. If the lag time is short, cause and effect are easier to identify. For example, highly toxic gas released from a chemical plant will likely have rapid effects on the health of people living nearby.

With an understanding of input and output, positive and negative feedback, stable and unstable systems, and systems at steady state, we have a framework for interpreting some of the changes that may affect systems.

Selected Examples of System Responses

Although environmental science deals with very complex phenomena, there are recurring relationships that we can represent with a small number of graphs that show how one part of a system responds to inputs from another part. These graphs include responses of individual organisms, responses of populations and species, responses of entire ecosystems and then large units of the **biosphere**, the planetary system that includes and sustains life, such as how the atmosphere responds to the burning of fossil fuels. Each of these graphs has a mathematical equation that can explain the curve, but it is the shape of the graph and what that shape represents that are key to understanding environmental systems. These curves represent, in one manifestation or another, the fundamental dynamics found in these systems. The graphs show (1) a straight line (linear); (2) the positive exponential; (3) the negative exponential; (4) the logistic curve; and (5) the saturation (Michaelis-Menton) curve. An example of each is shown in Figures 3.12 to 3.15.

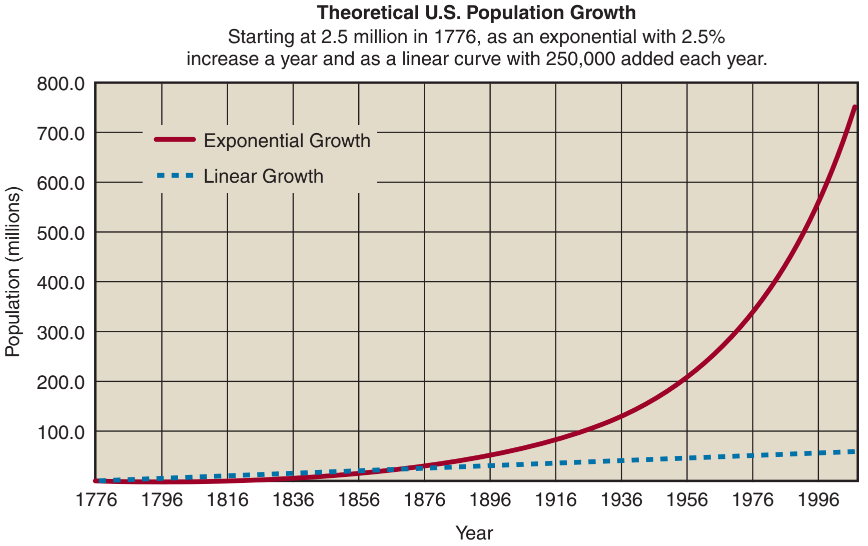


FIGURE 3.12 Curves 1 and 2: linear and positive exponential. This graph shows theoretical growth of the population of the United States, starting with the 2.5 million people estimated to have been here in 1776 and growing as an exponential and a linear curve. Even though the linear curve adds 250,000 people a year—10% of the 1776 population—it greatly lags the exponential by the beginning of the 20th century, reaching fewer than 100 million people today, while the exponential would have exceeded our current population.

