CHAPTER

2

The Science and Methods of Environmental Health

Learning Objectives

After studying this chapter, the reader will be able to:

- Define or explain the key terms introduced throughout the chapter
- Define and distinguish among the key scientific and methodologic domains of environmental health and explain how they relate to one another
- Explain how natural environmental processes and the characteristics of individual chemicals together affect the fate and transport of chemicals in the environment
- Describe routes of exposure and excretion, distinguish between exposure and dose and among different measures of dose, and interpret the key features of a dose–response curve based on a rodent bioassay
- Present a conceptual model of exposure, identifying key events and processes as well as estimates of a toxicant or its effects; distinguish between routes and pathways of exposure; and explain the standard units of absorbed dose
- Explain the distinction between descriptive and analytic epidemiologic study designs, compare and contrast the key measures used in surveillance, and discuss criteria for concluding that a statistical association represents a causal connection

- Describe the core principles of community-based participatory research
- Describe the major steps in a risk assessment for the noncancer and carcinogenic effects of a chemical, explaining the outcome or product of each step, and contrast procedures for the risk assessment of a chemical with those for the risk assessment of a site
- Define risk management, distinguishing it from risk assessment, and give examples of risk-management decisions or strategies
- Summarize the range of activities that fall under the rubric of risk communication
- Articulate the key elements of the precautionary principle as it is invoked in environmental health and describe some practical policy tools that reflect a precautionary mindset

As a branch of public health, the field of environmental health takes a population perspective. That is, our fundamental concern is not only with the health of individuals, but also with the health of populations—specifically, with environmental factors that pose a risk to the health of populations. This definition encompasses a wide range of hazards, from chemical and physical toxicants, including radiation and noise, to the biological agents of infectious disease and even interactions with genetic or social factors.

Yet many people, when they think of environmental health, think of pollution—and when they think of pollution, they think of chemicals. In fact, chemical contamination has been at the heart of environmental health concerns in the industrialized nations since the advent of synthetic organic chemicals in the mid-20th century. For this reason, much of this chapter is devoted to describing the science and methods related to chemical exposures and their effects. These approaches are also relevant to other toxicants, such as particulates and radiation, as well as to plant and animal toxins.

In this chapter, Section 2.1 describes the science base and research methods that inform our understanding of environmental hazards and their health effects on people.

- From environmental science, we learn about the behavior of contaminants in the environment—their chemical or physical transformations, and their movements with or between environmental media, such as air and water. Taken together, these events are commonly referred to as the **fate and transport** of contaminants in the environment.
- **Toxicology** is the science of the adverse effects of toxic agents—chemicals, including natural toxins, and also physical hazards such as asbestos fibers or radiation—on normal biological structure and function in humans and other living things. In a sense, toxicology continues the story of the fate and transport of environmental contaminants into the interior realm, studying their movements, transformations, and ultimate effects in the body.

- The applied science of **exposure assessment** provides methods to measure or estimate human contact with environmental contaminants. Exposure can be assessed both outside and inside the body, and so exposure assessment draws not only on an understanding of the processes of environmental fate and transport, but also on insights from toxicology.
- Despite the enormous breadth and diversity of environmental health hazards, there is one research method that spans them all. **Epidemiology** is a quantitative method for studying the distribution and determinants of health outcomes in human populations. By using specialized quantitative methods and drawing on exposure assessment science, epidemiology becomes a tool for documenting connections between environmental hazards and health effects. Methods have been developed to study hazards ranging from chemicals to infectious disease to social factors.
- Finally, in environmental health, as in other domains of public health, **community-based participatory research** is now a broadly accepted approach to the study of health hazards. As the name suggests, this approach explicitly incorporates community involvement as an integral part of a research effort.

Section 2.2 describes the principles and methods that underlie our actions in responding to environmental health hazards.

- Operating at the interface between science and regulation is **risk assessment**, an applied science. This process rests on a set of formal procedures for evaluating and integrating scientific information on exposure and toxicity in order to estimate the real-world public health risk of a hazard. As such, risk assessment is broadly integrative, bringing together information from environmental science, toxicology, exposure assessment, and epidemiology. In environmental health, the formal risk assessment approach is applied mostly to toxicants such as chemicals, particulates, and radiation; however, its influence can be seen in the evaluation of other hazards.
- **Risk management** encompasses the very broad range of actions taken to control or mitigate environmental health hazards. Risk management decisions are often informed by the results of a formal risk assessment, but of course many decisions must be made in the absence of such an assessment. Unlike risk assessment, risk management must balance risks, benefits, and costs, and also consider the social context of decisions.
- The term **risk communication**, as part of a trio with risk assessment and risk management, usually refers to the sharing of information about an environmental health hazard, such as a waste site, between experts and the public—a complex process because of differences in the way these two groups tend to conceptualize risk.

In contrast to risk assessment and risk management, which are methods for addressing environmental health hazards after the fact, the precautionary approaches discussed in Section 2.3 call for the exercise of forethought in deciding how (or whether) to undertake new actions or policies or to develop new substances or technologies. Such precautionary approaches to environmental health decision making offer an alternative to the more casual adoption of new chemicals and technologies, followed by efforts to assess and manage their impacts as these become apparent.

The assessment and regulation of environmental health hazards in the United States are complex processes, involving several major laws and numerous agencies. Moreover, many environmental health issues have international aspects. The federal agencies and other national and international bodies listed in **Table 2.1** play key roles in learning about and addressing environmental risks to health and will be mentioned at various points throughout this text.

Table 2.1 U.S. and International Agencies and Organizations Most Pertinent to Research and Practice in Environmental Health

Agencies within departments of the executive branch of the U.S. government

U.S. Department of Health and Human Services

- **National Institutes of Health**—conducts and supports research and dissemination of information on human health
  - **National Cancer Institute**—conducts and supports research and dissemination of information on the causes, prevention, diagnosis, treatment, and control of cancer
  - **National Institute for Environmental Health Sciences**—works to understand environmental influences on the development and progression of human disease
    - **National Toxicology Program—**evaluates agents of public health concern by developing and applying the methods of toxicology and molecular biology (an inter-agency program; core agencies are NIEHS, NIOSH, and FDA)
  - **National Library of Medicine**—collects and organizes biomedical science information and makes it available to scientists, health professionals, and the public
- **Centers for Disease Control and Prevention**—helps individuals and communities protect their health through the promotion of health; prevention of disease, injury, and disability; and preparedness for new threats
  - **National Institute for Occupational Safety and Health**—conducts research and provides information and recommendations to help prevent work-related injury and illness
- **Agency for Toxic Substances and Disease Registry**—implements health-related sections of laws that protect the public from hazardous wastes and spills, including waste facilities and Superfund sites, by assessing hazards and preventing exposures and health effects
- **Food and Drug Administration**—works to ensure the safety and efficacy of the food supply, drugs and vaccines, other biological products, supplements, cosmetics, and medical devices

U.S. Department of Labor

- **Occupational Safety and Health Administration**—works to ensure safe and healthful working conditions by setting and enforcing standards, and by providing training, outreach, education, and assistance
- **Mine Safety and Health Administration—**develops and enforces safety and health standards; inspects mines, investigates accidents, provides technical assistance and training

U.S. Department of Energy

- **Energy Information Administration**—collects, analyzes, and disseminates information on energy for policymakers and the public
- **Office of Civilian Radioactive Waste Management**—manages and disposes of high-level radioactive wastes and spent nuclear fuel

U.S. Department of Agriculture

- **Agricultural Marketing Service**—develops quality-grade standards for agricultural commodities and administers programs that regulate marketing
- **Food Safety and Inspection Service**—ensures that the nation's commercial supply of meat, poultry, and egg products is safe, wholesome, and correctly labeled and packaged
- **Animal and Plant Health Inspection Service**—protects and promotes U.S. agricultural health, including animal welfare

(continues)

Table 2.1 *(Continued)*

National Agricultural Statistics Service—conducts monthly and annual surveys and prepares USDA data and estimates of production, supply, prices, and other information **Economic Research Service**—provides economic research and analyses to inform decision making on issues related to agriculture, food, natural resources, and rural America
Independent agencies of the executive branch of the U.S. government
U.S. Environmental Protection Agency—responsible for protecting human health and the environment **U.S. Nuclear Regulatory Commission**—regulates commercial nuclear power plants and other civilian uses of nuclear materials through licensing, inspection, and enforcement **U.S. Consumer Product Safety Commission**—responsible for protecting the public from unreasonable risks of injury or death from consumer products
Private, nonprofit institutions in the United States
The National Academies—produce reports on matters of science and technology in support of policymaking, public understanding, and scientific advancement **National Academy of Sciences**—one of the National Academies; a society of scholars engaged in scientific and engineering research, who provide independent advice to government **Institute of Medicine**—one of the National Academies**;** a society of scholars in health, medicine, and health care, who provide independent advice to government **National Research Council—**the operating arm of the National Academies; produces independent expert reports and undertakes other scientific activities to inform policy and actions
Agencies of the United Nations
World Health Organization—the directing and coordinating authority for health within the U.N. system **International Agency for Research on Cancer**—coordinates and conducts international, interdisciplinary research on carcinogenesis and cancer prevention; evaluates evidence of carcinogenicity of specific agents through the IARC Monographs **United Nations Environment Programme**—promotes partnerships to care for the environment, with the goal of improving today's quality of life without compromising that of future generations **Intergovernmental Panel on Climate Change**—a scientific body set up by the United Nations Environment Programme and the World Meteorological Organization (also a U.N. agency) to report on the current state of knowledge on climate change and its impacts **U.N. Scientific Committee on the Effects of Atomic Radiation**—assesses and reports levels and effects of exposure to ionizing radiation
Note: Descriptions are derived directly from information on agency websites listed as sources (see references at end of chapter).

2.1 Understanding Environmental Hazards to Human Health

As already noted, our understanding of environmental health hazards rests on a wide-ranging set of scientific domains and research methods:

- The science of toxicants' behavior in the environment
- The science of toxicants' effects in human beings and other living things

- The measurement or estimation of human exposures to toxicants in the environment
- Quantitative estimation of the human health effects of such exposures
- Research which is grounded in a specific community, which will affect that community, and in which community members are genuine partners

Each of these is considered here in turn.

The Fate and Transport of Environmental Contaminants

The story of human exposure to environmental contaminants begins with the fate and transport of these chemicals—their transformations and movements—in the environment. Chemical contaminants in the ambient environment (the general surrounding environment) can be found in air, water, or soil, including soil that is dry and fine enough to become airborne (dust) and soil in bodies of water (sediment). Before describing the movements of air and water in the ambient environment, this section notes some key characteristics of chemicals, for although chemicals are mere passengers in environmental media, they are, in a sense, passengers with preferences.

Physical–Chemical Properties of Chemicals

Chemicals have characteristics, known as physical–chemical properties, that affect their behavior in the environment (see **Figure 2.1**). For example, the fate of a liquid chemical spilled on the ground depends partly on its **volatility** *(a)*: the tendency to change into gaseous form (to volatilize). In the environment, a highly volatile liquid chemical that is spilled will move rapidly into a gaseous form that cannot easily be cleaned up. Similarly, **aqueous solubility** *(b)* is the tendency of a chemical to dissolve in water; a highly water-soluble chemical spilled into a lake is likely to become widely dispersed in the water. (Aqueous solubility is often referred to simply as solubility.)

A third property—a chemical's affinity for water versus air *(c)*—reflects whether the chemical is more soluble than volatile, or vice versa. In conceptual terms, such an affinity represents the division, or partitioning, of the chemical between water and air that would occur if the process reached a state of equilibrium. In practice, the shift toward such an equilibrium state in the environment may be rapid or slow.

Chemicals also show an affinity for soil or sediment—actually, the organic carbon in soil or sediment—versus water *(d)*. Chemicals with a high affinity for organic carbon tend to cling to the sediments of a stream, for example, rather than being found in the water. Finally, chemicals vary in their tendency to move from water to an oily medium *(e)*. Chemicals having such a tendency are called **lipophilic** (fat-loving) or fat-soluble. Lipophilic chemicals in lakes or streams tend to move into the fatty tissues of aquatic organisms, or bioconcentrate; **bioconcentration** is a biological consequence of these chemicals' lipophilic tendency.*

*Some chemicals, including methylmercury, are not highly lipophilic but do concentrate in the muscle tissue of animals.

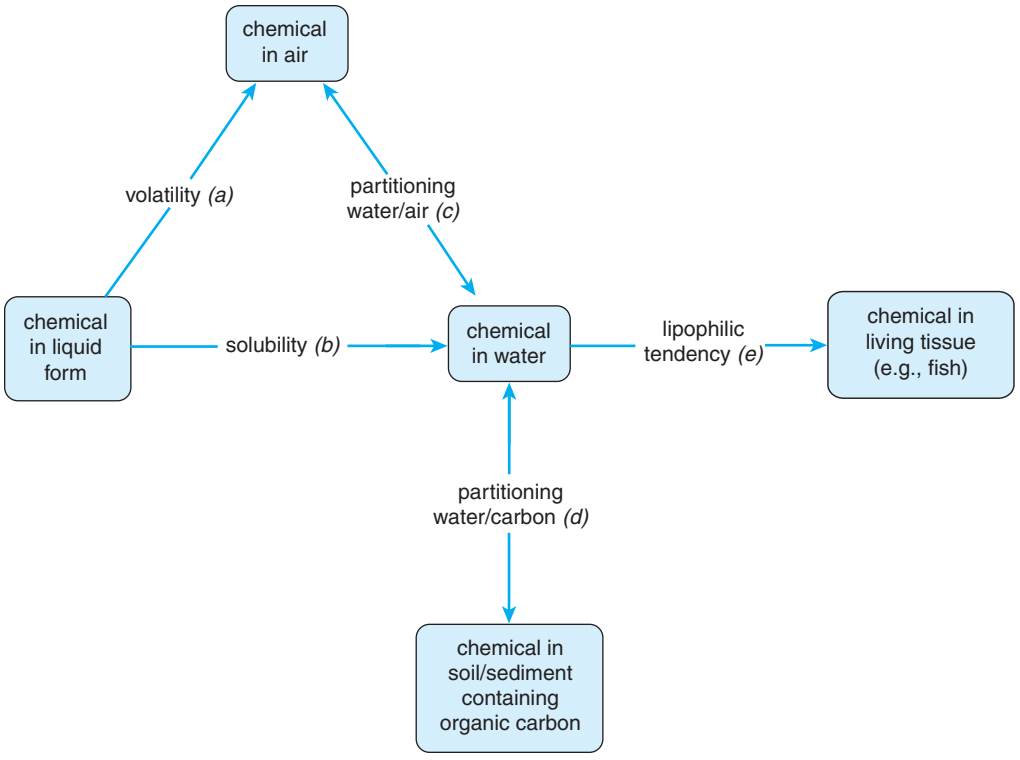

FIGURE 2.1 Physical–chemical properties of chemicals.

A chemical that tends to bioconcentrate poses a potential threat to organisms through two further processes. **Bioaccumulation** is the building up of a chemical in an individual organism's tissues over its lifetime as the organism continues to take in more than it excretes. **Biomagnification** is the process by which a chemical becomes more concentrated in the tissues of organisms at each higher level of a food chain; for example, in big fish that eat smaller fish, and in eagles (or people) that eat the big fish. In contrast to bioconcentration, bioaccumulation and biomagnification are not properties of individual chemicals, but rather processes that take place in organisms and ecosystems.

In practical terms, groups of chemicals with similar properties show similar environmental tendencies. For example, low-molecular-weight solvents such as trichloroethylene and benzene are highly volatile and moderately soluble; they are very likely to become air contaminants, but unlikely to cling to soil. At the other extreme, very heavy chemicals such as polychlorinated biphenyls (PCBs) and dioxins have very low solubility and volatility; they are unlikely to be air or water contaminants, but rather are found in soil or sediment and also reside in fat. Chemicals' behavior can also be affected by environmental conditions; for example, a volatile chemical moves from a liquid to a gaseous state more rapidly in warmer weather.

Finally, a chemical in the environment does not persist indefinitely as the same chemical but rather is transformed into other chemicals. A chemical's **persistence** in the environment is often quantified as its half-life in air, water, or soil. The **environmental half-life** of a chemical in a given medium is the period of time after which one-half of the original quantity is expected to have been chemically or biologically transformed. The term *half-life* is borrowed from radioactive decay; however, unlike radioactive half-life, the environmental half-life of a chemical is only approximate because it is greatly affected by environmental conditions, such as the presence of light or oxygen. The half-life of the pesticide DDT in soil, for example, ranges from about 8 to 15 years. In general, chemicals of higher molecular weight tend to be more persistent. The environmental persistence in soil or sediment of high-molecular-weight, lipophilic contaminants such as DDT or dioxin presents the opportunity for long-term exposures and thus greater potential for bioaccumulation and biomagnification. Even persistent chemicals, however, do not persist indefinitely in the environment, but gradually break down.

The Atmosphere

The Earth's atmosphere, though it may seem formless, has a clear structure and regular patterns of movement.

Layers of the Atmosphere

The innermost layer of the Earth's atmosphere, called the **troposphere**, extends to an altitude of approximately 8 miles (13 kilometers); within the troposphere, temperature declines with increasing altitude. Most of what we know as weather takes place in the troposphere.

Air in the troposphere is made up mostly of two colorless, odorless gases: by volume, about 78% nitrogen (N_2) and 21% oxygen (O_2). Of the remaining components, known as trace gases, the most abundant by volume is argon, which is chemically inert; that is, under ordinary conditions it does not react with other substances. Other trace gases are more important to life on Earth, and to public health: In particular, water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and ozone (O_3) all function as **greenhouse gases**. As the Earth radiates heat energy that it has absorbed from sunlight, greenhouse gases in the troposphere absorb some of that heat and reradiate it back toward the Earth's surface. This return of energy—a natural greenhouse effect—keeps the Earth's climate warm enough to support life.

Above the troposphere lies the **stratosphere**, reaching to an altitude of about 30 miles (48 kilometers). Within the stratosphere, temperature rises with increasing altitude. Roughly in the middle of the stratosphere is a layer in which the concentration of ozone is much higher than at other altitudes within the stratosphere. This **stratospheric ozone layer** absorbs much of the incoming ultraviolet radiation from the sun; without this protection, human beings could not live on Earth. (Ozone formed in the troposphere from anthropogenic pollutants, on the other hand, has negative effects on respiratory health, as described later in the context of burning fossil fuels to produce energy.)

Beyond the stratosphere lie the two outer layers of the atmosphere: the mesosphere and the thermosphere. The atmosphere does not have a sharply defined boundary at its outer edge but rather gradually becomes thinner and disappears.

Global and Local Patterns of Air Circulation

On a global scale, prevailing winds at the Earth's surface are easterly in the equatorial region (see **Figure 2.2**)—these are the trade winds, so named because they carried sailing ships on trade routes from Europe to the Americas. In the midlatitudes, both north and south, westerly winds prevail; in the polar regions, easterly winds again prevail. These wind patterns result from the combined effects of two processes—the Earth's rotation and vertical air circulation driven by temperature gradients—and can carry air pollutants over long distances, spreading them both horizontally and vertically.

Regular wind patterns also operate at smaller scales. For example, many coastal locations, where the land heats and cools more rapidly than the adjacent water each day, experience onshore winds during the daytime and nighttime winds that blow out to sea.

More generally, local and regional weather conditions affect the degree of horizontal and vertical mixing of air, and therefore the dispersion of pollutants in the air. Such dispersion may actually be visible near a source—for example, in the form of a **plume** of smoke trailing from a smokestack, becoming broader and less concentrated with increasing distance from the source.

