Second Edition

ENVIRONMENTAL HYDROGEOLOGY

Philip E. LaMoreaux
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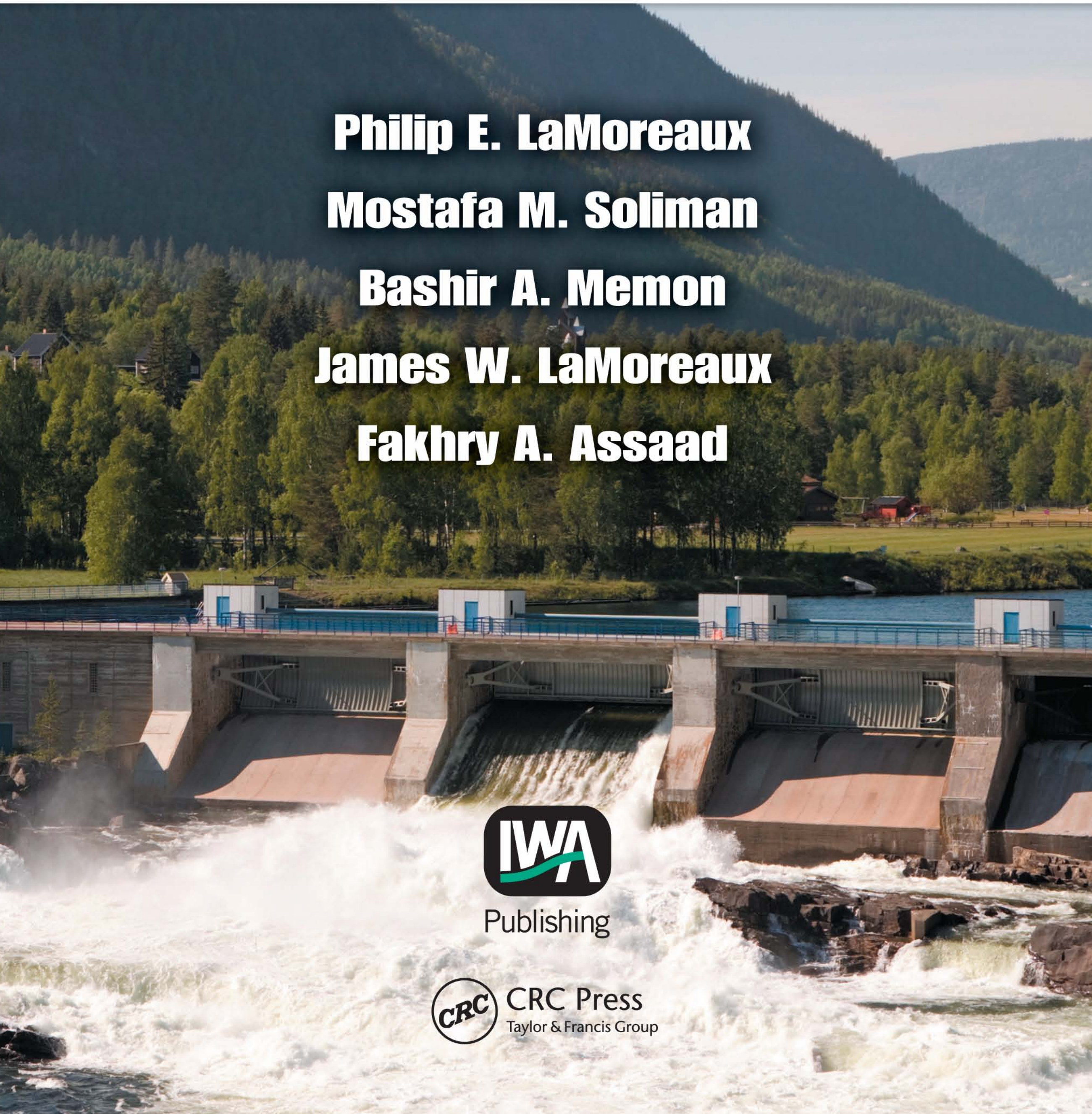

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Preface

When this book was first written the world's population was expected to grow over the next two decades by 1.7 billion, bringing the earth's inhabitants to about 7 billion. Now the world's population is 6.6 billion and continues to grow at an exponential pace. Regardless of the population, people must have adequate food, clothing, and shelter while minimizing additional impacts on the environment.

We have learned that there must be a readily accessible reserve of professionals, mainly geoscientists in the governmental infrastructure, to guide research, regulation, and remediation. We have also learned that environmental problems are complex and not only of local concern, but, national and global in scope. Some of these concerns such as global warming, water pollution, acid rain, and air pollution extend beyond political boundaries and span the gaps between continents. Experienced professional geoscientists are needed to develop solutions and implement them.

Our environmental growing pains resulted in a great flurry of professional acquisitions. Suddenly, experienced hydrogeologists are in great demand. Their knowledge is needed for the study of ground-water movement as influenced by geologic depositional environments and structures. Geophysicists and geochemists help describe "the bucket" containing the water. Hydrologists and engineers determine its hydrologic characteristics and identify, monitor, and safely remove pollutants.

We have learned by experience that much waste of financial resources and time occurs without trained professional geoscientists to perform the remedial tasks. One of the biggest problems associated with future environmental programs is directly related to the availability of professional staffing to do the job. As we consider the future, how do we assess this factor? This can be measured in part by the number of new courses, seminars, and training programs pertaining to the environment offered at universities, by professional associations, and by private training organizations. In the next few years these programs will provide a reserve of professionals trained in hydrogeology, environmental geology, environmental engineering, and environmental chemistry.

For the aforementioned reasons, this textbook was prepared to aid geoscientists in their understanding of environmental hydrogeology. Chapter 1 provides an introduction. Chapter 2 is devoted to geological aspects of potential disposal sites. Chapter 3 covers surface water hydrology, ground-water hydrology, and the design of wells. Chapter 4 enlightens the professional and graduate and undergraduate students about relationships between environmental impacts and hydrogeological systems. Chapter 5 describes the types and sources of wastes and their properties, including adverse affects on the environment. Chapter 6 focuses on environmental impacts on water resource systems, and Chapter 7 gives a clear idea about waste management for ground-water protection. Chapter 8 discusses environmental considerations for design and construction in karst terrains, while Chapter 9 covers groundwater modeling. Chapter 10 contains selected case studies from around the world as examples to show some of the environmental impacts on water resource systems and what has to be done to protect those hydrogeological systems.

The final section, includes four appendices: Appendix A, a glossary of important hydrogeological terms; Appendix B, conversion tables; and Appendix C, mathematical modeling of some of the hydrogeological cases with accompanying software manual and computer diskette containing an executable file and a solved problem with its data file for demonstration. Appendix D is a software manual of drawdown around multiple wells.

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1 Introduction

1.1 INTRODUCTION

It is not possible to read a daily newspaper or magazine—*The Wall Street Journal, USA Today, Newsweek,* or *Time*—without seeing the word *environmental* or reading about a tangential catastrophic event. We live with this constant reminder of local, statewide, national, and international issues, actions, or politics regarding our environment. The Earth Summit held in Brazil is an example.

On June 1, 1992, *Newsweek* blazoned headlines: "No More Hot Air, It's Time to Talk Sense About the Environment."[1] The article described the meeting of world leaders in Rio the following week. Their mission: "To save the ship from its passengers." The feature article was titled "The Future Is Here" and emphasized that Antarctica suffers an ozone hole; North America takes the lion's share of world's resources; South America is custodian of the world's largest rain forest; Australia is overcultivated; Africa faces population density doubling; and Asia has stressed resources.

Another smaller and less pretentious example: *Newsweek*, July 27, 1992, with a full-page color ad illustrating a relatively complicated geologic cross section at a nuclear waste disposal facility.[2] How many people 10 years ago would have known what a geologic cross section was, let alone understood it! The caption read: "To most people, it's a complex diagram. To scientists, it's a clear summary of safe nuclear waste disposal." The ad implied to a supposedly rather sophisticated reading public the Madison Avenue concept of a very controversial scientific, social, and political issue: nuclear power and its associated waste disposal. This concept relates to world energy needs and is a major geoscience issue. Two different objectives are described; both, however, illustrate the great need for capable geoscientists.

World population is expected to grow in the next two decades, with an increase of 1.7 billion. This will bring the Earth's total inhabitants to about 7 billion. The article describes the environmental situation with regard to water, air, land, trees, industry, energy, species risk, and climate change. The bottom line: this increased population must have adequate food, clothing, and shelter, with minimum additional impact on the environment. This population increase, with the corollary resource development, also clearly identifies another substantial need for expertise in geoscience.

