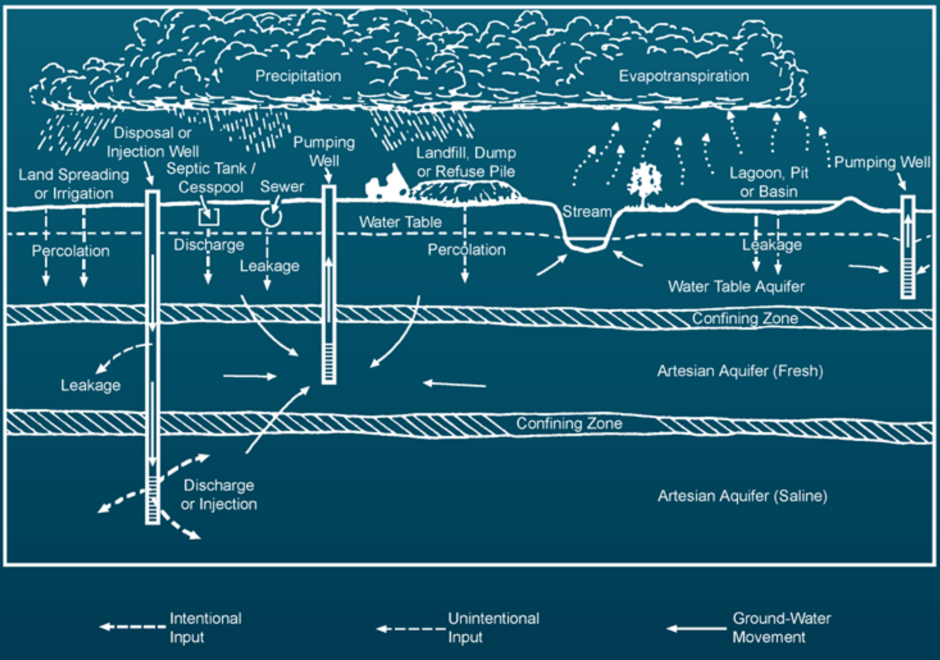
Practical Handbook of

SOIL, VADOSE ZONE, and GROUND-WATER CONTAMINATION

Assessment, Prevention, and Remediation



SECOND EDITION

J. Russell Boulding • Jon S. Ginn

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Preface to the Second Edition

I would like to think that the popularity of the first edition of this book is a measure of success in meeting the goals I outlined in the preface to the first edition. With this second edition I welcome Jon Ginn as a co-author. Since entering semiretirement in 1997, I have kept abreast of new developments in site characterization technologies through my part-time association with the Applied Geology and Environmental Management Section of the Environmental Research Division at Argonne National Laboratory. Jon's up-to-date expertise in remediation technologies has been essential for updating Part III of this book, and he has made valuable contributions to updating other sections of the book as well. The basic approach and organization of this book remain the same. Since the first edition was published in 1995, many of the advances that have taken place in the assessment and remediation of soil and ground-water contamination have been more refinements of existing techniques in terms of either instrumentation or computer processing. The text of this new edition has been revised throughout to note refinements or new applications of existing methods. Also, more than 600 new references have been indexed and added to the topical major reference lists at the end of each chapter. For those who may be familiar with the first edition, major revisions and new sections are identified below.

Part I (Basic Concepts) is essentially the same except for the following:

- In Chapter 2, Section 2.4.3 on soil moisture retention relationships has been added, and at the end of the chapter information on the U.S. Geological Survey's *Ground Water Atlas of the United States*, current as of 2002, has been added.
- In Chapter 3, Section 3.3.2 (Hydrolysis) and Section 3.5.4 (Biotransformation of Organic Contaminants) have been expanded.
- In Chapter 4, Section 4.5.3 (Retardation by Sorption) and Section 4.6 (Phase Partitioning to Assess Presence of DNAPLs in the Subsurface) have been added.

Part II (Assessment and Monitoring) has a number of new sections and subsections:

- Special Considerations for DNAPL Investigations (Section 5.1.4)
- Accelerated/Expedited Site Characterization Approaches (Section 5.1.5)
- CPT and Other Direct-Push Sensing Methods (Section 6.5)
- Alcohol Tracers (Section 8.3.5)
- Divergent-Line-Drive Techniques (Section 8.5.4)
- New Developments in Multilevel Sampling (Section 9.5.4)
- Neural Networks and Automated Image Processing (Section 10.5.6)

Part III (Prevention and Remediation) also has a number of new sections:

- Passive Soil Vapor Extraction (Section 13.2.5)
- Soil Thermal Extraction Methods (Section 13.4.4)
- Permeable Reactive Treatment Walls (Section 14.6.3)
- Phytoremediation (Section 14.6.4)
- Enhanced Natural Attenuation (Section 14.6.5)

In addition to revisions to Appendix A (Summary Information on Major Subsurface Characterization and Monitoring Techniques) to add a number of new techniques, a new Appendix B provides a comprehensive index and listing of more than 500 American Society for Testing and Material (ASTM) standard guides, practices, and test methods that may be useful in the field or laboratory for environmental site characterization. Appendix C (Tables and Figures for Estimation of Aquifer Parameters) includes several new empirical equations for estimating hydraulic conductivity from grain size and for estimation of hydrodynamic dispersivity. Finally, a new Appendix E has been added which includes simple problems (with solutions at the end) for determining aquifer properties and contaminant fate and transport behavior.

Preface to the First Edition

My goal in writing this book has been to create a single, convenient reference source to be used (1) as a starting point for obtaining answers to questions that any environmental manager or professional might have about contaminated soil or ground-water, or (2) as a textbook for a college course that focuses on technical aspects of soil and ground-water contamination assessment and management.

Environmental professionals, managers, and regulators without specialized training in soils, geology, geomorphology, vadose-zone and ground-water hydrology, soil and ground-water chemistry, and microbiology will find that the four chapters in Part I (Basic Concepts) provide a comprehensive, yet accessible introduction to those topics as they relate to soil and ground water contamination.

Project planning and field personnel involved in investigating contaminated sites will find that the six chapters in Part II (Assessment and Monitoring) provide up-to-date and comprehensive information on methods for characterizing contaminated sites and analyzing site data.

Decision makers, project planners, and other environmental professionals will find that the four chapters in Part III (Prevention and Remediation) provide systematic and practical information for identifying and implementing methods for (1) preventing or minimizing contamination and (2) cleaning up sites that are already contaminated.

NOTE ABOUT REFERENCE CITATIONS IN THIS HANDBOOK

In order to minimize duplication of references in this handbook, references are cited in four ways:

- Major references are grouped into 23 topics, which follow index tables at the end of each chapter. A master list of these index tables and bibliographies can be found at the end of the Table of Contents.
- Citations in the text are given as footnotes, unless they are contained in a reference table, in which case the reference table number is given. For example, Sara (2002/T9.10) indicates that the full citation can be found in Table 9.10.
- Increasingly, government documents are available electronically on the Internet. Internet sites are identified by brackets: < >. For example, one source of EPA documents is <clu-in/techpubs.htm>.
- Sources for figures and tables in Chapters 1 through 14 are given in Appendix F, which also serves as a master list with the page on which figures and tables can be found. Full citations for references cited in Appendices A through D appear at the end of each appendix.
- ASTM standard methods are cited by the ASTM designation number in the text. Full citations for ASTM test methods can be found in Appendix B, which provides a comprehensive index and listing of ASTM standards that may be useful for environmental site characterization.

Where government documents are cited, the place where documents can be obtained is given or, if the document is available from the National Technical Information Service, the NTIS acquisition number is given. U.S. EPA's National Service Center for Environmental Publications (NSCEP) is the best place to contact for obtaining EPA documents (NSCEP, P.O. Box 42419, Cincinnati, OH 45242-0419; 800-490-9198). This book may refer to earlier names for NSCEP: Center for Environmental Research Information (CERI) or National Center for Environmental Publications and Information (NCEPI). If NSCEP does not have the document, it will refer the request to the appropriate EPA office or provide the NTIS acquisition number. Table 5.3 identifies phone numbers for other EPA hotlines and information sources. Documents available from NTIS can be obtained by calling 800-553-6847 or writing to: National Technical Information Service, Springfield, VA 22161.

NOTE ABOUT GROUND WATER HYPHENATION CONVENTIONS

There are few words in the environmental literature that have greater editorial inconsistency than ground water. The preferred ASTM usage of two words for *ground water* (to parallel *surface water*, which is never written as a single word) is used in this handbook, except when reference citations use a single word, *groundwater*, in the title, in which case they are cited as written. Given the inconsistency in hyphenation practices for the terms *vadose zone* and *ground water* in the literature, I have chosen as a matter of personal preference to use the following conventions: (1) *neither* vadose zone nor ground water is hyphenated when it serves as a modifier in chapter, section, figure, and table titles because I think it looks better that way; (2) vadose zone is *not* hyphenated in normal text when it serves as a modifier because that seems to be the most common usage in the vadose zone literature; and (3) ground water *is* hyphenated when it serves as a modifier because that seems to be the more common usage in the ground-water literature. I think it was Ralph Waldo Emerson who said "Foolish consistency is the hobgoblin of little minds." I have tried to consistently follow the above inconsistent conventions, but am not overly concerned if I have not entirely succeeded.

