12 Waste Management

Sign protesting a hazardous waste disposal site in California. (*Edward A. Keller*)

How a society manages its waste is a measure of its commitment to the environment. Shown here is a sign to protest the Casmalia Toxic Dump in California. Although the disposal site, like many others, has been closed for environmental reasons, the legacy from hazardous waste continues on a global scale. For example, it is estimated that approximately 25 percent of the people in Russia live in areas where the concentrations of toxic pollutants exceed standards by ten times. As recently as 1991 a survey of 100 nations reported that 90 percent of those countries that responded stated that uncontrolled dumping of industrial hazardous waste was a problem and two-thirds of those reporting stated that hazardous chemical waste was disposed of in uncontrolled sites. It is believed that the casual treatment of hazardous waste and municipal solid waste (particularly in developing countries) has and will continue to adversely affect the overall environment and the health of people and have costly economic consequences in many locations of the world.*

12.1 Concepts of Waste Management: An Overview

People in the United States and throughout the world are facing a tremendous solid-waste disposal problem, particularly in growing urban areas. The problem boils down to the simple fact that urban areas are producing too much waste and there is far too little space for disposal. About half the cities in the United States are estimated to be running out of

*Source: Gardner, G., and Sampat, P. 1999. Forging a sustainable materials economy. In *State of the world 1999*, ed. L. Stark, pp. 41–59. New York: W. W. Norton.

LEARNING OBJECTIVES

Development of management strategies to deal with our waste problems is an important environmental concern. Learning objectives for this chapter are:

- *To gain an appreciation for the evolution of concepts of waste management from "dilute and disperse" to integrated waste management, to materials management with the visionary goal of zero production of waste.*
- *To understand the principles behind "reduce, recycle, and reuse."*
- *To know the various alternatives for solid-waste disposal.*
- *To understand important processes related to sanitary landfills, including generation of leachate, site selection, design, monitoring, and federal legislation.*
- *To understand the principles of hazardous chemical-waste management in terms of what responsible management is, alternative management strategies, and federal legislation pertaining to hazardous waste.*
- *To gain a basic understanding of the strategies and policies associated with radioactive waste management.*
- *To understand some of the problems and potential solutions associated with ocean dumping.*

Web Resources

Visit the "Environmental Geology" Web site at www.prenhall.com/keller to find additional resources for this chapter, including:

- ▶ Web Destinations
- ▶ On-line Quizzes
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landfill space (see *Case History: The Fresh Kills Landfill*). Cost is another limiting factor—expenditures for landfill disposal have skyrocketed in recent years (1).

All types of societies produce waste, but industrialization and urbanization have caused an ever-increasing effluence that has greatly compounded the problem of waste management. Although tremendous quantities of liquid and solid waste from municipal, industrial, and agricultural sources are being collected and recycled, treated, or disposed of, new and innovative programs remain necessary if we are to keep ahead of what might be called a waste crisis. Disposal or treatment of liquid and solid waste by federal, state, and municipal agencies costs billions of dollars every year. In fact, it is one of the most costly environmental expenditures of governments, accounting for the majority of total environmental expenditures (2).

A possible solution to the solid-waste problem would be to develop new disposal facilities. Unfortunately, no one wants to live near a waste-disposal site, be it a sanitary landfill for municipal waste, an incinerator facility that can reduce the volume of waste by 75 percent, or a disposal operation for hazardous chemical materials. This obviously creates serious siting problems even if the local geographic, geologic, and hydrologic environment is favorable. The siting problem also involves issues of *social justice*. Waste-management facilities are all too frequently located in areas where the people are of low social and economic status or belong to a minority ethnic group or race. Investigation of the issues involved in siting waste facilities to which many people object based on perceived environmental problems is part of an emerging field known as *environmental justice* (3). The consensus seems to be that people have little confidence in the ability of government or industry to preserve and protect public health as it relates to waste disposal (1).

The waste-disposal industry in the United States, which represents a $20 billion sector of the economy, is accustomed to the relatively simple system of collection of waste and landfill disposal (1). The rise in public consciousness concerning environmental problems and solutions is forcing the disposal industry to explore new solid-waste management systems. What has emerged is the concept known as **integrated waste management (IWM),** a complex set of management alternatives including source reduction, recycling, composting, landfill, and incineration (1).

Earlier Views

During the first century of the Industrial Revolution, the volume of waste produced was relatively small and the concept of "dilute and disperse" was adequate. Factories were located near rivers because the water provided easy transport of materials by boat, ease of communication, sufficient water for processing and cooling, and easy disposal of waste into the river. With few factories and sparse population, "dilute and disperse" seemed to remove the waste from the environment (4).

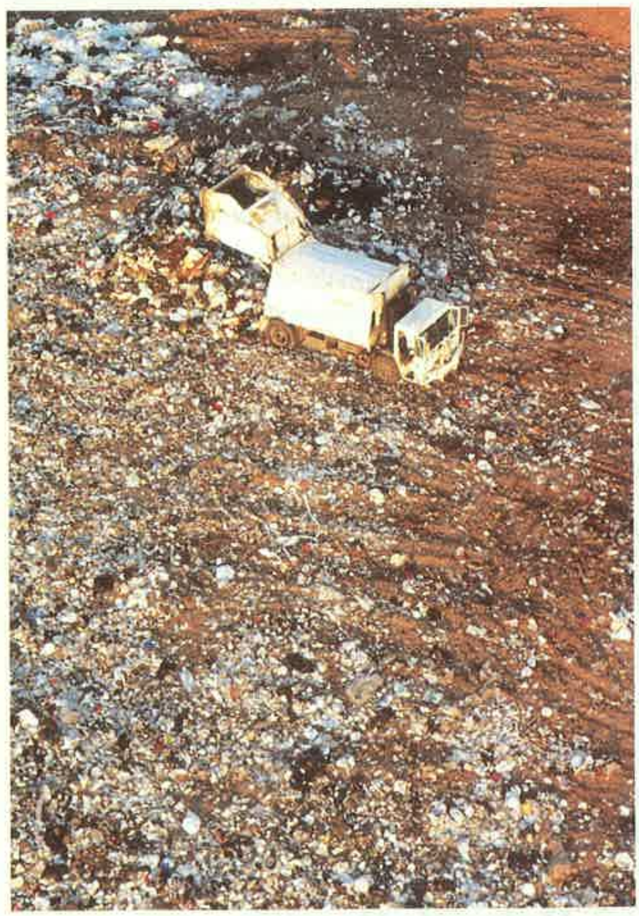
Unfortunately, as industrial and urban areas expanded, the concept of "dilute and disperse" became inadequate, and a new concept known as "concentrate and contain" became popular. It is now apparent, however, that containment was and is not always achieved. Containers, natural or artificial, may leak or break and allow waste to escape. As a result, another concept developed, known as "resource recovery." This philosophy holds that wastes may be converted to useful

CASE HISTORY The Fresh Kills Landfill

The Fresh Kills landfill is located on the western shore of Staten Island (Figure 12.A). The landscape is a mixture of wetlands (salt marsh), woodlands, and grasslands. The landfill opened in 1948 and is the only landfill operating in the city of New York. The landfill has an area of approximately 7500 ha and at its peak in 1986 received more than 21,000 tons of waste per day. During the 1990s the amount of waste the facility accepted began to slow down as the city eliminated commercial deliveries and the people of New York began to recycle returnable bottles, plastic containers, and newspapers. Currently Fresh Kills receives between 12,000 and 14,000 tons of waste per day, at a cost of approximately $44 per ton (5).

The Fresh Kills landfill is one of the largest such facilities in the world, but space for the waste generated by the city of New York is running out. Today less than about 2000 ha of the facility are actually used for landfilling. As a result the city is negotiating to begin trucking waste out of New York City at a cost of $50 to $70 per ton as the landfill enters its final closure stages. The cost of closing the landfill will be more than $1 billion, including 30 years of monitoring after closure in approximately December 2001. The city of New York has an ambitious plan to transform one of the world's largest landfills into an environmentally sound and aesthetically pleasing natural area. As a result of the disposal activities, the elevation of parts of the landfill, when closed, will be approximately 80 m, a sizable hill for coastal New York! As part of the closure plan, a slurry wall (underground concrete barrier) containment system designed to prevent the migration of untreated leachate (noxious, polluted liquid produced when water infiltrates through waste material) outside of the landfill has been constructed. A subsurface leachate collection system inside the containment wall has more than 30 wells to collect leachate for treatment. A leachate treatment center will be utilized to neutralize more than one million gallons (3800 m^3) of leachate per day. At the site, storm-water runoff is diverted to retention ponds and about 150 wells collect 283,000 m^3 (10 million ft^3) of methane daily from two sections of the landfill. The gas produced from the wells is purified and sold to Union Gas in Brooklyn (5).

The primary goal is ensure that following closure of the landfill, the Fresh Kills site will be environmentally safe. A secondary goal is to transform the site into an area that is aesthetically pleasing. It has been determined that maintaining a "lawn" of grass the size of the landfill site would be too costly, at more than $20 million over the 30-year monitoring period. Therefore, the city Sanitation Department has developed a series of test plots and experiments to reestablish native woodland communities at the site. The trees require minimal care, and the plan is to let nature take over. Thousands of shrubs and trees have been planted and to date the trees have grown moderately well and the shrubs have done great. A side benefit of the replanting is that many birds have come to perch in the trees, further dispersing seeds and therefore adding new species of plants to the site. Initially it was feared that replanting of the landfill site with trees would produce roots that might reach down and break the clay cap used to contain waterborne pollutants. To date this has not been a problem. The land reclamation plan of the site, if successful, will result in open space that is guaranteed to remain undeveloped in the future. The reclamation of the site to a mixture of marsh, woodland, and grasslands as it was before the landfill is a positive action that is being attempted in other landfills around the United States facing closure. Nevertheless, preservation of the original land 150 years ago as a natural reserve would have been environmentally preferred. Today, a large preserve would be a treasure, as is Central Park in New York City (6). The lesson learned from Fresh Kills, in spite of the positive aspects of land reclamation, is that waste management facilities are a tremendous financial burden to society. Furthermore, we have failed in the past 50 years to move from a throw-away waste-disposal-oriented society to sustain natural resources. We are now beginning to move in a new direction, toward a wasteless society, which is a real and pressing necessary goal.



▲ **FIGURE 12.A** Aerial view of a small part of the Fresh Kills landfill in New York. (*Comstock*) materials, in which case they are no longer wastes but resources. However, even with our state-of-the-art technology, large volumes of waste cannot be economically converted or are essentially indestructible. Therefore, we still have waste-disposal problems (4).

Modern Trends: Integrated Waste Management

There is a growing awareness that many of our waste-management programs simply involve moving waste from one site to another and not really properly disposing of it. For example, waste from urban areas may be placed in landfills, but eventually these may cause further problems from the production of methane gas, as mentioned above (which is a resource if managed properly), or noxious liquids that leak from the site to contaminate the surrounding areas. Disposal sites are also capable of producing significant air pollution. It is safe to assume that waste management is going to be a public concern for a long time. Of particular importance will be the development of new methods of waste management that will not endanger the public health or cause a nuisance.

Integrated waste management (IWM) emerged in the 1980s as a set of management alternatives, including resource reduction, recycling, reuse, compositing, landfill, and incineration (1). **Reduce, recycling, and reuse** are the three Rs of IWM, and it is believed that the primary objective of recycling could reduce the weight of urban refuge disposed in landfills by approximately 50 percent.

The recycling option of IWM, which has been seriously pursued for nearly two decades, has been responsible for the generation of entire systems of waste management that have produced tens of thousands of jobs while reducing the amount of urban waste from homes in the United States sent to landfills from 90 percent in the 1980s to about 65 percent today. In fact, many firms have combined waste reduction with recycling to reduce by 50 percent to 90 percent of the waste they deliver to landfills. In spite of this obvious success, IWM is being criticized for not effectively advancing policies to prevent waste production by over-emphasizing recycling. In the long term, waste management policies that rely on recycling cannot be successful. As human population continues to increase, in one doubling of the population, we will be where we are today with respect to waste disposal, if we depend upon landfilling for 50% of the waste we produce. That is, if we continue on with today's management of waste, in approximately 50 to 70 years, when the U.S. population has doubled again, we will be producing the same volume of waste sent to landfills that we do today, given a 50 percent rate of recycling. Clearly, emphasizing recycling is not a sustainable sollution to our waste problem. With this in mind, the concept of IWM needs to be rethought and expanded to include what is termed *materials management* (7).

12.2 Materials Management

Materials management is part of IWM, but it provides a new goal. That goal is "zero production of waste," so that what is now thought of as waste will be a resource! This is a visionary goal, requiring more sustainable use of materials combined with resource conservation. It is believed that materials management as an extension of IWM can be established by (7):

- Eliminating subsidies for extraction of virgin materials such as timber, minerals, and oil.
- Establishing "green building" incentives that use recycled materials and products in new construction.
- Establishing financial penalties for production of those products that do not meet the objectives of material management practices.
- Providing financial incentives for those industrial practices and products that benefit the environment by enhancing sustainability, such as encouraging products that reduce waste production and use recycled materials.
- Providing incentives for the production of new jobs in the technology of materials management and practice of reducing, recycling, and reusing of resources. This is the essence of materials management and sustainable resource utilization.

The concept of materials management for "zero waste" is part of what is known as **industrial ecology.** The idea is to produce urban and industrial systems that model natural ecosystems, where waste from one part of the system is a resource for another part.