Environmental problems are not new. About 2000 years ago, the first written religious documents, the *Bible* and the *Koran*, related humans' relationship to their environment and recognized the importance of water to their existence. Springs and wells are the subject of numerous stories of famine, migration, war, hate, greed, and jealousy. In fact, Dr. O.E. Meinzer, the father of "ground water," in Water Supply Paper 489 remarked that parts of the *Bible* read like a Water Supply Paper.[3]

Since the 1970s, the environmental movement has progressed from an emotional adolescence to maturity. In the beginning there was a great cry of anguish from the general population, similar to the biblical wail, "There was pestilence in the land." Symptoms included sores on children who had been playing in abandoned industrial fields, cancer in adults, and pollution in our waters. Problems ranged from minor to major, but all were given headlines. Love Canal was the "battle cry" and the beginning of "Not in my back yard!" or the NIMBY syndrome. Concern and hysteria reigned in many localities. The population was scared and was not sure of "the truth" from anyone—politician, government employee, or scientist. Confidence levels in these representatives were low. Everyone—individuals, politicians, industry, and government—agreed that "something" had to be done! Politicians responded, and the Resource Conservation and Recovery Act (RCRA) and the Comprehensive Emergency Response Compensation and Liability Act (CERCLA) resulted. There were companion bills and rules and regulations for each state. Initially, it was thought that money could solve the problem. It was soon learned it could not. Experienced professional geoscientists were needed to implement programs and solve problems. We have learned that there must be a readily accessible reserve of professionals, mainly geoscientists, for the governmental infrastructure to guide research, regulation, and remediation. We have also learned these problems are complex and not only of local, county, and state concern but national and oceanwide, and include water pollution, acid rain, and air pollution. Some environmental problems extended beyond country boundaries and between continents. Saddam Hussein showed the world what one individual could do to jeopardize the environment that we live in.

In the late 1980s, our environmental growing pains resulted in a great flurry of professional acquisition. Suddenly, hydrogeologists were in great demand. Advertisements for hydrologists appeared in the trade and technical magazines. New jobs were created for geoscientists capable of writing and implementing regulations as well as serving in regulatory roles in local, state, and federal government and, subsequently, in remedial roles in business and industry and the consulting fields. Geoscientists were suddenly charged with studies to provide the basis for intelligent remediation. Experienced hydrogeologists were particularly in demand, for it was their knowledge regarding the relationship between groundwater recharge, storage, and movement as influenced by geologic depositional environments and geologic structure that was needed. Geophysicists and geologists could help describe “the bucket” containing the water, and hydrologists and engineers could determine how fast water flowed through this complicated system. Polluting constituents had to be identified, monitored, removed, and safely disposed.

A new set of industries associated with environment and environmental clean-up developed at the same time. See the “Guide to Environmental Stocks,” published monthly, or refer to lists on the New York Stock Exchange, NASDAQ, or over-the-counter stocks and compare 1960 versus 1990 to learn about the large number of new firms becoming involved in environmental activities. There are old names and new ones. Companies retreaded or new ones formed to include names such as DuPont, Westinghouse, Weston, NUS, Chemical Waste Management, Rollins, Waste Management, Inc., as well as a host of other smaller specialized firms.

To evaluate the greater financial impact from the environmental movement, review the appropriations for environmental investigation and remediation in government. The U.S. Environmental Protection Agency (EPA), U.S. Department of Defense (DOD), and U.S. Department of Interior (DOI) are being appropriated each year to support research and remediation. To this we can add the corollary billions of dollars spent by commercial and industrial firms. This rapid injection of money into governmental and associated remediation has created a whole new set of demands on the geoscience community since the 1980s.

Our concept of the environment in the 2000s is much more comprehensive than in the 1960s. However, even with much progress, there remains much work to accomplish, including at least 20 years of greater emphasis on many complex problems. It will become necessary to quantify certain types of groundwater movement through rocks, geochemical interrelationships between rocks, natural constituents in water as well as pollutants, risk assessment, and one of the biggest problems of all—adequate communication about these factors and their solution with the public.

We have learned by experience that there is much waste of financial resources and time without trained professional geoscientists to carry out the task of clean-up and that one of the biggest problems associated with future environmental programs is directly related to the availability of professional staffing to do the job. As we consider the future, how do we assess this factor? This can be measured in part by the numbers of new courses, seminars, and training programs pertaining to the environment offered at universities, by scientific societies, and by a very substantial number of new environmental institutes inaugurated since 1980. Newly developed academic programs and degrees are now available in environmental geology, environmental engineering, and environmental chemistry, which in the next few years will provide a reserve of professionals. Another indicator would be the increased number of scientific papers in journals on the subject illustrating a reorientation of thought and emphasis on the environment. A search of the American Geological Institute GEOREF and Google Scholar* database provided the following:

Environmental

Key words: pollution, water quality, ecology, land use, reclamation, conservation, nonengineering aspects of geologic hazards, and nonengineering aspects of waste disposal, plus the general term environmental geology.

Period	Citations
1785–1979	41,000 over 194 years
1980–1987	75,000 over 7 years
1988–1991	60,000 over 3 years
1992–2000	222,000 over 8 years

Concurrently, within the geoscience societies there are a number of new environmental divisions, activities, and journals; for example, the Institute for Environmental Education of the Geological Society of America (GSA) established in 1991, the newly organized Division of Environmental Geoscience of the American Association of Petroleum Geologists (AAPG) established at Calgary in June 1992, and a major new emphasis by the American Geological Institute (AGI) (see Earth System Science, a current series in *Geotimes*).

In the U.S. government there is greater environmental awareness—the U.S. Army Corps of Engineers (COE), allocation of substantial funding during construction of the Tenn–Tom Waterway (TTW), to employ an "Environmental Advisory Board" with the specific assignment to provide guidance that included changes in construction, to minimize soil erosion, loss of wetlands, attention to wildlife, protection of groundwater supplies, and many other environmental considerations. One such recommendation changed the course of the waterway to protect a famous old geologic locality at Plymouth Bluff, Mississippi. This large project required the efforts of many geoscientists. One aspect of their work included communication with the public, politicians, and government about what should be considered proper planning and construction and the adequate consideration of environmental impacts. This illustrates the need for the geoscientist to communicate, a responsibility that will become more important in the future.

As we look into the future, environmental activities will exert the greatest demand for geoscientists. Specific identity of four of these activities will illustrate the point. The first two, RCRA and CERCLA, in the 1970s and 1980s provided a whole new body of law with significance to environmental activities that affected all facets of the private, agricultural, commercial, and industrial sectors, as well as to local, state, and federal governments.

1. RCRA was created in 1976 and applied to future waste management. It included criteria for location, groundwater monitoring, operations, and contingencies. The law was converted to comprehensive regulations and criteria to be implemented in each state by legislative and legal action.
2. CERCLA was created in 1980 and applied to the clean-up of old, abandoned hazardous-waste facilities. It was a massive program of investigation of climate, geology, hydrology, biology, botany, and other environmental risks. SARA (Superfund Amendments and Reauthorization Act), 1986, National Priority List (NPL) found in 40 CFR, Part 300, Appendix B. The last issue of list was in February 1991 (proposed listing as of March 1992) of 1179 NPL sites, and 84 sites removed from the list from 1980 to the present.
3. Environmental audits: The impact from the environmental laws of the 1970s was even more far reaching as the private sector as well as commercial and industrial activities began to need an environmental audit prior to property transfers. The EPA policy on July 9, 1986, *Federal Register*, recommends the use of environmental audits.[4] Banks and other loaning institutions require audits. Millions of property transfers now require an audit by

a certified environmental scientist. Criteria for audits have been established by the Resolution Trust, Small Business Administration, as well as by individual banks and American Society for Testng and Materials (ASTM). This represents a massive amount of work in the future.

4. LUST: To the uninitiated, LUST does not mean what you think it does. It means Leaking Underground Storage Tanks. In 1984, Congress responded to the problem by adding Subtitle I to RCRA. Subtitle I requires the EPA to develop regulations to protect human health and the environment from leaking USTs. Between three and five million underground storage tanks are currently being used in the United States to store motor fuels and chemical products. Nearly 80% of these tanks are constructed of bare steel. Not surprisingly, 60% of all leaks result from corrosion.