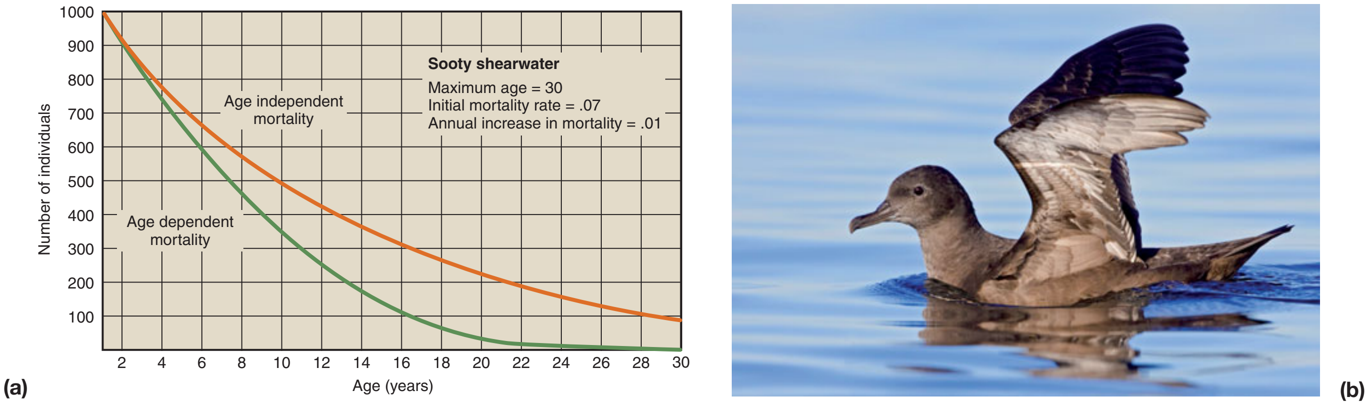


FIGURE 3.13 Negative exponential. Example: the decline in a population of a species of birds when there are no births and the mortality rate is 7% per year. The upper curve is a pure negative exponential. (*Source*: D.B. Botkin and R.S. Miller, 1974, Mortality rates and survival of birds, *American Nat.* 108: 181–192.)

Figure 3.12 shows both a linear relation and a positive exponential relation. A linear relation is of the form $y = a + bx$, where a is the y intercept (in this case, 0) and b is the slope of the line (change in y to change in x, where y is the vertical axis and x the horizontal). The form of the positive exponential curve is $y = ax^b$, where a is the y intercept (in this case 0) and b is the slope. However, b is a positive exponent (power). (See A Closer Look 3.2, Exponential Growth.)

Figure 3.13 shows two examples of negative exponential relations. Figure 3.14 is the logistic curve, which often has the shape of a lazy *S*; the logistic carrying *k* is the population eventually reached or approached, based on environmental factors. The saturation (Michaelis-Menton) curve (Figure 3.15) shows initial fast change, followed by a leveling off at saturation. At the point of saturation, the net CO_2 fixed (for soybean)is at a light-intensity value of about 3,000. As light intensity increases above about 3,000, net fixed CO_2 is nearly constant (that is, fixed CO_2 saturates at light intensity of 3,000 and does not change if intensity increases).

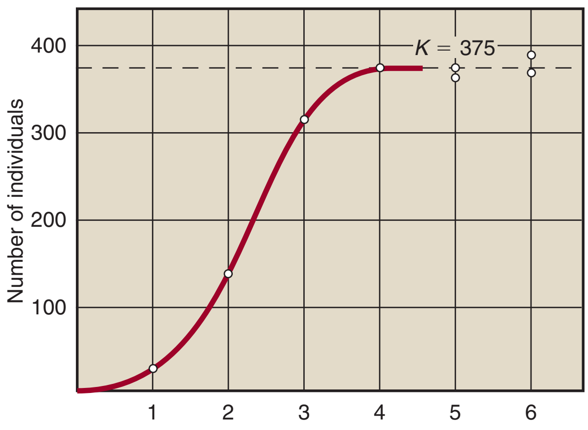
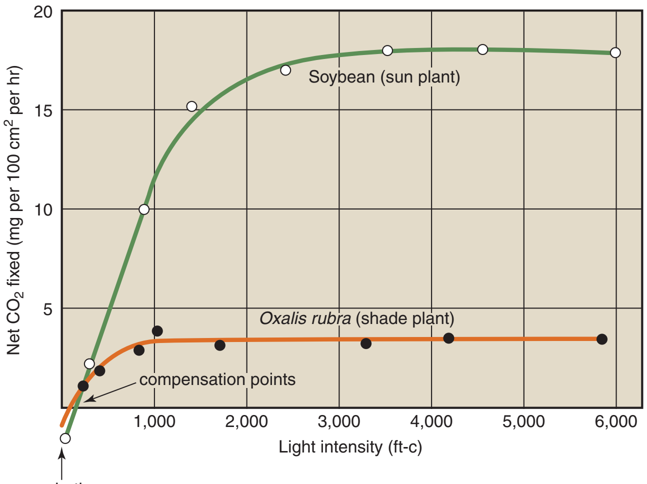


FIGURE 3.14 (a) The logistic curve. Growth of a population of a microorganism in a laboratory test tube under constant conditions with a constant supply of food. (From G.F. Gause, *The Struggle for Existence.*) The logistic carrying capacity is *k*. If you take a population of such bacteria into a laboratory and grow them under constant conditions, you might get the population to change according to the curve above, as Gause did in the 1930s with other microorganisms. (*Source:* D.B. Botkin, *Discordant Harmonies: A New Ecology for the 21st Century* [New York: Oxford University Press, 1990].)