It is sometimes said that "dilution is the solution to pollution"—a view that is both provincial and shortsighted. Yet, the reverse is certainly true: Local weather that *prevents* the dilution of air pollution can turn that pollution into an immediate public health threat. The extreme case of such conditions is a **temperature inversion**, in which a mass of cooler, heavier air becomes trapped at ground level—often in a valley—beneath a layer of warmer, less dense air. Under this "ceiling," little mixing occurs, and emissions from local sources can accumulate, causing pollutants to reach dangerously high concentrations.

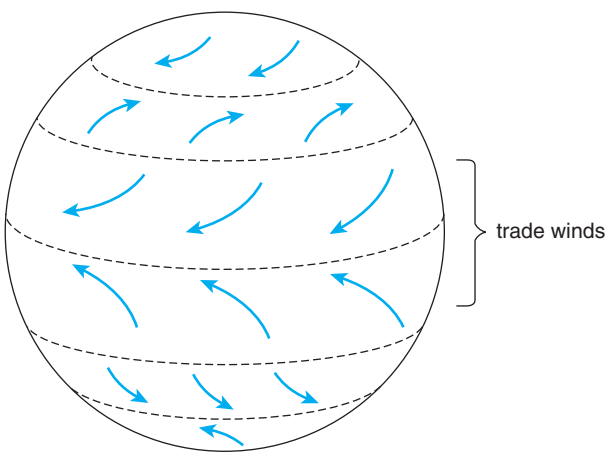

FIGURE 2.2 Global air circulation patterns.

Water in the Ambient Environment

Like the atmosphere, the Earth's water can transport pollutants at global and local scales, in ways both visible and invisible.

The Global Hydrologic Cycle

The Earth's water is connected via a complex web of processes, presented in simplified form in **Figure 2.3**. Not all aspects of this **hydrologic cycle** are readily apparent: Although oceans, lakes, and rivers are prominent features of the surface environment, both underground water and water vapor are largely invisible.

As shown in Figure 2.3, evaporation and precipitation create a continuous exchange of water between the atmosphere and the Earth's surface. The great majority of this exchange occurs between the atmosphere and the ocean. Further, the balance of precipitation and evaporation is different on land and sea: The oceans experience a net loss of water through these processes, while land areas experience a net gain. Most of the excess water from precipitation onto land returns to the oceans via rivers; a much smaller volume returns via groundwater.

Ocean Currents

Ocean currents play an integral role in moderating the Earth's climate, and they also create underwater "climates" supporting populations of fish on which humans depend for food. And, like prevailing winds, ocean currents can carry pollutants long distances. In January 1992, a ship en route from Hong Kong to Tacoma, Washington, lost overboard during a storm several

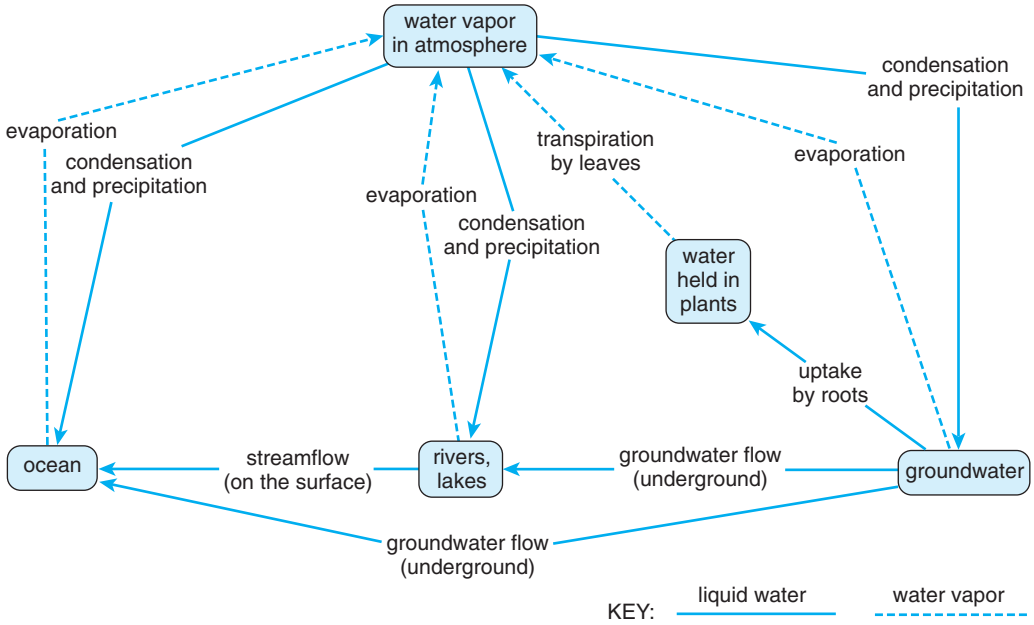

FIGURE 2.3 The hydrologic cycle.

containers of plastic bath toys, including 7200 yellow plastic ducks. The incident occurred near the International Date Line in the Northern Pacific Ocean, south of the Aleutian Islands that extend westward from Alaska. Over the next few years, plastic ducks were recovered at Shemya Island, near the western tip of the Aleutians, at several points along the coast of the Alaska panhandle, and on the Washington and Oregon coasts. In 2003, one well-weathered duck turned up near Kennebunkport, Maine, probably having spun off westward in the Pacific and traveled around the globe.[1]

The oceans' major surface currents are driven by friction between air and water, and so they mimic the global prevailing winds: easterly near the equator and westerly in the midlatitudes. But unlike the winds, ocean currents are deflected by the continents so that they form large rotating cells, flowing clockwise north of the equator and counterclockwise south of the equator (see **Figure 2.4**). Waters leaving the equatorial region form warm currents; waters returning from the polar regions form cold currents.

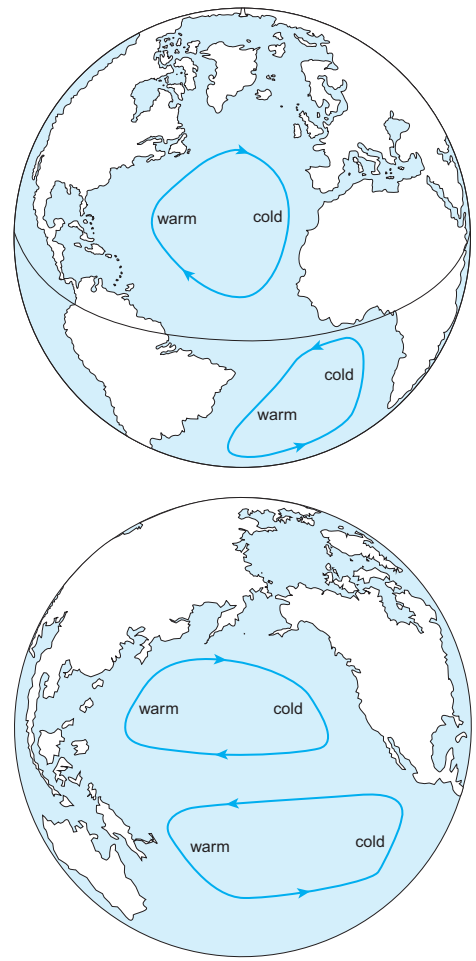

FIGURE 2.4 Major surface currents of the Atlantic and Pacific Oceans.

Deeper ocean waters also circulate along predictable paths, moving more slowly than surface waters and looping through all the world's oceans like a continuous conveyor belt. This process is largely independent of the surface currents, being driven mainly by differences in the density of the water related to temperature and salinity and therefore known as the **thermohaline circulation**.

The global thermohaline circulation is propelled by events in the North Atlantic. Here, deeper seawater is northbound along the European coast. The northbound water quickly becomes both colder and saltier (because salt is excluded from ice that is being formed). Both these changes make the seawater denser, and as a result, it drops suddenly to the ocean floor. This event drives the beginning of a new global circuit by the deep ocean waters.

The Earth's Fresh Water

Lakes and rivers are perhaps the Earth's most familiar water features. Typically, a river begins as a set of small streams that converge in stepwise fashion, ultimately uniting as a river. The area drained by a river and the streams that feed it is referred to as the river's **drainage basin**. Some surface water systems span very large geographic regions; for example, the drainage basin of the Amazon River, with all its tributaries, extends throughout Brazil. Pollutants can travel long distances in rivers and in the sediments they carry.

Confusingly, the term **watershed** is used in two ways: as a synonym for drainage basin (an area) and to refer to the divide between two drainage basins (a line). For example, in the Boston area, a community organization works to protect the Charles River watershed (drainage basin), whereas a three-way watershed (divide) in the Canadian Rockies sends glacial meltwater from the Columbia Icefield to the Atlantic, Pacific, and Arctic Oceans. The Continental Divide in the U.S. Rocky Mountains is another watershed on a grand scale. In environmental health, however, the term most often refers to a drainage basin, within which sources of pollution might be a concern.

Less visible than rivers, and far less familiar to most people, is the water located underground (see the conceptual model in Figure 2.3 and a more concrete diagram in **Figure 2.5**). Underground water resides in **aquifers**, geologic material that is porous enough to hold and transmit water. Aquifers are most often sand or gravel, but can be porous rock such as sandstone, or even fractured rock, and they are typically covered by surface soil.

As precipitation soaks into the ground above an aquifer, water trickles downward through pore spaces. In the topmost subsurface zone (above the dashed line in the diagram), water also moves upward and into the atmosphere. This can occur either via **evaporation** (within the top foot or so) or by a process called **transpiration**, through which water taken up by the roots of plants is released to the atmosphere through their leaves. Whenever more water enters the topmost zone from precipitation than leaves via evaporation and transpiration, water trickles farther downward.

Below this surface zone of two-way movement of water is a region known as the **zone of aeration**. In this zone, the pore spaces are partly filled by water. Here, water moves only downward, and it moves downward only when water from above disturbs it. Water that trickles downward through the zone of aeration **recharges** the aquifer—that is, feeds or replenishes it.

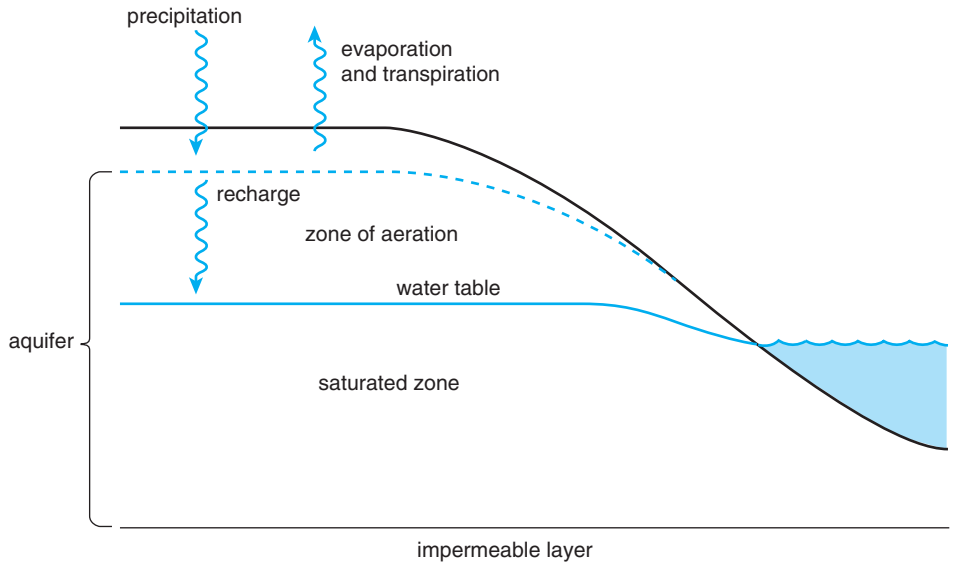

FIGURE 2.5 A water table aquifer.

Below the zone of aeration is the **saturated zone**, in which all pore spaces are filled with water. In the saturated zone, water (now called **groundwater**) can move in any direction. Usually, it seeps slowly in response to gradients of elevation and pressure toward a location where water is discharged continuously—for example, via a spring. In most locations, groundwater flows at a rate of only centimeters or inches per day.* In speaking of groundwater flow, the terms **upgradient** and **downgradient** are used in place of *upstream* and *downstream*.

The boundary between the zone of aeration and the saturated zone is called the **water table**. If more water is entering an aquifer (recharge) than is leaving it (discharge), the level of the water table rises; but if recharge is not enough to offset discharge, the water table falls. Typically, there is an annual cycle in the level of the water table related to patterns of precipitation and temperature, evaporation and transpiration.

The area on the ground surface through which rainfall feeds an aquifer is called the aquifer's **recharge area**. The lower limit of the aquifer (the floor) is an underlying layer of rock or clay that is impermeable, or nearly so. In a simple geologic setting like the one just described, the recharge area is directly above the aquifer, with no intervening impermeable layer. This is called an **unconfined aquifer** or **water table aquifer**. The surface of the water table often follows, in muted fashion, the contours of the land surface above. (In fact, contour lines are used to represent the water table surface in maps, much as they are used to represent differences in surface elevation.) If a well is drilled into a water table aquifer—leaving a cylinder made of a fine mesh so that water can flow into the borehole—the water level in the well will be the same as that in the surrounding aquifer.

*In formations of limestone, mildly acidic groundwater can dissolve the rock, carving out pipelike channels for groundwater, but such "underground rivers" are unusual.

Wastes or other products placed in the ground or on the Earth's surface within the recharge area of a water table aquifer can contaminate the aquifer. For example, if a chemical such as trichloroethylene is spilled on the ground surface, or dumped into a pit, it can trickle down to the water table. The contamination will then take the form of a plume as the chemical is carried along slowly with the groundwater, gradually dispersing horizontally and vertically—not unlike an airborne plume of smoke. A well that draws water from within such a plume will produce contaminated water.

Similarly, rainwater percolating downward through wastes placed on the ground surface (or in a pit) can dissolve out or suspend contaminants and carry them along, much as water poured through ground coffee beans dissolves out the substances that make the water into coffee. Water that has been contaminated by such **leaching** of contaminants is known as **leachate**.

An aquifer that is sandwiched between layers of impermeable (or nearly impermeable) rock is known as a **confined aquifer**. In a confined aquifer, the surface of the groundwater does not rise and fall in response to local rainfall as in an unconfined aquifer. Rather, it is largely isolated from local precipitation, although some confined aquifers are replenished by rainfall in a distant location. The water stored in a confined aquifer is under pressure. As a result, if a well is drilled into a confined aquifer, the water level in the well rises above the top of the aquifer. The water pressure may even be great enough that the water rises above the ground's surface, so that no pumping is needed. This type of well is called an **artesian well**.

Where the ground's surface intersects the water table, groundwater is connected to surface water. A spring may be visible on a hillside, for example, as the origin of a small stream. Less obviously, groundwater and surface water connect beneath lakes and streams. In humid regions, the local water table is often higher than a streambed so that groundwater moves into the stream. In arid locations, the local water table is sometimes lower than a streambed. Under these conditions, water drains from the stream into the ground.

Today's aquifers were formed long ago and bear the imprint of their geologic histories. In many geologic settings, layers of water-bearing rock alternate with impermeable layers so that aquifers are stacked beneath the Earth's surface. Aquifers vary widely in geographic scale. For example, some 25 aquifers are recognized within Massachusetts; in contrast, the extensive Ogallala Aquifer underlies parts of eight U.S. states from South Dakota to Texas.

Toxicology: The Science of Poisons

The term *environment* suggests something that merely surrounds us, but we are more permeable than we like to think. People contact—and absorb—environmental contaminants mainly by three major **routes of exposure**: **inhalation** (mostly through ordinary continuous breathing), **ingestion** (by eating and drinking), and **dermal contact** (via the skin). Toxicology is the study of how the body processes the toxicants to which it is exposed and of the ultimate effects of these toxicants in the body.

In toxicology, the term **toxin** is reserved for a naturally produced toxic substance, especially one produced by a plant or animal. The term **toxicant** usually refers to toxic substances that result from human activities, although this definition is stretched to include such naturally occurring agents as toxic metals (e.g., arsenic) or radiation, which are not produced by a plant or animal. In this text, the term *toxicant* is used except when referring specifically to natural plant or animal toxins.

The Disposition of Chemicals in the Body

Whatever the route of exposure, a chemical is absorbed into the body by passing through cell membranes. From the exposure perspective, the linings of the lungs and digestive tract may be thought of as part of the boundary between the external and internal environments—in effect, as extensions of the skin. In fact, absorption via inhalation and ingestion is much more rapid and complete than dermal absorption because the lungs and digestive tract are designed to absorb oxygen and nutrients, whereas the skin is fundamentally a protective barrier.

Exposure to environmental toxicants is often defined as *contact with the human envelope*, and the **human envelope** is defined in turn as the boundary that separates the interior of the human body from the exterior environment, as just described. Exposure is quantified as a **dose**, and the term **absorbed dose** refers specifically to the amount of some toxicant that passes through the human envelope, entering the body.

After being *absorbed*, chemicals are *distributed* around the body via the bloodstream or the lymph system, and may be *metabolized* (chemically transformed by enzymes) during the course of this journey. Much, though not all, metabolism of chemicals takes place in the liver. The processes of distribution and metabolism interact: A chemical's path through the circulatory system affects how it is metabolized, and how and where it is metabolized determines its chemical form, which in turn affects whether and how it is *stored* or *excreted*. These processes are shown in simplified form in **Figure 2.6**. The term **metabolite** refers to a product of the body's metabolism of a toxicant or toxin.

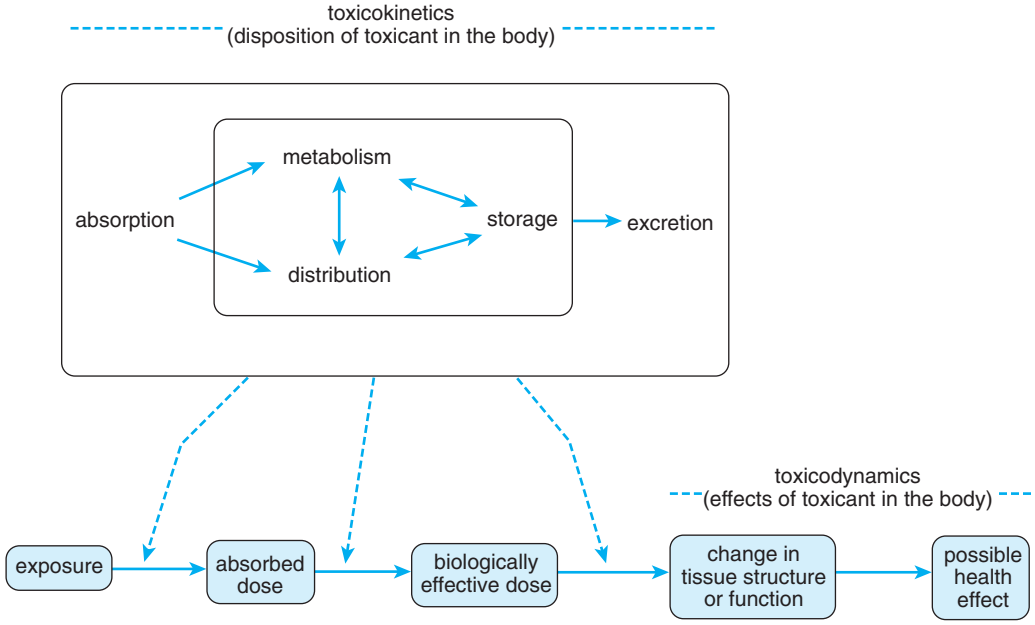

FIGURE 2.6 Disposition and effects of toxicants in the body.
Source: Special thanks to Wendy Heiger-Bernays and Michael McClean.