EPA UST rules are promulgated by 40 CFR Parts 280 and 281. Final rules on technical requirements were published in the *Federal Register* (September 23, 1988).[5] The most significant problem is the sheer size of the regulated community. Nationally, over 700,000 UST facilities account for over 3 million UST systems, an average per state of about 14,000 UST facilities and 40,000 UST systems. Estimates indicate that roughly 79% of existing UST systems are unprotected from corrosion. In addition, because a relatively high proportion of UST facilities (10–30%) already have had a leak, or will soon leak unless measures are taken to upgrade them, the average number of leaking UST systems may range from 1,400 to 4,200 per state in the near future. The LUST problems must be handled by knowledgeable geologists, hydrologists, and engineers.

Information on the magnitude of the problems relating to waste management, acid rain, and water pollution, and nonpoint sources of pollution such as agricultural use of insecticides and pesticides, mining activities, oil and gas activities, and construction of all types, and even the acquisition of any property transfers in the future will require an environmental assessment. These issues will require a whole new team of sophisticated scientists over the next 20 years.

In *Geotimes*, January 1991, there appeared two excellent articles, "Tomorrow's Geoscientist" by Marilyn Suiter[6] and "Geoscience Careers" by Nick Claudy,[7] which contain appropriate and accurate information about the demand for geoscientists in the future. Suiter makes the point that women and ethnic minorities will make up much of the human resources potential for the work force in the future. Also the demand in science and engineering for qualified workers will grow (Figure 1.1). Claudy concludes that the geosciences offer unparalleled diversity for career opportunities. He identifies by percentage their major employment categories—oil and gas (50%), mining (9%), federal/state (12%), research institutions (4%), consulting (11%), and academia (14%). Claudy also identifies correctly the need for geoscientists with MS degrees for professional categories and extensive job opportunities, as well as for geotechnicians with BA or BS degrees. These articles, however, do not call attention to the major shift to be expected in demand for scientists in the broad environmental activities area. The state and federal government agencies are limited by appropriation constraints; however, the biggest demand will be in the broad area of environmental work. We predict that at least 50% of the new jobs will fall in this category and the need will be critical.

If the solid earth sciences are to meet the demands of society's environmental problems, the profession must recruit, train, and place in the professional work force a sufficient number of well-qualified professionals to carry out the task ahead. According to a recent survey, about one half of earth scientists in the United States (about 120,000), including petroleum and mining engineers, are employed by the petroleum industry. The U.S. government employs about 14,000, and academia about 9,000. The remainder are employed on environmental work related to waste management, hazardous and toxic radioactive waste permitting litigation, underground storage problems, environmental audits, and environmental impact studies. The supply of and demand for earth scientists over the past 50 years has historically been out of phase. In the early 1980s, because of the dramatic decline in petroleum prices, employment in oil and gas activities decreased by about 30%. This was also a depressed period in the mining industry, and there resulted a loss of

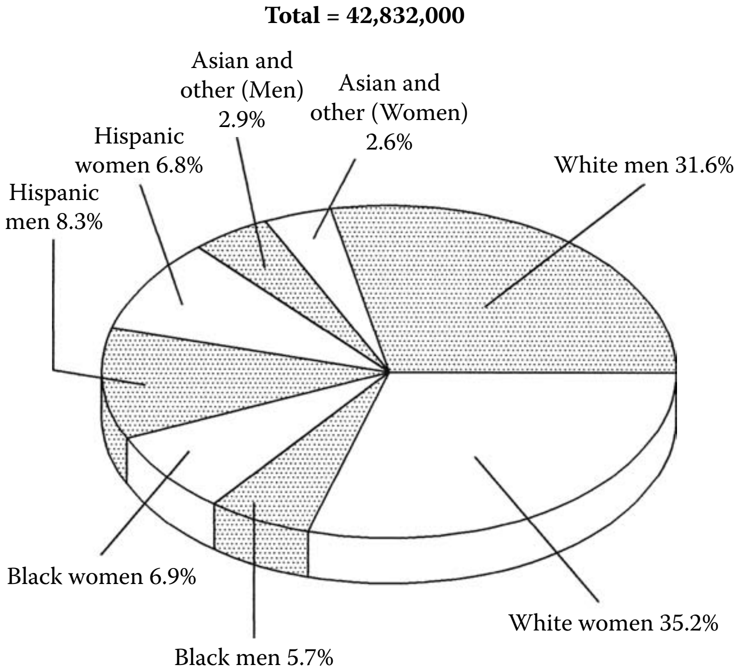

FIGURE 1.1 People entering the work force between 1988 and 2000 will be mostly women and minorities, according to the U.S. Bureau of Labor Statistics. (From Suiter, M., Tomorrow's Geoscientist, *Geotimes,* January 1991.)

thousands of jobs in the earth scientist categories. We are just recovering from this cycle. It was a traumatic period for the geosciences with over 4,000 laid off and geologists a glut on the market. Experienced PhDs were searching for any respectable employment. Qualified geoscientists, especially the younger generation, were unable to find jobs. This had a detrimental affect on the recruitment of geoscience majors and the production of professionals. Environmental legislation dealing with waste disposal was enacted in the early 1980s, and employment projections indicate employment in the earth sciences is growing rapidly, with emphasis on groundwater issues, the siting of waste repositories, and the need for environmental clean-ups. The down cycle in the oil industry had its detrimental impact in the decreased number of new scientists entering the field. In the future we must recognize that great opportunities exist in the environmental areas and that there will be critical needs for new vigorous members for the profession. With the recovery of the oil and gas and mining industries to produce resources for a rapidly expanding world population, the demand for earth scientists will become strong. Further, unless these reserves of competent professionals are forthcoming, the nation will face a critical situation. These are reasons for a textbook on *Environmental Hydrogeology* at this time.

1.2 SUGGESTIONS AND REFERENCES

Several recent publications provide important reference material for sound environmental geologic, geoscience, and hydrogeological programs. Each emphasizes the need for good communication between the scientific community and political, industrial, and private citizens.

Solid-Earth Science and Society, National Academy Press, 368 pp., 1993.
Citizens' Guide to Geologic Hazards, American Institute of Professional Geologists, 134 pp., 1993.
Societal Value of Geologic Maps, Circular 1111, U.S. Geological Survey, 53 pp., 1993.

A special journal, *Environmental Geology*, is published twelve times annually by Springer-Verlag and is available by subscription. It provides many good case histories on the subject.

A modified statement is taken from the Citizens' Guide to Geologic Hazards to illustrate the present:[8]

Hazardous geological processes most familiar to the public are those that occur as rapid events, i.e., over a period of minutes, hours, or days. Examples include: *earthquakes* produced by the process of rapid snapping movements along faults; *volcanoes* produced by upward-migrating magma; *landslides* produced by instantaneous failure of rock masses under the stress of gravity; and *floods* produced by a combination of weather events and land use. These events all produce massive fatalities and make overnight headlines. Other geologic processes, such as soil creep (slow downslope movement of soils that often produces disalignment of fence posts or cracked foundations of older buildings), *frost heave* (upheaval of ground due to seasonal freezing of the upper few feet), and land subsidence act more slowly and over wider regions. These slower processes, however, also take a toll on the economy. Human interaction can be an important factor in triggering or hastening these natural processes (see Table 1.1).

Lack of awareness induces human complacency, which sometimes proves fatal. It is difficult to perceive of natural dangers in any area where we and preceding generations have spent our lives in security and comforting familiarity. This is because most catastrophic geologic hazards do not occur on a timetable that makes them easily perceived by direct experience in a single lifetime. Yet development within a hazardous area inevitably produces consequences for some inhabitants. Hundreds of thousands of unfortunate people who perished in geological catastrophes such as landslides, floods, or volcanic eruptions undoubtedly felt safe up until their final moments. In June 1991, Clark Air Force Base in the Philippines was evacuated when Mount Pinatubo, a volcano dormant for over 600 years, began to erupt and put property and lives at risk.

Geologic hazards are not trivial or forgiving; in terms of loss of life, geologic hazards can compare with the most severe catastrophes of contemporary society. Where urban density increases and land is extensively developed, the potential severity of loss of life and property from geologic hazards increases.

We are often faced with the decision about whether we can wisely live in areas where geologic forces may actively oppose otherwise pleasant living conditions. There follows some guidelines:

Avoid an area where known hazards exist. Avoidance or abandonment of a large area is usually neither practical nor necessary. The accurate mapping of geologic hazards delineates those very specific areas that should be avoided for particular kinds of development. Otherwise, hazardous sites may make excellent green belt space or parks in areas zoned as floodplains, thus avoiding placing expensive structures where flooding will cause damage.

Evaluate the potential risk for hazards. Risks can never be entirely eliminated, and the process of reducing risk requires expenditures of effort and money. Assuming, without study, that a hazard will not be serious is insufficient. Life then proceeds as though the hazard were not present at all. "It can't happen here" expresses the view that is responsible for some of the greatest losses. Yet it is equally important not to expend major amounts of society's resources to remedy a hazard for which the risk is actually trivial.