ABBREVIATIONS AND ACRONYMS

AGWSE	Association of Ground Water Scientists and Engineers (NWWA/NGWA)
API	American Petroleum Institute
CERI	Center for Environmental Research Information (now NSCEP)
CPT	Cone penetration test
DNAPL	Dense nonaqueous phase liquid
EPA	U.S. Environmental Protection Agency
HEW	U.S. Department of Health, Education and Welfare
HMCRI	Hazardous Materials Control Research Institute
IGWMC	International Ground Water Modeling Center
LNAPL	Light nonaqueous phase liquid
NAPL	Nonaqueous phase liquid
NCEPI	National Center for Environmental Publications and Information (now NSCEP)
NSCEP	National Service Center for Environmental Publications (U.S. EPA)
NWWA/NGWA	National Water Well Association (named changed to National Ground Water Association in 1992)
PAH	Polynuclear aromatic hydrocarbon
PNA	Polynuclear aromatic compound
RCRA	Resource Conservation and Recovery Act
WHPA	Wellhead protection area

The Authors

J. Russell Boulding first began working in the environmental field in 1973 when he helped set up the Environmental Defense Fund's Denver Office, and has been a freelance environmental consultant since 1977 when he established Boulding Soil-Water Consulting in Bloomington, Indiana. Boulding Soil-Water Consulting was closed in 1997, but Mr. Boulding continues to work part-time with the Applied Geoscience and Environmental Management Section of the Environmental Research Division of Argonne National Laboratory. He has a B.A. in geology (1970) from Antioch College, Yellow Springs, Ohio, and an M.S. in water resources management (1975) from the University of Wisconsin–Madison. From 1975 to 1977 he was a soil scientist with the Indiana Department of Natural Resources and mapped soils in southern Indiana on a cooperative program with the U.S. Soil Conservation Service. From 1984 to 1997 he held the position of senior environmental scientist with Eastern Research Group, Inc., in Lexington, Massachusetts.

Mr. Boulding is the author of more than 160 books, chapters, articles, and consultant reports in the areas of soil and ground-water contamination assessment, geochemical fate assessment of hazardous wastes, mined land reclamation, and natural resource management and regulatory policy. From 1978 to 1980 he served as a member of the Environmental Subcommittee of the Committee on Surface Mining and Reclamation (COSMAR) of the National Academy of Sciences (NAS) and as a consultant to the NAS Committee on Soil as a Resource in Relation to Surface Mining for Coal. Mr. Boulding is an ARCPACS-certified professional soil classifier.

Since 1992 he has been a member of the American Society for Testing and Materials' Committee D18 (Soil and Rock) and active in Subcommittees D18.01 (Surface and Subsurface Characterization) and D18.21 (Ground Water and Vadose Zone Investigations). From 1993 to 1997 he chaired D18.01's Section on Site Characterization for Environmental Purposes, and he is the principal author of five ASTM standards, including D5730 (*Guide for Site Characterization for Environmental Purposes*), D6235 (*Practice for Expedited Site Characterization of Vadose Zone and Ground Water Contamination at Hazardous Waste Contaminated Sites*), and D6169 (*Guide for Selection of Soil and Rock Sampling Devices for Use with Drill Rigs*). In January 2001 he received the Ivan A. Johnson Outstanding Achievement Award for outstanding and significant contributions to ASTM Committee D18 on Soil and Rock.

Jon S. Ginn began work in the environmental field in 1995 for the Environmental Management Directorate, at Hill Air Force Base (HAFB), Utah. He worked as the program manager for innovative technology demonstrations and provided technical oversight, project management, and regulatory coordination for numerous innovative remedial technology demonstrations. During the 6 years he worked at Hill, he managed over $17 million in internal and external funded research, including surfactant enhanced aquifer remediation, partitioning interwell tracer tests for DNAPL characterization, thermally enhanced aquifer remediation, air sparging, bioventing of nonpetroleum hydrocarbons, three-dimensional seismic reflection, and enhanced bioremediation studies. He also served for 3 years as the HAFB regulatory compliance protocol manager for petroleum, oils, and lubricants (POL) under the Environmental Compliance Assessment and Management Program (ECAMP) at Hill Air Force Base.

In 2001, Dr. Ginn joined Select Engineering Services, Inc., Ogden, Utah. He provides technical oversight and program management for the Tactical Shelter and Radome Program office at Hill Air Force Base. Specific projects include the development and integration of composite technology for tactical shelters, radomes, and towers. He also provides technical oversight and program support for the Pollution Prevention Program Office at Hill Air Force Base regarding alternative energy, compliance site inventory, and process-specific opportunity assessments. He received his B.S. in civil engineering from Texas A&M University in 1987 and an M.S. in civil engineering from Texas A&M University in 1990. In 1997, he received his Ph.D. from Utah State University in environmental engineering.

Acknowledgments

This book represents the synthesis and, in a sense, the culmination of work done from 1989 to 1995 on a series of technology transfer documents written wholly or in part by the author for U.S. EPA's Center for Environmental Research Information. At the project management level, Heidi Schultz (Eastern Research Group) and Carol Grove and Sue Schock (U.S. EPA/CERI) require special recognition.

The starting point for this book was a 700-page manuscript that was an expanded and extensively revised version of EPA's 1987 *Ground Water Handbook* (EPA/625/6-87/016), which was written by Michael Barcelona, Joseph Keely, Wayne Pettyjohn, and Allen Wehrmann. Chapter 7 of that document drew heavily upon another EPA report, *Introduction to Ground Water Tracers* (EPA/600/2-85/022), by S.N. Davis, D.J. Campbell, H.W. Bentley, and T.J. Flynn, and Chapter 8 on Joseph Keely's monograph *The Use of Models in Managing Ground-Water Protection Programs* (EPA/600/8-87/003). As it turned out, the author's revised versions of Chapters 7 and 8 are the only ones that were published in EPA's second edition of the *Ground Water Handbook, Volume I: Ground Water and Contamination* (EPA/625/6-90-16a) and *Volume II: Methodology* (EPA/625/6-90-16a), both of which are available from the Center for Environmental Research Information. These, with third-generation revisions and updating, appear in this handbook as Chapter 8 (Soil and Ground Water Tracers) and Chapter 10 (Use of Models and Computers in Contaminant Investigations). To the extent that material originally written by the above-mentioned individuals can be found in this handbook, they deserve credit. Maureen Casey and Leslie Sparrow, HydroQual, Inc., New Jersey, made significant contributions to chapters on monitoring well design and construction, ground-water sampling, and ground-water restoration in the manuscript mentioned at the beginning of this paragraph, some of which has probably made its way into this handbook.

Other individuals who require special recognition for textual contributions to this handbook are Ron Sims and Judy Sims, whose chapters in EPA's *Site Characterization for Subsurface Remediation* on basic approaches to soil and ground-water remediation and on remediation techniques for contaminated soils formed the starting point for Chapters 12 and 13 in this handbook. I was technical editor of that document, and co-author with Michael Barcelona of chapters on basic statistical and analytical concepts and geochemical sampling of subsurface solids and ground-water, which provided the basis for much of Chapter 5 of this handbook.

Anyone bothering to read these acknowledgments may wonder if I can take credit for any of the contents of this handbook. I am the original author of Chapter 3 (Soil and Ground Water Geochemistry and Biology), Chapter 4 (Sources and Behavior of Subsurface Contaminants), Chapter 6 (Geophysical and Remote Sensing Techniques), Chapter 11 (Prevention and Minimization of Contamination), all reference tables and compilations, and all the appendices. All other chapters represent second- to fourth-generation edits, revisions, or updates on my part.

In various incarnations, the material in this handbook has benefited from the technical review and suggestions from many individuals: Gina Bochicchio, Fred Cornell, Larry Eccles, Lorne Everett, Malcolm Field, Pete Haeni, Paul Heigold, Jan Hendrickx, Beverly Herzog, Dave Kaminski, Jack Keeton, Scott Keys, Eric Koglin, Duncan McNeill, Gary Olhoeft, Robert Powell, Robert Puls, Charlie Riggs, Ron Schalla, Ron Sims, Jim Ursic, Paul van der Heijde, Mark Vendl, and John Williams. Special thanks are due to my colleagues on ASTM's Environmental Site Characterization Task Group (Joe Downey, Ed Gutentag, and Mario Fernandez) and to Gareth Davies and Mark Kram for review of individual or multiple chapters. Special thanks also to Cathy Wootton Clayton for her work on graphics and image production.

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List of Reference Index Tables

(See Appendix F for list of figures and other tables.)