Lipophilic contaminants, including some pesticides, are stored in fat cells, and lead is deposited in bone (where it substitutes for calcium). Toxicants in such storage depots have been taken out of circulation and are not available to interact with a vulnerable tissue. However, excretion, by removing some quantity of a toxicant from circulation, can allow some of the same toxicant to be released from storage. Chemicals are excreted from the body mostly in exhaled air, urine, and feces, but also in sweat and semen, and by deposition in hair and nails, which in this context are seen as being outside the human envelope. (This is why it doesn't hurt to cut your hair or nails.) Breast milk may also be a route of excretion; from the perspective of the infant, of course, breast milk becomes a source of ingestion exposure.

The combined processes of **absorption**, **distribution**, **metabolism**, **storage**, and **excretion** of toxicants are together referred to as **toxicokinetics** and determine the disposition of a chemical in the body. The net effect of these processes is reflected in the total burden of the chemical, or of some breakdown product, present in the body at some point in time (the **body burden**). Of more interest in toxicology, however, is the **biologically effective dose**: The quantity of a toxicant or its breakdown product that is available to interact with some vulnerable tissue in the body. Such interactions may result in changes in tissue structure or function, which in turn may have an adverse effect on health; the term **toxicodynamics** refers to these latter processes, which constitute the toxicant's actual effects in the body. Together, toxicokinetics and toxicodynamics describe the disposition and effects of toxicants in the body.

Many factors influence the processes of disposition. The characteristics of the exposure itself—for example, a brief exposure (**acute exposure**) versus a long-lasting and usually lower-level exposure (**chronic exposure**)—may influence disposition. Exposures to another toxicant may enhance a toxic effect (**synergism**) or interfere with it (**antagonism**). And finally, many individual characteristics—from age and sex to genetic makeup to health and nutritional status—can affect the fate of a toxicant in the body and make an individual more or less susceptible to its effects. In particular, children's capacity to detoxify chemicals is different from that of adults, and their bodily systems are vulnerable because they are still developing.

Carcinogenesis

The core scientific endeavor of toxicology is to elucidate how biochemical mechanisms actually lead to toxic effects in the body at the level of molecule, cell, organ, or organ system. This section expands in some detail on one toxic mechanism—carcinogenicity—because it is pertinent to all cancers and because the U.S. regulatory framework handles carcinogenicity differently from all noncancer health effects. The mechanisms of noncancer toxicity are many and diverse, and largely outside the scope of this text.

Cancer begins with a change to the genetic code. An organism's genetic code is found in molecules of **deoxyribonucleic acid (DNA)** present in the nucleus of each cell. This same type of genetic material, with different information encoded, is found in organisms from animals to plants to bacteria and viruses. In higher animals, including humans, chromosomes are matched up in twos: Human genetic material occurs as 46 chromosomes in 23 pairs. The now-familiar double helix structure of the DNA molecule (see the following

sidebar titled "About DNA and the Genetic Code") was first described by British scientists James Watson and Francis Crick in 1953; Crick's working sketch of the molecule appears in **Figure 2.7**.

About DNA and the Genetic Code

The structure of the DNA molecule is the well-known "double helix," a sort of spiraling ladder in which the long strands are composed of sugars and phosphate groups. Each rung is made up of a pair of bases, and it is the sequence of bases that encodes genetic information. A large molecule of DNA is known as a *chromosome*; sections of chromosomes, each encoding a specific heritable trait, are defined as *genes*, each made up of a set of base pairs. In the rungs of the DNA ladder, the same two bases always pair with one another: adenine with thymine, and guanine with cytosine. When a cell replicates, each chromosome unzips, splitting each of its rungs in two; in this way, each half of the chromosome becomes a template to replicate the other half.

Mutation is a change to the DNA of a cell. A mutation that causes local damage within a gene—a small part of the DNA molecule gets changed—is called a **point mutation**. Some point mutations occur spontaneously; others occur when some agent (a **mutagen**) binds chemically to the DNA, causing a change in its structure. Cells have mechanisms to repair DNA damage, but not all damage gets repaired. Mutations that cause broader structural damage to chromosomes—for example, the loss of large sections or reversing parts of a chromosome—are usually fatal to cells. In recent years, scientists have come to appreciate the importance of **epigenetic effects**—heritable changes in how a gene is *expressed*, without any change to the DNA sequence itself. For example, methyl groups overlaid onto a DNA molecule can change how or whether genes are transcribed, the first step toward gene expression. The study of epigenetic effects is a new and rapidly growing area of research. Mutations and epigenetic effects in the cells of the body have varied impacts. As just noted, some mutations are repaired by cellular mechanisms; others have effects so severe that they lead to the death of the cell. Still other mutations or epigenetic effects become the first step on the path to cancer.

Cancer is a disease of cells. A cancerous cell, dividing without restraint, operates outside of the body's normal controls. A malignant tumor, made up of such cells, first *invades* the tissue where it originated and then *metastasizes* into other tissues, eventually disrupting the functioning of the body. Both genetic and environmental factors can affect an individual's risk of cancer.

Most cancers are believed to result from an accumulation of mutations in genes that direct cell division. Some of these genes (called oncogenes) instruct the cell to divide; others (called tumor suppressor genes) instruct the cell to stop dividing. The mutations that are important for carcinogenesis do one of two things: They either *increase the activity* of genes that instruct the cell to *divide*, or they *inhibit* genes that instruct the cell to *stop dividing*. If enough such mutations accumulate, the result is the runaway proliferation of cells—cancer. Overall, however, the

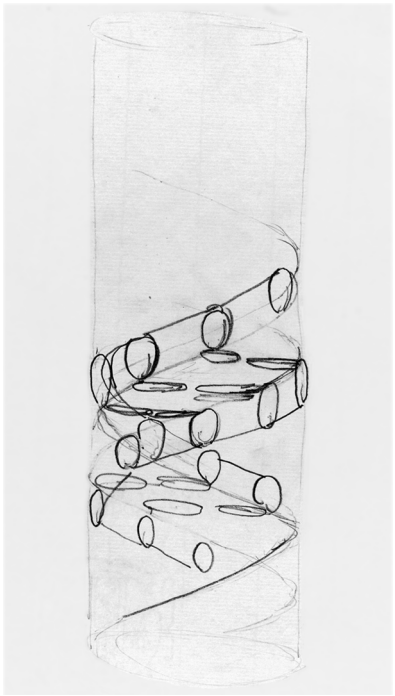

FIGURE 2.7 Francis Crick's early sketch of the DNA molecule still serves as a good representation of DNA's double helix structure: two spiral backbones linked by pairs of bases whose sequence encodes genetic information.

Source: Courtesy of Wellcome Images.

probability of getting enough of the right type of mutations in any given cell is low, making cancer a relatively rare event in the cells of the body.

For some years, the process of **carcinogenesis** has been described as occurring in stages:

- *Initiation*: A mutation occurs that either enhances instructions to the cell to divide or dampens instructions to stop dividing. This event makes the initiated cell more prone to becoming cancerous. If the mutation is not repaired before the initiated cell divides, the mutation becomes permanent, appearing in all subsequent generations.
- *Promotion*: Various substances, including natural hormones and cigarette smoke, can stimulate cells to divide; in this way, an initiated cell can become a population of cells. Such promotion of the initiated cell does not involve further damage to DNA. Instead, through repeated cell division, the initiated cell develops into a large group of identical cells—a benign tumor. Promotion has two effects: It increases the number of initiated cells, and, by making cells divide more often, it narrows the window of opportunity for repair of new mutations.
- *Progression*: Critical mutations (those that either enhance instructions to the cell to divide or dampen instructions to stop dividing) continue to occur in the initiated cells of the benign tumor. If enough of these mutations accumulate, the result is cascading cell division—a malignant tumor.

Environmental agents can play a role at each stage of carcinogenesis: as the cause of the critical mutation that initiates carcinogenesis; as promoters of the initiated cell; and as the cause of the critical mutations that constitute progression, leading to the runaway cell division that is cancer. The term **carcinogen** refers to any agent that increases cancer risk.

In more recent thinking, initiation, promotion, and progression are still key elements of carcinogenesis, but the process is no longer conceptualized as a neat time sequence, like a three-act play. These complexities are outside the scope of this text.

Gene–Environment Interaction

As noted at the outset of this text, purely genetic hazards do not fall within the scope of environmental health. However, genetic makeup sometimes affects risk through interaction with an environmental exposure, and such gene–environment interactions are currently of great scientific interest in environmental health.

There are at least three models of gene–environment interaction. First, a person's genetic makeup (genotype) can increase his or her exposure to an environmental **risk factor**; for example, a genetic predisposition to nicotine addiction tends to increase exposure to cigarette smoke. Second, genetic makeup can increase a person's susceptibility to an environmental risk factor; for example, different genotypes might result in the production of larger or smaller quantities of enzymes that determine the capacity of cells to repair DNA damage—damage that is the first step on the road to cancer. And finally, genotype and environmental factors can be independent risk factors for a disease, with a combined effect that is additive or more than additive; for example, both a specific genetic trait and cigarette smoking are known to be independent risk factors for Crohn's disease, a chronic inflammatory bowel disease.[2]

The Dose–Response Relationship

Whatever the mechanism of toxicity, it is useful to establish the quantitative relationship between dose and a toxic effect (response). Such a **dose–response relationship** is typically summarized in a graph plotting dose on the *x*-axis against response on the *y*-axis. In toxicology, the **slope** of the line in such a graph is typically positive—rising from left to right—reflecting increasing toxicity with increasing dose, as shown schematically in **Figure 2.8a**. A steeper slope indicates a more potent toxic effect—that is, a greater increase in toxic effect for a given increase in dose.

A second important characteristic of a dose–response relationship is the **threshold** (see **Figure 2.8b**). Again, in schematic terms, the threshold dose is the highest dose at which no toxic effect occurs. The practical importance of a threshold (e.g., *(a)* in Figure 2.8b) is that doses at or below the threshold dose are without toxic effect. If the threshold dose is zero *(b)*, then as a practical matter there is no threshold and no safe dose.

Now, giving our schematic dose–response relationship a more realistic shape, we show it as a flattened S, referred to as a **dose–response curve** (see **Figure 2.9a**). In such a curve, the flatter slope in the low-dose region *(c)* reflects the body's ability to partially metabolize, detoxify, or excrete a chemical before it causes a response; as these metabolic processes are overwhelmed at higher doses, the slope of the curve becomes steeper in the middle region *(d)*. At very high doses,

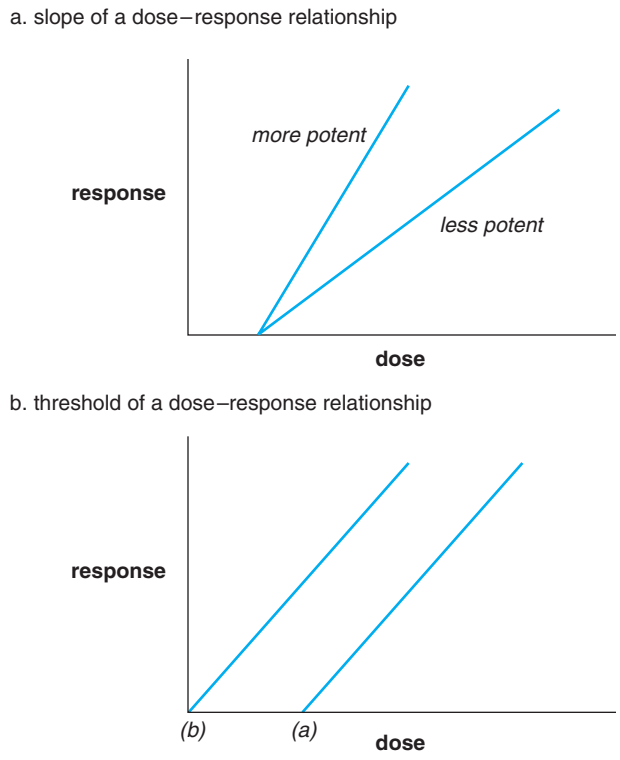

FIGURE 2.8 A schematic representation of the basic dose–response relationship.

the capacity for a toxic response may be overwhelmed, and this effect appears as a plateau at the top of the dose–response curve *(e)*.

Figure 2.9b shows dose–response curves with zero and nonzero thresholds. A wide range of toxicological evidence suggests that nearly all noncancer effects have thresholds; thus, a schematic dose–response curve for noncancer effects has the general form of *(f)*. In contrast, the mechanistic model of carcinogenesis as a multistage process suggests that any dose, however small, could produce an initiated cell that ultimately results in a malignant tumor; thus, the schematic dose–response curve for cancer has no threshold (i.e., the curve has a threshold of zero), taking the general form of *(g)*.

As described later in the context of the toxic effects of chemicals, certain synthetic organic chemicals mimic or otherwise disrupt the effects of the body's natural hormones. Recent toxicological evidence indicates that at least some of these endocrine-disrupting compounds have dose–response curves with a different shape from those in Figure 2.9.[3] In the classic curves shown in Figure 2.9, the response declines continuously with declining dose (moving from right to left in the graph). But for some endocrine-disrupting compounds, the dose–response curve shows a reversal: an upswing in response in the low-dose region. The result is a curve that is more U-shaped than S-shaped.

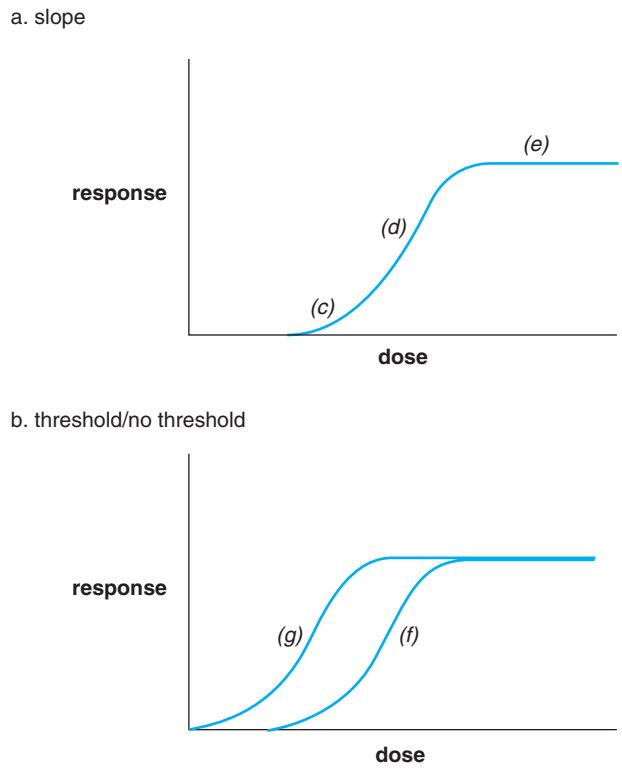

FIGURE 2.9 The dose–response curve.

Toxicity Testing

Toxicity testing—the practical work of assessing chemicals' **toxicity** to living things—complements the core scientific work of understanding the biochemical mechanisms of toxicity. This work, done in support of regulatory decision making, is often referred to as **regulatory toxicology**. In the United States, the National Toxicology Program is the lead entity in conducting regulatory toxicology studies.

In an ideal world, decisions about how to regulate chemicals would be based on studies of health effects in human beings, and in fact such information is used when it is available. But epidemiologic research is limited by ethical standards that rule out deliberately exposing humans to potentially harmful substances. In contrast, toxicity testing in laboratory animals to serve the interests of human health is generally considered to be ethical. As a result, much of the information used to estimate the toxicity of chemicals in humans comes from **bioassays**—toxicity tests in rodents and other laboratory animals. The relatively short lifespan of rodents (about 2 years for mice and rats) also makes such testing practical, because even testing for chronic toxicity can be completed in 2 years. Similarly, given that **cancer latency**—the period between the exposure that initiates a malignant tumor and the recognition of the cancer—is roughly proportional to lifespan, carcinogenicity can be assessed in a 2-year rodent study.

Preliminary Testing for Toxicity

A 2-year chronic rodent study, which gives information on both cancer and noncancer effects, is a costly undertaking. For this reason, such studies are done only after preliminary screening for toxicity. Toxicity screening is typically conducted in a tiered process, beginning with tests in microorganisms and cell cultures, proceeding to acute and subchronic studies in rodents, and finally to chronic rodent bioassays. Studies in cells or microorganisms are referred to as *in vitro* studies; those in living animals are referred to as *in vivo* studies.

Screening for mutagenic potential in bacteria reflects the current understanding that mutation is integral to carcinogenesis. The mainstay of mutagenicity testing is the Ames test, an assay in which *Salmonella typhimurium* bacteria are exposed to a chemical. The test compares the rate of occurrence of a specific point mutation at different levels of exposure to the test chemical, with and without the addition of rodent liver enzymes (to metabolize the test chemical) and in multiple strains of the bacterium. Most of the organic chemicals that have been clearly identified as human carcinogens have been shown to be genotoxic in laboratory screens such as the Ames test. A separate laboratory assay for larger-scale chromosomal damage in human or animal cell cultures may also be conducted.

In a study of acute oral toxicity, groups of rodents are administered a dose of the test chemical, usually given all at once; several dose levels are used, including some expected to be lethal. Data from such a study are used to calculate the dose that is acutely lethal to 50% of test animals exposed to it; this 50% lethal dose is abbreviated as the **LD_{50}**. The LD_{50} is expressed in units of milligrams of toxicant per kilogram of body weight (abbreviated as mg/kg). If exposure is by inhalation, an LC_{50} is calculated; this is the concentration of the chemical in air that is acutely lethal to 50% of test animals in a short time, often 4 hours. A more general concept is the ED_{50}, the dose that produces a specific effect (the effective dose) in 50% of test animals.

Further preliminary information about a chemical's toxicity in animals is obtained through the **subchronic rodent bioassay**, a 90-day study. These studies serve at least three purposes. They provide a basis for selecting the doses that will be used in a chronic rodent bioassay. They identify the **target organ**—in the language of toxicity testing, the organ that is affected first as the dose of a test chemical is increased from zero. And they also identify the need for specialized long-term study of particular effects, such as immunotoxicity, neurotoxicity, or effects on reproduction or fetal development. Although rodent bioassays are a standard approach for assessing the toxicity of chemicals, for some chemicals testing in rodents has not proved useful in predicting human risk.

The Chronic Rodent Bioassay

The **chronic rodent bioassay** is about 2 years long, approximately the lifetime of the test animals, and is designed to provide information on both cancer and noncancer effects. Parallel studies are typically conducted in rats and mice; in each study, groups of about 50 animals, male and female, are dosed at 3 levels; there is also an unexposed control group. Exposure is most commonly by ingestion (in water or food), less often by inhalation.

Because cancer is a rare disease, very large groups of rodents would be needed to study carcinogenicity at the low doses at which people are typically exposed to environmental chemicals. But such enormous rodent studies are impractical in both logistics and cost; instead, rodents are exposed to very high doses, effectively converting cancer from a rare disease to a common disease and enabling smaller-scale studies. This means that chronic rodent bioassays must be designed to include both a dose high enough to test for cancer without being fatal to the test animals and doses low enough to reveal a no-effect level for noncancer effects, if there is one.

Over the course of the study period, the animals are sacrificed, and a complete histopathologic examination is conducted on each animal. This allows the documentation of all cancers as well as a long list of other effects, ranging from gross changes (e.g., enlarged liver) to changes at the molecular level. The proportion of rodents showing each effect at each dose is recorded. Specialized testing (e.g., for neurotoxicity, immunotoxicity, or reproductive toxicity) is included.