Minimize the effect of the hazards by engineering design and appropriate zoning. Civil engineers who have learned to work with geologists as team members can be solid and effective contributors to minimizing effects of geologic hazards. More structures today fail as a result of incorrectly assessing (or ignoring) the geological conditions at the site than fail

TABLE 1.1
Economic costs of geologic hazards in the United States

Geologic hazard	Cost in 1990 dollars[a]	Source(s)
Hazards from materials		
Swelling soils	$6 to 11 billion annually	Jones and Holtz, 1973, *Civil Engrg*. Vol. 43, n. 8, pp. 49–51; Krohn and Slosson, 1980, *ASCE Proc. 4th Int. Conf. Swelling Soils*, pp. 596–608
Reactive aggregates[b]	No estimate	—
Acid drainage	$365 million annually to control; $13 to 54 billion cumulative to repair	USBM, 1985, IC 9027; Senate Report, 1977, 95–128
Asbestos	$12 to 75 billion cumulative for remediation of rental and commercial buildings; total well above $100 billion including litigation and enforcement. Costs depend on extent and kind of remediation doses; removal is most expensive option	Croke et al., 1989, *The Environmental Professional*, Vol. 11, pp. 256–263 Malcolm Ross, USGS, 1993, personal communication
Radon	$100 billion ultimately to bring levels to EPA recommended levels of 4 PCi/L. Estimate based on remediating about 1/3 of American homes at $2500 each plus costs for energy and public buildings	
Hazards from processes		
Earthquakes	$230 million annually decade prior to 1989; over $6 billion in 1989	USGS, 1978, Prof. Paper 950; Ward and Page, 1990, USGS Pamphlet, "The Loma Prieta Earthquake of October 17, 1989"
Volcanoes	$4 billion in 1980; several million annually in aircraft damage	USGS Circular 1065, 1991, and Circular 1073, 1992
Landslides/avalanches	$2 billion/50.5 million annually	Schuster and Fleming, 1986, *Bull. Assoc. Engrg. Geols.*, Vol. 23, pp. 11–28/ Armstrong & Williams, 1986, The Avalanche Book
Subsidence[c] and permafrost[d]	At least $125 million annually for human-caused subsidence; $5 million annually from natural karst subsidence	Holzer, 1984, GSA Reviews in Engrg. Geology VI; FEMA, 1980, Subsidence Task Force Report
Floods	$3 to 4 billion annually	USGS Prof. Paper 950
Storm surge[e] and coastal hazards	$700 million annually in coastal erosion; over $40 billion in hurricanes and storm surge 1989–early 1993	Sorensen and Mitchell, 1975 Univ. CO Institute of Behavioral Sci., NSF-RA-E-70-014; Inst. of Behavioral Sci., personal communication

[a] Costs from dates reported in "Source(s)" column have been reported in terms of 1990 dollars. This neglects changes in population and land use practice since the original study was done but gives a reasonable comparative approximation between hazards.

[b] Aggregates are substances such as sand, gravel, or crushed stone that are commonly mixed with cement to make concrete.

[c] Subsidence is local downward settling of land due to insufficient support in the subsurface.

[d] Permafrost consists of normally frozen ground in polar or alpine regions that may thaw briefly due to warm seasons or human activities and flow.

[e] Storm surge occurs when meteorological conditions cause a sudden local rise in sea level that results in water piling up along a coast, particularly when strong shoreward winds coincide with periods of high tide. Extensive flooding then occurs over low-lying riverine flood plains and coastal plains.

Source: From Nuhfer, E. B., Proctor, R. J., and Moser, P. H. (Eds.), American Institute of Professional Geologists, *The Citizens' Guide to Geologic Hazards,* Arvada, CO, 134 pp., 1993.

due to errors in engineering design. This fact has led many jurisdictions to mandate that geological site assessments be performed by a qualified geologist. Taking geological conditions into account when writing building codes can have a profound benefit. The December 1988 earthquake in northwestern Armenia that killed 25,000 people was smaller in magnitude (about 40% smaller) than the October 1988 Loma Prieta earthquake in California. The latter actually occurred in an area of higher population density but produced just 67 fatalities. Good construction and design practice in California was rewarded by preservation of lives and property.

Academic training for civil engineers must include basic courses in geology taught by qualified geologists. A more comprehensive geologic education is needed for civil and environmental engineers. Engineers should be cognizant of the benefits of a geological assessment and be able to communicate with professional geologists.

California, in 1968, became the first state to require professional geological investigations of construction sites and has reaped proven benefits for that decision. Since then, many states have enacted legislation to insure that qualified geologists perform critical site evaluations of the geology beneath prospective structures such as housing developments and landfills. Most of these laws were enacted after 1980.

Zoning ordinances and building codes that are based on sound information and that are conscientiously enforced are the most effective legal documents for minimizing destruction from geologic hazards. After a severe flood, citizens have often been relocated back to the same site with funding by a sympathetic government. This is an example of "living with a geologic hazard" in the illogical sense. A less costly alternative might be to zone most floodplains out of residential use and to financially encourage communities or neighborhoods that suffer repeated damage to relocate to more suitable ground. When damage or injuries occur from a geologic hazard in a residential area, the "solution" is often a lawsuit brought against a developer. The problem has not truly been remedied; the costs of the mistake have simply been transferred to a more luckless party—the future purchasers of liability and homeowners' insurance at higher premiums. A solution would be a map that clearly delineates those hazardous areas where residential development is forbidden. A suitable alternative would be a statute requiring site assessment by a qualified geologist before an area can be developed. Sound land use that takes geology into account can prevent unreasonable insurance premiums, litigation, and repeated government disaster assistance payments for the same mistakes.

Develop a network of insurance and contingency plans to cover potential loss or damage from hazards. Planners and homeowners need not be geologists, but it is useful to them to be able to recognize the geological conditions of the area in which they live and to realize when they need the services of a geologist. A major proportion of earthquake damage is not covered by insurance. Despite public awareness about earthquakes in California, the 1987 Whittier quake produced 358 million dollars worth of damage, of which only 30 million dollars was covered by insurance.

For the property owner—especially, the prospective homeowner—a geological site assessment may answer the following: Is the site in an area where landslides, earthquakes, volcanoes, or floods have occurred during historic times? Has the area had past underground mining or a history of production from wells? Did the land ever have a previous use that might have utilized underground workings or storage tanks that might now be buried? Does the site rest on fill, and is the quality of the fill and the ground beneath it known? Are there swelling soils in the area? Have geologic hazards damaged structures elsewhere in the same rock and soil formations that underlie the site in question? Has the home ever been checked for radon? If the home is on a domestic well, has the water quality been recently checked? Is the property on the floodplain of a stream? Is the property adjoining a body of water such as a lake or ocean where there have been severe shoreline erosion problems after infrequent (such as 20-yr or 50-yr) storms?

Insurance agents are not always familiar with local geological hazards. After risks have been assessed, the individual can then consult with insurance professionals (agents, brokers, salespersons) to learn which firms offer coverage that would include pertinent risks. Consulting with the state insurance boards and commissions can assist one in finding insurers who provide pertinent coverage.*

Local governments should make plans for zoning and for contingency measures such as evacuations with involvement from a professional geologist. The first line of help for local governments lies in their own state geological surveys. Hydrogeologists are employed for service to the public and can provide much of the available information that is known about the site or region in question and can direct the inquirer to other additional resources. Geologic maps and reports from public and private agencies are most useful in the hands of those trained to interpret them. Significant evidence that reveals a potential geologic hazard may be present in the reports and maps. If significant risks of hazards are thought to exist, then consultation with a professional geologist may be warranted.

Geologic hazards annually take more than 100,000 lives and take billions of dollars from the world's economy. Such hazards can be divided into those that result dominantly from particular earth materials or from particular earth processes. Most of these losses are avoidable, provided that the public at large makes use of state-of-the-art geologic knowledge in planning and development. A public ignorant of geology cannot usually perceive the need for geologists in many environmental, engineering, or even domestic projects. The result is a populace prone to making expensive mistakes, particularly in the area of public policy.

Education is one of the most effective ways of preparing to deal successfully with geologic hazards. Every state geological survey produces useful publications, distributes maps, and answers inquiries by the public. Unfortunately, lack of good earth science education leaves many citizens unaware of the resources that their geological surveys provide.

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2 Geological Aspects for Assessment, Clean-up, and Siting of Waste Disposal Sites

2.1 INTRODUCTION[1]

Geology and hydrogeology are broad-based multidisciplines developed from many different sciences. The development of hydrogeology required multidisciplinary concepts from mathematics, physics, chemistry, hydrology, geology, and the processes of evaporation, transpiration, and condensation. Meinzer noted that the science of hydrogeology could not be undertaken until the basic concepts of geology were understood.