Part I

Basic Concepts

CHAPTER 1

Geology, Soils, and Geomorphology

Geology, the study of the earth, includes the investigation of earth materials, the processes that act on these materials, the products that are formed, the history of the earth, and the origin and development of life-forms. There are several subfields of geology. *Physical geology* deals with all aspects of the earth and includes most earth science specialties. *Historical geology* is the study of the origin of the earth, continents and ocean basins, and life-forms. *Economic geology* is an applied approach focusing on the search and exploitation of mineral resources, such as metallic ores, fuels, and water. *Structural geology* deals with the various structures of the earth and the forces that produce them. *Geophysics* is the examination of the physical properties of the earth and includes the study of earthquakes and methods to evaluate the subsurface.

All of the geology subfields are used to some extent in the study of ground water. Probably the most difficult concept to comprehend by individuals with little or no geological training is the complexity of the subsurface, which is hidden from view and, at least presently, cannot be adequately sampled. A guiding principle in geologic and hydrogeologic studies is that the present is the key to the past. The processes occurring today are the same processes that have occurred throughout geologic history, although their magnitude may vary with time. Furthermore, an understanding of present processes, and how they have acted in the past, can be used as a guide to predict the future.

Soil science, also called *pedology*, and *geomorphology*, the study of surface landforms, are disciplines related to geology but focusing on the earth's surface. Geology, soil science, and geomorphology are intimately related and concerned with many of the same earth processes, such as weathering, erosion, and deposition. Nevertheless, each of these disciplines has a distinct perspective that is usually helpful and often essential in the study of ground-water contamination.

This chapter provides a brief description of fundamental concepts in geology, soil science, and geomorphology as they relate to ground-water contamination. Sections 1.1 (Geologic Materials), 1.2 (Geologic Processes), and 1.3 (Stratigraphy and Structure) focus on geology. Section 1.4 examines basic soil concepts and Section 1.5 geomorphic concepts, with special emphasis on karst geomorphic settings because of their distinctive hydrogeologic characteristics, which include very rapid movement of contaminants in the subsurface.

1.1 GEOLOGIC MATERIALS

Geologic materials result from constant changes at the earth's surface and subsurface. Over long periods of time these changes affect the location, quality, and movement of ground water. Rocks that rise as mountains over millions of years will be gradually eroded and transported by wind, water, or gravity to low-lying areas. Variations in these transport processes alter particles physically and chemically, giving rise to deposits of unique texture and composition. Grain-size variations and degree of sorting will cause differences in permeability and ground-water velocity, while changes in mineral composition can lead to variations in water quality.

1.1.1 Mineralogy

Minerals are the basic building blocks of rocks. Most minerals contain two or more elements, but of all the elements known, only eight account for nearly 98% of the rocks and minerals:

Oxygen	46%
Silicon	27.7%
Aluminum	8.1%
Iron	5.0%
Calcium	3.6%
Sodium	2.8%
Potassium	2.6%
Magnesium	2.1%

A general understanding of mineralogy is important to the study of ground water because it is the mineral composition of rocks that, to a large extent, controls the quality of water that a rock contains under natural conditions and the chemical reactions between rock and contaminants or naturally occurring substances.

The most common rock-forming minerals can be divided into four broad groups: (1) oxides, carbonates, and sulfates; (2) silicates; (3) clay minerals; and (4) common ores. Organic matter, from which oil shales, coal, and petroleum deposits form, is another important material that is discussed in Section 3.4.4 because of its geochemical importance in soil and ground-water chemistry.

Oxides, Carbonates, and Sulfates. *Quartz* (SiO_2), one of the most common minerals, is hard and resistant to both chemical and mechanical weathering. In sedimentary rocks, quartz occurs as sand-size grains (sandstone) or finer silt- and clay-size grains. It may also appear as a silica cement. Because of the low solubility of silica, it generally appears in ground water in concentrations of less than 25 mg/l.

Limonite is actually a group name for the hydrated ferric oxide minerals ($Fe_2O \cdot 3H_2O$) that occur so commonly in many types of rocks. Limonite is generally rusty or blackish with a dull, earthy luster. It is a common weathering product of other iron minerals. Because limonite and other iron-bearing minerals are nearly universal, dissolved iron is a very common constituent in water, causing staining of clothing and plumbing fixtures.

The major carbonate minerals are *calcite* ($CaCO_3$), the major component of limestone, and *dolomite* ($CaMg(CO_3)_2$). Dolomite is also the name of carbonate sediments enriched with this magnesium carbonate. *Gypsum*, a hydrated calcium sulfate ($CaSO_4 \cdot 2H_2O$), occurs as a sedimentary evaporite deposit and as crystals in shale and some clay deposits. Quite soluble, it is the major source of sulfate in ground water.

Silicates. The most common rock-forming silicate minerals include the feldspars, micas, pyroxenes, amphiboles, and olivine. Feldspars, the most abundant minerals on earth, are alumino-silicates of potassium or sodium and calcium. Most of the minerals in this group are white, gray, or pink. Upon weathering, they turn to clay and release the remaining chemical elements to water. Muscovite and biotite mica are platy alumino-silicate minerals that are common and easily recognized in igneous, metamorphic, and sedimentary rocks. Pyroxenes, a group of silicates of calcium, magnesium, and iron, as well as amphiboles, which are complex hydrated silicates of calcium, magnesium, iron, and aluminum, are common in most igneous and metamorphic rocks. They appear as small, dark crystals. Olivine, a magnesium–iron silicate, is generally green or yellow and is common in certain igneous and metamorphic rocks. None of the rock-forming silicate minerals has a major impact on water quality in most situations.

Clay Minerals. Next to organic matter (see Section 3.4.4), clay minerals are the most chemically active materials in soil and unconsolidated geologic materials. Both consolidated materials composed of clay minerals (shales) and clayey unconsolidated materials tend to have low permeabilities, and consequently, water movement is very slow. Because of their geochemical significance in the study of ground-water contamination, clay minerals are described in more detail here than the other major mineral groups. Two broad groups of clay minerals are recognized: silicate clays and hydrous oxide clays.

Silicate clays form from the weathering of primary silicate minerals such as feldspars and olivine. They have a sheet-like lattice structure with either silicon (Si) in coordination with four oxygen atoms (silica tetrahedra) or aluminum (Al) in coordination with six oxygen atoms (alumina octahedra). The strong sorptive capacity of clay derives from the negative charges created at the edges of these crystalline sheets where oxygen atoms (O^{-2}) have extra electrons that are not bonded to the cations in the crystalline structure. The negative charge can be further increased when ions with a lower valence substitute for ions with a higher valence in the sheet structure (for example, Al^{+3} substitutes for Si^{+4} in tetrahedral sheets, and Mg^{+2} substitutes for Al^{+3} in octahedral sheets).

Silicate clays are classified according to different stacking arrangements of the tetrahedral (silica) and octahedral (alumina) lattice layers and their tendency to expand in water. The stacking type strongly affects certain properties of clays, including (1) surface area, (2) the tendency to swell during hydration, and (3) *cation exchange capacity* (CEC), which is a quantitative measure of the ability of a mineral surface to adsorb ions. CEC is the sum of exchangeable cations that a material can adsorb at a specific pH. Standard International (SI) units for CEC are centimoles per kilogram, but it is also commonly reported as milliequivalents (meq) per 100 g, where 1 meq is defined as 1 mg of hydrogen or the amount of any other ion that will combine with or displace 1 mg of hydrogen. These units are interchangeable (1 cmol/kg = 1 meq/100 g).

Table 1.1 summarizes some properties of different silicate clay minerals. The montmorillonite group of silicate clays is most sensitive to swelling and has a high CEC. This type of clay has these characteristics because the 2:1 lattice structure (two octahedral sheets separated by a tetrahedral sheet) forms sheets that are loosely connected by exchangeable cations. The exchange sites between 2:1 lattice layers can be easily hydrated (i.e., adsorb water molecules) under certain

Table 1.1 Important Characteristics of Silicate Clay Minerals

	Type of Clay[a]				
Property	**Montmorillonite (Smectite)[b]**	**Vermiculite**	**Illite**	**Chlorite**	**Kaolinite**
Lattice type[c]	2:1	2:1	2:1	2:2	1:1
Expanding?	Yes	Slightly	No	No	No
Specific surface area (m^2/g)	700–800	700–800	65–120	25–40	7–30
External surface area	High	High	Medium	Medium	Low
Internal surface area	Very high	High	Medium	Medium	None
Swelling capacity	High	Medium-high	Medium	Low	Low
Cation exchange capacity (meq/100 g)	80–150	100–150+	10–40[e]	10–40[e]	3–15[e]
Other similar clays	Beidellite				Halloysite
	Nontronite				Anauxite
	Saponite				Dickite
	Bentonite[d]				Nacrite

[a] Clays are arranged from most reactive (montmorillonite) to least reactive (kaolinite).
[b] The term *smectite* is now used to refer to the montmorillonite group of clays (Soil Science Society of America, 1987/T1.3).
[c] Tetrahedral:octahedral layers.
[d] Bentonite is a clay formed from weathering of volcanic ash and is made up mostly of montmorillonite and beidellite.
[e] Upper range occurs with smaller particle size.