(a)

(b)

(c)

FIGURE 3.15 **(a) The saturation (Michaelis-Menton) curve.** (*Source:* F.B. Salisbury and C. Ross, *Plant Physiology* [Belmont, CA: Wadsworth, 1969, p. 292, Figure 14-9.] Data from R. Bohning and C. Burnside, 1956, *American Journal of Botany* 43:557].); **(b)** *Glycine max* (soybeans); **(c)** *Oxalis rubra* (shade plant).

A CLOSER LOOK 3.2

Exponential Growth Defined, and Putting Some Numbers on It

Exponential growth is a particularly important kind of feedback. Change is exponential when it increases or decreases at a constant rate per time period, rather than by a constant amount. For instance, suppose you have $1,000 in the bank and it grows at 10% per year. The first year, $100 in interest is added to your account. The second year, you earn more, $110, because you earn 10% on a higher total amount of $1,100. The greater the amount, the greater the interest earned, so the money increases by larger and larger amounts. When we plot data in which exponential growth is occurring, the curve we obtain is said to be **J**-shaped. It looks like a skateboard ramp, starting out nearly flat and then rising steeply.

Two important qualities of exponential growth are (1) the rate of growth measured as a percentage and (2) the doubling time in years. The **doubling time** is the time necessary for the quantity being measured to double. A useful rule is that the doubling time is approximately equal to 70 divided by the annual percentage growth rate. Working It Out 3.2 describes exponential growth calculations and explains why 70 divided by the annual growth rate is the doubling time.

WORKING IT OUT 3.2 Exponential Growth

If the quantity of something (say, the number of people on Earth) increases or decreases at a fixed fraction per unit of time, whose symbol is k (for example, $k = +0.02$ per year), then the quantity is changing exponentially. With positive k, we have exponential growth. With negative k, we have exponential decay.

The growth rate R is defined as the percent change per unit of time—that is, $k = R/100$. Thus, if $R = 2\%$ per year, then $k = +0.02$ per year. The equation to describe exponential growth is

$$N = N_o e^{kt}$$

where N is the future value of whatever is being evaluated; N_o is present value; e, the base of natural logarithms, is a constant 2.71828; k is as defined above; and t is the number of years over which the growth is to be calculated.

This equation can be solved using a simple hand calculator, and a number of interesting environmental questions can then be answered. For example, assume that we want to know what the world population is going to be in the year 2020, given that the population in 2003 is 6.3 billion and the population is growing at a constant rate of 1.36% per year ($k = 0.0136$). We can estimate N, the world population for the year 2020, by applying the preceding equation:

$$\begin{aligned} N &= (6.3 \times 10^9) \times e^{(0.0136 \times 17)} \\ &= 6.3 \times 10^9 \times e^{0.2312} \\ &= 6.3 \times 10^9 \times 2.718^{0.231} \\ &= 7.94 \times 10^9, \text{ or } 7.94 \text{ billion people} \end{aligned}$$

The doubling time for a quantity undergoing exponential growth (i.e., increasing by 100%) can be calculated by the following equation:

$$2N_T = N_0 e^{kTd}$$

where T_d is the doubling time.

Take the natural logarithm of both sides.

$$\ln 2 = kT_d \quad \text{and} \quad T_d = \ln 2/k$$

Then, remembering that $k = R/100$,

$$\begin{aligned} T_d &= 0.693/(R/100) \\ &= 100(0.693)/R \\ &= 69.3/R, \textit{ or about } 70/R \end{aligned}$$

This result is our general rule—that the doubling time is approximately 70 divided by the growth rate. For example, if $R = 10\%$ per year, then $T = 7$ years.

3.3 Overshoot and Collapse

Figure 3.16 shows the relationship between carrying capacity (maximum population possible without degrading the environment necessary to support the population) and the human population. The carrying capacity starts out being much higher than the human population, but if a population grows exponentially (see Working It Out 3.2), it eventually exceeds—**overshoots**—the carrying capacity. This ultimately results in the **collapse** of a population to some lower level, and the carrying capacity may be reduced as well. In this case, the lag time is the period of exponential growth of a population before it exceeds the carrying capacity. A similar scenario may be posited for harvesting species of fish or trees.