A knowledge of rock type, stratigraphy, and structure is imperative to understand groundwater, recharge, storage, and discharge characteristics. Knowledge of geology is a prerequisite to understanding the source, occurrence, availability, and movement of groundwater. The application of quantitative methods for groundwater requires an accurate description of the container (aquifer) or geologic framework.

State and federal regulations have established restrictions for the location of hazardous waste and municipal solid waste landfills. Regulations require owners/operators to demonstrate that the hydrogeology has been completely characterized at proposed landfills and that locations for monitoring wells have been properly selected. Owners/operators are also required to demonstrate that engineering measures have been incorporated in the design of both hazardous and municipal solid waste landfills, so that the site is not subject to destabilizing events as a result of location in unsuitable or unstable areas.[2]

Proposed, new, or existing landfills are subjects of controversy and sources of continuing debate as to whether an area can provide suitable sites for construction of landfills for hazardous or nonhazardous waste. Issues of concern are the potential threats to human health and the environment that could result from (1) collapse or subsidence, with the associated loss of structural integrity of the landfill; (2) release of contaminants through collapse, subsidence, or leakage from the landfill; and (3) contamination of groundwater or surface water, which may result from a release.

Conceptually, the selection of waste management sites involves collection of information necessary to answer a few simple questions, including: Will the natural hydrogeologic system provide for isolation of wastes, so that disposal will not cause potential harm to human health or the environment? Is the site potentially susceptible to destabilizing events, such as collapse or subsidence, which will result in sudden and catastrophic release of material from the facility and rapid and irrevocable transmission to important aquifers or bodies of surface water? Are the monitoring wells in proper positions to intercept groundwater flow from the facility? If minor releases (leakages) occur, will contaminants be readily detected in monitoring wells? If a release is detected, is knowledge of the hydrogeologic setting sufficient to allow rapid and complete remediation of release? Is the hydrogeologic system sufficiently simple to allow interception and remediation of contaminated groundwater?

Answers to the preceding questions depend on the thoroughness of geologic and hydrogeologic studies by which each site was assessed and evaluated prior to construction of a land disposal facility. In the experience of the authors, most significant environmental problems, resulting from releases from land disposal facilities, occur from facilities for which preliminary hydrogeologic studies were inadequate to answer the aforementioned questions. In many such cases, studies designed to gain an understanding of the hydrogeologic system did not begin until after a release was detected. Compliance monitoring and remediation of groundwater are costly processes, all of which can be avoided by assiduous care in selection of proper sites for land disposal.

Specific regulations for siting landfills in all geologic settings have not been promulgated. However, regulations for protection of groundwater and monitoring as well as other regulations[3,4] require characterization of the hydrogeologic system and proper location of monitoring wells at landfills. Figure 2.1 is a conceptual hydrogeological model showing the gradient flow, geologic setting, and monitoring wells.

Consideration of candidate sites for land disposal facilities is a process that requires careful screening of many potential sites, rejection of unsuitable sites, avoidance of questionable sites, and demonstration that the selected site is hydrogeologically suitable for disposal of waste.

The screening process typically includes the following: (1) selection of a large number of candidate sites within the geographic area of interest; (2) ranking of the candidate sites in order of apparent suitability for disposal of wastes; (3) rejection of areas or sites that are obviously not suitable for disposal of wastes; and (4) selection of one or more of the sites for further evaluation.

Tasks during screening typically involve review of published and unpublished engineering, geologic, and hydrologic literature, discussions with appropriate state or federal personnel, study of topographic maps, interpretation of sequential aerial photographs, and verification of studies by field reconnaissance. Most of the preliminary screening can be rapidly accomplished in the office at low cost. The stratigraphic intervals and structural anomalies, along with other geologic features, are defined in published geologic literature. General geologic maps are often available, and this knowledge can be extended to site-specific locations through use of aerial photographs, topographic maps, and fieldwork. The locations, depths, water levels, producing horizons, and rates of pumping for wells in the vicinity of the site are often available in the files of state or federal agencies.

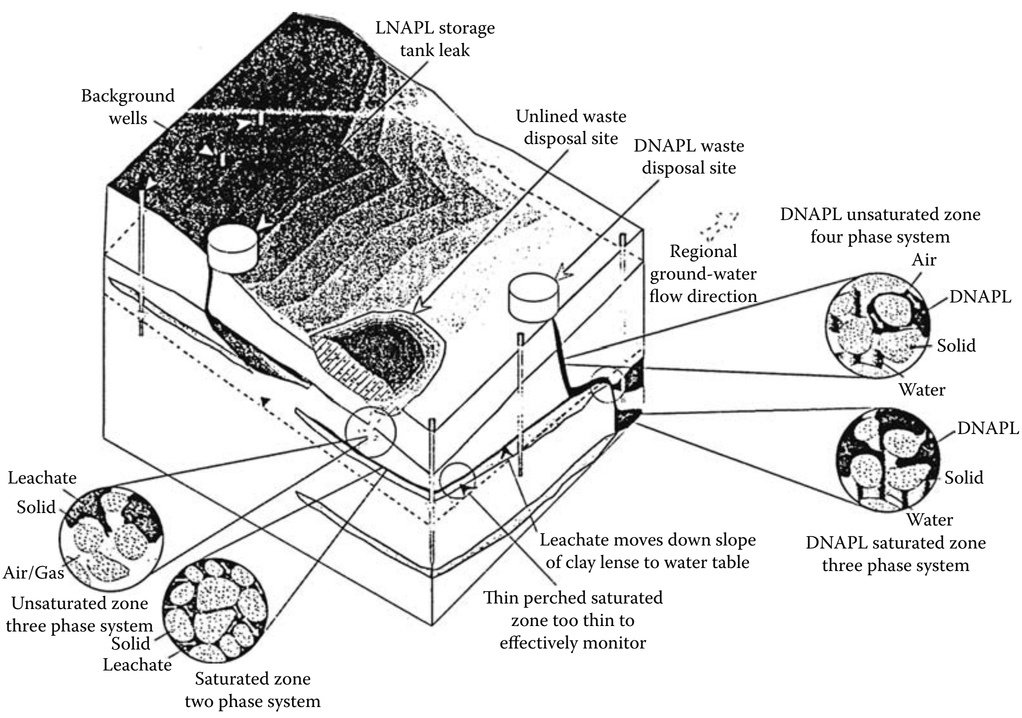

FIGURE 2.1 Conceptual flow models for NAPL sites. (From Sara, M.N., *Standard Handbook for Solid and Hazardous Waste Facility Assessments*, Lewis Publishers, Boca Raton, FL, 1994, pp. 10–68.)

A thorough review of published and unpublished literature must be done during the preliminary investigation. Older literature often contains more complete descriptions of the geology than more recent publications and should not be overlooked.

Table 2.1 illustrates concepts presented by many authors, including Hughes,[6] LeGrand,[7] LeGrand and Stringfield,[8,9] LeGrand and LaMoreaux,[10] LaMoreaux et al.,[11,12] Newton,[13,14] Parizek et al.,[15] Sweeting,[16] and White.[17–19] Sara provides a comprehensive review of the site assessment process.[5] His guide, *Standard Handbook for Solid and Hazardous Waste Facility Assessments*, is a comprehensive manual to assist in the planning, implementation, and interpretation of investigations for the facility's suitability for disposal of solid or hazardous waste. The manual also provides appropriate locations for groundwater monitoring and effectiveness of the landfill's leachate collection and contamination system. This guide was the result of a substantial team effort that included professionals from government, industry, and academia. It is a comprehensive compilation of information on solid and hazardous waste management that all professionals involved with environmental hydrogeology should be aware of and use.

Aerial photographs have been sequentially available in many parts of the United States since the late 1930s. Sets of aerial photographs, as stereo pairs, can be used to determine if karst features have changed, if collapse features have locally occurred, or if depressions have been enlarged with time and can serve as a means of cataloging changes in land use over a period of about 50 years. In addition, the aerial photographs can be used for preliminary mapping of stratigraphic contacts, structural features, and lineaments.

2.2 GEOLOGICAL ASPECTS

2.2.1 Rock Types

Rocks are classified according to their origin as igneous, metamorphic, and sedimentary, and according to their lithology, which describes the rock composition and texture.