Results of bioassays in laboratory animals are used to create a dose–response curve for each specific health effect—for example, kidney toxicity. Of course, the results of the assay can document effects only at the doses that were actually administered to the animals in the study, and therefore they give a limited view of the true underlying dose–response curve.

Some of the doses used in the study are later given special designations in light of the study's results (see **Figure 2.10a**). For a given effect, the *highest* nonzero dose at which *no* effect was observed in a study is called the **no observed adverse effect level** (**NOAEL**, pronounced "no-ell"), and the *lowest* dose at which an effect *was* observed in a study is called the **lowest observed adverse effect level** (**LOAEL**, pronounced "low-ell"). Neither the NOAEL nor the LOAEL pinpoints the actual threshold of a given effect, such as kidney toxicity, but we can infer that the threshold falls somewhere between the NOAEL and the LOAEL.

However, sometimes *all* the nonzero doses used in a rodent study show a given noncancer effect; that is, the study does not identify a NOAEL (see **Figure 2.10b**). In this situation, we can infer only that the threshold is lower than the LOAEL; the study gives no lower bound (other than zero) for the range within which the threshold falls. In this situation, the study does not indicate whether there is, in fact, a nonzero threshold. Further, the study does not indicate the shape of the curve between the LOAEL and zero; in particular, the upswing in effect in the low-dose region that is characteristic of some endocrine-disrupting compounds would not appear in the graph.[3]

For a given toxicant of concern, dose–response curves like these are developed for each cancer and noncancer effect documented in the chronic toxicity study, including the effects documented in specialized studies (e.g., of immunotoxicity, or reproductive or developmental toxicity). These data help toxicologists learn about mechanisms of action and the behavior of toxicants in living systems.

In the language of toxicology, **reproductive toxicity** is the occurrence of an adverse effect on the reproductive system or reproductive capacity of an organism; **developmental toxicity** is the occurrence of an adverse effect on the developing organism, either in utero or during infancy or childhood. The term **teratogenesis** refers specifically to the occurrence of a structural defect in the developing organism resulting from an exposure that occurs between conception and birth, and a **teratogen** is a substance that produces such defects.

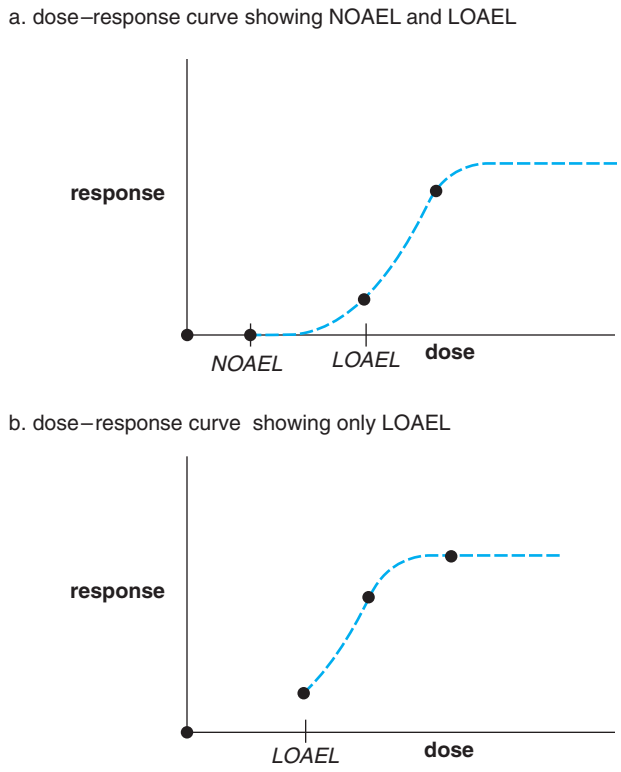

FIGURE 2.10 NOAEL and LOAEL in a dose–response curve.

Exposure Assessment: An Applied Science

The preceding two sections describe important processes by which chemicals are transported and transformed—in the environment and in the body—and may cause biological harm. The applied science of exposure assessment is a set of methods to quantify human beings' contact with environmental toxicants. Assessing exposure is quite distinct from assessing toxicity, and both exposure and toxicity are necessary for a health impact to occur. Exposure assessment is important in studying the human health effects of exposure and also in controlling exposures to prevent harm.

Exposure can be assessed both in the external environment and inside the body, drawing on insights from environmental science and toxicology. In describing exposure assessment, this section first develops a conceptual model of exposure and then describes how the model is quantified for the practical work of assessing exposure.

Completing the Conceptual Model of Exposure

As described earlier, a conceptual model for toxicology begins with the absorption of a toxicant and ends with its effects in the body (see Figure 2.6). To consider exposure fully, the model in Figure 2.6 needs to be extended backward to begin with the environmental source of a toxicant. This has been done in **Figure 2.11**, while omitting the details of toxicokinetics provided in the

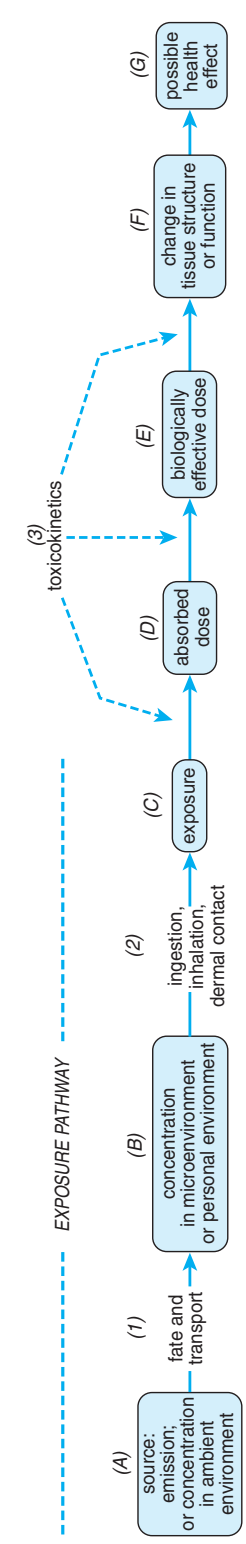

FIGURE 2.11 A conceptual model of fate and transport, exposure, dose, and effect.
Source: Special thanks to Wendy Heiger-Bernays and Michael McClean.

earlier diagram. In Figure 2.11, *boxes labeled with capital letters* represent quantifiable estimates or indicators of a toxicant or its effects in the body, and *links labeled with numbers* designate events or processes that connect those estimates.

Exposure Pathways

Exposure to an environmental contaminant occurs via an **exposure pathway** that begins with the environmental source of the contaminant *(A)* and ends with exposure *(C)*, defined as contact between a toxicant and the human envelope. In some circumstances, the source *(A)* is an ongoing emission—for example, the release of lead into the air from the smokestack of a lead smelter. In other circumstances, the origin of the contamination is harder to pin down in place and time. For example, the lead present in the soil of most U.S. cities today originates from the exhaust of countless moving sources—vehicles using leaded gasoline for decades in the past—and from the lead paint used on millions of houses, some of which are still shedding lead dust into the environment. It isn't really useful to think about these sources of lead as emissions. Rather, it is more useful to think of the source *(A)* of the lead as its widespread presence in soil, quantified as a concentration.*

From either type of source (*A* in Figure 2.11), chemicals may be transported in air, water, or soil, sometimes being chemically transformed along the way. These processes, together referred to as the fate and transport *(1)* of environmental contaminants, were described previously.

As a result of the processes of fate and transport, a contaminant may be present at some concentration in a person's immediate surroundings *(B)*. Exposure assessors distinguish between **microenvironments** where exposure can occur (e.g., a yard whose soil is contaminated by lead, or an office whose air is contaminated by volatile organic compounds) and the **personal environment**, which is the immediate vicinity of a person's body and includes any place that person goes. A microenvironment is stationary, whereas a personal environment is mobile.

Exposure Routes

Exposure *(C)*—contact between a toxicant and the human envelope—occurs by various routes. Most exposures to environmental toxicants occur via three routes: inhalation, ingestion, and dermal contact *(2)*. These are not the only possible routes of exposure to chemicals: Some pharmaceuticals, for example, are delivered by injection into the muscle and others are sprayed into the nostrils to be absorbed through the nasal lining. But exposure to chemicals present in environmental media is usually by inhalation, ingestion, or dermal contact.

Table 2.2 summarizes the environmental media most associated with these three major routes of exposure. People continuously inhale air, of course, and along with it, they inhale dust. At rest, an adult inhales about 360 to 600 liters of air per hour (about 8.6 to 14.4 cubic meters per day).[4] Although children's lung capacity is smaller, they spend more time outdoors

*In fact, environmental health practitioners often distinguish between natural background concentrations of a substance, such as the lead naturally present in soil as a result of weathering of the Earth's surface; urban background concentrations of the same substance, such as the lead that is widespread in urban soil from leaded gasoline and lead paint; and the amount of a substance contributed by a specific source of interest, above and beyond these background concentrations, such as the lead from a particular lead smelter.

Table 2.2 Key Environmental Media Associated with the Major Routes of Exposure

Medium of Exposure	Inhalation	Dermal Contact	Ingestion
Air	X		
Soil	X (dust)	X	X (incidental)
Water		X	X
Food			X

than adults do, exercise more, breathe more through the mouth, and tend to entrain a more intense personal dust cloud[5]—a phenomenon sometimes referred to as the "Pigpen effect," after the character in the comic strip *Peanuts*.

Skin, too, may come into contact with soil or dust (e.g., while gardening) or water (e.g., while swimming or bathing) or with the toxicant itself, particularly in occupational settings. For young children, even dermal contact with food could be substantial in some situations (not shown in table).

People routinely ingest water and food for sustenance. They may also inadvertently swallow small amounts of water (referred to as **incidental ingestion**), perhaps while swimming in a lake or pool. Similarly, if dust is present on the lips, licking the lips leads to incidental ingestion of soil. Touching the lips with the hands conveys soil to the mouth. Both eating and smoking, for example, result in such **hand-to-mouth exposures**. In certain circumstances, such incidental ingestion can be substantial—for farmers or construction workers, for example, or for toddlers, who spend a lot of time on the ground (and whose hands spend a lot of time in their mouths).

Contact with an environmental contaminant often occurs through multiple exposure routes. For example, a toddler is exposed to lead in the home mainly by ingestion (incidental ingestion of dust via hand-to-mouth activity) and by inhalation (of airborne dust).

Biological Markers of Exposure

The final elements of Figure 2.11, showing the events following exposure *(C)*, appeared previously in Figure 2.6 and are described in the earlier discussion of toxicology. From the perspective of exposure assessment, the absorbed dose *(D)* and the biologically effective dose *(E),* as quantifications of a toxicant in the body, are biological markers of the event of exposure, referred to as **biomarkers of exposure**. In contrast, a change in tissue structure or function *(F)* is a **biomarker of effect**, as is a health effect such as clinical disease.[6]

Quantifying Exposure

It is common wisdom that "the dose makes the poison"—an idea that dates back to Paracelsus, a physician of the late Middle Ages. So, to be of practical use, the conceptual model in Figure 2.11 needs to be filled out with quantitative information. The work of exposure assessment is to translate the event of exposure into an estimate of the dose of a toxicant. This can be done by measuring or modeling the dose, or an estimate can be made on the basis of questionnaires, records, or other data sources.

Measuring or Modeling Dose

In **Figure 2.12**, methods used to quantify fate and transport, exposure, dose, and effect have been added across the bottom of the diagram that appeared in Figure 2.11. Specifically, in Figure 2.12, *measurement approaches labeled with lowercase letters* correspond to the quantifiable estimates or indicators labeled with capital letters, and *modeling approaches labeled with lowercase roman numerals* correspond to the events or processes labeled with numbers. Figure 2.12 is complex, and so a detailed explanation is provided here.

Ideally, exposure is quantified inside the body—as the absorbed dose *(D)* or the biologically effective dose *(E),* or by measuring a change in tissue structure or function *(F)*—but often this is not feasible. Instead, external measurements are often made somewhere "upstream" in the exposure model, and mathematical modeling techniques are then used to estimate "downstream" concentrations or doses.

As shown in Figure 2.12, the most basic proxy for dose is simply the concentration of a toxicant in air, water, or soil *(A);* measurements of these concentrations are made by **environmental monitoring** *(a).* A somewhat better proxy is the concentration of the toxicant at or near the location where exposure occurs *(B).* Measurements may be taken in either the microenvironment or the personal environment:

- Measurements made in the microenvironment where exposure occurs (e.g., the concentration of a toxicant in the soil of a yard or the air of a room) are referred to as **area monitoring** *(b)* in Figure 2.12. For example, a modified vacuum cleaner might be used to collect dust samples (see **Figure 2.13a**).
- Alternatively, the measurement can be made in the personal environment—that is, the immediate vicinity of the body. For example, a subject in a research study might wear a portable air sampling device (see **Figure 2.13b**), collecting air samples from as close to his or her breathing zone as possible, even as he or she moves through different microenvironments. Measurements of this type are referred to as **personal monitoring** *(b)* in Figure 2.12.

Some sampling devices accumulate a sample throughout an exposure period; for example, a portable air sampling pump might collect a single integrated sample of particulate matter throughout a worker's shift, and the chemical makeup of the sample could be analyzed later in the laboratory. A different device might measure and record second-by-second concentrations of particulate matter throughout the same shift, without collecting any sample. Yet another approach is to collect samples (of soil, for example) from different locations within an area of interest and then mix these samples together to create one composite sample for analysis.

If it is not possible to take a measurement *(b)* of the concentration of a toxicant at or near the location of exposure *(B),* it may be necessary to derive an estimate of this concentration, using information from farther back along the exposure pathway. In this case, **environmental modeling** (*i*) can be used to estimate the concentration of a contaminant at the location of exposure *(B).* Such modeling rests on understanding of the processes of environmental fate and transport *(1)* and uses as inputs measurements *(a)* of the concentration of the contaminant

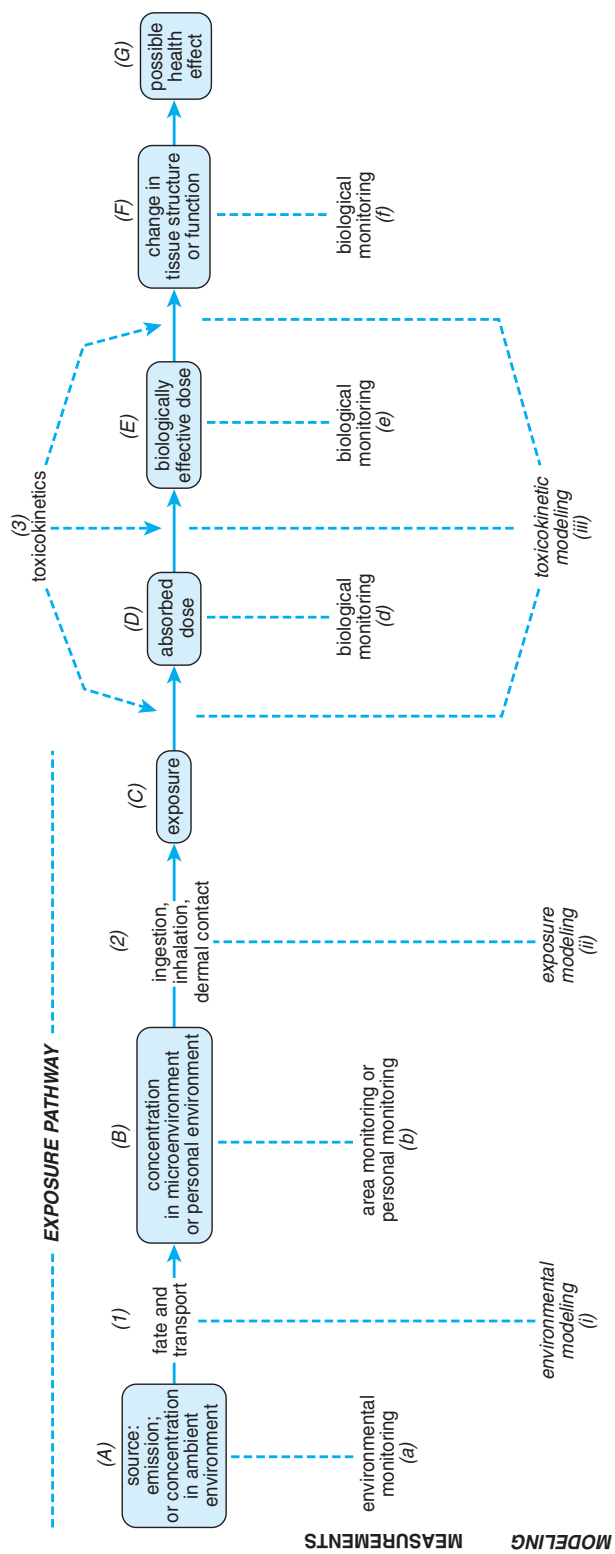

FIGURE 2.12 Measurement and modeling of fate and transport, exposure, dose, and effect.
Source: Special thanks to Wendy Heiger-Bernays and Michael McClean.

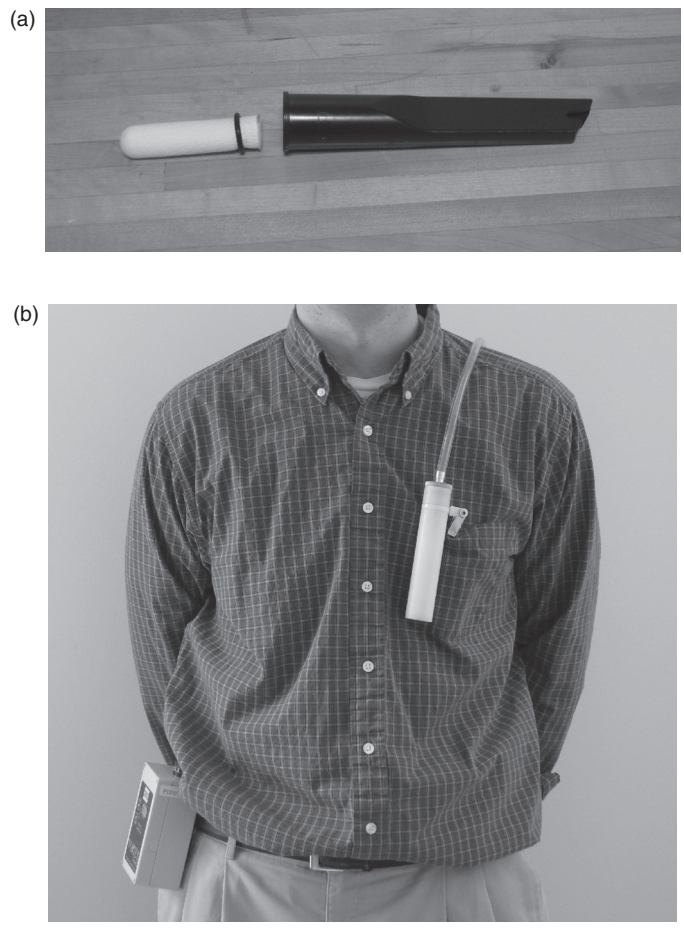

FIGURE 2.13 Area monitoring: A filter inserted into the nozzle of a vacuum cleaner (a) collects dust to be analyzed in a laboratory. Personal monitoring: A portable sampling device (b) incorporates a pump that takes a continuous air sample near the subject's breathing zone; the device also collects a sample of particulate matter over the whole period.

in the ambient environment *(A)*. As described earlier, the environmental fate and transport of chemicals is determined not only by movements of environmental media, such as air or groundwater, but also by the chemicals' own properties.