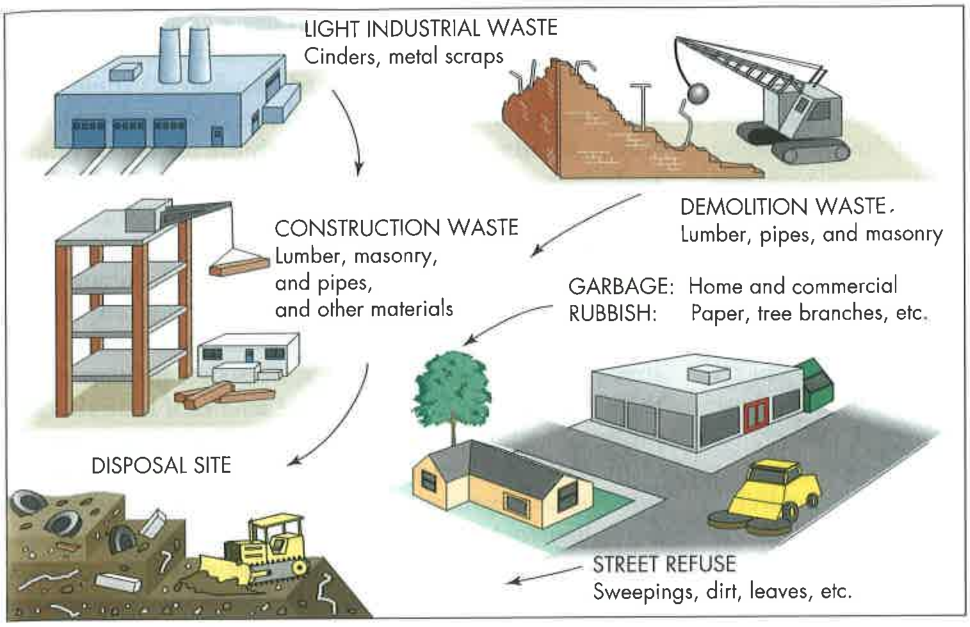
With this introduction to modern trends and integrated waste management, it is advantageous to break the management treatment and disposal of waste into several categories: solid-waste disposal; hazardous chemical-waste management; radioactive waste management; and ocean disposal.

12.3 Solid-Waste Disposal

Disposal of solid waste is primarily an urban problem. In the United States alone, urban areas produce about 640 million kg of solid waste each day, an amount that could cover more than 1.6 km^2 of land to a depth of 3 m (8). Figure 12.1 summarizes major sources and types of solid waste, and Table 12.1 lists the generalized composition of solid waste at a disposal site in 1986 and projected for the year 2000. We emphasize that this is only an average composition, and considerable variation can be expected because of differences in such factors as land use, economic base, industrial activity, climate, and season of the year. It is no surprise that paper is by far the most abundant solid waste.

In some areas, infectious wastes from hospitals and clinics can create problems if they are not properly sterilized before disposal. Some hospitals have facilities to incinerate such wastes. In large urban areas, huge quantities of toxic materials may also end up at disposal sites. Urban landfills are now being considered hazardous waste sites that will require costly monitoring and cleanup.

The common methods of solid-waste disposal, summarized from a U.S. Geological Survey report, include onsite disposal, composting, incineration, open dumps, and sanitary landfills (9).



◀ **FIGURE 12.1** Types of materials or refuse commonly transported to a disposal site.

Table 12.1 Generalized composition of urban solid waste (by weight) for 1986 and projected for the year 2000

Material	1986 (%)	2000 (%)
Paper	36	39
Yard waste	20	19
Plastics	7	9
Metals	9	9
Food waste	9	7
Glass	8	7
Wood	4	4
Other	7	6

Source: A. M. Ujihara and M. Gough, "Managing Ash from Municipal Waste Incinerators," in *Resource for the Future* (Center for Risk Management: 1989).

On-site Disposal

By far the most common on-site disposal method in urban areas is the mechanical grinding of kitchen food waste. Garbage disposal devices are installed in the wastewater pipe system from a kitchen sink, and the garbage is ground and flushed into the sewer system. This effectively reduces the amount of handling and quickly removes food waste, but final disposal is transferred to the sewage treatment plant where solids such as sewage sludge still must be disposed of (9).

Hazardous liquid chemicals may be inadvertently or deliberately disposed of in sewers, requiring treatment plants to handle toxic materials. Illegal dumping in urban sewers has only recently been identified as a potential major problem.

Composting

Composting is a biochemical process in which organic materials decompose to a humuslike material. It is rapid, partial decomposition of moist, solid, organic waste by aerobic organisms. The process is generally carried out in the controlled environment of mechanical digesters (2). Although composting is not common in the United States, it is popular in Europe and Asia, where intense farming creates a demand for the compost (4). A major drawback of composting is the necessity to separate the organic material from the other waste. Therefore, it is economically advantageous only when organic material is collected separately (10). Nevertheless, composting is considered part of integrated waste management, and its importance is expected to grow.

Incineration

Incineration is the reduction of combustible waste to inert residue by burning at high temperatures (900 to 1000°C). These temperatures are sufficient to consume all combustible material, leaving behind only ash and noncombustibles. Incineration ideally reduces the volume of waste that must be disposed of by 75 to 95 percent (9). However, because of maintenance and waste-supply problems, the actual reduction of waste by incineration is closer to 50 percent. As we have already mentioned, this is about the same savings that can be gained from waste reduction and recycling (8). The advantages of incinerating urban waste are twofold:

- Incineration can effectively convert a large volume of combustible waste to a much smaller volume of ash to be disposed of at a landfill.
- Combustible waste can be used to supplement other fuels in generating electrical power.

Burning urban waste is certainly not a clean process. The burning produces air pollution and toxic ash that must be disposed of at landfills. Smokestacks from incinerators may emit nitrogen and sulfur oxides, which are precursors of acid rain, as well as carbon monoxide and heavy metals such as lead, cadmium, and mercury. The smokestacks can be fitted with devices to trap some of the pollutants, but the process of pollution abatement is expensive. Furthermore, the incinerators themselves are expensive and often need government subsidies to be established. One study showed that an investment of $8 billion could construct incinerators capable of burning about 25 percent of the solid waste generated in the United States, whereas a similar investment in recycling and composting facilities could handle as much as 75 percent of the nation's solid urban waste (8).

The economic viability of incinerators depends upon revenue from the sale of energy produced by burning waste. As a result, incinerators need to run at near capacity to remain profitable. With the increase in composting and recycling, the economics are far from certain, because those processes compete directly with incineration. However, it is safe to say that waste reduction and recycling can reduce the volume of waste that must be disposed of at a landfill at least as much as incineration can (8).

Open Dumps

Open dumps are the oldest and most common way of disposing of solid waste. In many cases, open dumps are located wherever land is available, without regard to safety, health hazards, and aesthetic degradation. The waste is often piled as high as equipment allows. In some instances, the refuse is ignited and allowed to burn; in others, it is periodically leveled and compacted (9). In addition to being unsightly, open dumps generally create a health hazard by breeding pests, polluting the air, and often contaminating groundwater and surface water. In the United States, open dumps have given way to the better-planned and managed sanitary landfills, but they are still common in many poor countries of the world.

Sanitary Landfills

A **sanitary landfill** as defined by the American Society of Civil Engineering is a method of solid-waste disposal that functions without creating a nuisance or hazard to public health or safety. Engineering principles are used to confine the waste to the smallest practical area, reduce it to the smallest practical volume, and cover it with a layer of compacted soil or specially designed tarps at the end of each day of operation, or more frequently if necessary. It is this covering of the waste that makes the sanitary landfill sanitary. The cover effectively denies continued access to the waste by insects, rodents, and other animals. It also isolates the refuse from the air, thus minimizing the amount of surface water entering into and gas escaping from the wastes (10).

The sanitary landfill as we know it today emerged in the late 1930s. Two types are used: area landfill on relatively flat sites and depression landfill in natural or artificial gullies or pits. Normally, refuse is deposited, compacted, and covered at the end of each day. The finishing cover (cap) is at least 50 cm of compacted soil (clay) designed to minimize infiltration of surface water (9). Compaction and subsidence can be expected for years following completion of a landfill. Therefore, any subsequent development that cannot accommodate potential subsidence should be avoided.

Potential Hazards One of the most significant potential hazards from a sanitary landfill is groundwater or surface-water pollution. If waste buried in a landfill comes into contact with water percolating down from the surface or with groundwater moving laterally through the refuse, **leachate**—obnoxious, mineralized liquid capable of transporting bacterial pollutants—is produced (11). For example, two landfills dating from the 1930s and 1940s in Long Island, New York, have produced leachate plumes that are several hundred meters wide and have migrated several kilometers from the disposal site. Both the nature and the strength of leachate produced at a disposal site depend on the composition of the waste, the length of time that the infiltrated water is in contact with the refuse, and the amount of water that infiltrates or moves through the waste (9). The concentration of pollutants in landfill leachate is much higher than in raw sewage or slaughterhouse waste. Fortunately, the amount of leachate produced from urban waste disposal is much less than the amount of raw sewage.

Another possible hazard from landfills is uncontrolled production and escape of methane gas, which is generated as organic wastes decompose. For example, gas generated in an Ohio landfill migrated several hundred meters through a sandy soil to a housing area, where one home exploded and several others had to be evacuated. Properly managed, methane gas (if not polluted with toxic materials) is a resource. At new and expanded landfills, methane is often confined by barriers made of plastic liner and clay and collected in specially constructed wells. The technology for managing methane is advancing, and landfills across the country are now producing methane and selling the gas as one way to help reduce costs associated with waste management.

Site Selection Factors controlling the feasibility of sanitary landfills include:

- Topographic relief
- Location of the groundwater table
- Amount of precipitation
- Type of soil and rock
- Location of the disposal zone in the surface-water and groundwater flow system

The best sites are those in which natural conditions ensure reasonable safety in disposal of solid waste. This means that there is little (or acceptable) pollution of ground- or surface waters, and that conditions are safe because of climatic, hydrologic, geologic, or human-induced conditions or combinations of these (12).

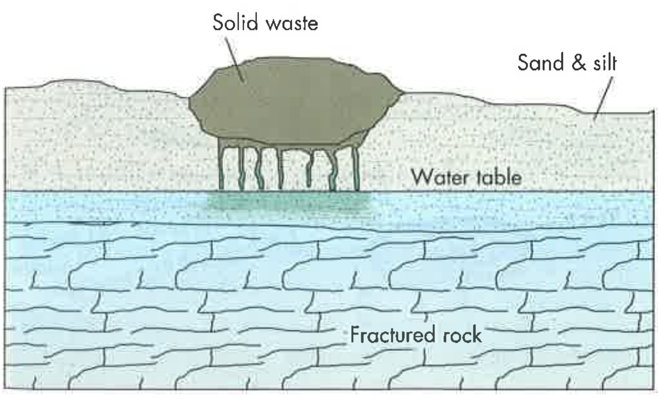
The best sites for landfills are in arid regions. Disposal conditions are relatively safe there because in a dry environment, regardless of whether the burial material is permeable or impermeable, little or no leachate is produced. On the other hand, some leachate will always be produced in a humid environment, so an acceptable level of leachate production must be established to determine the most favorable sites. What is acceptable varies with local water use, local regulations, and the ability of the natural hydrologic system to disperse, dilute, and otherwise degrade the leachate to a harmless state.

The most desirable site in a humid climate is one in which the waste is buried above the water table in clay and silt soils of low hydraulic conductivity. Any leachate produced will remain in the vicinity of the site, where it will be degraded by natural filtering and by exchange of some ions between the clay and the leachate. This holds even if the water table is fairly high, as it often is in humid areas, provided material with low hydraulic conductivity is present (13). For example, if the refuse is buried over a fractured-rock aquifer, as shown in Figure 12.2, the potential for serious pollution is low because the leachate is partly degraded by natural filtering as it moves down to the water table. Furthermore, the dispersion of contaminants is confined to the fracture zones (2). However, if the water table were higher or if the cover material were thinner with a moderate to high hydraulic conductivity, then widespread groundwater pollution of the fractured-rock aquifer might result.

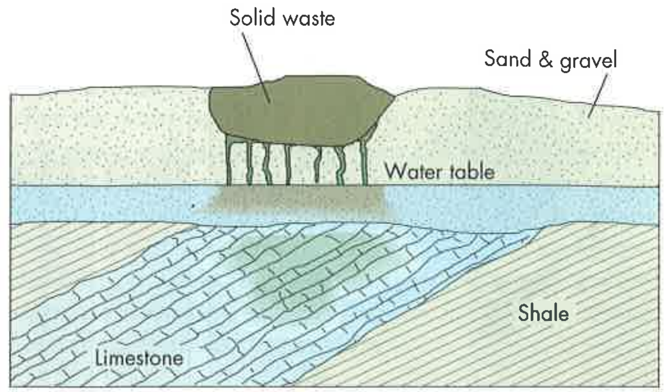
If a landfill site is characterized by an inclined limestone-rock aquifer overlain by sand and gravel with high hydraulic conductivity (Figure 12.3), considerable contamination of the groundwater could result. Leachate moves quickly through the sand and gravel soil and enters the limestone, where open fractures or cavities may transport the pollutants with little degradation other than dispersion and dilution. Of course, if the inclined rock is all shale, with low hydraulic conductivity, little pollution will result.

The following general guidelines (13) should be followed in site selection for sanitary landfills:

- Limestone or highly fractured rock quarries and most sand and gravel pits make poor landfill sites because these earth materials are good aquifers.
- Swampy areas, unless properly drained to prevent disposal into standing water, make poor sites.