Source: Boulding (1990).

conditions. Because the water molecules have a greater diameter than the cations that hold the sheets together, hydration pushes the layers farther apart. Vermiculite has stronger negative charges on its inner surfaces than montmorillonite because of the substitution of lower-valence magnesium ions for aluminum. This factor results in an even higher CEC than that found in montmorillonite, but it also has the effect of bonding the 2:1 sheets more strongly. Consequently, vermiculite clays are less susceptible to swelling.

In Table 1.1, the clays are listed in sequence from most reactive (montmorillonite and vermiculite) to least reactive (kaolinite). The 1:1 lattice structure in kaolinite creates strong bonds between the paired sheets, resulting in a low surface area and CEC. Illite and chlorite have intermediate surface areas, CEC, and sensitivities to swelling.

Clay minerals in sedimentary formations are usually mixtures of different groups. In addition, *mixed-layer* clay minerals can form. These minerals have properties and compositions that are intermediate between two well-defined clay types (i.e., chlorite-illite, illite-montmorillonite, etc.). Where soils have a high clay content, clay mineralogy is a criterion for classification of soils in the U.S. Department of Agriculture (USDA) soil taxonomy (Section 1.4.2). Such soils are identified by the dominant clay (hallosyite, illite, kaolinite, montmorillonite, etc.) or as having mixed mineralogy.

Hydrous oxide clays are less well understood than silicate clays. These clays are oxides of iron, magnesium, and aluminum that are associated with water molecules, although the exact mechanism by which the water molecules are held together is somewhat uncertain. Because of the lower overall valence of the cations in hydrous oxide clays compared to silicate clays, CEC is lower in hydrous oxide clays. However, hydrous oxides of magnesium (Mn) and iron (Fe) can furnish the principal control on the fixation of cobalt (Co), nickel (Ni), copper (Cu), and zinc (Zn) heavy metals in soils and freshwater sediments.[1]

Ores. The three most common ore minerals are galena, sphalerite, and pyrite. Galena, a lead sulfide (PbS), is heavy, brittle, and breaks into cubes. Sphalerite is a zinc sulfide (ZnS) mineral that is brownish, yellowish, or black. It ordinarily occurs with galena and is a major zinc ore. The iron sulfide pyrite (FeS), which is also called fool's gold, is common in all types of rocks. Weathering of this mineral leads to acid-mine drainage, a major surface and ground-water quality problem in certain coal mining areas of the Midwest and Appalachia and in metal sulfide mining regions.

1.1.2 Texture and Fabric

The term *texture* has different meanings in geology and soil science. In soil science it is simply the relative proportions of clay-, silt-, and sand-size particles in soil or unconsolidated material. In geology, describing the texture involves characterization of grain size, but also grain shape, degree of crystallization, and contact relationships of grains. The term *fabric* applies to the total of all physical features of a rock or soil that can be observed macroscopically and microscopically. In solid rock this includes texture, porosity, orientation of mineral grains, cleavage, joints, and fractures, all of which may influence water-transmitting characteristics. Soil fabric analysis involves the study of the distinctive physical features resulting from soil-forming processes, which also strongly influence the location and rate of water movement in soil.

A variety of scales are available for the classification of unconsolidated materials based on particle-size distribution. In geology, the *Wentworth–Udden* scale is most widely used: boulder (>256 mm), cobble (64–256 mm), pebble (4–64 mm), granule or gravel (2–4 mm), sand (1/16–2 mm), silt (1/256–1/16 mm), and clay (<1/256 mm). The USDA soil textural classification system is most widely used by soil scientists; engineers usually use the American Society for Testing and Materials (ASTM) version (ASTM D2488/TA.14) of the Unified Soil Classification System (USCS), and less commonly the American Association of State Highway Officials (AASTHO) soil

[1] Jenne, E.A. 1968. Controls on Mn, Fe, Co, Ni, Cu, and Zn Concentrations in Soils and Water: The Significant Role of Hydrous Mn and Fe Oxides. In: Adsorption from Aqueous Solution, ACS Advances in Chemistry Series 79, pp. 337–387, American Chemical Society, Washington, D.C.

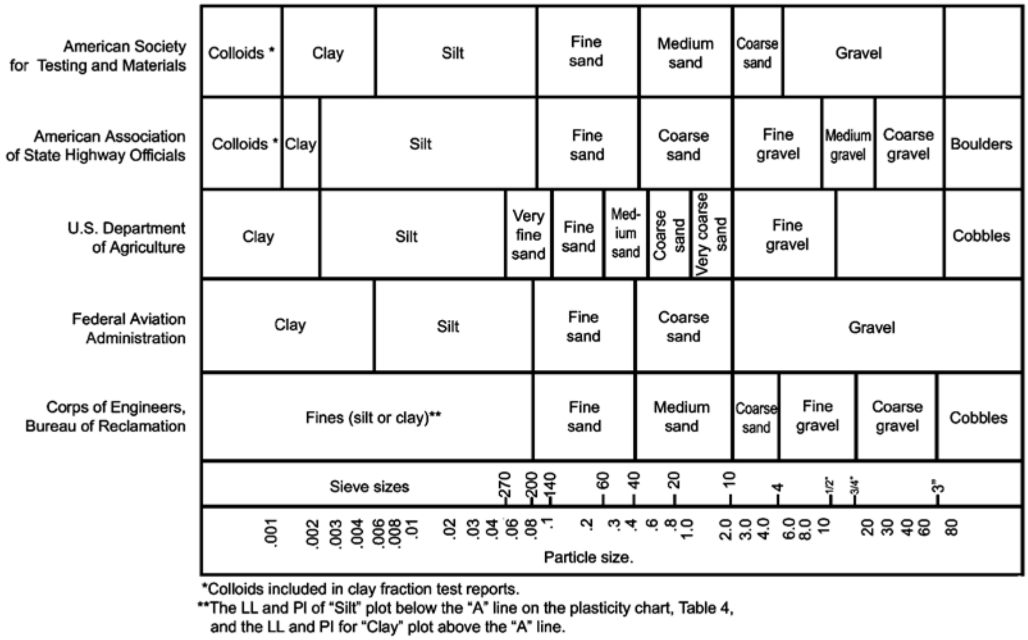

Figure 1.1 Particle-size limits of different U.S. textural classification systems (Mercer and Spalding, 1991b, after Portland Cement Association, 1973).

classification system. Figure 1.1 compares the grain-size limits for the ASTM, AASTHO, USDA, Federal Aviation Administration (FAA), and the U.S. Army Corps of Engineers/Bureau of Reclamation. Figure 1.2 shows the 12 USDA soil texture classes based on relative percentages of silt, sand, and clay. The hydrologic properties of soils are strongly related to particle-size distribution, and the USDA system is a useful system for estimating a number of these properties (see, for example, Figures C.2, C.8, and C.9).

For several reasons, the term *clay* may be confusing. First, the various particle-size distribution schemes define clay differently. The Wentworth–Udden scale for clay (<0.0039 mm) lies between the AASTHO (<0.005) and the USDA (<0.002) definitions. The ASTM and FAA systems define clay as <0.004 mm, which includes silt-size particles in the USDA system (see Figure 1.1). Second, clay minerals are usually clay-size particles, but may be silt-size. Similarly, nonclay minerals may be clay particles if they are small enough.

1.1.3 Rocks

Three major types of rock make up the earth. *Igneous rocks* have solidified from molten material either within the earth (intrusive) or on or near the surface (extrusive). *Metamorphic rocks* originally were igneous or sedimentary rocks that have subsequently been modified by temperature, pressure, or chemically active fluids. *Sedimentary rocks* result from the weathering of preexisting rocks, erosion, and deposition. While geologists have developed elaborate systems of nomenclature and classification of rocks, only basic rock descriptions having the most value in hydrogeologic studies will be presented here.

Igneous Rocks. Igneous rocks are classified on the basis of their composition and grain size. *Basic* igneous rocks consist mostly of feldspar and a variety of dark, iron- and magnesium-rich minerals (olivine, pyroxenes, and hornblendes). *Acidic* igneous rocks are lighter in color, with feldspar, quartz, and micas being the dominant minerals. If the parent molten material cools slowly deep below the surface, minerals will have an opportunity to grow and the rock will be coarse grained (*gabbro*, if cooled from basic magma, and *granites*, if cooled from acidic magma). Magma