An estimate of exposure *(C)*, defined as contact with the human envelope, provides a somewhat better proxy of absorbed dose than do measured or estimated concentrations in environmental media *(B)*. Estimates of exposure rest on two kinds of information: a measurement or estimate *(b)* of the concentration at the location of exposure *(B)*; and **exposure modeling** *(ii)* of contact by ingestion, by inhalation, or via the skin *(2)*. Such modeling rests on assumptions about, for example, the volume of water a person drinks each day, the volume of air he or she inhales (and then exhales), or the area of the skin that is exposed to a contaminant.

All the methods for measuring or modeling exposure described up to this point provide estimates of quantities or processes outside the body. However, for some toxicants, exposure can be quantified inside the body, either as a dose or as a measure of an early biological effect. These methods use a measure of one of these indicators:

- The absorbed dose *(D)*, the quantity that passed through the human envelope
- The biologically effective dose *(E)*, the concentration in a specific vulnerable tissue
- Some change in tissue structure or function *(F)* that is caused by the biologically effective dose

The corresponding biological measurement methods *(d, e, f)* are known collectively as biological monitoring, or **biomonitoring**. As noted previously, the measures themselves are called biomarkers.

For example, the concentration of mercury in hair or fingernails, the concentration of lead in blood (used to screen for childhood lead poisoning), and the concentration of alcohol in exhaled air (the police officer's breathalyzer test for drunk drivers) are all biomarkers offering a window onto an *absorbed dose*. Similarly, environmental chemicals such as pesticides, heavy metals, and nicotine (or their metabolites) have been measured postnatally in meconium, the fecal matter that accumulates in the fetus during gestation, providing a biomarker of the prenatal absorbed dose. DNA adducts, formed when a chemical binds to a DNA molecule in the nucleus of a cell, are biomarkers of exposure, and specifically of the *biologically effective dose*. In contrast, continuous firing of nerve cells is a biomarker of the *effect* of certain pesticides on these cells—*a change in tissue function*. Biomonitoring techniques are relatively expensive, and all impose some burden on the person whose exposure is being assessed, although providing fingernail clippings, for example, is less invasive than providing a sample of urine or blood. And for many toxicants, no techniques are available to make such measurements in the body.

Finally, biological modeling—specifically, **toxicokinetic modeling** *(iii)*—is sometimes used to predict the ultimate disposition of a chemical from what is known about its toxicokinetics *(3)*—the absorption, distribution, metabolism, storage, and excretion of the chemical. Toxicokinetic modeling is used to estimate the absorbed dose *(D),* the biologically effective dose *(E),* or an effect in the form of a change in tissue structure or function *(F)* from some upstream measure. Because sophisticated toxicological understanding is required to develop toxicokinetic models, these models are available for a relatively small number of environmental toxicants.

Units of Absorbed Dose

Absorbed dose is usually expressed in units of milligrams of toxicant per kilogram of body weight per day, written as mg/(kg × day). These units incorporate two important concepts that are probably familiar even if the terminology is not.

First, the mass of contaminant absorbed into the body is **normalized to (averaged over) the body weight** of the person exposed; that is, it is divided by the body weight. This adjustment accounts for the fact that, for example, 10 mg of Chemical X is a greater insult to a 75-kg man than it is to a 100-kg man.

Similarly, the mass absorbed into the body is **averaged over time**—usually, expressed as a daily dose. This adjustment accounts for the fact that, for example, 10 mg of Chemical X absorbed by a 75-kg woman at 5 mg/day over a 2-day period is a different insult from 10 mg of Chemical X absorbed by the same woman at 0.5 mg/day over 20 days.

Thus, to calculate someone's absorbed dose of Chemical X from drinking tap water, these pieces of information are needed:

- The concentration of Chemical X in the water
- The rate at which water is ingested (e.g., liters per day)
- The proportion of the Chemical X in the ingested water that is absorbed into the body
- The body weight of the exposed person

For example, the absorbed dose of trichloroethylene to a 70-kg individual who drinks 2 liters per day of water contaminated with trichloroethylene at 5 μg per liter, assuming 100% absorption of the chemical, is calculated as follows:

$$\frac{\frac{5\mu\text{g chemical}}{\text{liter water}} \times \frac{2\text{ liters water}}{\text{day}} \times 1.0}{70\text{ kg body weight}}$$

$$= 0.143\ \mu\text{g}/(\text{kg} \times \text{day})$$

$$\text{or, in standard dose units, } 0.000143\text{ mg}/(\text{kg} \times \text{day})$$

Similarly, in calculating inhalation exposures, information is needed on the concentration of the chemical in air, the exposed individual's inhalation rate, and the proportion absorbed via the lungs. Calculation of a dermal dose (e.g., a gardener's exposure to a chemical in soil) rests on information about the concentration in soil, how much skin area is exposed, how much soil clings to a given skin area, and the rate at which the chemical is absorbed through the skin.

Other Sources of Exposure Information

Approaches other than direct measurement and mathematical modeling are also used to estimate human exposures to environmental hazards. For example, information about contact with environmental media can be obtained using a questionnaire, in-person interview, telephone interview, or mail survey. Such surveys offer the possibility of direct answers to questions that can't be assessed in the field. For example, how often does the subject apply pesticides in the home? Or, for an exposure via tap water: How much tap water is consumed on a typical day? Does the subject take showers or baths? How often? How long? How hot? Surveys can also be used to gather information on past exposures, such as a woman's job history or her history of using hair dye.

In a variation on the questionnaire approach, subjects in an exposure assessment may keep personal records over a period of time; for example, they may keep diaries of food consumption or time spent in different activities or locations. Historical exposure information may also come from previously existing documentary sources, such as municipal records of

contaminant concentrations in drinking water or military records of soldiers' deployments and activities.

Surrogate measures of occupational exposures, such as a worker's job title or the industry in which he or she is employed, are particularly well developed. This is partly because workplace exposures, which may be high and long-lasting, are of special concern. In addition, the occupational setting, which is more regimented than residential or community settings, lends itself to these approaches.

For example, the classification system used in the U.S. Census Bureau's Economic Census defines thousands of industrial sectors ranging from synthetic rubber manufacturing to silver ore mining to shellfish farming. Similarly, job title might be used as a surrogate for potential exposure to latex gloves in a medical setting, distinguishing among nurses, midwives, physicians, medical technologists, and medical assistants. This approach can be taken a step further by developing a job-exposure matrix—a table that provides an estimate of exposure for each combination of job title (in rows) and hazard (in columns). For example, each job title's exposure to each hazard could be rated on a scale of none–low–medium–high based on measurements or even expert judgment.

In recent years, the **geographic information system** (GIS) has matured into a useful tool for integrating and assessing exposure data. A GIS is a computerized system that combines a database of spatially linked information with application software for spatial analyses and mapping. For example, a GIS might include information on locations where pesticides have been sprayed for mosquito control, or locations of plumes of solvent contamination in groundwater at different time points, or traffic volumes associated with each quarter-mile segment of a county's roads (representing the concentration of air pollutants produced by vehicles). In essence, such GIS assessments use location as a surrogate for exposure (see **Figure 2.14**).

Epidemiologic researchers can use geographic information systems to link subjects' addresses with environmental data. For example, in a study of the risk of cancer (a disease with a long latency) associated with contamination of private well water, researchers could link each subject's current home address, as well as past addresses, to environmental data on groundwater contamination for the appropriate time periods. This information can be used to estimate exposures at a series of addresses.

Epidemiology: A Quantitative Research Method

Epidemiology is a quantitative research method used to document the distribution of health and illness in human populations and also to link health outcomes to risk factors. Simple quantitative methods were first used in the mid-1800s to demonstrate geographic and social differences in the effects of the most pressing health problem of the day, infectious disease. By the mid-1900s, epidemiology had become focused on the chronic illnesses, such as heart disease, which by then were killing more people than were infectious diseases in the more developed countries. In the era of computerized data processing, epidemiologic methods have become heavily analytical and statistical, and they continue to evolve in ways that reflect new scientific understanding of the mechanisms and genetics of health risks. Infectious disease epidemiology has returned to the foreground in the age of the human immunodeficiency virus and acquired immune deficiency syndrome (HIV/AIDS) and other emerging infectious threats.

FIGURE 2.14 This GIS map of a chemical plume in groundwater shows that private wells on nearby properties located upgradient of the source are unaffected by the contamination, whereas wells on more distant properties located downgradient are at risk.

Source: Courtesy of Verónica Vieira.

The scope of epidemiology today is as broad as public health itself. **Environmental epidemiology** is one of the major sources of information about human health risks from environmental hazards. In environmental health, epidemiology is used mainly to study risks from chemicals and other toxicants, but also to study risks of noise, injuries, infectious disease, and even social factors. In the study of environmental toxicants, today's epidemiology often incorporates scientific insights from toxicology and practical tools from exposure assessment. In particular, biomarkers of exposure and disease are useful in environmental epidemiology, because an accurate identification of both exposure and disease is needed to document a relationship between them. But even when toxicologic understanding is lacking, strong epidemiologic data can form the basis for public health action because it provides information

about human beings. Further, actual human exposures are, by definition, within the range of concern, and the health effects studied, although they may be gross endpoints, are meaningful as outcomes.

Perhaps the most famous epidemiologic study in the history of public health was conducted by physician John Snow during an 1854 cholera epidemic in London. Hypothesizing that the illness was caused by contaminated drinking water, Snow compared the death rates from cholera according to the water company that supplied individual houses. He documented a more than eightfold increased mortality among people living in houses served by the Southwark and Vauxhall Company, which drew its water from a heavily polluted region of the Thames River, compared to those served by the Lambeth Company, which drew its water from a part of the Thames not contaminated by London's sewage.[7] The design of Snow's study is fundamentally similar to those in use today.

This section first defines the key measures used to quantify health status in populations, and then outlines descriptive epidemiologic approaches as well as the study designs used to link exposures to health outcomes. The focus is on epidemiologic methods used to study chronic disease, but two specialized branches of epidemiologic research, infectious disease epidemiology and animal epidemiology, are also described.

Key Measures of the Health Status of Populations

Two fundamental concepts—incidence and prevalence—underlie all epidemiology. **Incidence** is the occurrence of *new (incident) cases* of a disease in a given population *during a given period of time*. Because only newly diagnosed cases are counted, measures of incidence are useful in identifying factors that might be associated with the onset of disease.

Mortality can be thought of as the incidence of death: It is the total number of deaths in a given population during a given period of time. Cause-specific mortality can be reported in the same way. Mortality data have certain limitations from a research perspective because mortality from a particular disease can be affected by various factors that operate between diagnosis and death (e.g., treatment). Cause-specific mortality is also affected by deaths from other causes: Some people who would ultimately die of colon cancer, for example, die in car accidents instead. However, mortality data offer a practical advantage: Because death is the easiest health outcome to ascertain, mortality data are sometimes available when disease data are not. Historically, the earliest surveillance data collected were mortality statistics, and mortality is still an important indicator of the overall health of populations—witness the stark differences in mortality between more developed and less developed countries.*

*This text follows the United Nations in using the term *more developed countries* to refer to all European and Northern American countries, plus Japan, Australia, and New Zealand; the term *less developed countries* to refer to all of the world's other countries; and the term *least developed countries* to refer to a designated subset of the less developed countries (United Nations, Population Division, Department of Economic and Social Affairs, World Population Prospects: The 2010 Revision [table] (POP/DBWPP/Rev.2010/F0-1), 2011. Available at: http://esa.un.org/unpd/wpp/Excel-Data/WPP2010_F01_LOCATIONS.XLS. Accessed March 2, 2012. Among the less developed countries, China, India, and Brazil stand out as having large and rapidly growing economies. Although there is no widely agreed-upon definition of "development," the term generally connotes both population health and economic wellbeing.

In contrast to incidence, **prevalence** quantifies *existing cases* of a disease, specifically, the proportion of a population that has a disease *at a given point in time*. The prevalence of a disease in a population reflects both the incidence of the disease, which contributes to the pool of cases, and also the mortality rate for the disease, which removes cases from the pool. The prevalence of HIV/AIDS in Massachusetts on January 1, 2012, for example, reflects not only factors that affect the onset of the illness, but also factors that affect how long people survive with the illness, such as treatment options and the availability of medical care. For this reason, although prevalence figures may be useful, for example, in planning for health services, they are not generally useful in assessing potential risk factors for disease, including environmental risk factors.

The term **morbidity** refers to a diseased (morbid) state, and this can be quantified in a population as prevalence. For example, some sub-Saharan African countries bear a heavy burden of morbidity caused by malaria, as reflected in a high prevalence of malaria infection reported by the World Health Organization.[8]

Various definitions of **disability** have been used in the public health literature and in the movement to protect the rights of people with disabilities, but a core element of the definition is a limitation on a major life activity.[9] Typically, the term *disability* is used to refer to a substantial and/or long-term limitation in a major age-appropriate life activity related to work, school, or caring for oneself. This limitation might be physical or mental. For example, an inability to walk, bathe oneself, prepare food, make change, or remember one's address could all be considered disabilities. The Americans with Disabilities Act defines disability to include not only such an impairment, but also "a record of such an impairment" or "being regarded as having such an impairment."[9] A disability can make an individual more susceptible to the effects of environmental hazards. For example, those with impaired mobility were especially susceptible to injury and death in the wake of Hurricane Katrina, and individuals with chronic lung disease, such as asthma or emphysema, are more susceptible to the respiratory effects of common air pollutants.

Descriptive Epidemiology

Descriptive epidemiology, as the name suggests, simply describes patterns of disease in populations—that is, in existing groups rather than in groups assembled for the purpose of a research study. Further, descriptive epidemiology does not seek to link disease risk statistically to specific factors. Descriptive epidemiologic methods, particularly disease surveillance, are the everyday tools of environmental health practitioners in city, county, and state health departments. For this reason, this text gives greater emphasis to these descriptive approaches than to the research study designs that are the focus of most textbooks and courses in epidemiology.

Surveillance

To conduct environmental health **surveillance** is to survey the landscape of illness. Surveillance is fundamentally a comparative exercise. The objective of surveillance is to track and compare disease rates in populations across places, across diseases, or over time. In environmental health, surveillance data often highlight unusual patterns that may provide clues to an environmental risk factor for disease. In public health more broadly, surveillance data are used for policy and planning purposes.

In the United States, state departments of public health typically gather and report disease data. Most of the 50 states have a cancer registry—an agency that receives a report of each cancer diagnosis in the state (including the residential address of the patient) and uses this information to track the incidence of various types of cancer and document geographic patterns. The U.S. Centers for Disease Control and Prevention (CDC) gathers data from all these agencies. A separate program under the auspices of the National Cancer Institute (Surveillance Epidemiology and End Results, or SEER), gathers cancer data for selected locations around the country, including states with no central cancer registry. Between them, these two programs collect cancer data for the entire U.S. population.[10] Other health outcomes, from HIV/AIDS to birth defects to gunshot injuries, may also be tracked by state or federal agencies. At the federal level, the CDC conducts surveillance, including infectious disease surveillance (see **Figure 2.15**). In addition, the CDC helps states develop their surveillance capacities.

The concept of surveillance can be extended to include biomonitoring at the population level. Such **surveillance biomonitoring** often documents exposure rather than illness—for example, monitoring of blood lead concentrations in young children. The concept of surveillance can be further extended to include tracking of health hazards, such as releases of toxic chemicals.

FIGURE 2.15 CDC workers inspect specimens that may be connected to an outbreak of hantavirus, an emerging infectious threat.

Source: Reprinted courtesy of CDC Public Health Image Library. ID# 7271. Content provider: CDC. Available at: http://phil.cdc.gov/phil/home.asp. Accessed October 3, 2012.

The measure of incidence most commonly used in disease surveillance is the **crude incidence rate**, which is not an abstraction but rather is tied to a given population and time period. The numerator is simply the number of new cases that arose in the given population during the given time period. The denominator represents both the size of the population at risk and the time period of interest, and is quantified in person-years. A denominator of 2000 person-years, for example, might represent a population of 2000 over a 1-year period or a population of 200 over a 10-year period. A crude incidence rate is calculated by simply dividing the numerator by the denominator. For example, 300 new cases of a disease in a population of 100,000 over a 10-year period yields a crude incidence rate of 0.0003 per year.

The incidence of many diseases is different in males and females; similarly, incidence often varies by age group. Therefore, if the crude incidence of lung cancer is different in two towns, the difference may be caused partly or entirely by differences in the age and gender makeup of the towns' populations. Similarly, if the crude incidence of lung cancer is the same in two towns, this statistic may obscure a genuine difference in risk. In the example shown in **Table 2.3**, the annual incidence of female breast cancer is 60% higher in Location A than it is in Location B. However, the table also shows that the female population of Location A is somewhat older than that of Location B. Because it is well known that breast cancer is more common in older women, the age makeup in Location A may explain, or partly explain, the higher incidence there.

Given that comparing incidence across locations and time periods is a fundamental task of surveillance, issues like this one must be addressed. The effects of gender on incidence are usually resolved by reporting separately for males and females. The effects of age on incidence, on the other hand, are usually handled through reporting methods that adjust for differences in age distribution. (It is also possible to adjust for both age and gender differences.)

Any method of age adjustment must take account of the separate effects of two factors:

- A population's age distribution (the proportion of the population that falls into each age category)
- The age-specific incidence of disease in each age category

Two basic approaches are used to adjust crude incidence rates so that data for different populations can legitimately be compared. Both approaches use a third population as a reference—a sort of intermediary for comparison.

Table 2.3 Annual Incidence of Female Breast Cancer and Age Distribution of the Female Population in Two Locations for a Given Time Period

Location	Crude Annual Incidence	*Proportion of Population in Each Age Group*		
		Premenopausal	Perimenopausal	Postmenopausal
Location A	0.0021	0.55	0.09	0.36
Location B	0.0013	0.65	0.10	0.25

One approach is to apply the actual age-specific rates of disease in Location A and those in Location B in their respective populations, but substitute the age distribution of the reference population (see **Figure 2.16**). This yields a hypothetical total number of cases, and thus a hypothetical overall rate of disease, for Location A and Location B. These rates are called **standardized rates** because they have been *adjusted to a standard age structure*. For example, the standardized rate for Location A is *the overall rate that would occur* in Location A if its actual age-specific rates were operating, but its population had the age distribution of the reference population. In the United States, the population as reported in a decennial census is often used as a reference population.