Unfractured metamorphic and plutonic igneous rocks have maximum porosities of 2% with minute intercrystalline voids that are not interconnected. The primary permeabilities of these rocks are low because of the lack of void interconnection.[20]

Fractured plutonic igneous and crystalline metamorphic rocks have secondary (fracture) permeability developed along the fracture openings that are generally more common at a depth of less than 100 ft with some occurring at a maximum depth of 200 ft. The permeability of fracture zones in the crystalline rocks decreases with depth, where the fractures tend to close because of vertical and horizontal stresses imposed by overburden loads.

Volcanic rocks are formed from the solidification of magma, which when discharged at land surface flows out as lava. The rocks that form on cooling are generally very permeable. Columnar joints and bubblelike pore spaces are formed owing to rapid cooling and escape of gases. The blocky rock masses and associated gravel deposits that are interbedded in recent basalts create a very high permeability.

Sedimentary rocks such as sandstones, carbonate rocks, and coal beds form aquifers to store and transmit groundwater. Sandstones constitute 25% of the sedimentary rocks of the world, and the permeable zones in these types of rocks form regional aquifers that contain large quantities of potable water. Friable sandstones generally have a high porosity (30–50%), which diminishes greatly with depth because of compaction and the intergranular cementing materials, mainly quartz, calcite, iron, and clay minerals. The latter are precipitated from hydrothermal solution circulating into the sandstone aquifers at depths where temperature and pressure are high.[20]

Carbonate-type rocks such as limestone and dolomite consist mostly of calcite and dolomite minerals with minor inclusions of clay. Dolomitic rocks, or dolostones, are secondary in origin, formed by geochemical alternation of calcite, which creates an increase in porosity and permeability as the crystal lattice feature of dolomite occupies about 13% less space than that of calcite. Geo-

TABLE 2.1
Important characteristics of different geologic terrain

Stratigraphy

(Regional and Local)

- Stratigraphic column
- Thickness of each carbonate unit
- Thickness of noncarbonate interbeds
- Type of bedding
  - Thin
  - Medium
  - Thick
- Purity of each carbonate unit
  - Limestone or dolomite
    - Pure
    - Sandy
    - Silty
    - Clayey
    - Silicous
    - Interbeds

Overburden

(Soils and Subsoils)

- Distribution
- Origin
  - Transported
    - Glacial
    - Alluvial
    - Colluvial
- Residual
- Other
- Characteristics and variability
- Thickness
- Physical properties
- Hydrologic properties

Hydrology

- Surface water
  - Discharge
    - Variability
      - Seasonal
      - Gaining
      - Losing
- Groundwater
  - Diffuse flow
  - Conduit flow
  - Fissure flow
  - Recharge
  - Storage
  - Discharge
- Fluctuation of water levels
- Relationships of surface–water and groundwater flow

Geologic Structure

(Regional and Local)

- Nearly horizontal bedding
- Tilted beds
  - Homoclines
  - Monoclines
- Folded beds
  - Anticlines
  - Synclines
  - Monoclines
  - Domes
  - Basins
  - Other
- Fractures
  - Lineaments
  - Locations
  - Relationships with
    - Geomorphic features
    - Karst features
    - Stratigraphy
    - Structural features
- Joint System
  - Joint Sets
    - Orientation
    - Spacing
    - Continuity
    - Open
    - Closed
    - Filled
- Faults
  - Orientation
  - Frequency
  - Continuity
  - Type
  - Normal
    - Reverse
    - Thrust
    - Other

- Age of faults
    - Holocene
    - Pre-Holocene

Activities of Humans

- Construction
    - Excavation
    - Blasting
    - Vibration
    - Loading
        - Fill
        - Buildings
    - Changes in drainage
    - Dams and lakes
- Withdrawal of groundwater
    - Wells
    - Dewatering
    - Irrigation

Geomorphology

- (Regional and local)
- Relief-slopes
- Density of drainage network
- Characteristics of streams
    - Drainage pattern(s)
        - Dendritic
        - Trellis
        - Rectangular
        - Other
    - Perennial
    - Intermittent
- Terraces
- Springs and/or seeps
- Lakes and ponds
- Floodplains and wetlands
- Karst features—active, historic
    - Karst plains
    - Poljes
    - Dry valleys, blind valleys, sinking creeks
    - Depressions and general subsidence
    - Subsidence cones, in overburden
    - Sinkholes
    - Roof-collapse
    - Uvalas
    - Caverns, caves, and cavities
    - Rise pits
    - Swallow holes
    - Estavelles
    - Karren
    - Other
- Paleo-Karst

Climate

- Precipitation (rain and snow)
    - Seasonal
    - Annual
    - Long-term
- Temperature
    - Daily
    - Seasonal
    - Annual
    - Long-term
- Evapotranspiration
- Vegetation

Source: From Hughes, T.H., Memon, B.A., and LaMoreaux, P.E., Landfills in karst terrains, *Bulletin of the Association of Engineering Geologists*, Vol. 31, No. 2, 1954, p. 203.

logically young carbonate rocks commonly have porosities that range from 20% for coarse, blocky limestone to more than 50% for poorly indurated chalk.[21] At depth, the soft minerals that constitute the matrix of the carbonate rock are normally compressed and recrystallized into a more dense, less porous rock. Fractures or openings along bedding planes of carbonate beds create appreciable secondary permeability, whereas secondary openings due to stress conditions may be enlarged as a result of dissolution of calcite or dolomite by circulating groundwater.

Karst terrains have specific hydrologic characteristics and are composed of limestone, dolomites, gypsum, halite, or other soluble rocks. Karst landscapes that exhibit irregularities of the land surface are caused by surface and subsurface removal of rock by dissolution of limestone, calcite, or dolomite by circulating groundwater and erosion. Figure 2.2 shows the complex physical and geochemical processes involved in forming karst and the phenomenon of karst and karstification.[22]

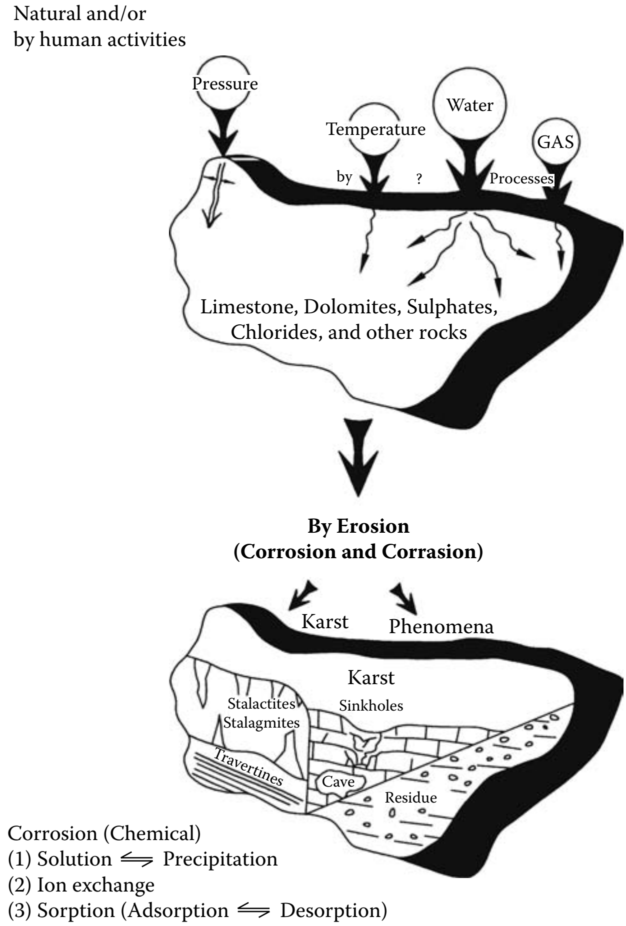

FIGURE 2.2 A flow diagram showing karstification and karst. (Modified from Assaad, F.A. and Jordan, P., *Karst Terranes and Environmental Aspects,* Vol. 23, 228–237, 1994.)

Table 2.1 includes a list of generic categories of rock types and other relevant information that should be considered during evaluation of potential sites for land disposal. It includes broader categories, an understanding of which is necessary during the preliminary screening of sites, and it provides a basis for formulating a conceptual hydrogeologic model.

Coal beds are lithologic units within sequences of sedimentary rocks formed in floodplain or deltaic environments.

Shale beds constitute the thickest semipervious units in most sedimentary basins. Shale beds originate as mud laid down in the gentle-water areas of deltas, on ocean bottoms, or in the back-swamp environments of floodplains. Clay is transformed to shale by digenetic processes related to compaction and tectonic activity. In outcrop areas, shale is commonly brittle and fractured with appreciable amounts of permeability, whereas, at depth, it is less fractured and permeability is generally very low. Unfractured shale, clay, anhydride, gypsum, and salt usually provide good seals against upward or downward flow of fluids.