▲ **FIGURE 12.2** Waste-disposal site where the refuse is buried above the water table over a fractured rock aquifer. Potential for serious pollution is low because leachate is partially degraded by natural filtering as it moves down to the water table. (*After* W. J. *Schneider.* 1970. U.S. *Geological Survey Circular* 601F.)

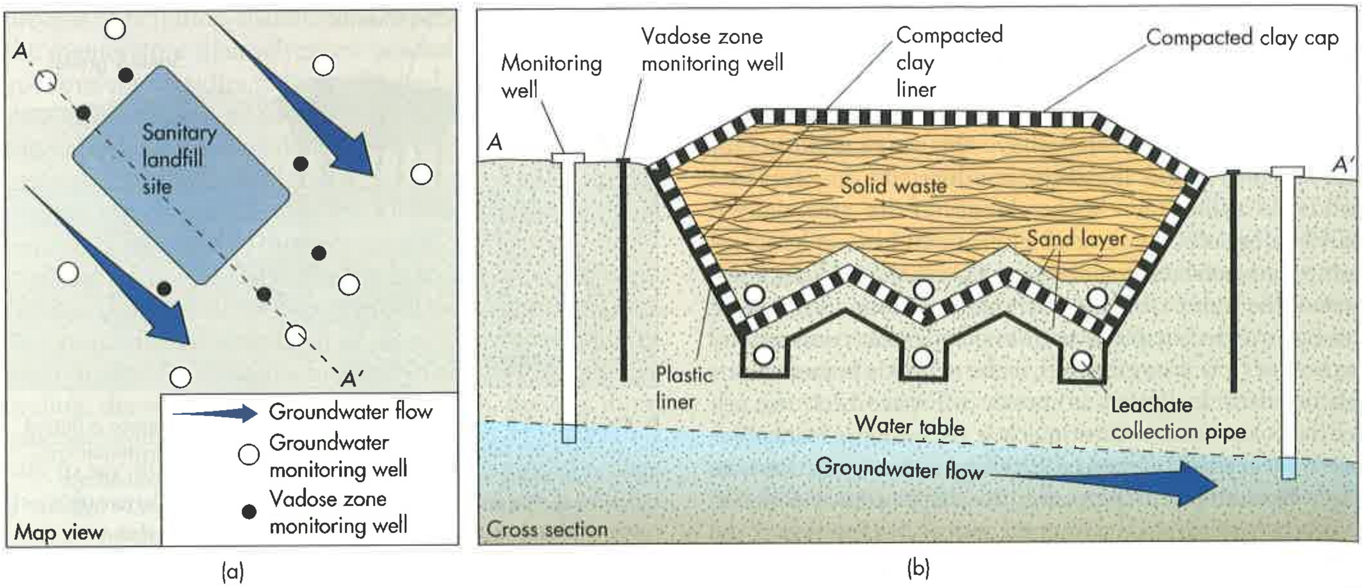


▲ **FIGURE 12.3** Solid-waste disposal site where the waste is buried above the water table in permeable material with high hydraulic conductivity in which leachate can migrate down to fractured bedrock (limestone). The potential for groundwater pollution may be high because of the many open and connected fractures in the rock. (*After* W. J. *Schneider.* 1970. U.S. *Geological Survey Circular* 601F.)

- Floodplains likely to be periodically inundated by surface water should not be considered as acceptable sites for refuse disposal.
- Areas in close proximity to the coast, where trash (transported by wind or surface water) or leachate in ground- or surface water may pollute beaches and coastal marine waters, are undesirable sites.
- Any material with high hydraulic conductivity and with a high water table is probably an unfavorable site.
- In rough topography, the best sites are near the heads of gullies where surface water is at a minimum.
- Clay pits, if kept dry, may provide satisfactory sites.
- Flat areas are favorable sites, provided an adequate layer of material with low hydraulic conductivity, such as clay and silt, is present above any aquifer.

We emphasize that, although these guidelines are useful, they do not preclude the need for a hydrogeological investigation that includes drilling to obtain samples, permeability testing to determine hydraulic conductivity, and other tests to predict the movement of leachate from the buried refuse (10).

Design of Sanitary Landfills Design of modern sanitary landfills is complex and employs the multiple-barrier approach. Barriers include a compacted clay liner, leachate collection systems, and a compacted clay cap. Figure 12.4 is an idealized diagram showing these features, and Figure 12.5 shows such a landfill being constructed. Depending upon local site conditions, landfills may also have additional synthetic liners made of plastics or other materials and a system to collect natural gas that might accumulate. Finally, sanitary landfills must have a system of monitoring wells and other devices to evaluate potential for groundwater pollution. The subject of monitoring is an important one, and we will now address that issue in greater detail.



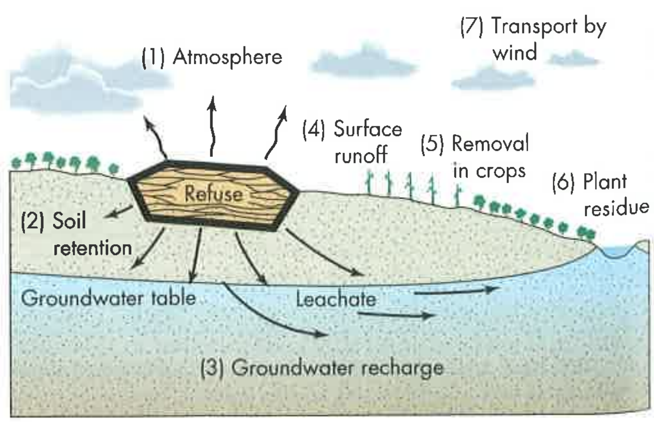
▲ **FIGURE 12.4** Idealized diagrams showing map view (a) and cross section (b) of a landfill with a double liner of clay and plastic and a leachate collection system.

Monitoring Sanitary Landfills Once a site is chosen for a sanitary landfill, **monitoring** the movement of groundwater should begin before filling commences. After the operation starts, continued monitoring of the movement of leachate and gases should be continued as long as there is any possibility of pollution. This is particularly important after the site is completely filled and the permanent cover material is in place, because a certain amount of settlement always occurs after a landfill is completed. If small depressions form as a result of settlement, surface water may collect, infiltrate the fill material, and produce leachate. Therefore, monitoring and proper maintenance of an abandoned landfill will reduce its pollution potential (10).

▲ **FIGURE 12.5** Rock Creek municipal landfill, Calaveras County, California, under construction. The light brown slope in the central part of the photograph is a compacted clay liner. The sinuous ditch is part of the leachate collection system, and the square pond in the upper part of the photograph is the leachate evaporation pond under construction. (*Courtesy of John Kramer*)

Hazardous waste pollutants from a solid-waste disposal site can enter the environment (14) by as many as seven paths (Figure 12.6):

- Gases in the soil and fill, such as methane, ammonia, hydrogen sulfide, and nitrogen, may volatilize and enter the atmosphere.
- Heavy metals such as lead, chromium, and iron are retained in the soil.
- Soluble substances, such as chloride, nitrate, and sulfate, readily pass through fill and soil to the groundwater system.
- If there is surface runoff, the runoff may pick up leachate and transport it into the surface-water network.
- Some crops and cover plants growing in the disposal area may selectively take up heavy metals and other toxic substances to be passed up the food chain as people and animals ingest them.



▲ **FIGURE 12.6** Several ways that hazardous waste pollutants from a solid-waste disposal site may enter the environment.

- If the plant residue left in the field contains toxic substances, it will return these materials to the environment through soil-forming and runoff processes.
- Paper, plastics, and other undesirable waste may be transported off-site by wind.

A thorough monitoring program would consider the seven possible paths by which pollutants enter the environment. Potential atmospheric pollution by gas from landfills is a growing concern, and a thorough monitoring program would include periodic analysis of air samples to detect toxic gas before it becomes a serious problem. Many landfills have no surface runoff; therefore, monitoring of on-site surface water is not necessary. However, if surface runoff does occur, thorough monitoring is required, and monitoring of nearby down-gradient streams, rivers, and lakes is necessary. Monitoring of soil and plants should include periodic chemical analysis at prescribed sampling locations.

If permeable water-bearing zones exist in the soil or bedrock below a sanitary landfill, monitoring wells (see Figure 12.4) are needed for frequent sampling of groundwater quality and monitoring of the movement of any leachate that has entered the groundwater (14). Even if the landfill is in relatively impermeable soil overlying dense permeable rock, minimal monitoring of groundwater quality through monitoring wells is still needed. In this case, leachate and groundwater movement may be less than 30 cm/yr. Water in the unsaturated (vadose) zone above the water table must also be monitored to identify potential pollution problems before they contaminate groundwater resources, where correction is very expensive. Waste transported off-site by wind is monitored, collected as necessary, and disposed of.

Sanitary Landfills and Federal Legislation Federal legislation regulates new landfills strictly. The intent of the legislation is to strengthen and standardize the design, operation, and monitoring of sanitary landfills. Those landfills that are unable to comply with the regulations might be shut down. Specific regulations include:

- Landfills may not be sited in certain areas, including floodplains, wetlands, unstable land, and earthquake fault zones. They may not be sited near airports because birds attracted to landfill sites present a hazard to aircraft.
- Landfill construction must include liners and a leachate collection system.
- Operators of landfills must monitor groundwater for specific toxic chemicals.
- Operators of landfills must meet financial assurance criteria. This may be met through posting bonds or insurance to ensure that monitoring of the landfill continues for 30 years after closure.

Under the law, states may opt to obtain approval of a solid-waste-management plan from the Environmental Protection Agency (EPA). A state that opts not to seek approval of its own plan must comply rigidly with the federal standards. Those states with EPA approval are allowed more flexibility. For example, alternative materials for the daily cover over the waste are allowed, as are different groundwater protection standards, documentation of groundwater monitoring, and financial assurance mechanisms. Furthermore, under certain circumstances, expansion of landfills in wetlands and fault zones may be allowed. Given the additional flexibility, it would appear advantageous for states to develop waste-management plans for their landfill facilities and have them approved by the EPA.

12.4 Hazardous Waste Management

The creation of new chemical compounds has proliferated tremendously in recent years. In the United States alone, approximately 1000 new chemicals are marketed annually and about 50,000 chemicals are currently on the market. Although many of these chemicals have been beneficial to people, several tens of thousands of them are classified as definitely or potentially hazardous to people's health (Table 12.2).

The United States is currently generating more than 150 million metric tons of **hazardous waste** each year. In the recent past, as much as half of the total volume of wastes was being indiscriminately dumped (15). This is now illegal, and we do not know how much illegal dumping is going

Table 12.2 Examples of products we use and potentially hazardous waste they generate

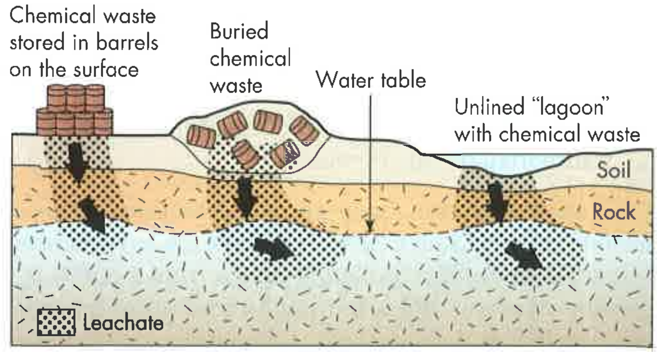
Products We Use	Potential Hazardous Waste
Plastics	Organic chlorine compounds
Pesticides	Organic chlorine compounds, organic phosphate compounds
Medicines	Organic solvents and residues, heavy metals (mercury and zinc, for example)
Paints	Heavy metals, pigments, solvents, organic residues
Oil, gasoline, and other petroleum products	Oil, phenols and other organic compounds, heavy metals, ammonia salts, acids, caustics
Metals	Heavy metals, fluorides, cyanides, acid and alkaline cleaners, solvents, pigments, abrasives, plating salts, oils, phenols
Leather	Heavy metals, organic solvents
Textiles	Heavy metals, dyes, organic chlorine compounds, solvents

Source: U.S. Environmental Protection Agency. SW-826, 1980.

on—certainly there is some, particularly in urban sewer systems. Past uncontrolled dumping of chemical waste has polluted soil and groundwater resources in several ways (Figure 12.7).

- Barrels in which chemical waste is stored, either on the surface or buried at a disposal site, eventually corroded and leaked, polluting the surface, soil, and groundwater.
- Liquid chemical wastes dumped in unlined lagoons (shallow ponds for collection of wastes) percolated through the soil and rock and eventually reached the groundwater table.
- Liquid chemical waste has been illegally dumped in deserted fields or along dirt roads.

Old abandoned hazardous landfills and other sites for the disposal of chemical waste have caused serious problems that have been very difficult to correct. A site near Elizabeth, New Jersey, provides an example of the casual dumping of chemicals that was once so widespread. At that site, the remains of about 50,000 charred drums were left standing next to a brick and steel building once owned by a now-



▲ **FIGURE 12.7** Ways that uncontrolled dumping of chemical waste may pollute soil and/or groundwater.

CASE HISTORY Love Canal

In 1976, in a residential area near Niagara Falls, New York, trees and gardens began to die. Children found the rubber on their tennis shoes and on their bicycle tires disintegrating. Dogs sniffing in a landfill area developed sores that would not heal. Puddles of toxic, noxious substances began to ooze to the soil surface; a swimming pool popped its foundations and was found to be floating on a bath of chemicals.