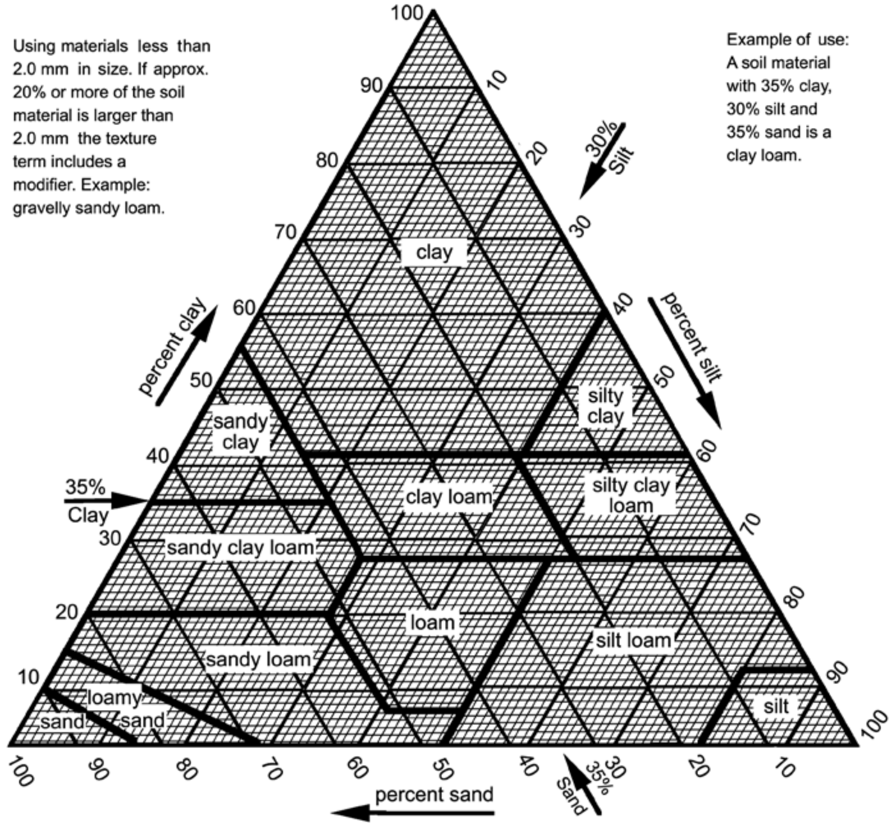

Figure 1.2 Guide for USDA soil textural classification (SCS, 1971).

that cools rapidly, such as that derived from volcanic activity, is so fine grained that individual minerals generally cannot be seen even with a hand lens. *Basalt* is the fine-grained equivalent of gabbro, and *andesite* is the fine-grained equivalent of granite. In some cases, the molten material initially cools slowly, allowing large mineral crystals to grow. If the cooling rate increases, rapid cooling crystallizes the remaining melt into a fine-grained matrix. This texture, consisting of large crystals in a fine-grained matrix, is called *porphyritic*.

Intrusive igneous rocks can only be seen where they have been exposed by erosion. They are *concordant* if they generally parallel the bedding of the enclosing rocks and *discordant* if they cut across the bedding. The largest discordant igneous masses are called batholiths and occur in the eroded centers of many ancient mountains. Their dimensions are in the range of tens of miles. Batholiths usually consist largely of granite, which is surrounded by metamorphic rocks. Other discordant igneous rocks include *dikes* ranging in thickness from a few inches to thousands of feet. Many are several miles long. *Sills* are concordant bodies that have invaded sedimentary rocks along bedding planes. They are relatively thin. Both sills and dikes, when intruded into existing rocks, tend to cool quite rapidly and are fine grained. *Pegmatite* dikes, on the other hand, form in the last stages of a magma's cooling, and can form centimeter- to meter-length crystals.

Extrusive rocks include lava flows or other types associated with volcanic activity, such as the consolidated ash called *tuff*. These are fine grained or even glassy. Some extrusive rocks, like pumice, have sufficiently high porosity resulting from gas bubbles in the magma during cooling that they can float on water.

Igneous rocks are typically dense and have very low porosity and permeability. Most, however, are fractured to some degree and can store and transmit a modest amount of water. These fractures form preferential flow paths for contaminants, resulting in relatively rapid movement, even though the overall hydraulic conductivity is low. Some lava flows are notable exceptions because they contain large-diameter tubes or a permeable zone at the top of the flow where gas bubbles migrated to the surface before the rock solidified. These rocks are called scoria.

Metamorphic Rocks. Metamorphism is a process that changes preexisting rocks into new forms because of increases in temperature, pressure, and chemically active fluids. Metamorphism may affect igneous, sedimentary, or other metamorphic rocks. The changes brought about include the formation of new minerals, increase in grain size, and modification of rock structure or texture, all of which depend on the original rock's composition and the intensity of the metamorphism.

Some of the most obvious changes are in texture, which serves as a means of classifying metamorphic rocks into two broad groups: foliated and nonfoliated rocks. *Foliated* metamorphic rocks typify regions that have undergone severe deformation, such as mountain ranges. Shale, which consists mainly of silt and clay, is transformed into slate by the change of clay to mica. Mica, a platy mineral, grows with its long axis perpendicular to the principle direction of stress, forming a preferred orientation. This orientation, as in the development of cleavage in slate, may differ greatly from the original bedding.

With increasing degrees of metamorphism, the grains of mica grow larger so that the rock has a distinct foliation texture, characteristic of the metamorphic rock *schist*. At even higher grades of metamorphism, the mica may be transformed to a much coarser grained feldspar, producing the strongly banded texture of *gneiss*.

Nonfoliated rocks include the hornfels and another group formed from rocks that consist mainly of a single mineral. The *hornfels* occur around an intrusive body and were changed by "baking" during intrusion. The second group includes marble and quartzite, as well as several other forms. *Marble* is metamorphosed limestone, and *quartzite* is metamorphosed quartz sandstone.

There are many different types of metamorphic rocks, but from a hydrogeologic viewpoint, they neither store nor transmit much water and are of only minor importance as aquifers. Their primary permeability is notably small, if it exists at all, and fluids are forced to migrate through secondary openings, such as faults, joints, or other types of fractures. As with igneous rocks, the concentration of flow in fractures means that contaminants may move relatively rapidly, especially in response to ground-water pumping.

Sedimentary Rocks. Sedimentary rocks are deposited either in a body of water or on the land by running water, wind, and glaciers. Sediments are first derived by the weathering and erosion of preexisting rocks, and each depositional agent leaves a characteristic stamp on the material it deposits (Section 1.2.3). The change from a loose, unconsolidated sediment to a rock is the process of *lithification*. Unconsolidated sediments are discussed in Section 1.1.4. The most common sedimentary rocks are shale, siltstone, sandstone, and limestone. Although sedimentary rocks appear to be the dominant type, in reality they make up but a small percentage of the earth. They are most readily evident, however, because they form a thin crust over much of the earth's surface. Sedimentary rocks and the unconsolidated materials that serve as precursors to sedimentary rocks are the primary sources of ground water.

Most sedimentary rocks are deposited in a sequence of layers or strata. Each layer or stratum is separated by a bedding plane, which reflects variations in sediment supply or short-term erosion. Bedding planes commonly represent changes in grain size. *Stratigraphic correlation* is the process of matching strata between wells or outcrops (Section 1.3).

Sedimentary rocks are classified on the basis of texture (grain size and shape) and composition. *Clastic* rocks consist of particles of broken or worn material and include shale, siltstone, sandstone, and conglomerate. These rocks were lithified by compaction, in the case of shale, and by cementation. The most common cements are clay, calcite, quartz, and limonite. The last three, carried by ground water, precipitate in the unconsolidated material under specific geochemical conditions.

The *organic* or *chemical* sedimentary rocks consist of strata formed from or by organisms and by chemical precipitates from seawater or other solutions. Most have a crystalline texture. Some consist of well-preserved organic remains, such as reef deposits and coal seams. Chemical sediments include limestones, dolomites, and evaporites such as halite (sodium chloride), gypsum, and anhydrite (anhydrous calcium sulfate).

The major features of marine sedimentary rocks are their widespread occurrence and generally uniform thickness and composition. If not disturbed by some type of earth movement, they are stratified and horizontal. Furthermore, each lithologic type is unique relative to adjacent units. The bedding planes or contacts that divide them represent distinct differences in texture or composition. From a hydrologic perspective, differences in texture from one rock type to another produce boundaries that strongly influence ground-water flow. Ground water tends to flow parallel to these boundaries, that is, within particular geologic formations rather than across them.

1.1.4 Unconsolidated Materials

Unconsolidated materials may result from the *in situ* weathering of rock or, more commonly, from erosion of weathered material with subsequent deposition at another location. The major characteristics of unconsolidated material are *sorting*, *rounding*, and *stratification*. A sediment is well sorted if the grains are nearly all the same size. Wind is the most effective sorting agent, followed by water. Glacial till is unsorted and consists of a wide mixture of material that ranges from large boulders to clay. Section 1.2.3 describes further the characteristics of waterborne, windborne, and glacial deposits.

While being transported, sedimentary material loses its sharp, angular configuration and develops some degree of rounding. The amount of rounding depends on the original shape, composition, transporting medium, and distance traveled.

Sorting and rounding are important features of both consolidated and unconsolidated material because they are key to controlling permeability and porosity. The greater the degree of sorting and rounding, the higher will be the water-transmitting and storage properties (see Table 7.2). This is why a sand deposit, in contrast to glacial till, can be such a productive aquifer.

1.2 GEOLOGIC PROCESSES

Generally speaking, a rock is stable only in the environment in which it was formed. Once removed from that environment, it begins to change, rapidly in some cases, but more often slowly, by weathering. The two major processes of weathering are mechanical and chemical, and they usually proceed in concert.