Alluvial deposits are unconsolidated materials deposited by streams in river channels or on floodplains. They consist of particles of clay, silt, and sand and gravel. Alluvial deposits include alluvial cones, which consist of loose material washed down the mountain slopes by ephemeral streams and deposited at the mouth of gorges, alluvial fans that are formed by a tributary of high declivity in the valley of a stream, or those deposits built by rivers issuing from mountains upon lowlands. Numerous other alluvial features are associated with alluvial processes.

2.2.2 Candidate Sites

On the basis of knowledge gained during the preliminary assessment of geologic framework, a rank-ordered list of candidate sites can be prepared. One or more of the candidate sites, which have the highest rankings, are typically selected for site-specific hydrogeologic and geotechnical studies. The additional studies may be performed on each of two or three selected sites or for one site with the highest ranking. The hydrogeologic studies should be designed to seek and discover fatal flaws, if they are present. In the absence of fatal flaws, detailed studies provide a means of completely characterizing the hydrogeology of the site, demonstrating the suitability of the site for a potential land disposal facility, and defining locations for monitoring the site.

Some conditions that may, but do not always, lead to rejection of a candidate site include the following: areas that contain well-developed karst features and recent karst activity; recharge areas for aquifers (i.e., particulate stratigraphic intervals); specific geologic structures (e.g., some folds, faults, and lineaments); areas that contain thin or geotechnically unsuitable soil; areas of wellhead protection for public water supplies; and areas of significant pumping (e.g., quarries, mines, and industrial wells).

The U.S. Environmental Protection Agency[3] (EPA) has established definite landfill siting requirements and some restrictions on location of municipal solid waste landfills, which locally may also constitute cause of rejection of proposed sites. The restrictions include proximity to airports, floodplains, wetlands, Holocene faults, seismic impact zones, and unstable areas. When hydrogeologic conditions are unfavorable, or when costs of overcoming deficiencies of the site are too high, the site should be rejected from further consideration as a potential site for disposal of wastes to land.[2]

The EPA and state governments have established the following landfill siting requirements for waste disposal facilities and practices.

Location Restrictions

1. *Fault areas*: Landfills should not be located within 200 ft of the active fault zones that have undergone displacement in Holocene time.
2. *Airport safety*: Landfills should be located at least 10,000 ft from airports handling turbojets and 5,000 ft from airports handling piston-type aircraft to avoid bird hazard to aircraft.
   EPA requires that landfills should not be located in a 100-year floodplain. Landfills shall not restrict the flow of a 100-year flood, reduce the temporary water storage capacity of the floodplain, or result in the washout of solid waste and pose a hazard to human health and to the environment. However, new MSWLFs or existing landfills, if located in a 100-year floodplain, should be designated and operated to mitigate and minimize adverse impacts on the flow of 100-year flood and water storage capacity of the floodplain.
3. *Wetlands*: New landfill units cannot be placed in wetlands unless the owner or operator gives specific assurances to the state that the facility will not result in "significant degradation" of the wetlands.

Dredged or fill material should not be deposited or discharged into the aquatic ecosystem unless it can be demonstrated that such actions will not have an unacceptable adverse impact either individually or in combination with known or probable impacts of other activities affecting the ecosystems of concern. The degradation or destruction of special aquatic sites, such as filling operations in wetlands, is considered to be among the most severe environmental impacts.

Operating Criteria

EPA has established operating requirements for landfills, such as application of daily cover and post-closure care, random inspections of incoming waste loads, and record keeping of inspection results.

1. *Explosive gases control*: The concentration of methane generated by landfills should not exceed 7.5% of the lower explosive limit (LEL) in facility structures and at the property boundary.
2. *Air criteria*: Air criteria prohibit the open burning of waste but allow infrequent burning of agricultural wastes, silviculture wastes, land-cleaning debris, diseased trees, and debris from emergency clean-up operations. Any of these infrequent burnings should be conducted in areas dedicated for that purpose and at such a distance from the landfill unit so as to preclude the accidental burning of other wastes.

2.2.3 Stratigraphy

Stratigraphy is the study of the thickness, age, lithology, and chronological sequence of rocks. The lithostratigraphic column, a graphic representation of the rock units, is the basic display of data used in stratigraphic studies. Figure 2.3 is a generalized columnar section for northeast Illinois, showing a variety of rock types typical of the east-central states.

Cross sections show the sequence of stratigraphic data constructed from the material penetrated in several deep wells. The stratigraphic correlation aids in understanding the depositional environment of subsurface material. Understanding of depositional environment of subsurface material beneath the potential site for land disposal is important as the flow of groundwater and its recharge, storage, and discharge are controlled by various lithologies of stratigraphic section of the geologic column.

2.2.4 Structural Geology[23]

Structural geology is related to folding and faulting and the geographic distribution of these features, which greatly affect the fluid flows, the physical properties of rocks, and the localization of mineral deposits and earthquakes.

Faults are fractures in the rock sequence along which displacement of two blocks took place. Such fractures may range from inches to miles in length, and displacements are of comparable magnitudes. Faults may act either as barriers to or as channels for fluid movement. Generally, geologists should consider any significant fault to be a potential flow path for purposes of preliminary evaluation of its importance. Accordingly, the fault would be an environmental hazard according to this assumption. If further investigation indicates this assumption to be true, it would be necessary to abandon potential disposal sites. Fractures that occur without any movement lead to cracks or joints, which are important to the development of porosity and permeability in some aquifers, but can be undesirable when there could be potential for draining fluids rapidly away from the disposal site. Joints can be examined from core samples obtained through drilling, by well logging, and by testing methods and evaluated on the basis of experience with other deep wells drilled in the same region.

Structural geologic data are commonly shown on maps and cross sections. Structure contour maps show the elevation of a particular stratigraphic horizon relative to a selected datum. These maps can be used to estimate the depth to a mapped rock unit, the direction and magnitude of dip, and location of faults and folds that may influence decisions concerning the location of the proposed disposal site and associated network of monitoring wells.

2.2.5 Physical Properties

Physical properties[1] of fluid and porous media that describe the hydraulic aspects of saturated groundwater flow include density, ρ, viscosity, μ, and compressibility, β, for the fluid, whereas for the media