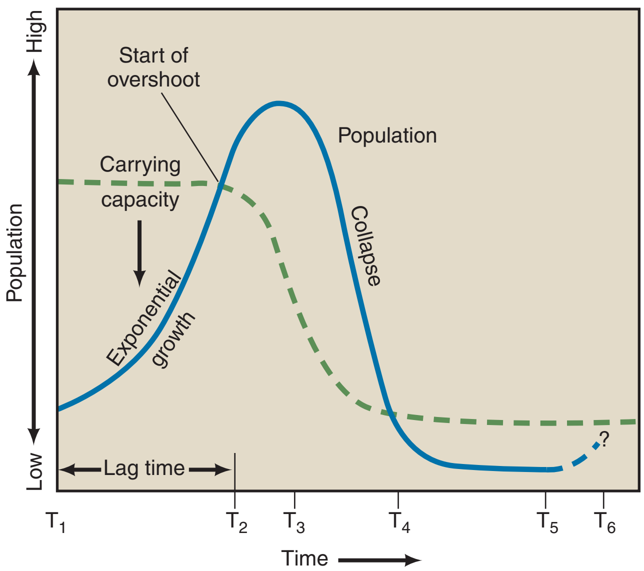


FIGURE 3.16 The concept of overshoot. A population starts out growing exponentially, but as this growth cannot continue indefinitely, it reaches a peak, then declines sharply. Sometimes the population is assumed to have a carrying capacity, which is the maximum number possible, and if the population's habitat is damaged by too great an abundance, the carrying capacity also decreases. (*Source*: Modified after D.H. Meadows and others, 1992.)

3.4 Irreversible Consequences

Adverse consequences of environmental change do not necessarily lead to irreversible consequences. Some do, however, and these lead to particular problems. When we talk about irreversible consequences, we mean

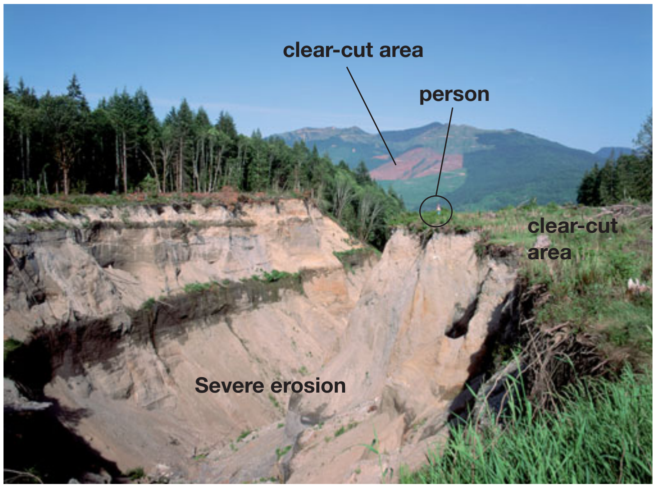


FIGURE 3.17 **Timber harvest (clear-cut) can result in soil erosion.** Once soil is removed, it can take such a long time for it to rebuild that the damage may be viewed as irreversible on a human time scale.

consequences that may not be easily rectified on a human scale of decades or a few hundred years.

Good examples of this are soil erosion and the harvesting of old-growth forest (Figure 3.17). With soil erosion, there may be a long lag time until the soil erodes to the point where crops no longer have their roots in active soil that has the nutrients necessary to produce a successful crop. But once the soil is eroded, it may take hundreds or thousands of years for new soil to form, and so the consequences are irreversible in terms of human planning. Similarly, when old-growth forests are harvested, it may take hundreds of years for them to be restored. Lag times may be even longer if the soils have been damaged or eroded by timber harvesting.

3.5 Environmental Unity

Our discussion of positive and negative feedback sets the stage for another fundamental concept in environmental science: **environmental unity**—the idea that it is impossible to change only one thing; everything affects everything else. Of course, this is something of an overstatement; the extinction of a species of snails in North America, for instance, is hardly likely to change the flow characteristics of the Amazon River. However, many aspects of the natural environment are in fact closely linked, and thus changes in one part of a system often have secondary and tertiary effects within the system, and on adjacent systems as well. Earth and its ecosystems are complex entities in which any action may have many effects.