1.2.1 Mechanical Weathering

Mechanical weathering is the physical breakdown of rocks and minerals. Fracturing results when water in a crack turns to ice, or from thermal expansion and contraction resulting from daily and seasonal temperature fluctuations. Abrasion occurs during transport by water, ice, or wind. Gravity causes rocks to fall and shatter. Weathering detritus ranges in size from boulders to silt. Mechanical weathering alone only reduces the size of the rock; its chemical composition does not change. Quartz, for example, is very resistant to chemical weathering. However, it does mechanically weather to quartz sand.

1.2.2 Chemical Weathering

Chemical weathering is an actual change in composition as minerals are modified from one type to another. Many, if not most, of the changes are accompanied by a volumetric increase or decrease, which in itself further promotes additional chemical weathering. The rate depends on temperature, surface area, and available water. The major reactions that occur during chemical weathering are oxidation, hydrolysis, and carbonation. *Oxidation* is a reaction with oxygen (air) to form an oxide, *hydrolysis* is a reaction with water, and *carbonation* is a reaction with CO_2 to form a carbonate. Section 3.3 discusses these chemical processes further. Some of the feldspars weather to clay and release calcium, sodium, silica, and many other elements that are transported in water. The iron-bearing minerals leach iron and magnesium weathering products.

1.2.3 Erosion and Deposition

Once a rock begins to weather, material is transported or eroded and deposited. The major agents involved in this part of the rock cycle are running water, wind, and glacial ice.

Waterborne Deposits. Sediment reaching a stream by gravity or surface erosion is carried to a temporary or permanent site of deposition. During transportation some sorting occurs and the finer silt and clay are carried farther downstream. The streams, constantly filling, eroding, and widening their channels, deposit material that provides clues to much of the history of the region. Alluvial deposits are distinct but highly variable in grain size, composition, and thickness. Where they consist of glacially derived sand and gravel, called *outwash*, they form some of the most productive water-bearing units in the world.

Windborne Deposits. Wind-laid or *eolian* deposits are relatively rare in the geologic record. The massively cross-bedded sandstone of the Navajo Sandstone in Utah's Zion National Park and surrounding areas is a classic example in the U.S. Other deposits are more or less local and are represented by dunes formed along beaches of large water bodies or streams. Their major characteristic is the high degree of sorting. Dunes, being relatively free of silt and clay, are very permeable and porous, unless the openings have been filled by cement. They allow rapid infiltration of water and, if the topographic and geologic conditions are such that the water does not rapidly drain, can form major water-bearing units.

Another wind-deposited sediment is *loess*, which consists largely of silt- and clay-size particles. It lacks bedding but is typified by vertical jointing. Silt is transported by wind from deserts, flood plains, and glacial deposits. Loess weathers to a fertile soil and is very porous. It is common along the major rivers in the glaciated parts of the U.S. and in China, parts of Europe, and adjacent to deserts and deposits of glacial outwash.

Glacial Deposits. Glaciers erode, transport, and deposit sediments that range from clay to huge boulders. They rework the land surface over which they flow and bury former river systems. The areas covered by glaciers during the last Ice Age in the U.S. are shown in Figure 1.3, but the deposits extend far beyond the former margins of the ice. The two major types of glaciers include valley or mountain glaciers and the far more extensive continental glaciers. The deposits they leave are similar, differing for the most part only in scale.

As a glacier passes slowly over the land surface, it incorporates material from the underlying rocks into the ice mass. This material is transported and deposited elsewhere when the ice melts. During this process, glaciers modify the land surface, both through erosion and deposition. The debris associated with glacial activity is collectively termed *glacial drift*. Unstratified drift, usually deposited directly by the ice, is *glacial till*, a heterogeneous mixture of boulders, gravel, sand, silt, and clay. Till often has low porosity due to the extreme pressure exerted on it by the glacial overburden, with ground-water flow concentrated in fractures, as with igneous rocks (Section 1.1.3). Glacial debris reworked by streams and in lakes is stratified drift. Stream-laid deposits are called *glacial outwash*. Although stratified drift may range widely in grain size, the sorting far surpasses that of glacial till. Glacial lake or *lacustrine* clays are particularly well sorted.

Glacial geologists usually map on the basis of landforms resulting from glacial action, such as moraines, outwash, drumlins, etc. The various kinds of moraines and associated landforms are composed largely of unstratified drift with incorporated layers of sand and gravel. Stratified drift is found along existing or former stream valleys or lakes that were either in the glacier or extended

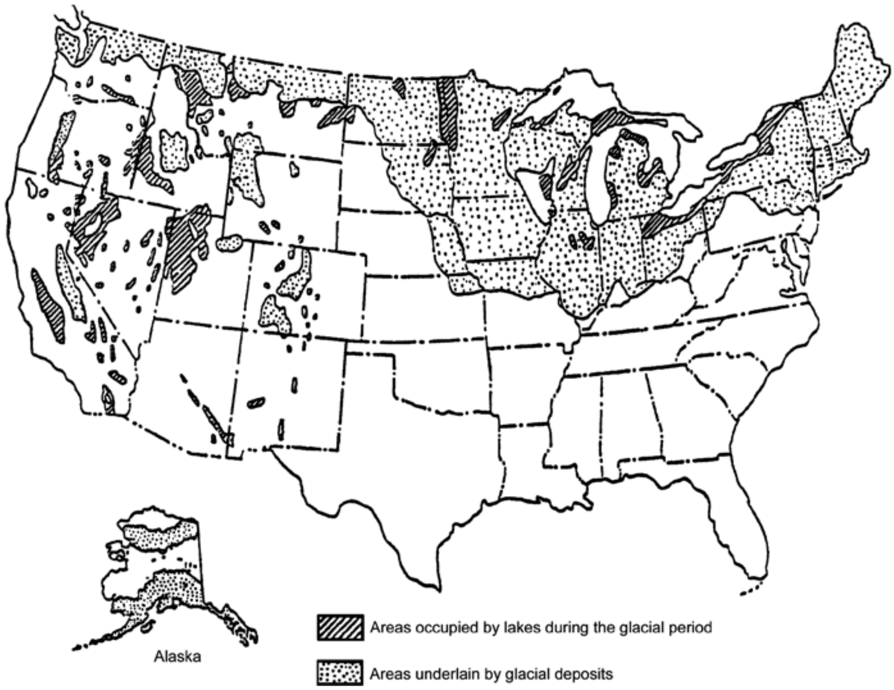

Figure 1.3 Areal extent of glacial deposits in the U.S. (Heath, 1984).

downgradient from it. Meltwater stream deposits are mixtures of sand and gravel. In some places, they have coalesced into extensive outwash plains.

Glaciers advanced and retreated many times, reworking, overriding, and incorporating sediments from previous advances into the ice, subsequently redepositing them elsewhere. There was a constant inversion of topography as buried ice melted, causing adjacent, waterlogged till to slump into the low areas. During advances, the ice might have overridden older outwash layers so that upon melting, these sand and gravel deposits were covered by a younger layer of till. Regardless of the cause, the final effect is a complex history and stratigraphy. When working with glacial till deposits, it is nearly always impossible to predict the lateral extent or thickness of a particular lithology in the subsurface. Surficial stratified drift is more uniform than till in thickness, extent, and texture.

1.3 STRATIGRAPHY AND STRUCTURE

Stratigraphy and structural geology strongly influence the occurrence and behavior of ground water, although structural geology is less important where sediments are flat lying and undisturbed by folding or faulting.

1.3.1 Stratigraphic Relationships

A general principle of geology is that the youngest unit is on the top in any sequence of sedimentary rocks that has not been disturbed by folding or faulting. A second general principle is that sedimentary rocks are deposited in a horizontal or nearly horizontal position. The fact that rocks are found overturned, displaced vertically or laterally, and squeezed into open or tight folds clearly indicates that the earth's crust is a dynamic system.

An *unconformity* is a break in the geologic record. It is caused by a cessation in deposition that is followed by erosion and subsequent deposition. When periods of erosion are protracted and over large geographic areas, significant portions of the geologic record can be destroyed.

If a sequence of strata is horizontal but the contact between two rock groups in the sequence represents an erosional surface, that surface is said to be a *disconformity*. Where a sequence of strata has been tilted and eroded and then younger, horizontal rocks are deposited over it, the contact is an *angular unconformity*. A *nonconformity* occurs where eroded igneous or metamorphic rocks are overlain by sedimentary rocks. A *paraconformity* exists where underlying horizontal sedimentary layers have been eroded and then covered by sediments deposited above them. This type of unconformity is difficult to identify because there is no obvious inconsistency in the strata type or orientation.

1.3.2 Age and Relationship of Stratigraphic Units

Dating of rock units deals with the relation between the emplacement or disturbance of rocks and time. The geologic timescale was developed to provide a standard classification system (Table 1.2) and is based on a sequence of rocks that were deposited during a particular time interval. The divisions are commonly based on some type of unconformity. In considering geologic time, three types of units are defined: rock units, time-rock units, and time units.