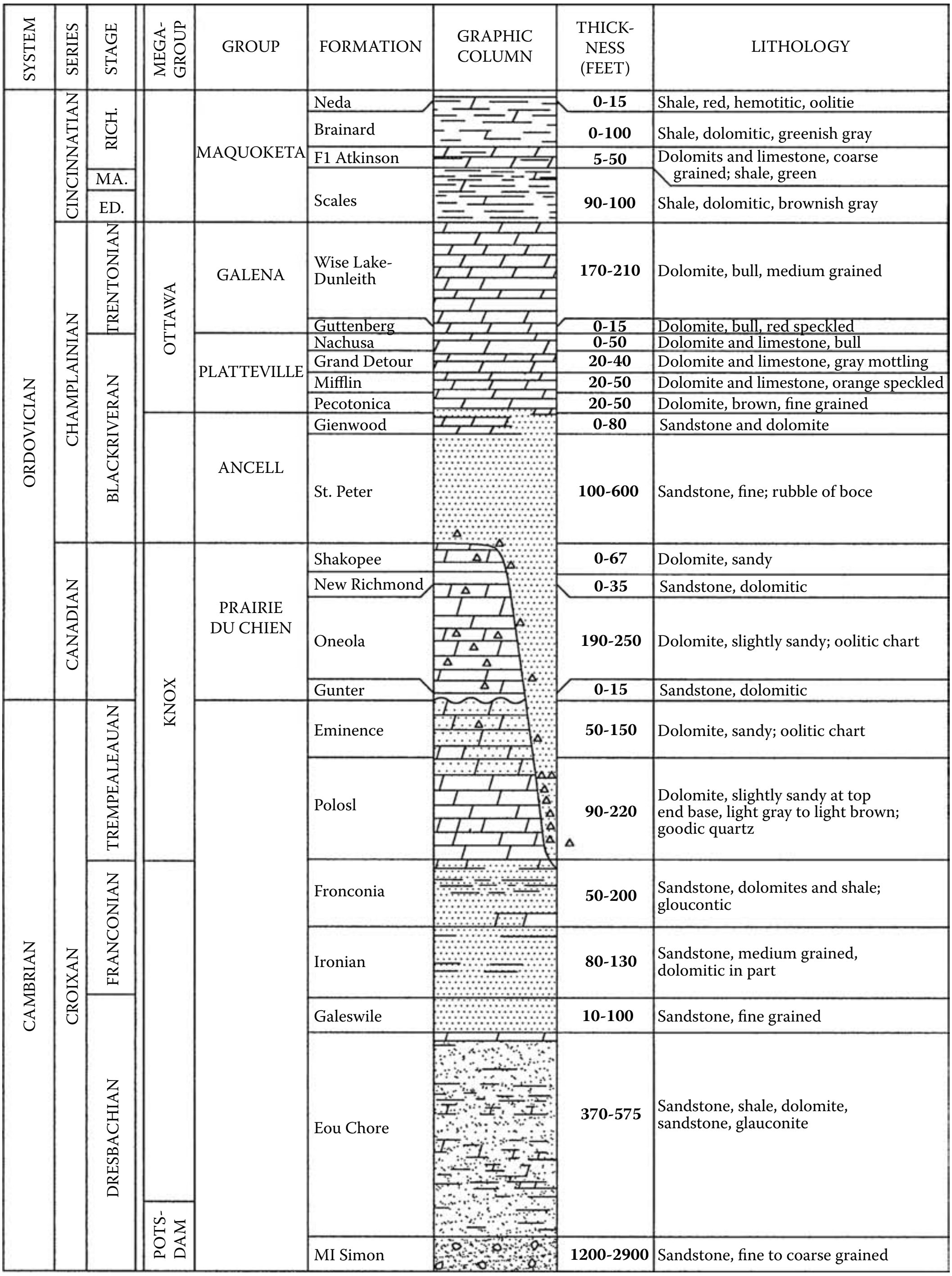

FIGURE 2.3 Generalized columnar section of Cambrian and Ordovician strata in northeastern Illinois. (From U.S. EPA 600/2-77-240, An introduction to the technology of subsurface wastewater injection, in *Environmental Protection Technology Series*, USEPA, Cincinnati, OH, 1977, pp. 21–47, 64–91, 329–344.)

(aquifers), they are porosity, Ø, permeability, *k*, and compressibility, α. These parameters are essential to quantitatively evaluate the hydrogeologic conditions of the potential sites for land disposal.

Porosity

Porosity is basically grain formation dependent on grain size and degree of roundness.

$$\text{Quantitatively, Porosity } (\theta) = \frac{Vv}{Vt} \tag{2.1}$$

where

Ø = porosity (expressed as a percentage)
Vv = volume of voids
Vt = total volume of soil sample

Total porosity is a measure of all void space, whereas effective porosity is defined as the hydraulic properties of a rock unit, which considers the volume of interconnected voids available only to fluids flowing through the rock.[23]

A distinction must be made between primary and secondary porosity.[24] **Primary porosity** is intergranular or intercrystalline. Intergranular porosity in a sandstone depends on the size distribution, shape, angularity, packing arrangements, mineral composition, and cementation.[23] **Secondary porosity** results from fractures, solution channels, cavities or space (particularly in karst), and recrystallization processes and dolomitization.

Permeability

Permeability is expressed as the coefficient of permeability (k in cm^2). It is a formation property that allows the flow of liquids within the rock under an applied potential gradient, and it is a rock parameter that influences the flow velocity. In general, the permeability is usually much lower in vertical directions than in horizontal.[24]

Permeability depends on the grain size. The smaller the grains, the larger will be the surface area exposed to the flowing fluid. As the frictional resistance of the surface area lowers the flow rate, the smaller the grain size, the lower the permeability. Shales, which are formed from extremely small grains, have very small permeability and are classified as confining intervals. The fracture permeability, due to fracturing, as well as the secondary permeability caused by the creation of karst in limestone and dolomite, may be significant for fracture flow.[24] Intrinsic permeability is expressed as follows:

$$k = \frac{Q\mu}{A\rho g \bullet \frac{dh}{dL}} \; (cm^2) \tag{2.2}$$

where

k = coefficient of permeability
Q = flow rate through porous medium
A = cross-sectional area through which flow occurs
μ = fluid viscosity
ρ = fluid density
L = length of porous medium through which flow occurs
h = fluid head loss along L
g = acceleration due to gravity

A simple form of Darcy's law used in shallow groundwater is

$$K = \frac{Q}{A} \Big/ \frac{dh}{dL} \tag{2.3}$$

where K is the hydraulic conductivity (cm/s).

Transmissivity (or transmissibility), T, can be interpreted as the rate at which fluid of a certain viscosity and density is transmitted through a unit width of an aquifer at a unit hydraulic gradient. It is measured as the product of the thickness of the aquifer (b) and its hydraulic conductivity (K). Its unit is generally gallons per day per foot^2 (gpd/ft^2) or m/day.

Compressibility

The compressibility of an aquifer, α, encompasses not only the formation or the skeleton of the aquifer but also the contained fluids. Compressibility and the coefficient of storage are combined as a function of the aquifer thickness.

Quantitatively, compressibility of an elastic medium is defined as

$$\alpha = \frac{\delta v}{V\delta p} \tag{2.4}$$

where

α = compressibility of aquifer (psi^{-1})
δv = differential volume V
δp = differential pressure P

The compressibility of the aquifer ranges from 5×10^{-6} to 10×10^{-6} psi^{-1} as compared with that of water alone, which is about 3×10^{-6} psi^{-1}.

Storativity

The storage coefficient for a confined aquifer, which is a parameter related to compressibility, indicates the capacity of the formation to accept water and is defined as the volume of water that an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in the hydraulic head normal to the surface and is quantitatively expressed as follows:[23]

$$S = \phi\gamma b\left(\beta + \frac{\alpha}{\emptyset}\right) \tag{2.5}$$

where

S = storage coefficient
$\emptyset$ = porosity
γ = pg = specific weight of water per unit area
b = aquifer thickness
β = compressibility of water
α = compressibility of aquifer formation

Values of S are dimensionless and normally range between 5 and 10^{-5} to 5 and 10^{-3} for confined aquifers and 10^{-1} and 10^{-3} for unconfined aquifers.

Viscosity

The viscosity of the formation water in a porous rock influences the velocity of flow. As temperature increases, viscosity decreases and the velocity of flow increases.

Hydrodynamic Dispersion

Hydrodynamic dispersion is a mixing process in which a liquid diffuses with another liquid on the condition that both are miscible. The coefficient of dispersion is inversely proportional to temperature, porosity, and grain form, whereas an increase in grain size, grain roundness, and the degree of irregularity promotes dispersion.[20–24]

2.2.6 Hydrogeologic Considerations

The subsurface rocks are subdivided into groups, formations, and members in descending order. These terms imply mappable rock subdivisions based on mineralogy, fossil contents, or other geological characteristics. However, such subdivisions may or may not be applicable to subsurface flow systems, as the geologic boundaries are not related to the physical properties (porosity and permeability). The following hydrogeologic terms are used to describe rock subdivisions according to their capacity to keep and transmit water:

An *aquifer* is a saturated permeable geological unit (i.e., a formation or part of it or a group of formations) that can transmit significant quantities of water under ordinary hydraulic gradients to wells and springs.

An *aquiclude*, on the other hand, stores water but does not transmit significant amounts. An *aquitard*, which has been used to describe the less permeable beds in a stratigraphic sequence, is in between an aquifer and an aquiclude and transmits enough water to be regionally significant but not enough to supply a well.[23]

A *confined aquifer* is confined between two aquicludes and occurs at depth. It may be under artesian conditions when the water level in a well rises above the ground surface. The water level elevations in wells that are tapping a confined aquifer are plotted and contoured to construct a potentiometric surface map that shows the hydraulic head in the aquifer and provides an indication of the direction of groundwater flow.

An *unconfined aquifer*, or water-table aquifer, is one in which the water table forms the upper boundary and occurs near the ground surface. A *perched aquifer* is a saturated lens of a formation that is bounded by a perched water table at the top and lenses of relatively low permeable material at the bottom. It is a special case of an unconfined aquifer.

An *aquifuge* will not transmit water. The basement rock, which is igneous or metamorphic, lies beneath the sedimentary mantle and is generally nonporous and impermeable.[3] The groundwater flow theory and well hydraulics are discussed in Chapter 3.

2.3 DATA ACQUISITION OF ROCK AND FORMATION FLUID TESTINGS

2.3.1 Data Obtained Prior to Drilling Potential Disposal Sites

Geologic data should be obtained for evaluation of the site selected for drilling a well. Surface geophysical methods, including seismic, gravity, magnetic, and electrical surveys, may provide considerable subsurface geological information, but because of high costs, surface geophysical surveys are not widely used for water-well site studies. Literature and logs on the basic geological formations are available through national and state geological surveys, state oil and gas agencies, state water resources agencies, and some universities. The available geologic information should be collected