We will find many examples of environmental unity throughout this book. Urbanization illustrates it. When cities, such as Chicago and Indianapolis, were developed in the eastern and midwestern United States, the clearing of forests and prairies and the construction of buildings and paved streets increased surface-water runoff and soil erosion, which in turn affected the shape of river channels—some eroded soil was deposited on the bottom of the channel, reducing channel depth and increasing flood hazard. Increased fine sediment made the water muddy, and chemicals from street and yard runoff polluted the stream.[5,6] These changes affected fish and other life in the river, as well as terrestrial wildlife that depended on the river. The point here is that land-use conversion can set off a series of changes in the environment, and each change is likely to trigger additional changes.

3.6 Uniformitarianism

Uniformitarianism is the idea that geological and biological processes that occur today are the same kinds of processes that occurred in the past, and vice versa. Thus, the present is the key to the past, and the past the key to the future. For example, we use measurements of the current rate of erosion of soils and bedrock by rivers and streams to calculate the rate at which this happened in the past and to estimate how long it took for certain kinds of deposits to develop. If a deposit of gravel and sand found at the top of a mountain is similar to stream gravels found today in an adjacent valley, we may infer by uniformitarianism that a stream once flowed in a valley where the mountaintop is now. The concept of uniformitarianism helps explain the geologic and evolutionary history of Earth.

Uniformitarianism was first suggested in 1785 by the Scottish scientist James Hutton, known as the father of geology. Charles Darwin was impressed by the concept, and it pervades his ideas on biological evolution. Today, uniformitarianism is considered one of the fundamental principles of the biological and Earth sciences.

Uniformitarianism does not demand or even suggest that the magnitude and frequency of natural processes remain constant, only that the processes themselves continue. For the past several billion years, the continents, oceans, and atmosphere have been similar to those of today. We assume that the physical and biological processes that form and modify the Earth's surface have not changed significantly over this period. To be useful from an environmental standpoint, the principle of uniformitarianism has to be more than a key to the past; we must turn it around and say that a study of past and present processes is the key to the future. That is, we can assume that in the future the same physical and biological processes will operate, although the rates will vary as the environment is influenced by natural change and human activity. Geologically short-lived landforms, such as beaches (Figure 3.18) and lakes, will continue to appear and disappear in response to storms, fires, volcanic eruptions, and earthquakes. Extinctions of animals and plants will continue, in spite of, as well as because of, human activity.

Obviously, some processes do not extend back through all of geologic time. For example, the early Earth atmosphere did not contain free oxygen. Early photo-

FIGURE 3.18 This beach on the island of Bora Bora, French Polynesia, is an example of a geologically short-lived landform, vulnerable to rapid change from storms and other natural processes.

synthetic bacteria converted carbon dioxide in the atmosphere to hydrocarbons and released free oxygen; before life, this process did not occur. But the process began a long time ago—3.5 billion years ago—and as long as there are photosynthetic organisms, this process of carbon dioxide uptake and oxygen release will continue.

Knowledge of uniformitarianism is one way that we can decide what is "natural" and ascertain the characteristics of nature undisturbed by people. One of the environmental questions we ask repeatedly, in many contexts, is whether human actions are consistent with the processes of the past. If not, we are often concerned that these actions will be harmful. We want to improve our ability to predict what the future may bring, and uniformitarianism can assist in this task.

3.7 Earth as a System

The discussion in this chapter sets the stage for a relatively new way of looking at life and the environment—a global perspective, thinking about our entire planet's life-supporting and life-containing system. This is known as Earth systems science, and it has become especially important in recent years, with concerns about climate change (see Chapter 20).

Our discussion of Earth as a system—life in its environment, the biosphere, and ecosystems—leads us to the question of how much life on Earth has affected our planet. In recent years, the **Gaia hypothesis**—named for Gaia, the Greek goddess Mother Earth—has become a hotly debated subject.[7] The hypothesis states that life manipulates the environment for the maintenance of life. For example, some scientists believe that algae floating near the surface of the ocean influence rainfall at sea and the carbon dioxide content of the atmosphere, thereby significantly affecting the global climate. It follows, then, that the planet Earth is capable of physiological self-regulation.