A *rock unit* refers to some particular lithology or type of rock. These may be further divided into geologic formations that are of sufficient size and uniformity to be mapped in the field. The Pierre Shale, for example, is a widespread and, in places, thick geologic formation that extends over much of the Northern Great Plains. Formations can also be divided into smaller units called members. Formations have a geographic name that may be coupled with a term that describes the major rock type. Two or more formations comprise a group.

Time-rock units refer to the rock that was deposited during a certain period of time. These units are divided into system, series, and stage. *Time units* refer to the time during which a sequence of

Table 1.2 Geologic Timescale

Era	Period	Epoch	Millions of Years Ago
Cenozoic	Quaternary	Recent	0–0.01
		Pleistocene	0.01–2
	Tertiary	Pliocene	2–5
		Miocene	5–23
		Oligocene	23–34
		Eocene	34–55
		Paleocene	55–65
Mesozoic	Cretaceous		65–144
	Jurassic		144–206
	Triassic		206–250
Paleozoic	Permian		250–290
	Pennsylvanian		290–314
	Mississippian		314–360
	Devonian		360–409
	Silurian		409–439
	Ordovician		439–500
	Cambrian		500–540
Precambrian			540–4600

Note: Dates have an accuracy range of about ±1%, but boundary dates continue to change as dating methods are refined.

Source: Update of U.S. EPA (1987a) as of 2002.

rocks was deposited. The time-rock term *system* has the equivalent time term *period*. That is, during the Cretaceous Period, for example, rocks of the Cretaceous System were deposited, consisting of many groups and formations. Time units are named in such a way that the eras reflect the complexity of life-forms that existed, such as the Mesozoic or "middle life." System or period nomenclature is largely based on the geographic location in which the rocks were first described, such as Jurassic, which relates to the Jura Mountains of Europe.

The terms used by geologists to describe rocks relative to geologic time are useful for ground-water investigations in providing a general overview of the regional geology of an area. The terms alone have no significance as far as water-bearing properties are concerned.

1.3.3 Folds and Fractures

Folds and fractures are the major types of structural features described by geologists. Structural features are usually mapped using a combination of surface outcrop observations, subsurface geophysical measurements, and borehole observations.

Folds. Rocks folded by compressional forces are common in and adjacent to former or existing mountain ranges. The folds range from a few inches to 50 mi or so across. *Anticlines* are rocks folded upward into an arch; their counterpart, *synclines*, are folded downward like a valley (Figure 1.4). A *monocline* is a flecture in which the rocks are horizontal, or nearly so, on either side of the flecture.

Although many rocks have been folded into various structures, this may not be reflected by the topographic features. As uplift proceeds, erosion removes weathering products from the rising mass and deposits them elsewhere. The final topography is related to the erodibility of the rocks, with resistant strata such as sandstone forming ridges, and the less resistant material such as shale forming valleys. Consequently, the geologic structure of an area may bear little resemblance to its topography.

The structure of an area can be determined from field studies or a geologic map, if one exists. Various types of folds and their dimensions appear as unusual patterns on geologic maps. An anticline, for example, will be depicted as a series of rock units in which the oldest is in the middle, while a syncline is represented by the youngest rock in the center (Figure 1.4). More or less equidimensional anticlines and synclines are termed domes and basins, respectively.

The inclination of the top of a fold is the plunge. Folds may be symmetrical, asymmetrical, overturned, or recumbent in relation to the fold axis. The inclination of the rocks is indicated by

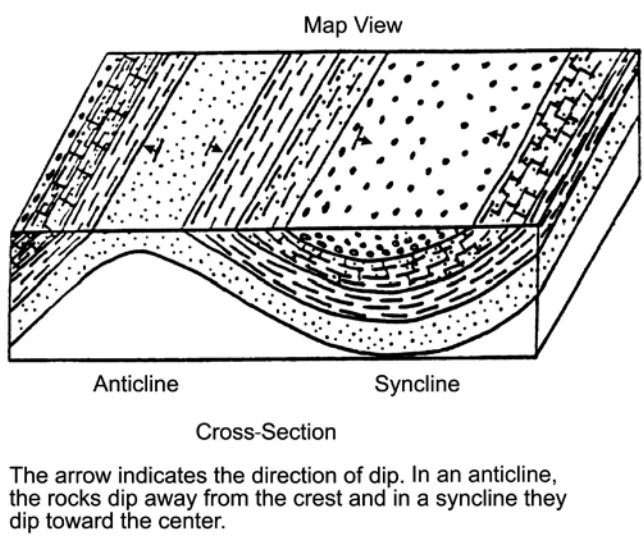

Figure 1.4 Block diagram of an anticline and syncline (U.S. EPA, 1987a).

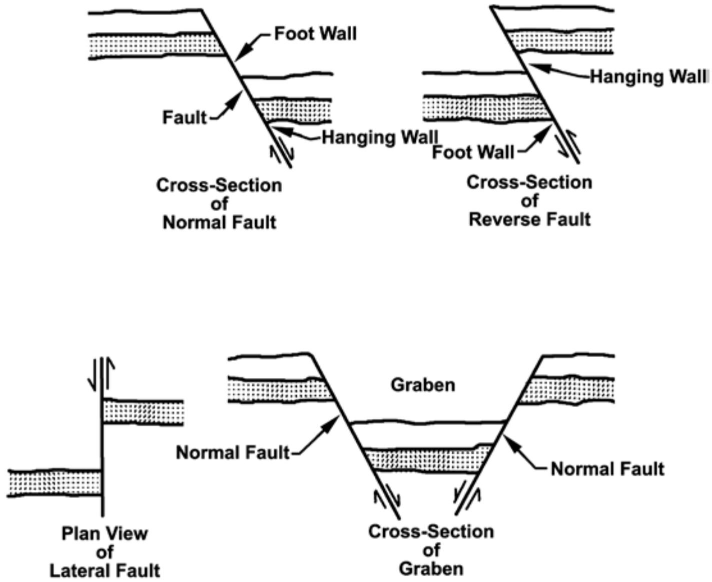

Figure 1.5 Cross sections of normal and reverse faults and a graben; plan view of a lateral fault (U.S. EPA, 1987a).

dip and strike symbols. The strike is perpendicular to the dip, and dip is commonly recorded as the number of degrees with respect to the horizontal plane. The dip may range from less than a degree to vertical.

Fractures. Fractures in rocks are either joints or faults. A *joint* is a fracture along which no movement has taken place; a *fault* implies movement. Movement along faults is as little as a few inches to tens of miles. Probably all consolidated rocks and a good share of the unconsolidated deposits contain joints. Joints exert a major control on ground-water movement and chemical quantity. Characteristically, joints are open and serve as major conduits or pipes. Water can move through them quickly, perhaps carrying contaminants, and being open, the filtration effect is lost. The outbreak of many waterborne diseases can be traced to ground-water supplies containing infectious agents that have been transmitted through fractures to wells and springs.

Faults are most common in the deformed rocks of mountain ranges, suggesting either lengthening or shortening of the crust. Movement along a fault may be horizontal, vertical, or a combination of both. The most common types of faults are called normal, reverse, and lateral (Figure 1.5). A *normal* fault, which indicates stretching of the crust, is one in which the upper or hanging wall has moved down relative to the lower or footwall.

Death Valley in California, the Red Sea, and the large lake basins in the east African highlands, among many others, lie in a *graben*, which is a block bounded by normal faults (Figure 1.5). A *reverse* or *thrust* fault implies compression and shortening of the crust. It is distinguished by the fact that the hanging wall has moved up relative to the footwall. A *lateral* fault is one in which the movement has been largely horizontal. The San Andreas Fault, extending some 600 mi from San Francisco Bay to the Gulf of California, is the most notable lateral fault in the U.S.

1.3.4 Geologic Maps and Cross Sections

Geologists use a number of techniques to graphically represent surface and subsurface conditions. Some of the more important methods that may have value in ground-water investigations are described here briefly:

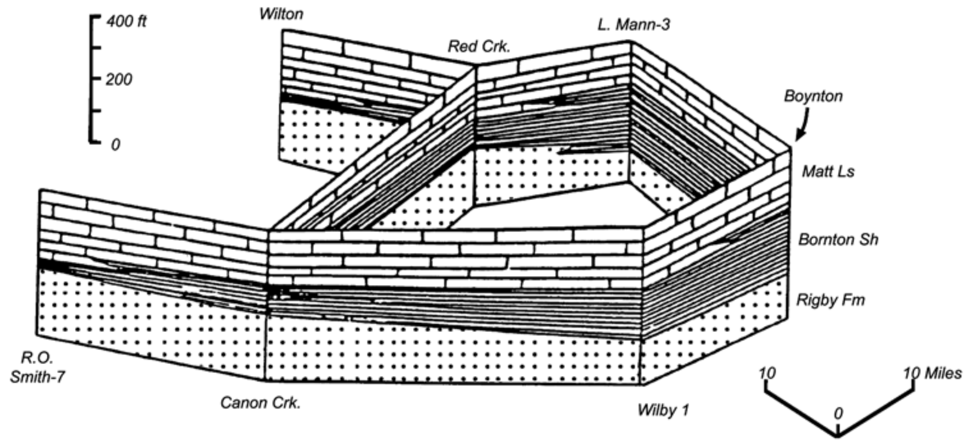

Figure 1.6 Sample fence diagram construction (Mercer and Spalding, 1991b, after Compton, 1962).