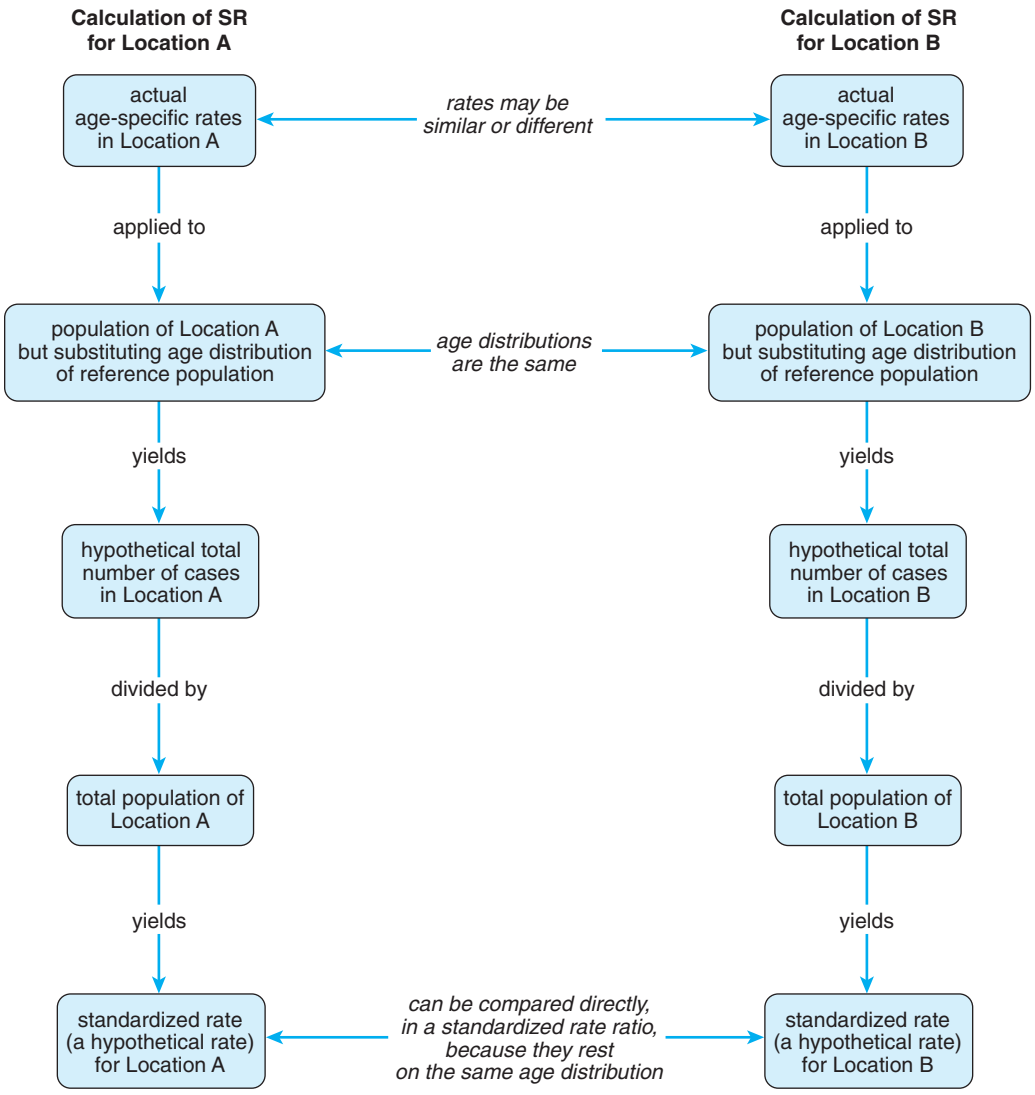

FIGURE 2.16 Standardized rate (SR) and standardized rate ratio (SRR).

Because the standardized rates for Locations A and B rest on the same age distribution, they can be compared directly (see Figure 2.16). This is typically done in a ratio, called a **standardized rate ratio**, or **SRR** (standardized rate in Location A/standardized rate in Location B). For example, if the standardized rate in Location A is 0.0005 per year, and the standardized rate in Location B is 0.00025 per year, the standardized rate ratio is 2.0, which means that the rate of illness in Location A is twice that in Location B. A standardized rate for just one location is not useful, given that it is a hypothetical rate; the point of this approach is to be able to compare standardized rates for different populations by using the ratio.

The inverse approach is taken in calculating a **standardized incidence ratio (SIR)**: The age-specific rates of a reference population are applied to the populations of Locations A and B, using their actual age distributions (see **Figure 2.17**). This yields the *total number of cases that would be expected* in Locations A and B if the reference age-specific rates were operating in the actual local populations. For Location A and Location B, this expected total number of cases is then compared to the actual (or observed) total number in a ratio, called the standardized incidence ratio (observed cases/expected cases). By convention, the ratio is multiplied by 100, so that a ratio of 1.25 becomes an SIR of 125. For example, an SIR of 125 for Location A means that the observed number of cases there is 25% higher than the expected number. Here, the term *standardized* refers to the fact that the expected numbers are *adjusted to a standard set of age-specific rates*. In contrast to the standardized rate, an SIR for a single location is useful, because it incorporates the comparison to a reference population. A ratio of observed deaths to expected deaths calculated in the same way is called a **standardized mortality ratio (SMR)**.

Unlike standardized rates, SIRs (and SMRs) for different locations rest on their local age distributions; as a result, the comparability of SIRs depends on how similar or different the local age distributions are. In practice, the effects of differences in local age distributions might be substantial or might be so small as to have no practical significance. This effect can and should be assessed in deciding whether it is appropriate to compare SIRs (or SMRs) in a given situation.

The key methodological drawback of the standardized rate, on the other hand, is its reliance on local age-specific rates. In small populations, age-specific rates are statistically unstable (i.e., a change of just a few cases causes a dramatic change in the age-specific rate), and this effect is passed through to the standardized rate. This is why the Massachusetts Department of Public Health, for example, publishes SIRs for cancer, rather than standardized rates, for the state's 351 cities and towns, many of which have small populations.

In addition, as time goes by, the reference population used to calculate a standardized rate becomes increasingly remote. Many health departments used the 1940 U.S. Census for decades, and then changed to the 1970 Census, and more recently changed to the 2000 Census. Of course, standardized rates calculated using these different reference populations are not comparable, but most health departments do not have the resources to recalculate standardized rates and SRRs calculated earlier using a different reference population.

From the community perspective, ordinary citizens are more likely to be able to obtain the total number of cases needed to calculate an SIR than the age-specific case data needed to

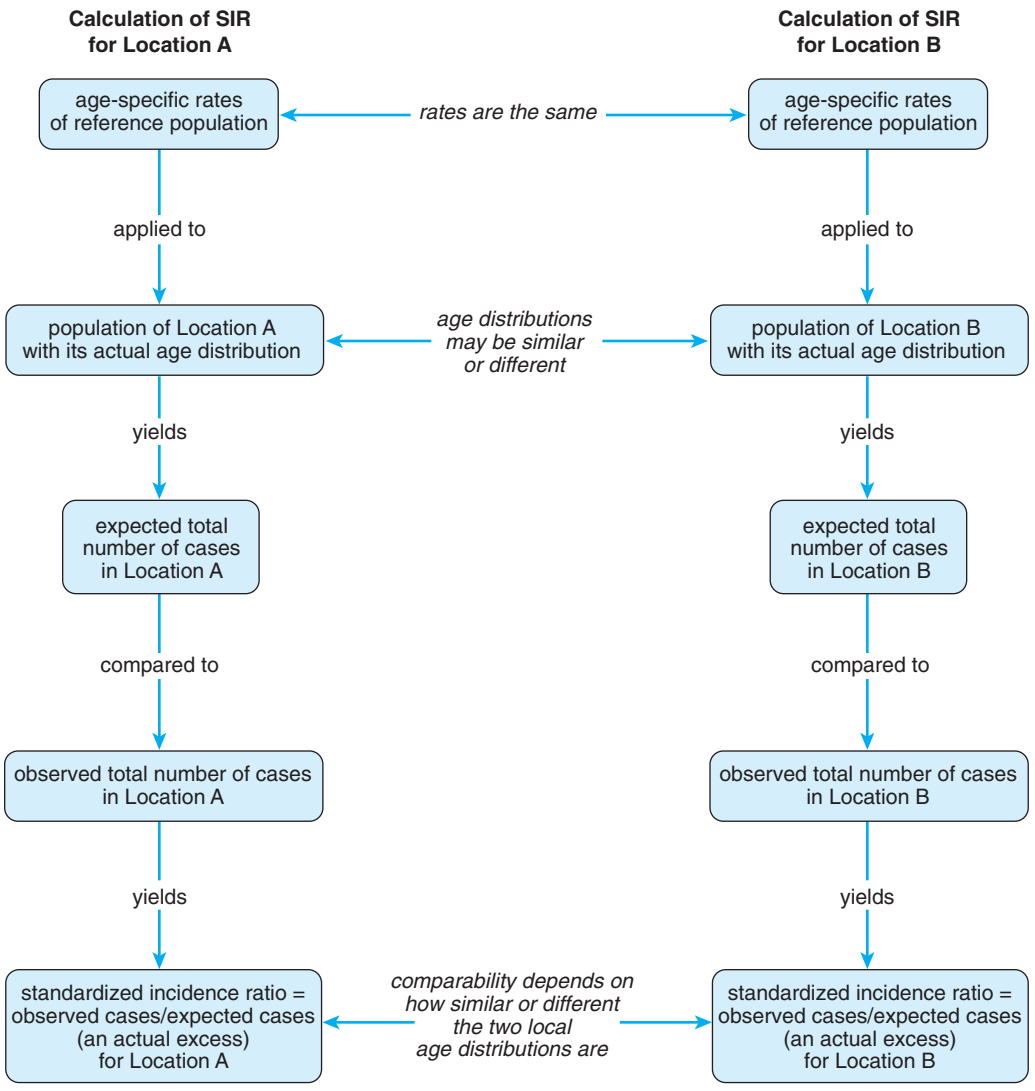

FIGURE 2.17 Standardized incidence ratio (SIR).

calculate a standardized rate. This is because health departments, protecting the confidentiality of health data, do not release case numbers so small that individuals might be identified. As a result, the SIR is often the statistic of choice for health activists who are concerned about disease in their communities.

When presenting an SRR or SIR, it is accepted practice to indicate the statistical stability of the ratio by presenting a confidence interval around it. For an example, an SIR of 121 (95% confidence interval 110–133) indicates that the best estimate of the SIR is 121, and there is a 95% probability that the true value lies between 110 and 133.

The Case Series

As described earlier, disease surveillance is conducted on a systematic, ongoing basis in populations. In contrast, the **case series** is simply a set of cases of some disease or condition, often identified by a clinician, that have some noteworthy characteristic in common. Taken together, the cases might simply be a medical mystery, or they might be seen as an early clue to a risk factor for an illness. For example, a case series of a rare cancer in homosexual men, published in 1982, first flagged the condition that eventually came to be known as AIDS.[11] Similarly, a series of cases of a rare vaginal cancer in young women provided an early clue to the effects of prenatal exposure to the synthetic hormone diethylstilbestrol (DES),[12] prescribed for more than 20 years in the mid-20th century in the belief that it would prevent miscarriage.

Observational and Experimental Study Designs in Epidemiology

In contrast to descriptive epidemiology, observational and experimental study designs explicitly evaluate associations between risk factors and health outcomes. In an **observational study**, as the name suggests, the investigator does not manipulate exposures, but merely observes and gathers information on exposures and outcomes. In contrast, in an **experimental study**, the investigator assigns study subjects to different exposure or treatment groups, and then gathers information on outcomes.

Observational studies that use information on exposures and health outcomes ascertained at the community level are called **ecologic studies**. That is, these studies use available community-level data on exposures of interest and previously collected surveillance data on health outcomes. All ecologic studies are observational.

In contrast, studies that use individual-level data on exposures and health outcomes compare the experience of two sets of individuals assembled by the investigator for the purpose of the study—either people with and without a disease, or people exposed and not exposed to a risk factor. Unlike the ecologic design, an individual-level study design can be either observational or experimental.

Research on environmental health hazards, like other branches of public health research, relies heavily on epidemiologic research. However, only a thumbnail sketch of study designs is provided here, partly because their methodological complexities are beyond the scope of this text, but also because most students of public health will take at least one course in epidemiology.

Group-Level Observational Studies (Ecologic Studies)

As just described, community surveillance documents patterns in rates of disease or death in populations, mostly without attempting to explain these patterns or even identify factors that might be associated with these health outcomes. An ecologic study, on the other hand, documents associations between characteristics of communities. In the public health context, the association of interest is often between a health outcome and some other factor. For example, across all the towns of a state, is the mortality rate associated with the volume of toxic industrial releases? With lower average educational attainment? Is the incidence of childhood

lead poisoning associated with the presence of an older housing stock? With the percentage of the population in poverty? By providing a rich portrait of the public's health, analyses such as these can enhance our understanding of bare surveillance figures.

However, all ecologic studies have limitations, because they use data on populations rather than individuals. Most important, they cannot link exposure to disease in the same person. Lead poisoning may be more common in towns with old housing, for example, but are the children living in old houses the ones who are being poisoned? Using only data at the population level, it is impossible to know. Further, for methodological reasons too complex to discuss here, analysis of an association using data at the population level can give an incorrect (biased) estimate of the same association at the individual level; this effect is called the *ecologic fallacy*. For these reasons, the ecologic study design is considered useful to *generate* a hypothesis about an association but not to *test* such a hypothesis. Because the work of surveillance is to describe patterns of disease, and because surveillance focuses on patterns across communities, the ecologic study is a natural enhancement to the standardized incidence ratio, as well as a source of new hypotheses for individual-level study.

Interestingly, despite the focus in contemporary epidemiology on individual-level study designs (see the following subsection), there is also a growing interest in the effect of truly community-level factors on individual health. For example, a feature of the **built environment**, or a social stressor such as racial segregation, can be defined only at the community level, though of course any health effects of these factors occur via physiologic mechanisms in individual people. The study of the social determinants of health is known as **social epidemiology**, and analytic methods for **multilevel studies**—which include both individual-level and community-level variables—are emerging in epidemiology.

Individual-Level Observational and Experimental Studies

Unlike ecologic studies, individual-level epidemiologic study designs are used to test a hypothesized association between exposure and outcome. (The term **analytic epidemiology** refers to epidemiologic studies designed to test such a hypothesis.) The three major types of individual-level observational studies are cross-sectional studies, cohort studies, and case-control studies.

In any such study, in which individuals are enrolled and information is gathered from them, research standards require that participants give their **informed consent** to participate, after having been given information about the potential risks and benefits of taking part in a study. Without informed consent, research subjects may be exposed to risks that are not apparent to them; historically, members of disenfranchised groups have been particularly at risk of such treatment. In one infamous episode, U.S. Public Health Service researchers at the Tuskegee Institute in Alabama studied the progression of syphilis in African American men for 4 decades beginning in 1932, without offering them treatment with penicillin after it became the accepted treatment for syphilis in the mid-1940s.[13] These events led to reforms at the U.S. Public Health Service and ultimately to current requirements for the informed consent of participants in research.

The simplest individual-level study design is the **cross-sectional study**. In this study design, the subjects (e.g., a group of workers at a particular facility or in a given industry) are classified on a specific exposure (e.g., exposed or not exposed to a chemical in the workplace) and on a

health outcome (e.g., a neurological deficit). The analysis tests the hypothesis that there is a statistical association between exposure and outcome. A key limitation of the cross-sectional design is that it does not make clear whether the exposure preceded the outcome.

In a **cohort study** (e.g., a study of smoking as a risk factor for lung cancer) subjects are selected according to their exposure status (smoker, nonsmoker) and are then compared on disease status (lung cancer, no lung cancer). The key question in a cohort study is: Other things being equal, are the smokers more likely than the nonsmokers to be diagnosed with lung cancer? Cohort studies can be done either prospectively or retrospectively. That is, the subject can be enrolled in a cohort study *before* the health outcome of concern has occurred (a prospective design), and the investigator follows up to learn what health outcomes occur. Alternatively, the subjects can be enrolled in a cohort study *after* the health outcome of concern has occurred, though the health outcome is unknown to the investigator at the time of enrollment (a retrospective design); again, the investigator follows up to document the health outcomes.

In a **case-control study**, subjects are selected according to their disease status (e.g., lung cancer [cases], no lung cancer [controls*]), and their past exposures are then compared (e.g., smoker, nonsmoker). The key question in a case-control study is: Other things being equal, are the lung cancer cases more likely than the controls to have smoked? The case-control design is often used to study rare diseases, such as cancer, because it is impractical to select and follow a cohort of the size needed to generate enough cases for a statistically robust analysis.

In any epidemiologic study, careful assessment of both the risk factor of concern and the health outcome of interest is essential. If subjects are misclassified on either risk factor or outcome, this misclassification will cloud any association that might actually exist, making it difficult or even impossible to discern. The assessment of exposure to environmental risk factors poses unique challenges and uses a distinct set of methods, as described earlier. Long latency periods, cross-generational effects, and modest relative risks for specific exposures pose methodological challenges in environmental epidemiology.

The epidemiologic study designs just described are considered observational; that is, the investigator sets up a framework for assessing exposures and outcomes and then observes how the data play out. Other studies have experimental designs, in which the investigator controls the exposure and then follows up on outcome; these designs are variations on the cohort study. One type of experimental study is familiar to the general public: the randomized clinical trial of a new drug or other treatment. This is a variation on the prospective cohort study in which subjects are randomly assigned to an exposure group (drug, placebo; or new drug, standard drug) and the health outcome of interest is followed up. In the context of environmental health, it would of course be unethical to expose subjects deliberately to some hazard. Instead, this type of design is used in **intervention studies**, in which the "exposure" of interest is actually something positive introduced by the researcher. For example, study subjects who have asthma and live in public housing might be randomly assigned to one of two groups: one in which

*In fact, in modern epidemiology, the definition of a control has become more complex than simply "not diseased," but the simple definition is adequate for the purposes of this overview.

standard best practices in pest control are used in their residences, and another in which a new approach to pest control is used; the impacts on asthma rates of the two approaches are then compared.

Evaluating Individual-Level Epidemiologic Studies

In evaluating the results of an individual-level epidemiologic study, the researcher must first assess the statistical significance of the association—that is, assess whether the finding might be due simply to chance. To be considered **statistically significant**, the probability that a finding is due simply to chance must be acceptably low. Often, a less than 5% probability (expressed as $p < .05$) is considered acceptable.

In addition, for a study finding to be considered valid, it must not be attributable to bias or confounding. **Bias** is a systematic error in the way subjects were selected or information was gathered. **Confounding** (from the Latin, to pour together) occurs when a factor that is associated with the risk factor of interest is itself a risk factor for the health outcome of concern. For example, in a study of body mass index (BMI) and risk of heart attack, if people with a higher BMI are also likely to be older (and if older age is itself a risk factor for heart attack), then part of the apparent effect of higher BMI is actually a result of older age. To see beyond this "pouring together" of the two effects and avoid mistakenly attributing the effect of age to BMI, information on age must be collected and the separate effects of the two risk factors must be teased out by statistical analysis. The phrase "other things being equal" is a colloquial expression of the notion of controlling for confounding.

The term **effect modification** is used in epidemiology when the joint effect of two risk factors is either greater than or less than the effect expected to result from adding their individual effects. Effect modification is analogous to the toxicologic concepts of synergism (the enhancement of a toxic effect) and antagonism (interference with a toxic effect), discussed earlier in the context of toxicology. For example, epidemiologic studies of the lung cancer risk of asbestos exposure have shown that cigarette smoking multiplies the risk of asbestos exposure—a synergistic effect. Unlike bias and confounding, which are nuisance effects to be controlled, effect modification is of substantive interest.

Finally, in judging whether a causal connection has been shown, as opposed to merely a valid and statistically significant association, researchers generally consider several factors, including these put forward by British epidemiologist Sir Austin Bradford Hill in a seminal 1965 article:[14]

- The strength of the association documented (e.g., a finding of a 5-fold risk is more convincing than a finding of a 1.5-fold risk)
- The consistency of findings across epidemiologic studies
- An appropriate temporal relationship—that is, exposure to the putative risk factor precedes the development of the disease
- The finding of a dose–response relationship—that is, risk increases with increasing exposure
- The biological plausibility of the finding in light of current scientific understanding

Infectious Disease Epidemiology

The distinctive feature of infectious disease, of course, is that it can be transmitted from one individual to another. This feature makes the methods of infectious disease epidemiology very different from those of chronic disease epidemiology. The core of infectious disease epidemiology is the mathematical modeling of transmission, which is affected by the characteristics of the pathogen (e.g., its virulence), of the vector (e.g., mosquito versus bird), of individual people (e.g., their immune status), and of the physical and social environment (e.g., the nature and frequency of people's contact with one another).