A study revealed that the residential area had been built on the site of a chemical dump. The area was excavated in 1892 by William T. Love as part of a canal between the upper and lower reaches of the Niagara River. The idea was to produce inexpensive hydroelectric power for a new urban-industrial center. When that plan failed, because alternating current was discovered and industry could be located far from the source of power, the canal was unused (except for recreation such as swimming and ice skating) for decades. It seemed a convenient place to dump wastes. From the 1940s to the 1950s, more than 80 different substances from a chemical company were dumped there. More than 20,000 tons of chemical waste, along with urban waste from the city of Niagara Falls, was disposed of in the canal (17). Finally, in 1953, the company dumping the chemicals donated the land to the city of Niagara Falls for one dollar. Eventually, several hundred homes adjacent to an elementary school were built near the site (Figure 12.B). Heavy rainfall and snowfall during the winter of 1976–77 set off the events that made Love Canal a household word.

A study of the site identified a number of substances present there—including benzene, dioxin, dichlorethylene, and chloroform—that were suspected of being carcinogens. Although officials readily admitted that very little was known about the impact of these chemicals and others at the site, there was grave concern for the people living in the area. During the next few years there were allegedly higher-than-average rates of miscarriages, blood and liver abnormalities, birth defects, and chromosome damage. However, a study by the New York State health authorities suggested that no chemically caused health effects had been absolutely established (18–20).

The cleanup of the Love Canal is an important demonstration of state-of-the-art technology in hazardous waste treatment. The objective is to contain and stop the migration of wastes through the groundwater flow system and to remove and treat dioxin-contaminated soil and sediment from stream beds and storm sewers (17). The method being used to minimize further production of contaminated water is to cover the dump site and adjacent contaminated area with a 1-m-thick layer of compacted clay and a polyethylene plastic cover to reduce infiltration of surface water. Lateral movement of water is inhibited from entering or escaping the site by specially designed perforated-tile drain pipe. These procedures will greatly reduce subsurface seepage of water through the site, and the water that does seep out will be collected and treated (18–20).

The homes adjacent to Love Canal were abandoned and bought by the government. Approximately 200 of the homes had to be destroyed. During the 1980s, approximately $175 million was spent for cleanup and relocation at Love Canal. The EPA now considers some of the area clean, and some of the remaining homes were scheduled to be sold in the early 1990s. Because the price of the homes is approximately 20 percent below the market of other areas in Niagara Falls, they are expected to sell. Sales contracts for four homes were approved in late 1990, this despite the reputation of the area and the adverse publicity it attracted. In early 1995 the maintenance and operation of the area was transferred from New York State to a consulting company, which will continue long-term sampling and monitoring (17,21).

What went wrong in Love Canal to produce a suburban ghost town? How can we avoid such disasters in the future? The real tragedy of Love Canal is that it is probably not an isolated incident. There are many hidden "Love Canals" across the country, "time bombs" waiting to explode (18,19).

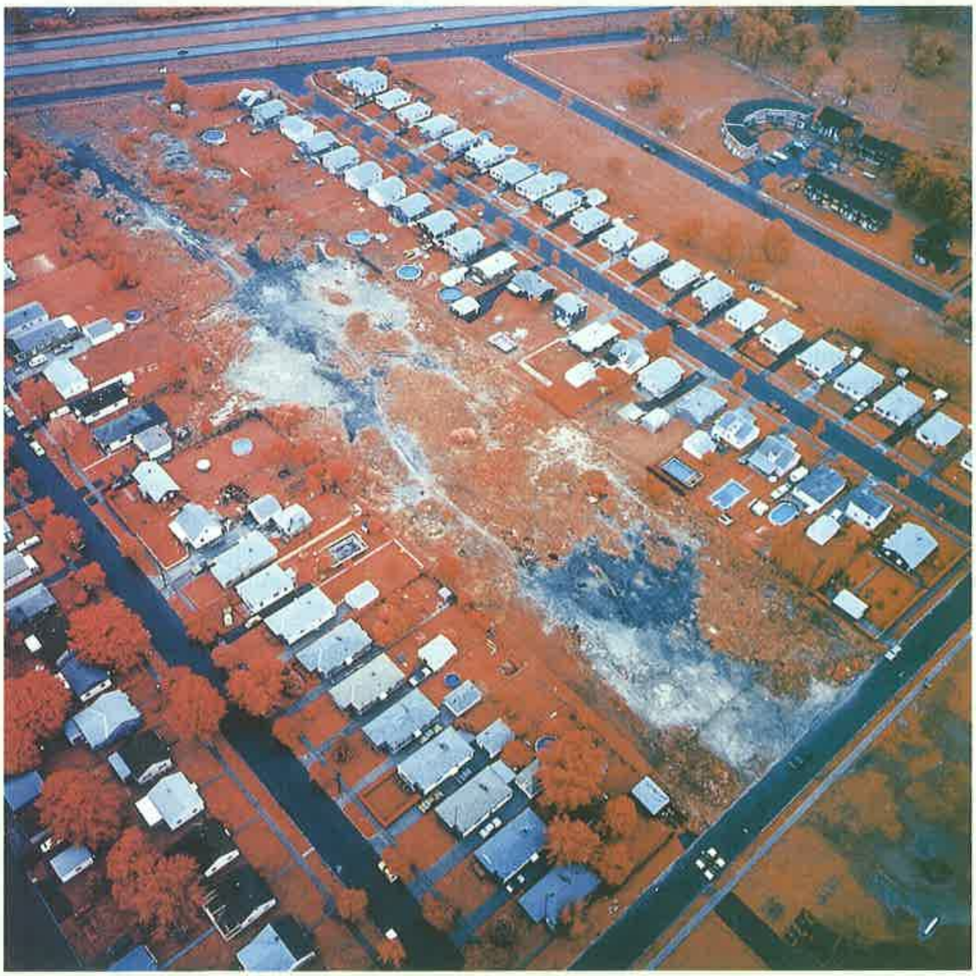
bankrupt chemical corporation. The drums and other containers, which were stacked four high in places, had been corroding for nearly 10 years. Many of them had been improperly labeled or burned so badly that the nature of the chemicals could not be determined from outside markings. Leaking barrels had allowed unknown quantities of waste to seep into an adjacent stream that eventually flows into the Hudson River.

The New Jersey site was so polluted that cleanup efforts were very difficult. Identification of some of the materials at the site showed that there were two containers of nitroglycerine, numerous barrels of biological agents, cylinders of phosgene and gaseous phosphorus (which are extremely volatile and ignite when exposed to air), as well as a variety of heavy metals, pesticides, and solvents, some of which are very toxic. It took months of work with a large crew of people to remove most of the material from the New Jersey site. Unfortunately, it is difficult to know if all the waste has been removed; additional material may be buried at other sites that are more difficult to locate (16).

There are many such stories of terrible problems resulting from chemical waste disposal, but the best known comes from the Love Canal near Niagara Falls, New York (see *Case History: Love Canal*).

Responsible Management

In 1976 the U.S. government moved to begin the management of hazardous waste with the passage of the Resource Conservation and Recovery Act (RCRA), which is intended to provide for "cradle-to-grave" control of hazardous waste. At the heart of the act is the identification of hazardous wastes and their life cycles. Regulations call for stringent record keeping and reporting to verify that wastes do not present a public nuisance or a public health problem. The act also identifies hazardous wastes in terms of several categories:



▲ **FIGURE 12.B** This is an aerial infrared photograph of the Love Canal area in New York. Healthy vegetation is bright red. This portion of Love Canal runs from the upper left corner to the lower right. It appears as a scar on the landscape. Buried chemical waste seeped to the surface to cause numerous environmental problems and concern here. The site became a household name for toxic waste. (*New York State Department of Environmental Conservation*)

- Materials that are highly toxic to people and other living things
- Wastes that may explode or ignite when exposed to air
- Wastes that are extremely corrosive
- Wastes that are otherwise unstable

Recognizing that a great number of waste disposal sites presented hazards, Congress in 1980 passed the Comprehensive Environmental Response Compensation and Liability Act (CERCLA), which established a revolving fund (popularly called the *Superfund*) to clean up several hundred of the worst abandoned hazardous chemical-waste-disposal sites known to exist around the country. The EPA developed a list of Superfund sites (National Priorities List). Figure 12.8 summarizes environmental impact statistics and lists some of the pollutants encountered at Superfund sites.

Although the Superfund has experienced significant management problems and is far behind schedule, a number of sites have been treated. Unfortunately, the funds available are not sufficient to pay for decontamination of all the targeted areas. That would cost many times more, perhaps as much as $100 billion. Furthermore, because of concern that the present technology is not sufficiently advanced to treat all the abandoned waste-disposal sites, the strategy may be simply to confine the waste to those areas until better disposal methods are developed. It seems apparent that the danger of abandoned disposal sites is likely to persist for some time to come.

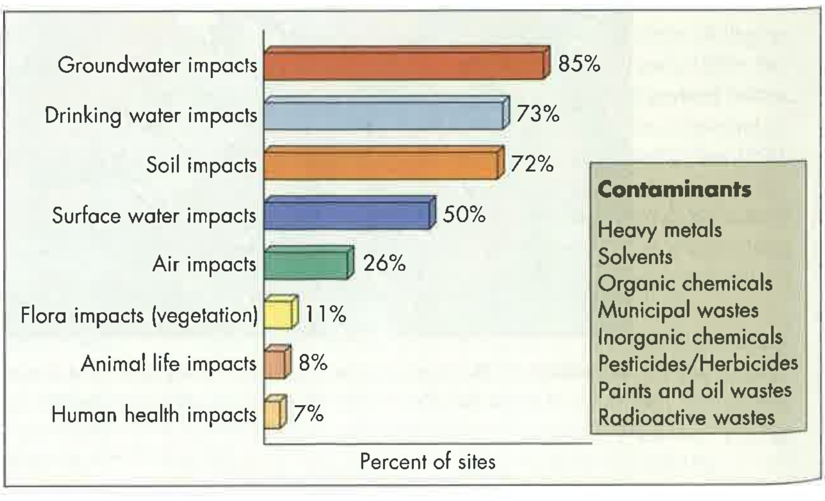
The federal legislation also changed the way the real estate industry did business. The act has tough liability provisions, and property owners could be liable for costly cleanup of hazardous waste found on their property (even if they did not cause the problem). Banks and other lending institutions could be liable for release of hazardous materials on their property by their tenants. In 1986 the Superfund Amendment and Reauthorization Act (SARA) provided a possible defense for real estate purchasers against liability provided they completed an environmental audit prior to purchase. The audit is a study of past land use at the site (determined by analyzing old maps and aerial photographs, and may involve drilling and sampling of soil and groundwater) to determine if pollutants are present. Such audits now are done on a routine basis prior to purchase of property for development.

The SARA legislation required that certain industries report all releases of hazardous materials into the environment. The list of companies releasing such substances became public and was known as the "Toxic 500 list." Unwanted publicity to companies on the list is thought to have resulted in better and safer handling of hazardous waste by firms that formerly were identified as polluters of the environment. No owner wants his or her company to be the No. 1 (or even the twenty-fifth or hundredth) most serious polluter among U.S. firms (22).

Management of hazardous chemical waste includes several options: recycling, on-site processing to recover byproducts with commercial value, microbial breakdown, chemical stabilization, high-temperature decomposition, incineration, and disposal by secure landfill or deep-well injection. A number of technological advances have been made in the field of toxic waste management, and as land disposal becomes more and more expensive, the trend toward on-site treatment that has recently started is likely to continue. However, on-site treatment will not eliminate all hazardous chemical waste; disposal will remain necessary. Table 12.3 compares hazardous waste reduction technology in terms of treatment and disposal. Notice that all of the technologies available will cause some environmental disruption. No one simple solution exists for all waste-management issues.