The idea of a living Earth can be traced back at least to Roman times in the writing of Lucretius.[3] James Hutton, whose theory of uniformitarianism was discussed earlier, stated in 1785 that he believed Earth to be a superorganism, and he compared the cycling of nutrients from soils and rocks in streams and rivers to the circulation of blood in an animal.[7] In this metaphor, the rivers are the arteries and veins, the forests are the lungs, and the oceans are the heart of Earth.

The Gaia hypothesis is really a series of hypotheses. The first is that life, since its inception, has greatly affected the planetary environment. Few scientists would disagree. The second hypothesis asserts that life has altered Earth's environment in ways that have allowed life to persist. Certainly, there is some evidence that life has had such an effect on Earth's climate. A popularized extension of the Gaia hypothesis is that life *deliberately* (consciously) controls the global environment. Few scientists accept this idea.

The extended Gaia hypothesis may have merit in the future, however. We have become conscious of our effects on the planet, some of which influence future changes in the global environment. Thus, the concept that we can consciously make a difference in the future of our planet is not as extreme a view as many once thought. The future status of the human environment may depend in part on actions we take now and in coming years. This aspect of the Gaia hypothesis exemplifies the key theme of thinking globally, which was introduced in Chapter 1.

3.8 Types of Change

Change comes in several forms. Some changes brought on by human activities involve rather slow processes—at least from our point of view—with cumulative effects. For example, in the middle of the 19th century, people began to clear-cut patches of the Michigan forests. It was commonly believed that the forests were so large that it would be impossible to cut them all down before they grew back just as they were. But with many people logging in different, often isolated areas, it took less than 100 years for all but about 100 hectares to be clear-cut.

Another example: With the beginning of the Industrial Revolution, people in many regions began to burn fossil fuels, but only since the second half of the 20th century have the possible global effects become widely evident. Many fisheries appear capable of high harvests for many years. But then suddenly, at least from our perspective—sometimes within a year or a few years—an entire species of fish suffers a drastic decline. In such cases, long-term damage can be done. It has been difficult to recognize when harvesting fisheries is overharvesting and, once it has started, figuring out what can be done to enable a fishery to recover in time for fishermen to continue making a living. A famous example of this was the harvesting of anchovies off the coast of Peru. Once the largest fish catch in the world, within a few years the fish numbers declined so greatly that commercial harvest was threatened. The same thing has happened with the fisheries of Georges Banks and the Grand Banks in the Atlantic Ocean.

You can see from these few examples that environmental problems are often complex, involving a variety of linkages among the major components and within each component, as well as linear and exponential change, lag times, and the possibility of irreversible consequences.

As stated, one of our goals in understanding the role of human processes in environmental change is to help manage our global environment. To accomplish this goal, we need to be able to predict changes, but as the examples above demonstrate, prediction poses great challenges. Although some changes are anticipated, others come as a surprise. As we learn to apply the principles of environmental unity and uniformitarianism more skillfully, we will be better able to anticipate changes that would otherwise have been surprises.

CRITICAL THINKING ISSUE

Is the Gaia Hypothesis Science?

According to the Gaia hypothesis, Earth and all living things form a single system with interdependent parts, communication among these parts, and the ability to self-regulate. Are the Gaia hypothesis and its component hypotheses science, fringe science, or pseudoscience? Is the Gaia hypothesis anything more than an attractive metaphor? Does it have religious overtones? Answering these questions is more difficult than answering similar questions about, say, crop circles, described in Chapter 2. Analyzing the Gaia hypothesis forces us to deal with some of our most fundamental ideas about science and life.

Critical Thinking Questions

1. What are the main hypotheses included in the Gaia hypothesis?
2. What kind of evidence would support each hypothesis?
3. Which of the hypotheses can be tested?
4. Is each hypothesis science, fringe science, or pseudoscience?
5. Some scientists have criticized James E. Lovelock, who formulated the Gaia hypothesis, for using the term *Gaia*. Lovelock responds that it is better than referring to a "biological cybernetic system with homeostatic tendencies." What does this phrase mean?
6. What are the strengths and weaknesses of the Gaia hypothesis?