An infectious disease that is typically present at a low to moderate level in a population or location is considered to be **endemic** there. For example, malaria is endemic in parts of sub-Saharan Africa, but not in Canada. An **epidemic** is the occurrence of disease at an unusually high rate in a population. For example, three deadly epidemics of cholera swept through the United States in 1832, 1849, and 1866.[15] Although the term *epidemic* originally referred only to infectious disease, its use has now been extended to chronic diseases. For example, the rising incidence of childhood asthma is sometimes referred to as an epidemic. The term **pandemic** is reserved for an infectious disease epidemic of global proportions. The influenza pandemic of 1918–1919 infected about one-third of the world's population and cost about 50 million lives worldwide.[16] Today's infectious disease specialists are concerned that a small shift in the genetic makeup of the current avian influenza virus (designated the H5N1 variant) could produce another pandemic.

Animal Epidemiology

Epidemiologic methods are sometimes used in animal populations, an endeavor known as **animal epidemiology**, and this research can be useful not only to veterinary science and practice, but also in support of human health. For example, farm animals or wild animal populations can serve as sentinels in infectious disease surveillance, with the goal of anticipating or preventing an epidemic outbreak in human populations.[17] During the outbreak of bovine spongiform encephalopathy ("mad cow disease") that began in the 1980s in Great Britain, epidemiologic methods were critical to understanding the nature of the disease, its transmission from cow to cow, and the risk to humans.

Analytic epidemiologic methods have been used to study risk factors for cancer in pet dogs, who get many of the same cancers that humans do and can serve as sentinels for human risk.[18, 19] Dogs share with their owners many exposures of the residential environment, indoors and out. In fact, dogs may be more highly exposed to some environmental contaminants, such as environmental tobacco smoke, because they spend more time breathing indoor air; or pesticides, because they have more contact with household dust indoors or grass and soil outdoors. Dogs offer certain advantages as a study population: They generally eat a consistent diet and have fewer other lifestyle confounders than people do (e.g., alcohol consumption), and they have shorter lifespans than humans, which simplifies the study of cancer.[18] Further, participation rates by dog owners in epidemiologic studies of their pets tend to be very high.[19] Pet cats have come to be seen as potential sentinels for human exposure to flame-retardant chemicals in the home, and especially in household dust;[20] cats' exposure to household dust is enhanced by frequent licking of their paws.

Community-Based Participatory Research

As important as informed consent is, it reflects a one-way, top-down model of public participation in research. In the 1970s and 1980s, social activism in response to industrial pollution led to fundamental changes in the paradigm of research and the communication of scientific information. In Niagara Falls, New York, a buried industrial dumpsite known as Love Canal was discovered under a working-class neighborhood (see **Figure 2.18**). In the manufacturing city of Woburn, Massachusetts, industrial solvents dumped near a wetland contaminated the local water supply. In both cities, it was angry residents who first hypothesized connections between pollution and local health problems, pressed for health studies, and then helped shape those studies to be useful to local residents—a new form of activism that has been called "popular epidemiology."[21] This was research driven by the need for change.

Today, community participation in health research is not unusual. People who have a stake in the outcome of a study—women with breast cancer, for example, or residents of a community being studied—may have a direct role in planning or conducting the research. Such an approach recognizes that community members often have pertinent and useful knowledge that researchers do not. Participation can be limited to an advisory role grafted onto a traditional top-down research paradigm, or it can be much more extensive, as in the model known as community-based participatory research. This approach to research rests on three

FIGURE 2.18 The Love Canal neighborhood, built over a chemical waste dump, became the scene of bulldozers and boarded-up houses.

Source: Reprinted courtesy of CDC Public Health Image Library. ID# 5534. Content providers CDC. Available at: http://phil.cdc.gov/phil/home.asp. Accessed October 3, 2012.

core principles: that those who will be affected by the outcome of a research project should participate in it, from defining the research question at the outset to interpreting the results at the conclusion of the study; that there is an equitable sharing of power between researchers and community members; and that the effort emphasizes practical solutions over abstract analysis.[22] Community-based participatory research is tied to a specific community, usually in a specific physical location (e.g., a native American tribal community, or a city's public housing residents), and is often conducted as a partnership that includes a community group and an academic research group.

2.2 Responding to Environmental Hazards to Human Health

As noted in the introduction to this chapter, scientific understanding of environmental health hazards is translated into real-world outcomes through three major activities:

- The applied science (or regulatory science) of risk assessment
- Risk management, through which assessment is translated into action
- Risk communication, a two-way sharing of understanding between experts and communities

Each of these activities is considered here in turn.

Risk Assessment: A Regulatory Science

Research in epidemiology and toxicology tells us much about the health effects of chemicals in humans and laboratory animals. However, such scientific knowledge accumulates slowly, and questions about a particular chemical, or gaps in theoretical understanding, may be pending for years or even decades.

Meanwhile, government agencies are charged with regulating hazards, such as setting a limit for the concentration of a chemical in drinking water or deciding how to deal with a hazardous waste site. Such policy actions fall under the general rubric of *risk management*: actions taken to control or manage risks to human health. In deciding what action to take, regulators do not have the luxury of waiting for scientific certainty to make their decisions easier. In effect, regulators need working answers for scientific questions that scientists have not yet answered to their own satisfaction.

The process used to bridge this gap is known as *risk assessment*. Operating in the boundary zone between science and policy, risk assessment is an agreed-upon set of procedures for integrating and interpreting scientific data for the practical purpose of making a decision. Sometimes referred to as a "regulatory science," risk assessment is a formal process for estimating the human health risk of a toxicant or a site by bringing together information on exposure and toxicity. Formal risk assessment guidelines establish default procedures for bridging gaps in scientific knowledge in a manner that is both consistent and health-protective.

The same basic framework is used whether an individual chemical or a contaminated site is being assessed. The four-step framework shown in **Figure 2.19**, used in most risk

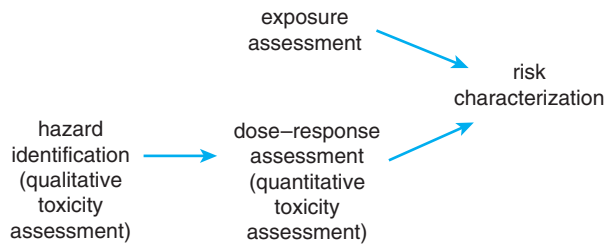

FIGURE 2.19 Basic framework of a risk assessment.

assessments conducted by the U.S. Environmental Protection Agency (EPA) and other government agencies in the United States, was put forward in 1983 in an influential report by the National Academy of Science.* In the *exposure assessment* step, the risk assessor estimates how much exposure the populations of concern have to the chemical or chemicals of concern. **Hazard identification** is a qualitative evaluation of toxicity with the purpose of establishing the scope of a chemical's health effects (or the presence of multiple chemicals, in the case of a site risk assessment). **Dose–response assessment** quantifies the relationship between dose and effect—that is, it characterizes the dose–response curve for specific toxic effects of the chemical or chemicals of concern. The final **risk characterization** step brings together information on exposure with information on toxicity at different exposures, allowing the risk assessor to estimate risks to human health. The risk characterization includes an estimate of the uncertainties that are built into it. Each of these four steps plays out somewhat differently in the context of an individual chemical or a contaminated site, as described in the following subsections.

In the real world, the exposure assessment and the toxicity assessment (consisting of the hazard identification and dose–response assessment steps) are not performed in isolation, as it appears in this simplified diagram (Figure 2.19), but rather inform one another. Perhaps most importantly, the exposure assessment must consider populations identified in the toxicity assessment as being particularly susceptible to the chemical's effects, while at the same time the toxicity assessment must take account of the exposures estimated for these susceptible populations and also for those identified as most highly exposed.

The basic risk assessment framework—estimating health risk on the basis of exposure and toxicity—can be applied to more than individual chemicals or hazardous waste sites. For example, it can be used to estimate the health risk to workers from an industrial process or population risks from air pollutants in automobile exhaust. However, this description focuses on risk assessment methods used for individual chemicals and contaminated sites, for which formal procedures have been developed.

*This 1983 NAS report, *Risk Assessment in the Federal Government: Managing the Process*, is commonly referred to as "The Red Book."

Risk Assessment Framework for a Chemical

Somewhat different approaches are typically used to assess the cancer and noncancer effects of chemicals, as described here. Not all toxic chemicals are carcinogenic, although all carcinogenic chemicals do have some noncarcinogenic toxicity. For this reason, in considering a given chemical, risk assessors integrate what is known about the actual mechanisms of toxicity.

Risk Assessment for the Noncancer Effects of a Chemical

In assessing the noncancer health effects of a chemical, the objective of *exposure assessment* is first to identify populations exposed to the chemical of concern, including susceptible or highly exposed subgroups, and then to estimate their exposures. The exposure assessment considers all important sources of exposure, with their associated pathways and routes of exposure, taking account of the physical–chemical properties of the chemical. Exposures are typically quantified using dose units of mg/(kg × day)—that is, the dose is normalized to body weight and averaged over time, as described earlier.

The qualitative step in toxicity assessment—*hazard identification*—establishes the range of noncancer health effects of a chemical. This is accomplished through a review of human case reports, epidemiologic studies of acute and chronic health effects, and short-term and chronic animal bioassays.

The procedures used for the quantitative step in toxicity assessment, *dose–response assessment*, are shaped by the assumption that noncancer effects have a threshold.* Specifically, the existence of a threshold implies that, in principle, there is a safe dose. For this reason, dose–response assessment is directed at defining what is called a **reference dose (RfD)**, with units mg/(kg × day). The reference dose is a dose that is expected to have no adverse effects in people—specifically, in people who are particularly sensitive to the chemical's effects and who are exposed over a 70-year lifetime.

Unfortunately, the literature on a chemical rarely includes an epidemiologic study of lifelong exposure in a sensitive subpopulation. Indeed, the literature might include no dose–response information at all in humans. Therefore, the reference dose for a chemical is usually derived by starting with some other dose that is available in the literature and then adjusting it downward to ensure that it is protective of sensitive human beings.

For example, if a reference dose is derived from the NOAEL in a chronic rodent bioassay, the starting value (the rodent NOAEL) is adjusted downward to account for the fact that people may be more sensitive than rodents, and then adjusted downward again to account for the fact that some people may be more sensitive than most people. If the starting value is a chronic rodent LOAEL rather than a NOAEL, or if the value comes from a short-term rodent study rather than a chronic rodent study, additional downward adjustments are made in deriving the reference dose to account for these limitations in the toxicological knowledge base. A further downward adjustment may be made to account for gaps in the toxicity data for a chemical.

*Research now indicates that there is at least one exception: The neurotoxicity of lead appears to have no threshold. The EPA does not publish a reference dose for lead.

The actual procedure for making these downward adjustments is to divide the starting value (such as a chronic rodent LOAEL) by one or more **uncertainty factors**, each of which is a hedge against the effects of a specific limitation in the available toxicity data. There are two key decisions in this process. The first is the selection of the dose to be used as the starting value (often the dose for the most sensitive effect in the most sensitive species—a health-protective choice). The second is the assignment of values of the specific uncertainty factors by which the starting value is reduced in deriving the reference dose. For example, should the starting value be reduced by a factor of 3 to account for a specific limitation in the available data? Or more conservatively, by a factor of 10? These decisions are made by an expert panel, with the opportunity for review by others.

The development of a reference dose is a lengthy process that requires that existing research findings be reviewed and an array of new toxicity studies be undertaken. As a result, the EPA currently publishes a reference dose for about 370 chemicals of the many thousands that are produced and used in the United States.

Because the result of a dose–response assessment for noncancer effects is a dose, the *risk characterization* step is a simple comparison of the actual or estimated dose (from the exposure assessment step) to this reference dose:

$$\text{hazard quotient (unitless)} = \frac{\text{actual or estimated dose (mg/[kg} \times \text{day])}}{\text{reference dose (mg/[kg} \times \text{day])}}$$

A **hazard quotient** greater than 1.0 shows that the actual or estimated dose exceeds the reference dose, indicating potential harm to people who are exposed at the actual or estimated dose of the substance. If people are exposed to a set of substances that affect the same organ or organ system (and ideally, by the same toxicologic mechanism), a **hazard index** is calculated as the sum of the hazard quotients for the individual substances.

Risk Assessment for the Carcinogenic Effect of a Chemical

The basic procedures of *exposure assessment* in a risk assessment for carcinogenicity are analogous to those in a risk assessment for noncancer effects.

The *hazard identification* step focuses specifically on a chemical's potential to cause cancer in humans. This qualitative evaluation of a chemical's carcinogenicity considers the results of epidemiologic studies as well as chronic animal bioassays, mutagenicity assays, and other short-term tests. The outcome of hazard identification is a designation of the chemical's likely human carcinogenicity, based on expert evaluation of the full body of scientific evidence. Agencies including the EPA and the International Agency for Research on Cancer (IARC, an arm of the World Health Organization) have defined **weight-of-the-evidence categories** for carcinogenicity (see **Table 2.4**).

In a risk assessment, *dose–response assessment* for carcinogenicity is shaped by the assumption that the carcinogenic effect has no threshold. This assumption implies that in principle, any dose, no matter how low, carries some risk of cancer. In this context, the concept of a reference dose, or safe dose, is not useful. Rather, the objective of dose–response assessment is to quantify

Table 2.4 Weight-of-the-Evidence Categories for Carcinogenicity, as Defined by the International Agency for Research on Cancer and the U.S. Environmental Protection Agency

International Agency for Research on Cancer	U.S. Environmental Protection Agency
Group 1: Carcinogenic to humans	Carcinogenic to humans
Group 2A: Probably carcinogenic to humans	Likely to be carcinogenic to humans
Group 2B: Possibly carcinogenic to humans	Suggestive evidence of carcinogenic potential
Group 3: Not classifiable as to carcinogenicity to humans	Inadequate information to assess carcinogenic potential
Group 4: Probably not carcinogenic to humans	Not likely to be carcinogenic to humans

the **cancer slope factor (CSF)**: the slope of the dose–response curve, for humans, in the low-dose range wherein human exposures actually occur. The cancer slope factor has units of incremental risk (probability of cancer) per unit increase in dose.

The derivation of a cancer slope factor poses substantial methodological challenges. Only occasionally does the epidemiologic literature provide dose–response information, and therefore the cancer slope factor is typically derived from a rodent bioassay. And, as described earlier, for practical reasons, rodents in such studies are given very high doses of the test chemical. Thus, the carcinogenicity data yielded by a rodent bioassay must be extrapolated in two ways: from rodents to people, and from very high experimental doses to much lower real-world exposures.

Sophisticated mathematical models are used to estimate the slope of the human dose–response curve in the low-dose range from rodent data at high doses. Ideally, these models take account of differences in species and differences in dose regimens, while incorporating a health-protective stance. Specifically, assumptions that lead to a steeper slope estimate in the low-dose region are protective of public health.

The cancer slope factor for a particular chemical is decided by an expert panel, with opportunity for review by others. At present, the EPA publishes a cancer slope factor for fewer than 100 chemicals.

Because the result of a dose–response assessment for cancer effects is a slope, with units of risk (probability) per unit dose, *risk characterization* is accomplished by multiplying the actual or estimated dose (from the exposure assessment step) by the cancer slope factor:

$$\text{dose (mg/[kg} \times \text{day])} \times \text{cancer slope factor (risk per mg/[kg} \times \text{day])} = \text{risk}$$

This estimated risk is the **incremental lifetime cancer risk**—the additional cancer risk, over a 70-year lifetime, that would result from the exposures that were assessed.

Table 2.5 summarizes the key steps in a risk assessment for the noncancer and cancer effects of a chemical.

Table 2.5 The Four Major Steps in Risk Assessment as Applied to a Chemical

Step	Noncancer Effects	Cancer
Exposure assessment	Estimate doses at which populations of concern are exposed to the chemical	
Hazard identification	Identify noncancer effects	Assign weight-of-the-evidence classification
Dose–response assessment	Derive reference dose (mg/[kg × day]); assumes noncancer health effect has a threshold	Derive cancer slope factor (incremental risk per unit dose in mg/[kg × day]); assumes carcinogenic effect has no threshold
Risk characterization	Calculate hazard quotient (unitless)	Calculate incremental lifetime cancer risk (probability)

Risk Assessment Framework for a Site

Risk assessment is used to estimate not only the human health risks of individual chemicals, but also risks associated with sites—for example, an operating industrial facility or an abandoned industrial site on which hazardous wastes have been found. Hazardous sites vary widely as to the set of chemicals present, the concentrations at which chemicals are found, the environmental and geographic setting, and the availability of reference doses and cancer slope factors for the chemicals of concern. These complexities are not reflected in the procedural sketch given here. In particular, site risk assessors must draw heavily on the scientific literature and on professional judgment in evaluating potential exposures and in characterizing the toxicity of chemicals for which no reference doses or cancer slope factors have been developed.

A site risk assessment is framed in the same four steps as a chemical risk assessment, but the framework plays out somewhat differently in this context, as shown in **Table 2.6**; for this reason, the first two steps in the risk assessment process are discussed here in reverse order.

In a site risk assessment, the work of *hazard identification* is to characterize the chemical contamination on and from the site. Samples of water, soil, sediments, and/or air are collected and analyzed for the presence of a long list of chemicals. The concentrations at which individual chemicals are found, in different environmental media at different locations, are reported.

In the context of a site risk assessment, *exposure assessment* comprises two major tasks. First, the risk assessor constructs plausible scenarios for exposure, identifying groups of people who might be exposed to contaminated environmental media on the site (or from the site) and the activities that could bring them into contact with these media. Assumptions made about exposure are intended to include the great majority of the population that is exposed to the site. The exposure scenarios often cover not only current uses of the site, but also reasonably foreseeable future uses.

In defining exposure scenarios, the risk assessor identifies likely exposure pathways leading to ingestion, inhalation, or dermal exposures to chemicals in various environmental media. For example, the exposure assessment component of a risk assessment for an industrial site

Table 2.6 The Four Major Steps in Risk Assessment as Applied to a Site

Step	Noncancer	Effects Cancer
Hazard identification	Through environmental sampling, identify the chemicals present on the site; characterize locations and concentrations of the chemicals in various environmental media	
Exposure assessment	Develop scenarios by which specific populations might be exposed to chemicals on the site; estimate corresponding doses	
Dose–response assessment	For each chemical, obtain published reference dose or develop new one as needed	For each chemical, obtain published cancer slope factor or develop new one as needed
Risk characterization	For each exposure scenario and population, calculate hazard quotient for each chemical and sum across chemicals	For each exposure scenario and population, calculate incremental lifetime cancer risk for each chemical and sum across chemicals

abutting a residential neighborhood might include some of these potential exposure pathways for nearby residents:

- Ingestion, inhalation, and dermal exposures to contaminated well water used as tap water
- Dermal and incidental ingestion exposures to contaminated surface water and dermal contact with sediment in a neighborhood pond used for swimming
- Exposures to dust carried from the site by air movements
- Incidental ingestion of soil, dermal contact with soil, or inhalation of vapors on the site itself (e.g., by children cutting through the site on their way to and from school)
- Consumption of homegrown produce or of fish caught in contaminated waters
- Ingestion of breast milk by infants

The second major task of exposure assessment is to translate each relevant pathway into a concrete dose estimate. Such calculations require a number of inputs, which can be measured, estimated or modeled, or assumed. For example, the risk assessor must quantify the following factors:

- Concentrations of chemicals in various media on the site
- The fate and transport of chemicals or environmental media (e.g., the movement of airborne dust from the site into a residential area, or the bioconcentration of a chemical from pond water into fish tissue)
- People's contact with environmental media resulting from various activities (e.g., the quantity of fish ingested)
- The likely frequency and duration of people's exposures caused by various activities

Research data provide some basic information, for example, on how much water people typically drink each day, as well as typical inhalation rates and skin areas—and the EPA has established default values for these factors. However, a site risk assessment often requires many other assumptions to be made. Some are concrete: How often do residents eat locally caught fish, and how much do they eat? How often and for how long do children swim in a contaminated pond? Others require the use of environmental data and scientific understanding, perhaps in the form of mathematical models.