Secure Landfill

The basic idea of the **secure landfill** is to confine the waste to a particular location, control the leachate that drains from the waste, collect and treat the leachate, and detect possible leaks. Figure 12.9 demonstrates these procedures. A dike and liners (made of clay and impervious material such as plastic) confine the waste, and a system of internal drains concentrates the leachate in a collection basin from which it is pumped out and transported to a wastewater treatment



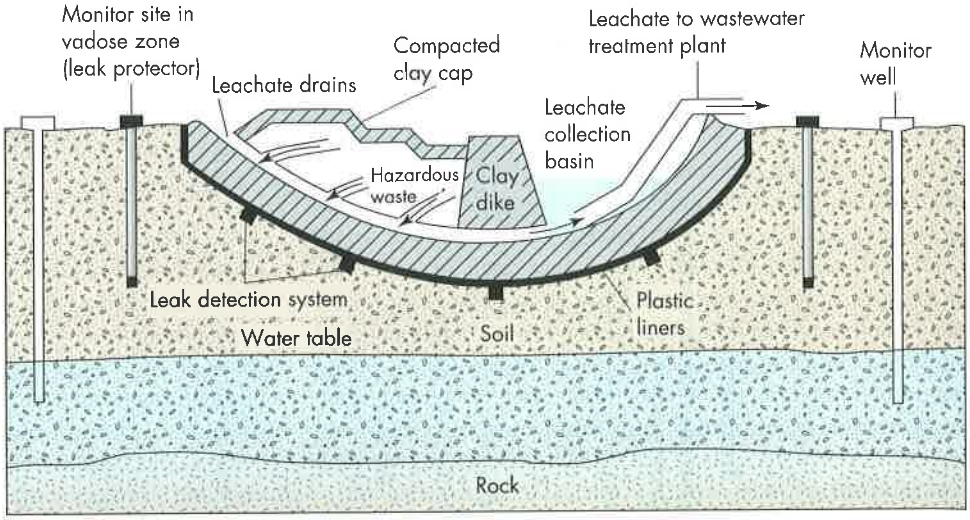
▶ **FIGURE 12.8** Environmental impacts at Superfund sites (National Priorities List) and some of the pollutants encountered at the sites. (*Source:* National Priorities List and U.S. Water News, *November* 1993)

Table 12.3 Comparison of hazardous waste reduction technologies

	Disposal		Treatment		
	Landfills and Impoundments	**Injection Wells**	**Incineration and Other Thermal Destruction**	**Emerging High-Temperature Decomposition[a]**	**Chemical Stabilization**
Effectiveness: How well it contains or destroys hazardous characteristics	Low for volatiles, questionable for liquids; based on lab and field tests	High, based on theory, but limited field data available	High, based on field data, except little data on specific constituents	Very high; commercial scale tests	High for many metals; based on lab tests
Reliability issues	Siting, construction, and operation Uncertainties: long-term integrity of cells and cover, linear life less than life of toxic waste	Site history and geology; well depth, construction, and operation	Monitoring uncertainties with respect to high degree of DRE: surrogate measures, PICs, incinerability[c]	Limited experience Mobile units, on-site treatment avoids hauling risks Operational simplicity	Some inorganics still soluble Uncertain leachate test, surrogate for weathering
Environment media most affected	Surface and ground water	Surface and ground water	Air	Air	Groundwater
Least compatible wastes[b]	Liner reactive, highly toxic, mobile, persistent, and bioaccumulative	Reactive; corrosive; highly toxic, mobile, and persistent	Highly toxic and refractory organics, high heavy metals concentration	Some inorganics	Organics
Relative costs: Low, Moderate, High	L-M	L	M-H	M-H	M
Resource recovery potential	None	None	Energy and some acids	Energy and some metals	Possible building material

[a]Molten salt, high-temperature fluid well, and plasma arc treatments.
[b]Wastes for which this method may be less effective for reducing exposure, relative to other technologies.
[c]DRE = destruction and removal efficiency. PIC = product of incomplete combustion.

Source: Council on Environmental Quality, 1983.



▶ **FIGURE 12.9** A secure landfill for hazardous chemical waste. The impervious liners and systems of drains are an integral part of the system to ensure that leachate does not escape from the disposal site. Monitoring in the vadose zone is important and involves periodic collection of soil water with a suction device.

plant. Designs of new facilities today must include multiple barriers consisting of several impermeable layers and filters as well as impervious covers. The function of impervious liners is to ensure that the leachate does not contaminate soil and, in particular, groundwater resources. However, this type of waste-disposal procedure must have several monitoring wells to alert personnel if and when leachate migrates out of the system possibly to contaminate nearby water resources.

It has been argued that there is no such thing as a really secure landfill, implying that all landfills leak to some extent. This is probably true; impervious plastic liners, filters, and clay layers can fail, even with several backups, and drains can become clogged, causing overflow. Yet landfills that are carefully sited and engineered can minimize problems. Preferable sites are those with good natural barriers, such as thick clay-silt deposits, an arid climate, or a deep water table that minimizes migration of leachate. Nevertheless, land disposal should be used only for specific chemicals suitable for the method.

Land Application

Application of waste materials to the surface-soil horizon is referred to as **land application,** *land spreading,* or *land farming.* Land application may be a desirable treatment method for certain biodegradable industrial wastes, including petroleum oily waste and certain organic chemical-plant waste. A good indicator of the usefulness of land application for disposal of a particular waste is the waste's **biopersistence** (the measure of how long a material remains in the biosphere). The greater or longer the biopersistence, the less suitable the waste is for land-application procedures. Land application is not an effective treatment or disposal method for inorganic substances, such as salts and heavy metals (23).

Land application of biodegradable waste works because, when such materials are added to the soil, they are attacked by microorganisms (bacteria, molds, yeast, and other organisms) that decompose the waste material. The soil may thus be thought of as a microbial farm that constantly recycles matter by breaking it down into more fundamental forms useful to other living things in the soil. Because the upper soil zone contains the largest microbial populations, land application is restricted to the uppermost 15 to 20 cm of the soil profile (23). As with other types of land-disposal technology, the vadose zone and groundwater near the site must be carefully monitored to ensure the disposal system is working as planned and not polluting water resources.

Surface Impoundment

Excavations and natural topographic depressions have been used to hold hazardous liquid waste. These **surface impoundments** are primarily formed of soil or other surficial materials, but they may be lined with manufactured materials such as plastic. The impoundment is designed to hold the waste; examples include aeration pits and lagoons at hazardous-waste facilities. Surface impoundments have been criticized because they are especially prone to seepage, resulting in pollution of soil and groundwaters. Evaporation from surface impoundments can also produce an air-pollution problem. For these reasons, hazardous-waste facilities have been prohibited from receiving noncontainerized liquid waste.

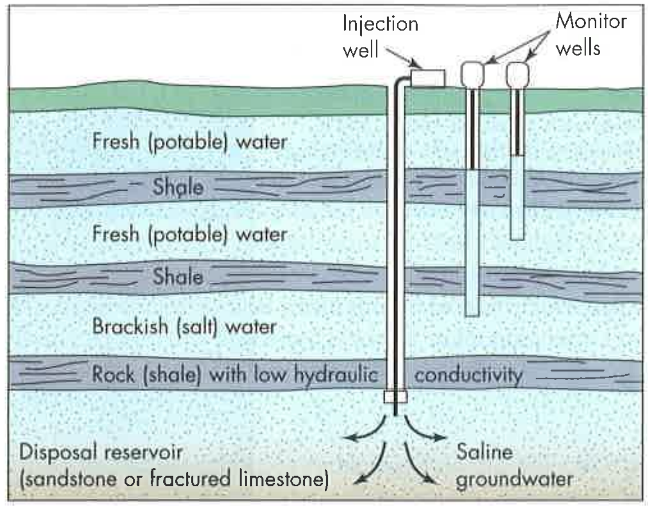
Deep-well Disposal

Another method of hazardous-waste disposal is by injection into deep wells. The term *deep* refers to rock (not soil) that is below and completely isolated from all freshwater aquifers, thereby assuring that injection of waste will not contaminate or pollute existing or potential water supplies. This generally means that the waste is injected into a permeable rock layer several hundred to several thousand meters below the surface in geologic basins confined above by relatively impervious, fracture-resistant rock, such as shale or salt deposits (4).

Deep-well injection of oil-field brine (salt water) has been important in controlling water pollution in oil fields for many years, and huge quantities of liquid waste (brine) pumped up with oil have been injected back into the rock.

Today, several billion liters per day are pumped into subsurface rocks (24). In recent years, the technique has been used more commonly for permanent storage of industrial waste deep underground. A typical well is about 700 m deep, and wastes are pumped into a 60-m-thick zone at a rate of about 400 liters per minute (25).

Deep-well disposal of industrial wastes should not be viewed as a quick and easy solution to industrial-waste problems (26). Even where geologic conditions are favorable for deep-well disposal, natural restrictions include the limited number of suitable sites and the limited space within these sites for disposal of waste. Possible injection zones in porous rock are usually already filled with natural fluids, mostly brackish or briny water. Therefore, to pump in waste, some of the natural fluid must be displaced by compression (even slight compression of the natural fluids in a large volume of permeable rock can provide considerable storage space) and by slight expansion of the reservoir rock as the waste is being injected (25).



▲ **FIGURE 12.10** A deep-well injection system. The disposal reservoir is a sandstone or fractured limestone capped by impermeable rock and isolated from all fresh water. Monitor wells are a safety precaution to ensure that there is no undesirable migration of the liquid waste into freshwater aquifers above the injection zone.

Problems with Deep-well Disposal Several problems associated with disposal of liquid waste in deep wells have been reported (25,26). Perhaps the best known are the earthquakes that were caused by injecting waste from the Rocky Mountain Arsenal near Denver, Colorado (see Chapter 7). These earthquakes occurred between 1962 and 1965. The injection zone was fractured gneiss at a depth of 3.6 km, and the increased fluid pressure evidently initiated movement along the fractures. This is not a unique case. Similar initiations of earthquakes have been reported in oil fields in western Colorado, Texas, and Utah (25). Similar activation of faults in southern California caused by injection of fluids into the Inglewood oil field for secondary recovery is thought to have contributed to the failure of the Baldwin Hills Reservoir (see Chapter 2).

Feasibility and General Site Considerations The feasibility of deep-well injection as the best solution to a disposal problem depends on four factors: the geologic and engineering suitability of the proposed site; the volume and the physical and chemical properties of the waste; economics; and legal considerations (27). The geologic considerations for disposal wells are twofold (27):

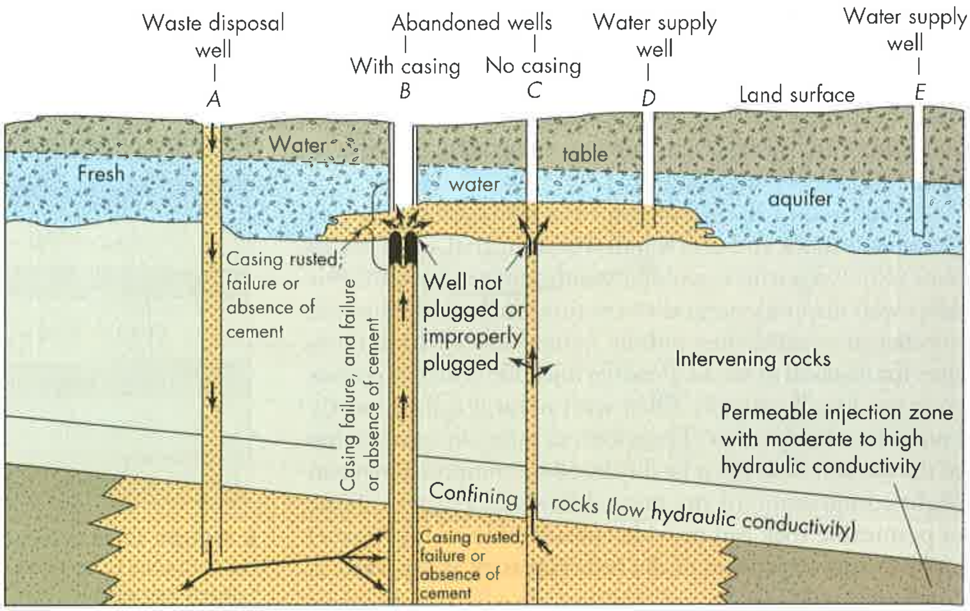
- The injection zone must have sufficient porosity, thickness, hydraulic conductivity, and size to ensure safe injection. Sandstone and fractured limestone are the commonly used reservoir rocks (26).
- The injection zone must be below the level of freshwater circulation and confined by a relatively impermeable rock with low hydraulic conductivity, such as shale or salt, as shown in Figure 12.10.

Optimal use of limited underground storage space is achieved if deep-well injection is used only when more satisfactory methods of waste disposal are not available and when the volume of injected wastes is minimized by good waste management (27). Optimal use includes thorough evaluation of the physical and chemical properties of the waste to ensure that it will not adversely affect the ability of the rock reservoir to accept it. Adverse effects can be minimized in some instances by preinjection treatment of the waste to enhance compatibility with the reservoir rock and the natural fluids present there. It is also advisable to take advantage of natural buffers. For example, if the waste is acidic, use of limestone as a reservoir rock may be advantageous because the acid waste tends to increase the reservoir's permeability and hydraulic conductivity by chemically attacking and enlarging natural fractures, thus allowing more waste to be injected. Care must be taken, however, because certain acids, such as sulfuric acid, may react to plug the porosity of limestone.

Construction and operating costs often determine the feasibility of deep-well injection as the preferred method of waste treatment. Important geologic factors pertaining to construction costs are the depth of the well and the ease with which drilling proceeds. Operating costs depend on the hydraulic conductivity, porosity, and thickness of the injection zone, and the fluid pressure in the reservoir. All of these are important in determining the rate at which the reservoir will accept liquid waste (27).

Consideration of legal aspects of deep-well disposal suggests that existing laws, regulations, and policies are probably adequate. Injection well use in the United States is regulated by federal laws, and certain hazardous wastes are prohibited from being injected underground (22).

Monitoring Disposal Wells An essential part of any disposal system is monitoring. It is very important to know exactly where the wastes are going, how stable they are, and how fast they are migrating. It is especially important in deep-well disposal where toxic or otherwise hazardous materials are involved.