SUMMARY

- A system is a set of components or parts that function together as a whole. Environmental studies deal with complex systems, and solutions to environmental problems often involve understanding systems and their rates of change.
- Systems respond to inputs and have outputs. Feedback is a special kind of system response, where the output affects the input. Positive feedback, in which increases in output lead to increases in input, is destabilizing, whereas negative feedback, in which increases in output lead to decreases in input, tends to stabilize or encourage more constant conditions in a system.
- Relationships between the input (cause) and output (effect) of systems may be linear, exponential, or represented by a logistic curve or a saturation curve .
- The principle of environmental unity, simply stated, holds that everything affects everything else. It emphasizes linkages among parts of systems.
- The principle of uniformitarianism can help predict future environmental conditions on the basis of the past and the present.
- Although environmental and ecological systems are complex, much of what happens with them can be characterized by just a few response curves or equations: the straight line, the exponential, the logistic, and the saturation curves.
- Exponential growth, long lag times, and the possibility of irreversible change can combine to make solving environmental problems difficult.
- Change may be slow, fast, expected, unexpected, or chaotic. One of our goals is to learn to better recognize change and its consequences in order to better manage the environment.

REEXAMINING THEMES AND ISSUES

Human Population

Due partly to a variety of positive-feedback mechanisms, Earth's human population is increasing. Of particular concern are local or regional increases in population density (the number of people per unit area), which strain resources and lead to human suffering.

Sustainability

Negative feedback is stabilizing. If we are to have a sustainable human population and use our resources sustainably, then we need to put in place a series of negative feedbacks within our agricultural, urban, and industrial systems.

Global Perspective

This chapter introduced Earth as a system. One of the most fruitful areas for environmental research remains the investigation of relationships between physical and biological processes on a global scale. More of these relationships must be discovered if we are to solve environmental problems related to such issues as potential global warming, ozone depletion, and disposal of toxic waste.

Urban World

The concepts of environmental unity and uniformitarianism are particularly applicable to urban environments, where land-use changes result in a variety of changes that affect physical and biochemical processes.

People and Nature

People and nature are linked in complex ways in systems that are constantly changing. Some changes are not related to human activity, but many are—and human-caused changes from local to global in scale are accelerating.

Science and Values

Our discussion of the Gaia hypothesis reminds us that we still know very little about how our planet works and how physical, biological, and chemical systems are linked. What we do know is that we need more scientific understanding. This understanding will be driven, in part, by the value we place on our environment and on the well-being of other living things.

KEY TERMS

average residence time **46**
balance of nature **46**
biosphere **50**
classical stability **44**
closed system **44**
doubling time **52**
dynamic equilibrium **46**
dynamic system **44**
ecosystem **46**
environmental unity **54**
equilibrium **44**
exponential growth **52**
feedback **48**
flow **50**
flux **50**
Gaia hypothesis **55**
input **44**
lag time **50**
linear process **50**
materially closed system **44**
negative feedback **48**
nonlinear process **50**
open system **44**
output **44**
overshoot and collapse **53**
positive feedback **48**
static system **44**
steady-state system **45**
system **44**
uniformitarianism **54**

STUDY QUESTIONS

1. What is the difference between positive and negative feedback in systems? Provide an example of each.
2. What is the main point concerning exponential growth? Is exponential growth good or bad?
3. Why is the idea of equilibrium in systems somewhat misleading in regard to environmental questions? Is it ever possible to establish a balance of nature?
4. Why is the average residence time important in the study of the environment?
5. Is the Gaia hypothesis a true statement of how nature works, or is it simply a metaphor? Explain.
6. How might you use the principle of uniformitarianism to help evaluate environmental problems? Is it possible to use this principle to help evaluate the potential consequences of too many people on Earth?
7. Why does overshoot occur, and what could be done to anticipate and avoid it?

FURTHER READING

Botkin, D.B., M. Caswell, J.E. Estes, and A. Orio, eds., *Changing the Global Environment: Perspectives on Human Involvement* (NewYork: Academic Press, 1989). One of the first books to summarize the effects of people on nature; it includes global aspects and uses satellite remote sensing and advanced computer technologies.

Bunyard, P., ed., *Gaia in Action: Science of the Living Earth* (Edinburgh: Floris Books, 1996). This book presents investigations into implications of the Gaia hypothesis.

Lovelock, J., *The Ages of Gaia: A Biography of Our Living Earth* (New York: Norton, 1995). This small book explains the Gaia hypothesis, presenting the case that life very much affects our planet and in fact may regulate it for the benefit of life.