For example, given the measured concentration of a chemical in groundwater on the industrial site, what is the expected concentration in water from a private well located downgradient of the site?

As part of a site risk assessment, the core work of *dose–response assessment* is to gather the available toxicity values (reference dose, weight-of-the-evidence classification, and cancer slope factor) for chemicals found on the site, and to derive missing toxicity values for chemicals that are important on the site. Depending on circumstances, the dose–response step may be relatively straightforward or may require sophisticated scientific work.

In the *risk characterization* step of a site risk assessment, the risk assessor summarizes the cancer risk and noncancer hazard associated with exposure to chemicals on the site, under the exposure scenarios considered. This characterization includes a discussion of the uncertainties embedded in the risk assessment. The risk characterization provides essential information for later decisions about how best to remediate the site in a manner that will protect public health.

Risk Management: From Assessment to Action

The term *risk management* refers to the very broad range of actions taken, often by government agencies, to control or reduce environmental risks to human health. The risk management process sometimes begins with the risk characterization derived as the final step in a risk assessment—that is, with a quantitative estimate of the magnitude of a health hazard. However, as risk managers decide whether and how to reduce a given risk, they must consider not only this quantitative estimate of risk, but also the regulatory framework, the range of technical options available for controlling the hazard at hand, cost, and the social context. This is not a simple matter. Historically, *acceptable risk* has been defined at different times and in different contexts as a specific numerical risk, the lowest risk that is reasonably achievable, the lowest risk that can be achieved using the best available technology, a negligible risk (too small to be of concern), a risk that is comparable to similar existing risks, a risk that takes account of costs, or a risk that takes account of balancing benefits.

The federal decision-making process also incorporates broader concerns, including the goal of **environmental justice**, which the EPA defines as "the fair treatment and meaningful involvement of all people regardless of race, color, national origin, or income with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies."[23] In 2005, the agency named several areas in which it has made environmental justice a priority, including reducing the incidence of elevated blood lead levels and asthma attacks, reducing exposure to toxic air pollutants, ensuring that water is safe to drink and that fish and shellfish are safe to eat, and restoring contaminated sites so that they can be put to use. These remain the agency's priorities.[24] The concept of environmental justice also includes equitable access to such positive environmental factors as clean water or the cleanup and redevelopment of contaminated industrial sites (sometimes called **brownfields**), as well as participation in decision making by government.

There are many U.S. regulatory provisions or international agreements related to various environmental health hazards. Nearly all of these are efforts at risk management, although this term is not always used. What follows here is a brief preview of the range of activities that fall within the scope of risk management.

Risk Management for Individual Chemicals and Sites

Some risk management decisions are based closely on the results of a risk assessment; for example, EPA standards for concentrations of individual chemicals in drinking water are derived from the results of chemical risk assessments.[25] Thus, if a risk assessment has shown that Chemical X is a carcinogen, any exposure to the chemical is assumed to carry some cancer risk, and the goal for the concentration of Chemical X in drinking water is set at zero. The enforceable standard is then set at a concentration that is considered feasible to achieve. Both policy decisions—the choice of a goal and of a feasible standard—are risk management decisions.

Similarly, if a risk assessment has shown Chemical Z to be noncarcinogenic, and a reference dose has been derived, a drinking water standard can be derived from the reference dose. This is done by back-calculating the concentration in drinking water that corresponds to the reference dose, given certain assumptions about body weight and daily consumption of drinking water. For example, suppose that the reference dose for Chemical Z is 0.000143 mg/(kg × day), or 0.143 μg/(kg × day). Then, a backward calculation would look like this*:

$$\frac{0.143\ \mu\text{g Chemical Z}/(\text{kg} \times \text{day}) \times 70\ \text{kg body weight}}{2\ \text{liters water}/\text{day}} = \frac{5\ \mu\text{g Chemical Z}}{\text{liter water}}$$

The enforceable standard for the concentration of Chemical Z in drinking water might then be set at a concentration somewhat lower than 5 μg/L to account for the fact that people will have additional exposures from sources other than drinking water.

Risk management decisions about cleaning up contaminated sites are often very complex for several reasons: Numerous chemicals are usually present in more than one environmental medium (e.g., in both water and soil), contamination is not evenly distributed across the site, and there may be several approaches to cleaning up the site using different technologies with different effects and different price tags. In such a context, risk management is not simply a matter of deriving acceptable target concentrations for individual chemicals. Rather, in making complex decisions about how to remediate contamination, risk managers must incorporate not only information about the toxicity of all the chemicals (including cancer slope factors and reference doses), but also anticipated future uses of the site, the effectiveness of available cleanup options, and costs.

Other Examples of Risk Management

Various approaches can be used to reduce ambient environmental pollution from industrial processes. For example, regulations can require that specific technologies be used to treat wastes before they are released, or industries might be granted allowances to release specified quantities of pollutants. Changes to industrial processes might enable a manufacturer to produce less waste or to substitute less toxic chemicals for those currently being used. Within the occupational setting, federal regulations set limits for the concentrations of some

*The corresponding forward calculation appeared earlier in this chapter as an example of calculating a dose of trichloroethylene in drinking water.

chemicals in workplace air. In some work settings, a hazardous process can be isolated from the rest of the workplace, or individual workers can wear protective gear. All of these approaches to controlling pollution are strategies for risk management.

Not all risk management provisions involve the direct control of pollution. Some regulations set incentives for compliance with standards—or set penalties for noncompliance. Other regulations require information to be gathered and released. For example, federal law requires employers to provide workers with certain information about the chemicals to which they are exposed on the job. Similarly, industrial facilities are required to provide local communities with certain information about chemical releases. Such information can create a powerful incentive to reduce exposures. Other kinds of information are also important in anticipating and managing environmental health risks. For example, various government agencies gather surveillance data on infectious diseases, lead poisoning in children, and other health outcomes.

Finally, much of the work done by local health departments involves the management of environmental health risks. Many city and town governments are responsible for providing water supply, sewer service, and trash removal. Local governments inspect and regulate food service establishments, manage episodes of foodborne illness, and respond to other infectious disease outbreaks. Local health departments also work to manage various environmental hazards related to housing conditions, from controlling rodents to preventing lead poisoning and asthma. Noise is also regulated through local ordinances.

Whatever the hazard, sharing information about a specific risk is usually an important part of risk management. Such activities are referred to as *risk communication*.

Risk Communication: A Two-Way Street

Clearly, communication between substantive experts and members of the public about environmental health concerns is important. Informed consent by participants in research studies, as well as community-based participatory research partnerships between community members and scientists, are examples of such communication, as is the consensus conference, described later. However, the term *risk communication* is more often used narrowly to refer to the exchange or transmission of information about an environmental health hazard between experts and those affected by the hazard. The affected group might be people living near a hazardous waste site, for example, or those affected by a new law or policy.

Communication about environmental health hazards between members of the public and scientists or other experts is often complicated by differences in the way these groups perceive risks. Technical experts tend to think of risks in strictly quantitative terms, whereas the public's perception of risks is more affected by other factors. Indeed, the public perception of risk has been formulated as "hazard plus outrage"[26]—that is, the quantitative estimate of risk can be ramped up by a sense of outrage, which is elicited by certain characteristics of the risk.

Research during the 1970s and 1980s identified a number of characteristics of hazards that tend to contribute to public outrage. During this period, research by engineers sought to understand the public's tendency to under- or overestimate risks relative to engineering

estimates, while research by psychologists sought to uncover how nonexperts conceptualize risk. Taken together, these two lines of research identified features of hazards that, for members of the public, tend to make the associated risk seem numerically higher and also somehow less bearable.[27–31] That is, these features of hazards tend to generate outrage:

- The consequences of the hazard are serious or irreversible (e.g., death or permanent disability).
- The hazard kills large numbers of people at one blow (e.g., the risk of a single plane crash that causes 300 deaths, as opposed to the risk of 200 car accidents that cause 300 deaths).
- The hazard simply evokes a gut dread in most people (e.g., radiation).
- The hazard is new or unfamiliar, or its consequences are unknown (e.g., genetic engineering as opposed to car accidents).
- The hazard was not appreciated as such before an unexpected event (e.g., the flood of molasses that killed 21 people after the rupture of a large storage tank in Boston in 1919).
- The consequences of the hazard are delayed (e.g., cancer, with its long latency period) rather than immediate.
- The hazard is perceived as not being within an individual's personal control (e.g., a commercial aviation accident as opposed to a car accident while driving).
- The hazard is taken on involuntarily or without knowledge of the risk (e.g., the risk of exposure to secondhand smoke as opposed to the risk of smoking).
- The hazard is not natural, but rather manmade (e.g., toxic synthetic chemicals).
- The hazard is seen as avoidable or unnecessary, as opposed to, for example, occupational hazards or chemotherapy to treat cancer.
- The victims are nearby (although faraway victims can be brought close by media coverage, especially coverage of identifiable individuals, such as miners trapped by a cave-in).

Many environmental health hazards have one or more of these outrage-generating characteristics. In addition, risks that affect people in their homes, such as chemical contamination of drinking water, elicit a powerful emotional response because they strike at the heart of family, security, and even personal identity.[32] Further, the public's outrage tends to be magnified if there are no benefits clearly associated with a risk, if the risk receives a lot of media attention, if the risk results from unethical activities or an unfair process, or if the risk was created by people or institutions they do not trust.[33] Outrage may also be particularly acute in those with past experience of injustice, including residents of lower-income neighborhoods or members of historically disadvantaged racial or ethnic groups.

Professionals who communicate about environmental health risks must understand and acknowledge the roots of outrage in a given situation, and they must be committed to genuine two-way communication with diverse stakeholders—those who are affected by the problem at hand and who will be affected by the chosen solution. As a general rule, effective risk communication about environmental health issues requires careful planning, genuine collaboration with stakeholders, careful listening and clear speaking, acknowledgment of outrage, honesty, and compassion, as well as skill in working with the media.[33]

2.3 Precautionary Approaches in Environmental Health Policy

On the whole, the risk assessment/risk management paradigm that is dominant in U.S. regulation calls for existing health hazards to be quantified and then managed, one by one. This approach is by nature slow and cumbersome. More fundamentally, the absence of foresight that it embodies has led to numerous missed opportunities for primary prevention of human health impacts from environmental hazards. In some other locations—most clearly in the European Union—prevention and precaution figure more prominently in the mindset of policymakers.

This concluding section discusses three approaches that reflect a precautionary mindset. The first is a principle to guide decision making in environmental health policy (and public policy more broadly); the second is an inclusive consensus-building process in support of informed policymaking; and the third is a more concrete assessment tool for such policymaking.

The Precautionary Principle

We can learn a great deal about individual toxicants and their health risks from environmental science, toxicology, exposure assessment, and epidemiology. In the United States today, such knowledge informs decisions and actions mainly through two activities already described: risk assessment, an applied science that offers a structured approach for estimating health effects; and risk management, the amalgam of decisions and actions that are taken to reduce or control the risks of chemicals, sites, or activities. Both risk assessment and risk management now involve formal opportunities for risk communication—an exchange of information and viewpoints between technical experts and members of the public.

But for the most part, all three of these activities occur after the fact—after an industrial process has been put into use, after a toxicant has been released into the environment, after the opportunity to prevent or minimize a hazard has been lost. Historically, the tendency in the United States has been to introduce new chemicals or processes freely and only later consider their ramifications. At the other end of the spectrum, a strict preventive approach would require full knowledge of all potential impacts before introducing any new chemical or process—an impossible prerequisite.

The **precautionary principle** acknowledges this impossibility while also paralleling our commonsense notions about taking precautions (e.g., "look before you leap," "better safe than sorry"). Three statements of a precautionary approach in the context of environmental health are provided in **Table 2.7**. Although they are worded differently, they share these key elements: If a significant potential for serious harm exists, but conclusive evidence of harm is lacking, protective action should be taken as a precaution against the harm. In effect, this approach shifts the burden of proof: Rather than demonstrating harm as grounds to regulate a chemical or process after it is in use, we should take steps to prevent or minimize harm from the outset.

The precautionary principle embodies the long-standing preference in public health for primary prevention over secondary prevention whenever possible. Efforts toward **primary prevention** aim to head off health problems before they happen (e.g., by eliminating an

Table 2.7 Three Formulations of the Precautionary Principle

Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation. —Rio Declaration on Environment and Development, 1992
When an activity raises threats of harm to human health or the environment, precautionary measures should be taken even if some cause and effect relationships are not fully established scientifically. —Wingspread Statement on the Precautionary Principle, 1998
When human activities may lead to morally unacceptable harm that is scientifically plausible but uncertain, actions shall be taken to avoid or diminish that harm. —United Nations Educational, Scientific and Cultural Organization (UNESCO), 2005

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exposure to a carcinogenic chemical); **secondary prevention** efforts seek to reduce the impacts of an existing health problem (e.g., through early detection of cancer).

Essentially, decisions made in the spirit of precaution avoid the worst possible outcome of a decision made under conditions of uncertainty. If our decision lines up with the subsequent outcome (i.e., if we take precautionary steps and the harm turns out to be serious, or if we do not take precautionary steps and the harm is not serious), then we have made the "right" decision. The challenge lies in the other two possible outcomes. On the one hand, if we take precautionary steps but the harm is not serious, then any benefit gained is small in light of the effort and money spent. On the other hand, if we do *not* take precautionary steps and the harm turns out to be serious, then we have gambled and lost. When human health or environmental sustainability is at stake, the precautionary principle calls for the avoidance of this outcome.

The broader policies in which the three formulations of the precautionary principle in Table 2.7 are embedded all specify that the burden of proof should rest with the party initiating a new activity, that a wide range of alternatives for action should be considered, and that the decision-making process should be broadly inclusive.[34] Thus, the precautionary approach is tied to societal goals, asking whether an activity is needed, to what degree its negative impacts can be prevented while still meeting the societal goals, and whether there are other ways to

meet the goals with less risk.[35] The list of lost opportunities for precaution is a long one and includes depletion of global fisheries, broad use of asbestos and various synthetic organic chemicals, and the practices that led to the outbreak of "mad cow disease" and human illness in the 1980s and 1990s.[36]

In fact, some U.S. policy initiatives and some international agreements, described elsewhere in the context of the manufacturing industry, reflect a precautionary approach. For example, the U.S. Toxic Substances Control Act is precautionary in spirit, despite practical barriers to its full implementation. Two major international agreements that directly affect public health—the Kyoto Protocol on global climate change and the Montreal Protocol on Substances that Deplete the Ozone Layer—reflect a precautionary approach to problems that are global in scale and respond only slowly to control measures. Further, the European Union has recently established a program for the **R**egistration, **E**valuation, **A**uthorisation and Restriction of **Ch**emicals (REACH), under which new chemicals can be authorized only after toxicity testing (with more testing required for higher-volume chemicals) and a weighing of their potential risks against their potential socioeconomic benefits.[37]

The Consensus Conference

A Danish-style **consensus conference** brings together a diverse group of citizens to deliberate a complex issue and offer its collective judgment to government and scientists. In this 3-day process, the panel of citizens is briefed on the issue at hand, given the opportunity to question a panel of experts, allowed to deliberate as a group, and then asked to prepare a report on the issue.

In Denmark, the Danish Board of Technology arranges occasional consensus conferences, whose reports are passed on to the Parliament. More than 20 consensus conferences have been held in Denmark since 1987 on such topics as the use of gene technology in industry and agriculture, the future of fishing, and the use of electronic identification cards. As a general rule, topics are chosen for a consensus conference because they are controversial and scientifically complex, and are the subject of current policymaking. Participating in a consensus conference is seen as a civic obligation in Denmark, much like jury duty in the United States.

Although the consensus conference has no formal place in U.S. policymaking, in 2006 a consensus conference on the subject of biomonitoring—measuring environmental chemicals in people's bodies—was held in Boston by university researchers. The panel's consensus statement[38] was made publicly available and was sent to U.S. policymakers and scientists in the public health arena. Like community-based participatory research, the consensus conference engages members of the public in the development of scientific knowledge, combining the unique perspectives and expertise of technical experts and laypersons to grapple with an emerging hazard.

The Health Impact Assessment

At a more concrete level, an approach known as **health impact assessment**—the assessment of the likely population health impacts of a proposed policy or action before it is implemented—has been gaining some traction in the United States. For some years, the World Health

Organization has supported the use of health impact assessments.[39] The U.S. Centers for Disease Control and Prevention, as well as various state and local governments, have embraced the health impact assessment approach more recently.[40]

The U.S. National Environmental Policy Act of 1969 calls for an evaluation of the *environmental* impacts of proposed federal projects, known as an environmental impact assessment. As a result, many such assessments have been conducted in the United States, and this has contributed to the growing interest in the health impact assessment. A health impact assessment may run parallel to an environmental impact assessment, or it may be folded into an assessment of environmental impacts, broadly defined.

A health impact assessment is distinct from a risk assessment for a specific site (or activity), described earlier in this chapter. A site risk assessment provides a quantitative estimate of the human health risks posed by specific hazards on the site (usually a set of chemicals), using a detailed set of assumptions about how and to what degree people come into contact with the site. A risk assessment takes the site as it is; decisions about whether to enclose it, how to remediate it, or how it might be used in the future are the province of risk management.

In contrast, a health impact assessment looks forward in time, and it considers a much broader range of factors than a list of chemical pollutants, including factors in the social and economic environment that may be important determinants of health. These features make the health impact assessment a natural partner to the environmental impact assessment. A health impact assessment seeks to anticipate impacts on the entire population, including vulnerable subgroups, and including positive as well as negative impacts. This process seeks input from the communities that will be affected by important decisions, and it does so before those decisions are made. In that it is anticipatory, this approach is seen as compatible with a sustainable approach to development. However, it stops short of asking communities for their collective judgment of a proposed policy or action.

Study Questions

1. Contrast the typical profiles of higher- and lower-molecular-weight chemicals as to their physical–chemical properties and their behavior in the environment.
2. Assess the advantages and disadvantages of epidemiology and rodent bioassays as sources of information about the human health effects of environmental chemicals.
3. Suppose that a surveillance biomonitoring program has measured concentrations of polybrominated diphenyl ethers (PBDEs) in women's breast milk, with the goal of describing exposure at the population level. Much is still unknown about the toxicity of these common flame-retardant chemicals. Would you recommend that the results of the biomonitoring be reported back to the study participants? Why or why not?
4. Explain why risk assessors use a reference dose to quantify noncarcinogenic toxicity, but use a cancer slope factor to quantify carcinogenic toxicity.
5. Identify two environmental health topics that you think are ripe for a Danish-style consensus conference, and formulate the specific question to be addressed.

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