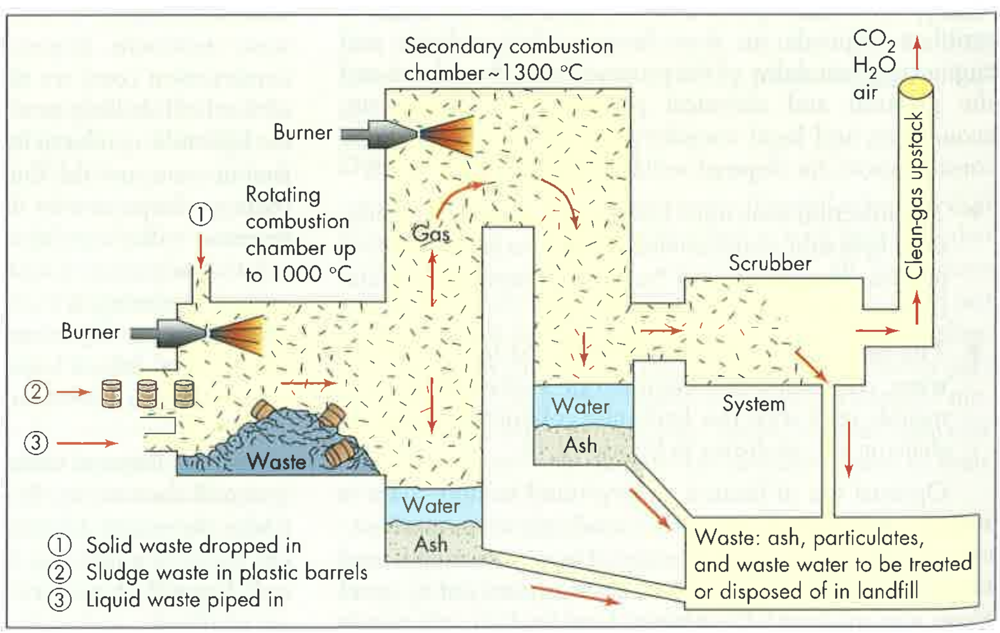


▶ **FIGURE 12.11** How liquid waste might enter a freshwater aquifer through abandoned wells. This diagram illustrates why the location of all abandoned wells should be known, and it emphasizes the necessity of monitoring wells. (*After Irwin and Morton*. 1965. U.S. *Geological Survey Circular* 630.)

Effective monitoring requires that the geology be precisely defined and mapped before initiating the disposal program. Especially important is locating all freshwater-bearing zones and old or abandoned oil or gas wells that might allow the waste to migrate up to freshwater aquifers or to the surface (Figure 12.11). A system of deep monitoring wells drilled into the disposal reservoir in the vicinity of the well can monitor the movement of waste, and shallow monitoring wells drilled into freshwater zones can monitor the water quality to identify quickly any upward migration of the waste.

Incineration of Hazardous Chemical Waste

Hazardous waste may be destroyed through high-temperature incineration. Incineration is considered to be a waste treatment rather than a disposal method because the hazardous waste is not disposed of directly; rather, it undergoes a treatment (incineration) that produces an ash residue to be disposed of in a landfill (23). The technology used in incineration and other high-temperature decomposition or destruction is changing rapidly. Figure 12.12 diagrams one type of high-temperature incineration system that may be used to burn toxic waste. Waste—as liquid, solid, or sludge—enters the rotating combustion chamber, where it is rolled and burned. Ash from this burning process is collected in a water tank, and the remaining gaseous materials move into a secondary combustion chamber, where the process is repeated. Remaining gas and particulates move through a scrubber system that eliminates particulates and acid-forming components. Carbon dioxide, water, and air then are emitted from the stack. As shown in Figure 12.12, ash particulates and wastewater are produced at various parts



▶ **FIGURE 12.12** High-temperature incinerator system to burn toxic waste.

of the incineration process; these must be either treated or disposed of in a landfill.

More advanced types of incineration and thermal decomposition of waste are being developed. One of these utilizes a molten salt bed that should be useful in destroying certain organic materials. Other incineration techniques include liquid-injection incineration on land or sea, fluidized-bed systems, and multiple-hearth furnaces. Which incineration method is used for a particular waste depends upon the nature and composition of the waste and the temperature necessary to destroy the hazardous components. For example, the generalized incineration system shown in Figure 12.12 could be used to destroy PCBs.

Alternatives to Land Disposal

Direct land disposal of hazardous waste is often not the best initial alternative. Even with extensive safeguards and state-of-the-art designs, land-disposal alternatives cannot guarantee that the waste is contained and will not cause environmental disruption in the future. This holds true for all land-disposal facilities, including landfill, surface impoundments, land application, and injection wells. Pollution of air, land, surface water, and groundwater may result from failure of a land-disposal site to contain hazardous waste. Groundwater pollution is perhaps the most significant result of such failure, because it provides a convenient route for pollutants to reach humans and other living things. Figure 12.13 shows some of the paths that pollutants may take from land-disposal sites to contaminate the environment. These paths include:

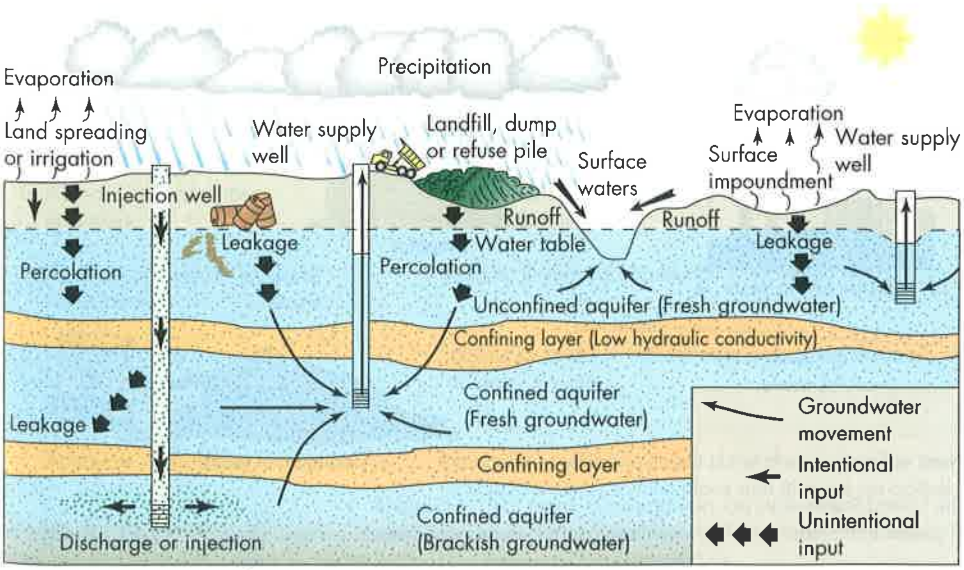
- Improper landfill procedures that eventually produce leakage and runoff to surface water or groundwater
- Seepage, runoff, or air emissions from unlined lagoons
- Percolation and seepage resulting from surface application of waste to soils
- Leaks in pipes or other equipment associated with deep-well injection
- Leaks from buried drums, tanks, or other containers

It has been argued that alternatives to land disposal are not being utilized to their full potential. That is, the volume of waste could be reduced and the remaining waste could be recycled or treated prior to land disposal of the residues of the treatment processes. The philosophy of handling hazardous chemical waste should be multifaceted and should include such processes as source reduction, recycling and resource recovery, and treatment; in other words, materials management (28).

Source Reduction Source reduction has the objective of reducing the amount of hazardous waste generated by manufacturing or other processes. For example, changes in the chemical processes, equipment, raw materials, or maintenance measures employed may be successfully utilized to reduce either the amount or the toxicity of the hazardous waste produced (28).

Recycling and Resource Recovery Hazardous chemical waste may contain materials that can be successfully recovered for future use. For example, acids and solvents collect contaminants when they are used in manufacturing processes. These acids and solvents can be processed to remove the contaminants and can then be reused in the same or different manufacturing processes (28).

Treatment Hazardous chemical waste can be treated by a variety of processes to change the physical or chemical composition of the waste in such a way as to reduce its toxic or hazardous characteristics. Examples include neutralizing acids, precipitation of heavy metals, and oxidation to break up hazardous chemical compounds. Incineration, as we have pointed out, is also a type of waste treatment.



◀ **FIGURE 12.13** Examples of how land disposal/treatment methods of managing hazardous wastes may contaminate the environment. (*Modified after* C. B. Cox. 1985. The buried threat. *No.* 115-5. *Sacramento, CA: California Senate Office of Research.*)

The advantages of source reduction, recycling, and treatment include:

- The waste that must be later disposed of is reduced to a much smaller volume, which produces less stress on the dwindling number of acceptable landfill sites.
- Treatment of wastes may make them less toxic and therefore less likely to cause problems in landfills.
- Useful chemicals may be reclaimed and reused.

12.5 Radioactive Waste Management

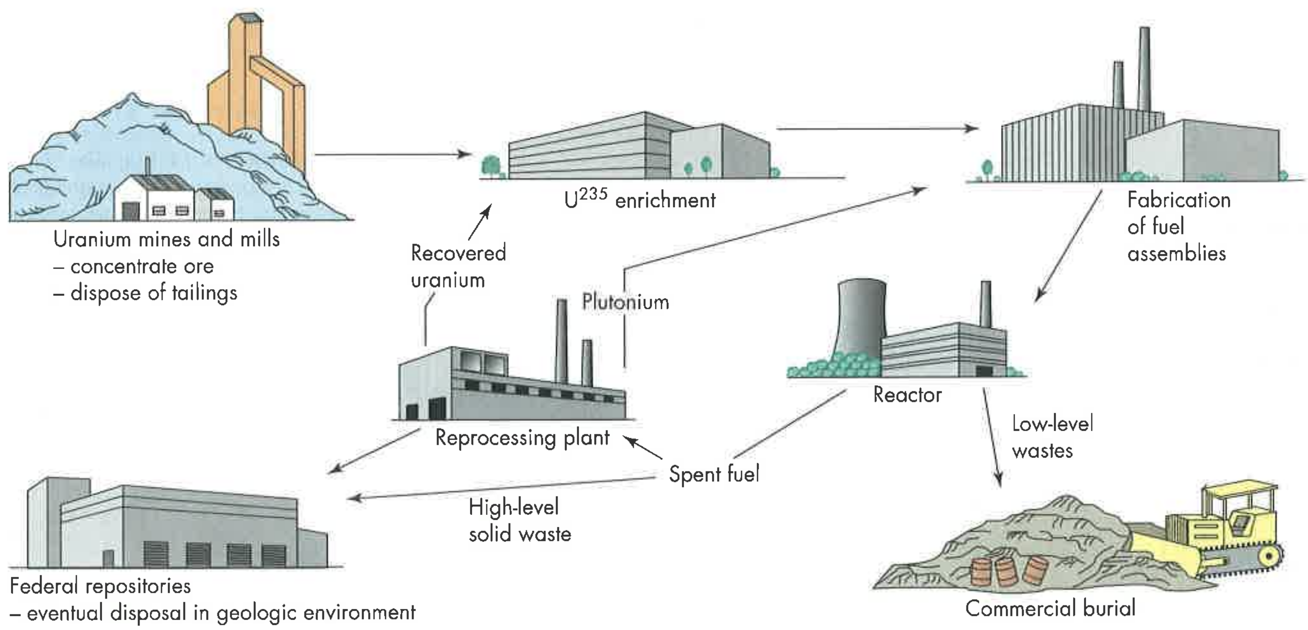
Radioactive wastes are by-products that must be expected as electricity is produced from nuclear reactors or weapons are manufactured from plutonium. Considering waste-disposal procedures, radioactive waste may be grouped into two general categories: low-level waste and high-level waste. In addition, the tailings (materials that are removed by mining activity but are not processed and remain at the site) from uranium mines and mills must also be considered very hazardous (Figure 12.14). In the western United States, more than 20 million tons of abandoned tailings will produce radiation for at least 100,000 years.

Disposal of Low-level Radioactive Wastes

Low-level radioactive wastes are materials containing only small amounts of radioactive substances. These low-level wastes include a wide variety of items such as residuals or solutions from chemical processing; solid or liquid plant waste, sludges, and acids; and slightly contaminated equipment, tools, plastic, glass, wood, fabric, and other materials (29). Prior to disposal, liquid low-level radioactive waste is solidified or packaged with material capable of absorbing at least twice the volume of liquid present (30).

Radioactive decay of low-level waste does not generate a great deal of heat, and a rule of thumb is that the material must be isolated from the environment for about 500 years to ensure that the level of radioactivity does not produce a hazard. In the United States the philosophy for management of low-level radioactive waste has been "dilute and disperse." Experience suggests that low-level radioactive waste can be buried safely in carefully controlled and monitored near-surface burial areas in which the hydrologic and geologic conditions severely limit the migration of radioactivity (29). Such waste has been buried at 15 main sites in states including Washington, Nevada, New Mexico, Missouri, Illinois, Ohio, Tennessee, Kentucky, South Carolina, and New York.

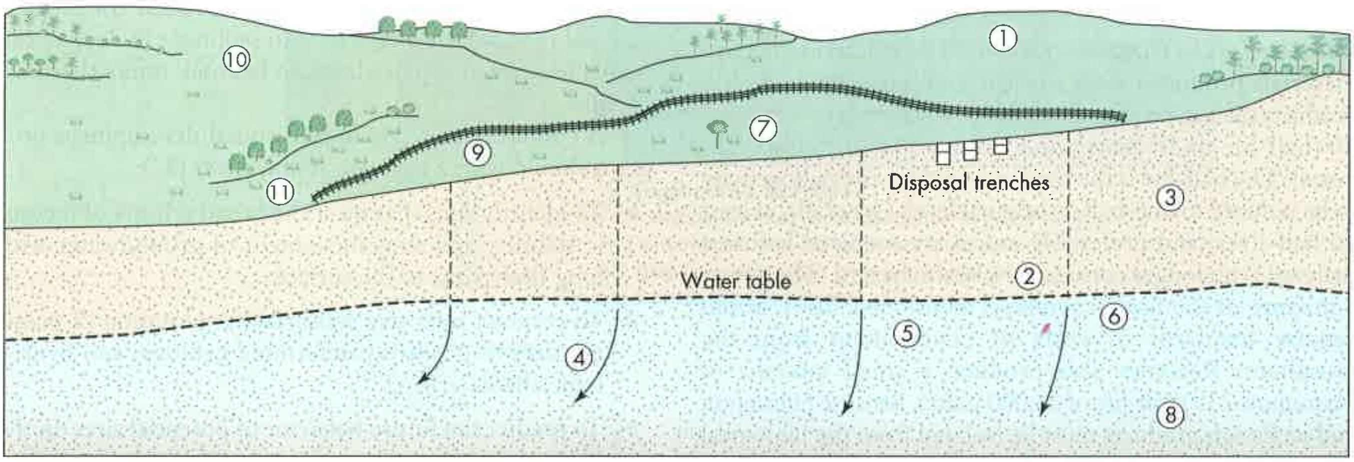
Several of the burial sites for low-level radioactive waste have not provided adequate protection of the environment. This failure has been due at least in part to a poor understanding of the local hydrologic and geologic environment (30). For example, a study of the Oak Ridge National Laboratory in Tennessee suggests that the water table is less than 7 m below the ground surface in places. The investigation identified migration of radioactive materials from one of the burial sites and concluded that containment of the waste is difficult because of the short residence time of water in the vadose zone. In other words, leachate generated from the disposal sites does not take long to infiltrate the vadose zone and percolate down to the groundwater (30). On the other hand, the depth to the water table at the low-level radioactive waste-disposal facility near Beatty, Nevada, is about 100 m. That site has apparently successfully contained radioactive



▲ **FIGURE 12.14** The nuclear fuel cycle. The United States does not now reprocess spent fuel. Disposal of tailings, which because of their large volume can be more toxic than high-level radioactive wastes, has been treated casually.

waste, partly because it takes a long time for any leachate generated to enter the groundwater environment (30).

Both the hydrology and the geology of a particular disposal site play major roles in containing radioactive materials at a low-level radioactive-waste facility. Environmental hazards associated with low-level radioactive waste can persist for 500 years, and unfortunately most investigations of sites receiving waste have been ongoing for only about 20 years. This time span is obviously inadequate to estimate properly the success of particular sites. Nevertheless, several criteria for disposal sites have been delineated in an attempt to create a multiple-barrier approach to disposal. Figure 12.15 shows an idealized disposal site and some of the natural factors that provide the multiple barriers likely to help confine the waste material (30). It is emphasized that no one site is likely to have all of these natural factors, so site selection must carefully consider options to minimize migration of radioactive waste from the burial area.



Explanation

1. Low rainfall:	Means less surface infiltration and thus less production of leachate.
2. Deep water table:	In general, the deeper the water table, the longer the time necessary for leachate to reach the groundwater.
3. Modest soil hydraulic conductivity:	High hydraulic conductivity leads to rapid transport rates of fluids and very low hydraulic conductivity may lead to surface ponding; therefore, moderate hydraulic conductivity is deemed more desirable.
4. Slow moving groundwater:	Provides for or facilitates longer residency time and thus time of travel of contaminants from the disposal site to other locations.
5. High adsorption and ion exchange rates:	Facilitates adhesion of radioactive molecules to the surface of other earth materials, resulting in removal of contaminants.
6. Homogeneous geology:	Makes it easier to predict likely movement of contaminants. Complex geology consisting of faults, folds, and other structures provides discontinuities along which waste may preferentially migrate.
7. Topography and soils that minimize erosion:	Reduces the likelihood of exposure of waste by erosional processes.
8. Absence of exploitable resources:	Waste must be isolated for hundreds of years, and so obviously we do not want to pick a site with needed resources.
9. Absence of surface-water bodies:	Reduces likelihood of pollution of water bodies.
10. Low probability for faulting or volcanic activity:	Faulting or volcanic activity at or near a site obviously might jeopardize containment of low-level radioactive waste.
11. Adequate buffer zone:	Recognizes that containment is not always possible and buffer zones provide additional time for radioactive decay to take place and thus are an added safety precaution.

▲ **FIGURE 12.15** Idealized diagram illustrating natural factors associated with suitability for burial of low-level radioactive waste. (*After* J. N. Fischer. 1986. U.S. *Geological Survey Circular* 973.)

Disposal of High-level Radioactive Wastes

High-level radioactive wastes are produced as fuel assemblages in nuclear reactors become contaminated with large quantities of fission products. This spent fuel must periodically be removed and reprocessed or disposed of. Fuel assemblies will probably not be reprocessed in the near future in the United States (reprocessing is more expensive than mining and processing new uranium); therefore, the present waste-management problems involve removal, transport, storage, and eventual disposal of spent fuel assemblies (31).

The Scope of the Disposal Problem Hazardous radioactive materials produced from nuclear reactors include fission products such as krypton-85 (half-life of 10 years), strontium-90 (half-life of 28 years), and cesium-137 (half-life of 30 years). The half-life is the time required for the radioactivity to be reduced to one-half its original level. Generally, at least 10 half-lives (and preferably more) are required before a material is no longer considered a health hazard. Therefore, a mixture of the fission products mentioned above would require hundreds of years of confinement from the biosphere. Reactors also produce a small amount of plutonium-239 (half-life of 24,000 years). Because plutonium and its fission products must be isolated from the biological environment for a quarter of a million years or more, their permanent disposal is a geologic problem.

High-level radioactive waste is extremely toxic, and a sense of urgency surrounds its disposal as the total volume of spent fuel assemblies slowly accumulates. But there is also conservative optimism that the waste-disposal problem will be solved. It has been projected that without a disposal program, 40,000 metric tons of spent fuel elements from commercial reactors will be in storage at U.S. reactor sites by the year 2000, awaiting disposal or eventual reprocessing to recover plutonium and unfissioned uranium (31). With reprocessing, solid high-level radioactive waste would occupy only several thousand cubic meters, a volume that would not even cover a football field to a depth of 1 m (32).

Production of plutonium for nuclear weapons also generates high-level radioactive waste. By the year 2000 there will be about 8000 metric tons of this solidified high-level waste being stored at U.S. Department of Energy repositories at Hanford, Washington; Savannah River, Georgia; and Idaho Falls, Idaho. Serious problems have occurred with liquid radioactive waste buried in underground tanks. Sixteen leaks involving 1330 m^3 were located at Hanford from 1958 to 1973. An incident in 1973 involved a leak of 437 m^3 of low-temperature waste. Since then, various improvements, including stronger, double-shelled storage tanks, reduction of the volume of liquid waste stored through the solidification program, and increased reserve capacity, have been made. It is hoped these changes will reduce the chance of future incidents (33).

Storage of high-level radioactive waste is at best a temporary solution that allows the federal government to meet its commitments for accepting waste. Regardless of how safe any "storage" program is, it requires continuous surveillance and periodic repair or replacement of tanks or vaults. Therefore, it is desirable to develop more permanent "disposal" methods in which retrieval may be possible but is not absolutely necessary.

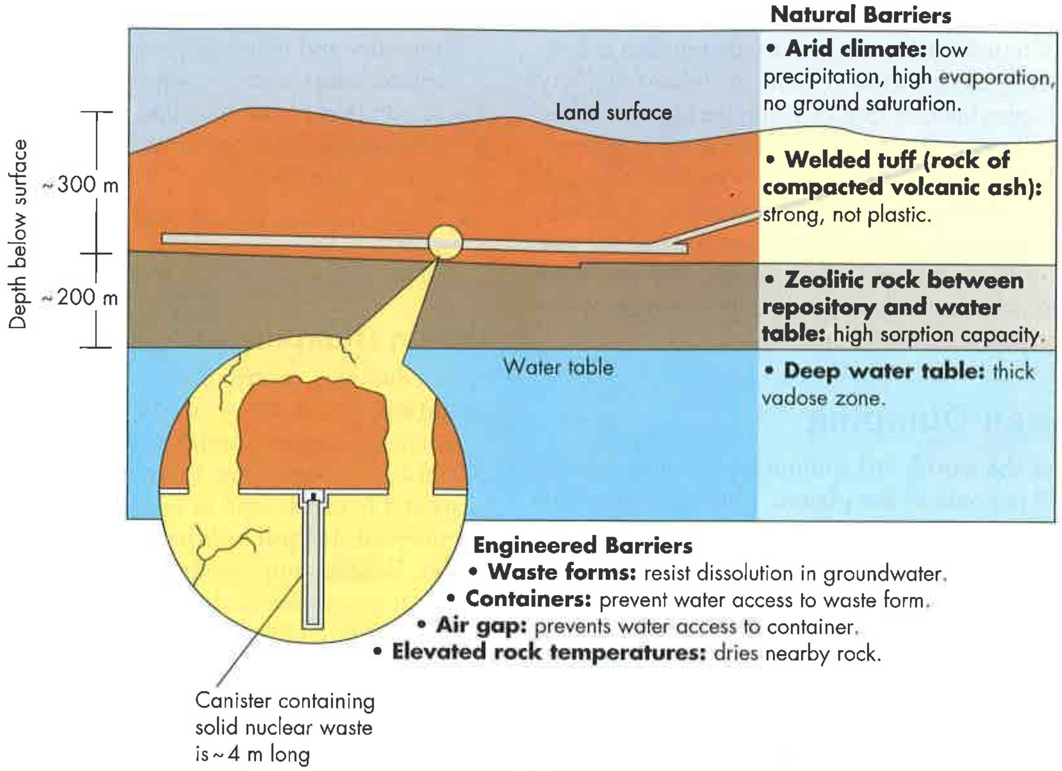
Disposal in the Geologic Environment There is fair agreement that the geologic environment can provide the most certain safe containment of high-level radioactive waste. Because disposal of this waste is a necessity, the federal government is actively pursuing and developing possible alternative methods. Although such concepts as disposal into polar ice caps or into sediment in deep ocean basins have been explored, stable bedrock offers the most promise.

A comprehensive geologic disposal development program should have a number of objectives (32):

- To identify sites that meet the broad criteria of tectonic stability and slow movement of groundwater with long flow paths to the surface
- To conduct intensive subsurface exploration of possible sites to positively determine geologic and hydrologic characteristics
- To predict the future behavior of potential sites on the basis of their present geologic and hydrologic characteristics and possible changes in such variables as climate, groundwater flow, erosion, and tectonics
- To evaluate the risk associated with various predicted changes
- To make a political decision as to whether the risks are acceptable to society

The Nuclear Waste Policy Act of 1982 initiated a comprehensive federal–state, high-level nuclear waste disposal program. The Department of Energy was responsible for investigating several potential sites, and the act originally called for the President to recommend a site by 1987. In December 1987, Congress amended the act to specify that only the Yucca Mountain site in southern Nevada would be evaluated to determine if high-level radioactive waste could be disposed of there. Some scientists and others believe that the site was chosen not so much for its geology (although the rock type at the site does have several favorable qualities for disposal) as because it is an existing nuclear reservation and therefore might draw minimal social and political opposition (33,34).

The rock at the Yucca Mountain site is densely compacted tuff (naturally welded volcanic ash). Fortunately, the site is located in an extremely dry region. Precipitation is about 15 cm/yr and most of this runs off or evaporates. Hydrologists have estimated that less than 5 percent of the precipitation infiltrates the surface and eventually reaches the water table, which is several hundred meters below the surface. The depth to the potential repository is about 300 m below the mountain's surface and, as a result, the repository could be constructed about 200 m above the water table in the vadose zone (35).



(a)

(b)

▲ **FIGURE 12.16** (a) Idealized diagram of proposed Yucca Mountain repository. Listed are natural and engineered barriers. The waste would be retrievable for 50 years. (*Source: Lawrence Livermore Laboratory.* 1988. LLL-TB-92.) (b) Aerial view of the Yucca Mountain Site that is being investigated for the disposal of high-level nuclear waste. The site is on the boundary of the Nevada Test Site where the United States has conducted underground nuclear tests. (*Mark Marten/U.S. Department of Energy/Photo Researchers, Inc.*)

During the 1990s the Department of Energy and the U.S. Geological Survey completed extensive scientific evaluation of the Yucca Mountain site. These studies will help determine how well the geologic and hydrologic setting can isolate high-level nuclear waste from the environment. The site is attractive because there are several natural barriers present (Figure 12.16):

- An arid climate, which greatly restricts downward movement of water
- A strong rock (welded tuff that has a high sorption capacity for radioactive material)
- A thick vadose zone (deep water table)

Additional engineering and construction is expected to provide additional barriers to the waste escaping the storage canisters.

If the studies indicate that the Yucca Mountain site could safely isolate radioactive waste, then the Department of Energy will apply to the U.S. Nuclear Regulatory Commission for a license to construct a disposal facility. If opposition from the state of Nevada is worked out and environmental and safety factors are met, the repository might be ready for acceptance of high-level radioactive waste by the year 2010.

Long-term Safety A major problem with the disposal of high-level radioactive waste remains: How credible are long-range geologic predictions, that is, predictions of conditions thousands to millions of years in the future (32)? There is no easy answer to this question because geologic processes vary over both time and space. Climates change over long periods of time, as do areas of erosion, deposition, and groundwater activity. For example, large earthquakes hundreds or even thousands of kilometers from a site may permanently alter groundwater levels. The seismic record for the western

United States is known only for about the past hundred years, so estimates of future earthquake activity are tenuous at best. The result is that geologists can evaluate the relative stability of the geologic past, but they cannot guarantee future stability. Therefore, decision makers (not geologists) need to evaluate the uncertainty of prediction in light of pressing political, economic, and social concerns (32). These problems do not mean that the geologic environment is not suitable for safe containment of high-level radioactive waste, but care must be taken to ensure that the best possible decisions are made on this very critical and controversial issue.

12.6 Ocean Dumping

The oceans of the world, 361 million km^2 of water, cover more than 70 percent of the planet. They play a part in maintaining the world's environment by providing the water necessary to maintain the hydrologic cycle, contributing to the maintenance of the oxygen–carbon dioxide balance in the atmosphere, and affecting global climate. In addition, the oceans are very valuable to people, providing such necessities as foods and minerals.

It seems reasonable that such an important resource as the ocean would receive preferential treatment, yet all too often this is not the case. In much of the developing world, untreated sewage is disposed of in the oceans of the world, as are many industrial and agricultural wastes. The types of wastes that have been dumped in the oceans off the United States include (36):

- **Dredge spoils**—solid materials such as sand, silt, clay, rock, and pollutants deposited from industrial and municipal discharges—removed from the bottom of bodies of water, generally to improve navigation
- **Industrial waste**—acids, refinery wastes, paper mill wastes, pesticide wastes, assorted liquid wastes, and sewage sludge
- **Construction and demolition debris**—cinder block, plaster, excavation dirt, stone, tile, and other materials
- **Solid waste**—refuse, garbage, or trash; explosives
- **Radioactive waste**

In the United States federal law now prohibits ocean dumping of radiological, chemical, and biological warfare agents and any high-level radioactive waste. Furthermore, it provides for regulation of all other waste disposal in the oceans off the United States by the Environmental Protection Agency or, in the case of dredge spoil, by the U.S. Army Corps of Engineers. In addition to materials prohibited by law from being dumped, the EPA has prohibited:

- Material whose effect on marine ecosystems cannot be determined
- Persistent inert materials that float or remain suspended, unless they are processed to ensure that they sink and remain on the bottom
- Material containing more than trace concentrations of mercury and mercury compounds, cadmium and cadmium compounds, organohalogen compounds (organic compounds of chlorine, fluorine, and iodine), and compounds that may form from such substances in the oceanic environment
- Crude oil, fuel oil, heavy diesel oil, lubricating oils, and hydraulic fluids

Ocean Dumping and Pollution

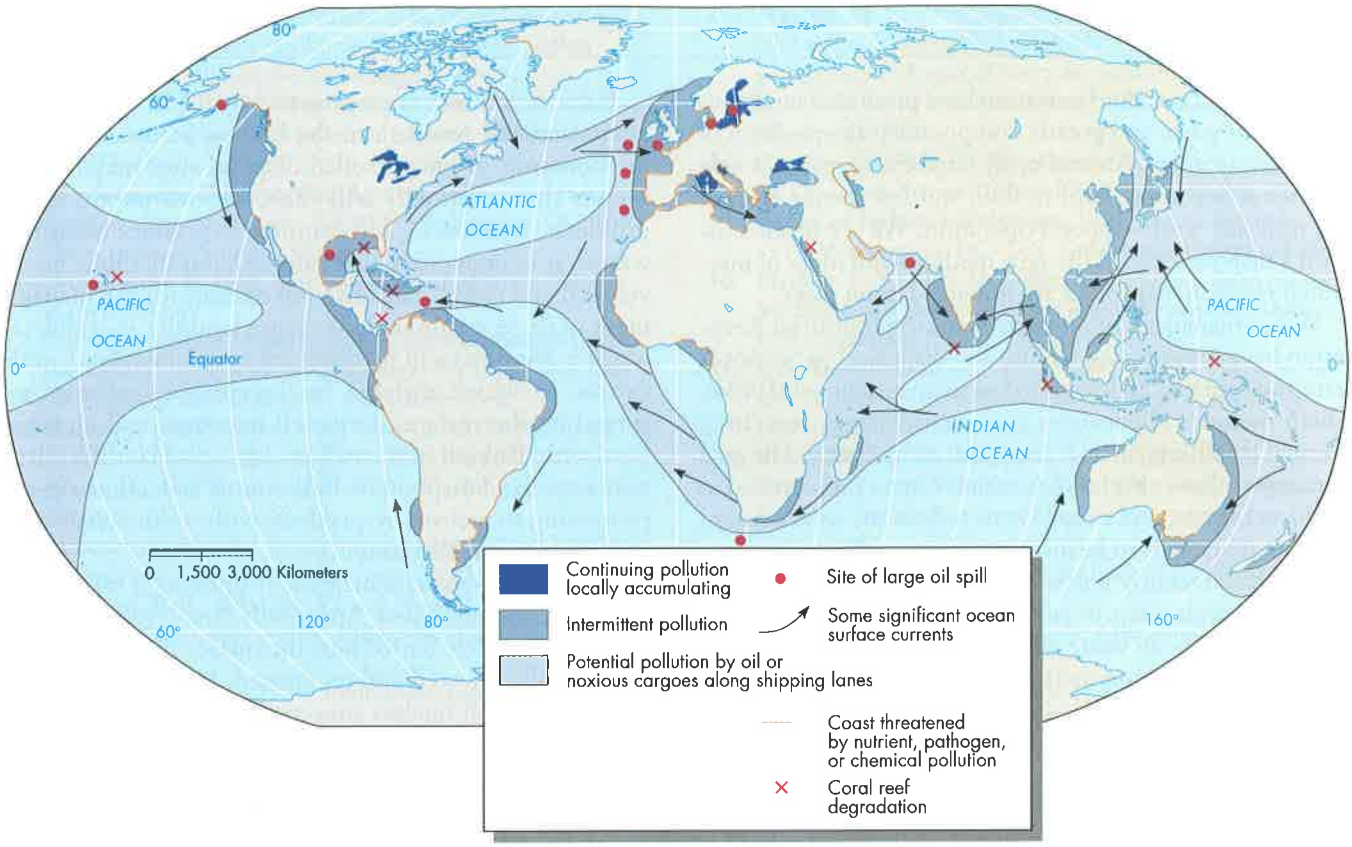
Ocean dumping contributes to the larger problem of **ocean pollution,** which has seriously damaged the marine environment and caused a health hazard to people in some areas. Shellfish have been found to contain pathogens such as polio virus and hepatitis, and at least 20 percent of the nation's commercial shellfish beds have been closed because of pollution. Beaches and bays have been closed to recreational uses. Lifeless zones in the marine environment have been created. Heavy kills of fish and other organisms have occurred, and profound changes in marine ecosystems have taken place (36). Some of the world's major ecosystems, including estuaries, salt marshes, mangrove swamps, beaches, rocky intertidal areas, and coral reefs are threatened by ocean pollution. Ocean pollution is also impacting people and society directly as pollution and contaminated marine organisms may transmit toxic elements and disease to people (37).

Major impacts of marine pollution on oceanic and coastal life (36) include:

- Killing or retarding growth, vitality, and reproductivity of marine organisms by toxic pollutants
- Reduction of the dissolved oxygen necessary for marine life because of increased oxygen demand from organic decomposition of wastes
- Biostimulation by nutrient-rich waste (usually nitrogen and phosphorus), causing excessive blooms of algae (cultural eutrophication; see Chapter 11) in shallow waters of estuaries, bays, and parts of the continental shelf, resulting in depletion of oxygen and subsequent killing of algae that may wash up and pollute coastal areas (as, for example, beaches)
- Habitat change caused by waste-disposal practices that subtly or drastically change entire marine ecosystems

Major impacts on people and society caused by marine pollution include:

- A public health hazard caused by marine organisms transmitting toxic elements and disease to people
- Loss of visual and other amenities as beaches and harbors become polluted by solid waste, oil, and other materials
- Economic loss—the loss of shellfish from pollution in the United States amounts to many millions of dollars annually. In addition, a great deal of money is being



▲ **FIGURE 12.17** Sites of ocean and coastline pollution throughout the world. Impacts are variable, ranging from periodic closure of some beaches in southern California and reduced water quality in Florida Bay due to intermittent pollution to more serious, continuous pollution of areas in the Mediterranean Sea, parts of the Baltic and North seas, and parts of the Great Lakes. (*Adapted from Council on Environmental Quality.* 1981. Environmental Trends. *With data from* McGinn, A. P. 1999. *Safeguarding the health of oceans.* World Watch, *Paper* 145. *Washington,* DC: *Worldwatch Institute, pp.* 22–23.)

spent cleaning solid waste, liquid waste, and other pollutants in coastal areas (36)

- Closure of beaches to recreational activities such as swimming and surfing

Ocean Dumping: The Conflict

It is unfortunate that the people interested in ocean dumping and those interested in harvesting marine resources such as fish and shellfish both prefer to do their jobs near the shore—the former because of convenience and transportation costs and the latter because of the richness of nearshore fisheries. Figure 12.17 shows the locations in the world's oceans, large lakes, and coastlines that are continually polluted or experience intermittent pollution, have degraded coral reefs or are considered threatened. These areas often coincide with nearshore productive areas of the marine environment and constitute a global problem (36–38).

The solution to the problem of ocean dumping is: first, recognizing that the marine environment is a limited resource, and second, developing economically feasible and environmentally safe alternatives to ocean dumping and pollution. We need to manage the oceans and coastal waters to support sustainable use of resources. Untreated wastewater and chemical wastes need to be treated, and agricultural and urban runoff controlled. Finally, we need to develop better scientific understanding and public awareness at local to international levels of the problems our oceans and coasts are facing as a result of human processes that cause pollution. The United States (and eight other countries) could start by ratifying of the 1982 United Nations Law of the Sea, which, by 1998, 130 other nations had ratified. The Law of the Sea establishes a broad management framework for the oceans and the common heritage of its resources within an environmental context of protecting and conserving marine resources (38).

SUMMARY

Industrialization and urbanization have produced enormous amounts of waste and greatly compounded the problem of waste management. Around many large cities, space for new landfills is becoming hard to find, and few people wish to live near any waste-disposal operation. We are headed toward a disposal crisis if the new methods and ideas of integrated waste management are not acted upon soon.

Waste-management practices since the Industrial Revolution have moved from "dilute and disperse," to "concentrate and contain," to integrated waste management (IWM), which includes alternatives such as reducing, recycling, reusing, landfilling, incineration, and composting. The goal of many of these alternatives, which can be summarized as "reduce, recycle, and reuse," is to reduce the total amount of waste that needs to be disposed of in landfills or incinerators. More recently a new concept of materials management is emerging as part of IWM. The ultimate objection is "zero waste"—all waste will become resources.

The most common method for disposal of urban waste in the United States today is the sanitary landfill, in which the waste deposited each day is covered with a layer of compacted soil. Potential hazards from sanitary landfills are pollution of groundwater by leachate (polluted water) from the site and uncontrolled production of methane. However, if methane is contained, it is a useful by-product of landfill operations. Under arid conditions, buried waste produces little leachate; the most suitable sites for landfills in humid regions are where waste can be buried well above the water table in clay and silt soil of low hydraulic conductivity. Modern sanitary landfills have multiple barriers to prevent leachate from infiltrating the vadose zone and systems of monitoring the vadose zone and groundwater through monitoring wells. The siting and operation of sanitary landfills is regulated by federal laws.

Hazardous waste management may be the most serious environmental problem in the United States. Hundreds or thousands of uncontrolled disposal sites may be time bombs that eventually will cause serious public health problems. Because we will continue to produce hazardous wastes, it is imperative that safe disposal methods be developed and used. Land-disposal options for the management of these wastes include secure landfills, in which the waste is confined and the leachate controlled; land application, in which suitable biodegradable materials are spread on the surface; deep-well injection; and incineration, with disposal of the residue by secure landfill. Alternatives to land disposal include source reduction, on-site processing to recover by-products with commercial value, and chemical stabilization.

Radioactive-waste management presents a serious and ever-increasing problem. Apparently, low-level radioactive waste can be safely buried near the surface if the burial sites are carefully selected and monitored. High-level radioactive wastes from nuclear power plants and weapons-production facilities remain hazardous for thousands of years; those currently being stored will eventually have to be permanently disposed of. The most promising method appears to be disposal in a carefully and continuously monitored area in stable bedrock. The site most extensively studied is Yucca Mountain, Nevada.

Indiscriminate ocean dumping is a significant source of marine pollution. Federal law now prohibits ocean dumping of certain dangerous materials and regulates all waste disposal in U.S. ocean waters. Alternatives to ocean dumping of materials such as polluted dredge spoils and other potentially hazardous materials are being developed, but in many cases such alternatives are not yet practical or economically feasible.

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KEY TERMS

integrated waste management (IWM) (p. 318)
reduce, recycle, and reuse (p. 320)
materials management (p. 320)
industrial ecology (p. 320)
composting (p. 321)
incineration (p. 321)
sanitary landfill (p. 322)
leachate (p. 322)
monitoring (p. 324)
hazardous waste (p. 325)
secure landfill (p. 328)
land application (p. 330)
biopersistence (p. 330)
surface impoundments (p. 330)
deep-well disposal (p. 331)
low-level radioactive waste (p. 334)
high-level radioactive waste (p. 336)
ocean pollution (p. 338)

SOME QUESTIONS TO THINK ABOUT

1. Complete an audit of your personal waste production and disposal where you live. How much are you presently recycling and how much do you estimate you might recycle at the high end? If everyone in your neighborhood did this, what would be the impact on the local waste situation?
2. Defend or criticize the statement that management strategies consisting of recycling and incineration compete with one another and therefore we should emphasize one of these based upon environmental considerations.
3. For the region in which you live, identify potential hazardous wastes that are produced by homes, businesses, and industry or agriculture. How are these wastes currently being treated and what could be done to develop a better management strategy if there are problems?
4. Some people argue that we should not dispose of high-level radioactive waste deep in the geologic environment where such waste is not retrievable. One alternative would be to store the waste at several different sites on the surface for a period of perhaps as long as 100 years. The idea is that during that time we will find better ways to deal with the radioactive waste. Develop arguments for and against these ideas.