- *Surface geologic maps* depict the geographic extent of formations and their structure at the earth's surface. The map view portion of Figure 1.4 represents such a map.
- *Subsurface geologic maps* show the areal location of buried rock and other geologic units. These include (1) *structure contour* maps that show the elevation of a particular rock unit such as bedrock below glacial deposits or the top of a single rock formation; and (2) *isopach maps* that show variations in thickness of a unit and are based largely or entirely on well logs.
- *Cross sections* may take several forms: (1) *geologic cross sections*, which illustrate the subsurface distribution of rock units between points of control, such as outcrops or well bores; (2) *columnar sections*, which describe the vertical distribution of rock units, their lithology, and thickness; and (3) graphical representation of borehole logs without interpolation, as is required for geologic cross sections.
- *Three-dimensional* representations of geologic data can be accomplished by *block diagrams* (Figure 1.4) and *panel diagrams* (also called *fence diagrams*), in which cross sections are combined to create a three-dimensional image (Figure 1.6).

Whatever the graphic techniques, they are not exact because the features they attempt to show are complex, nearly always hidden from view, and difficult to sample. Nevertheless, graphic representations are valuable, if not essential, to subsurface studies.

1.4 BASIC SOIL CONCEPTS

Although the term *soil* is often loosely used to refer to any unconsolidated material, soil scientists distinguish it from other unconsolidated geologic materials by observable features that result from soil-forming processes, such as accumulation of organic matter, formation of soil structure, and leaching. Soil forms at the land surface in geologic materials, and consequently, the study of soil is at the interface between geology (particularly glacial and quaternary geology) and geomorphology.

1.4.1 Factors of Soil Formation

The soil at a particular location is the result of the interaction of five factors: (1) parent material, (2) topography, (3) climate, (4) biota, and (5) time:

- *Parent material*, in the form of unweathered consolidated or unconsolidated geologic material, provides the initial physical and chemical framework for soil formation.
- *Topography* affects soil formation by its influence on erosion and wetness. For example, soils on steep slopes tend to be thin and poorly developed because the rate of erosion tends to counterbalance the effects of weathering by climate and biota.

- *Climate* influences soil formation primarily by the amount of precipitation. Soils can be broadly classified based on the relationship between precipitation and evapotranspiration. In humid climates, where precipitation exceeds evapotranspiration, soluble constituents leach from the soil. Where evapotranspiration exceeds precipitation, as in arid and semiarid climates, salts tend to accumulate in the soil profile.
- *Biota* affects soil formation primarily through the process of organic matter formation. Vegetation is the major biological factor. For example, in the same parent material, prairie grassland will form an entirely different type of soil than a forest.
- The length of *time* that parent material is subjected to the weathering processes of climate and biological activity strongly influences soil type. A young soil in fresh geologic materials will look very different from a soil in the same material where weathering processes have operated for tens or hundreds of thousands of years.

The interaction of the above factors of soil formation results in the formation of a soil *profile*, the description of which forms the basis for classifying a soil. Specific soil-forming processes that influence soil profile development include (1) organic matter accumulation; (2) weathering of minerals to clays; (3) the depletion of clay and other sesquioxide minerals from upper horizons, called *eluviation*, with subsequent enrichment in lower horizons, called *illuviation*; (4) leaching or accumulation of soluble salts; (5) the formation of *soil structure* by the aggregation of soil particles into larger units called *peds*; and (6) the formation of slowly permeable layers, such as *fragipans* in humid climates and *duripans* in arid climates.

Perhaps the most distinctive feature of a soil profile is its major horizons:

- The *O horizon*, if present, is a layer of partially decomposed organic material.
- The *A horizon* is a mineral horizon characterized by maximum accumulation of organic matter lying at or near the ground surface. It usually has a distinctly darker color than lower horizons.
- The *E horizon*, whose main feature is the loss of silicate clay, iron, or aluminum, is typically found between the A and B horizons. (Note: Soil textbooks published before 1981 call this the B1 horizon.) It may also occur within a B horizon above a fragipan.
- The *B horizon* is the zone of most active weathering, is often enriched in clays, and has a well-defined soil structure. In humid climate soluble cations, such as calcium, are often depleted, whereas in drier climates calcium carbonate and other soluble salts often accumulate in this horizon. Soil formed in recent geologic materials typically is missing a B horizon, or it is observable only by a slightly redder color compared to the C horizon.
- The *C horizon* is unconsolidated material that has experienced little or no weathering. In arid zones minerals may precipitate in the C horizon to form cemented petrocalcic layers (also called *caliche*) or duripans (cementation by silica).
- The *R horizon* is solid rock.

Depending on the interaction between the five factors of soil formation at a site, the transport of contaminants in the subsurface can be increased or decreased relative to unweathered materials with similar physical and chemical composition (Sections 1.4.3 and 1.4.4). Many soil properties that affect the potential for contaminant transport in the subsurface can be evaluated using soil profile descriptions, prepared using USDA soil description procedures. Section 1.7 identifies major references on these methods.

1.4.2 Soil Classification

The dominant system for classifying soils in the U.S. is the USDA soil taxonomy. This system went through seven "approximations" before being formalized in 1975 with the publication of *Soil Taxonomy* (Agricultural Handbook 436). The second edition was published in 1999 (Soil Survey Staff, 1999/T1.3). It is still an evolving system, which is updated biannually by the Soil Survey Staff of the Natural Resources Conservation Service (formerly called Soil Conservation Service (SCS)) in *Keys to Soil Taxonomy* (the ninth edition was published in 2002). Although the nomenclature may seem intimidating to the uninitiated, the USDA soil classification system is a very useful tool for assessing potential for transport of contaminants in the subsurface. The agricultural origins of the system resulted in a strong emphasis on features affecting soil water and nutrient status. These are the same soil properties that are most significant when evaluating soil and ground water contamination. The following is a brief overview of the system.

The USDA soil taxonomy is a hierarchical classification system with six levels:

- *Orders* and *suborders* form the highest level. The original system had 10 orders (see legend to Figure 1.7) and 47 suborders, which are differentiated by the presence or absence of diagnostic horizons and the kind and degree of dominant soil-forming processes. In 1990 an 11th order called andosols was added for soils formed in volcanic ashes.
- *Great groups* and *subgroups* are the next level. There are about 185 great groups and about 970 subgroups. Great groups are differentiated based on the whole assemblage of soils horizons and moisture and temperature regimes. Subgroups are defined based on significant subordinate soil processes that result in intergrades or transitional forms to other orders, suborders, or great groups.
- *Families* are a category within a subgroup that have similar physical and chemical properties, including (1) particle-size distribution, (2) mineralogy, (3) temperature regime, and (4) rooting depth. About 4500 families are currently recognized in the U.S.
- *Series* is the lowest category in the system and is defined by a more limited range of characteristics than the family grouping. Over 10,500 soil series have been recognized in the U.S. In soil mapping a soil series is further subdivided into *map units* reflecting occurrence on different slope classes and sometimes degrees of erosion. However, soil map units are not considered to be a level in the classification system.

Figure 1.7 shows the patterns of soil orders and suborders in the U.S. The legend describes their salient characteristics and the origin of major word roots. Familiarity with this system provides a powerful tool for interpreting soil conditions at any site where a soil survey conducted by the U.S. Soil Conservation Service (now Natural Resources Conservation Service) is available.

1.4.3 Soil Physical Properties

Soil physical properties such as texture (see Section 1.1.2), structure, and pore-size distribution are the major determinants in water movement in soil and, consequently, of major concern in ground-water contamination studies. Depending on the specific soil, water movement may be enhanced or retarded compared to unweathered geologic materials. Organic matter enhances water-holding capacity and infiltration. The formation of soil structure also enhances permeability, particularly in clayey soils. Buried soil horizons form zones of preferential lateral movement of contaminants in the subsurface, which may be overlooked by environmental professionals who are not trained to recognize such horizons. On the other hand, the formation of restrictive layers such as fragipans may substantially reduce infiltration compared to unweathered materials.

The study of soil water is primarily the domain of the soil physicist. Physical properties affecting movement of water in soil are discussed further in Section 2.2.2 (Infiltration) and Section 2.4 (Water in the Vadose Zone). Soil micromorphology and fabric analysis are methods for studying other soil physical properties. These methods typically involve the preparation of thin sections and examination of pores and other ordered features through a microscope.

Micromorphological and general fabric analysis of soil is used infrequently in the study of ground-water contamination, more because of unfamiliarity with the methods than their lack of value. For example, Collins and McGown (1981)[2] used micromorphologic and fabric analysis of layered alluvial soils and glacial soils to evaluate discontinuities for engineering purposes. Paglai

[2] Collins, K. and A. McGown. 1981. Micromorphological studies in soil engineering, in *Soil Micromorphology, Vol. 1. Techniques and Applications,* P. Bullock and C.P. Murphy, Eds., Academic Publishers, New York, pp. 195–217.

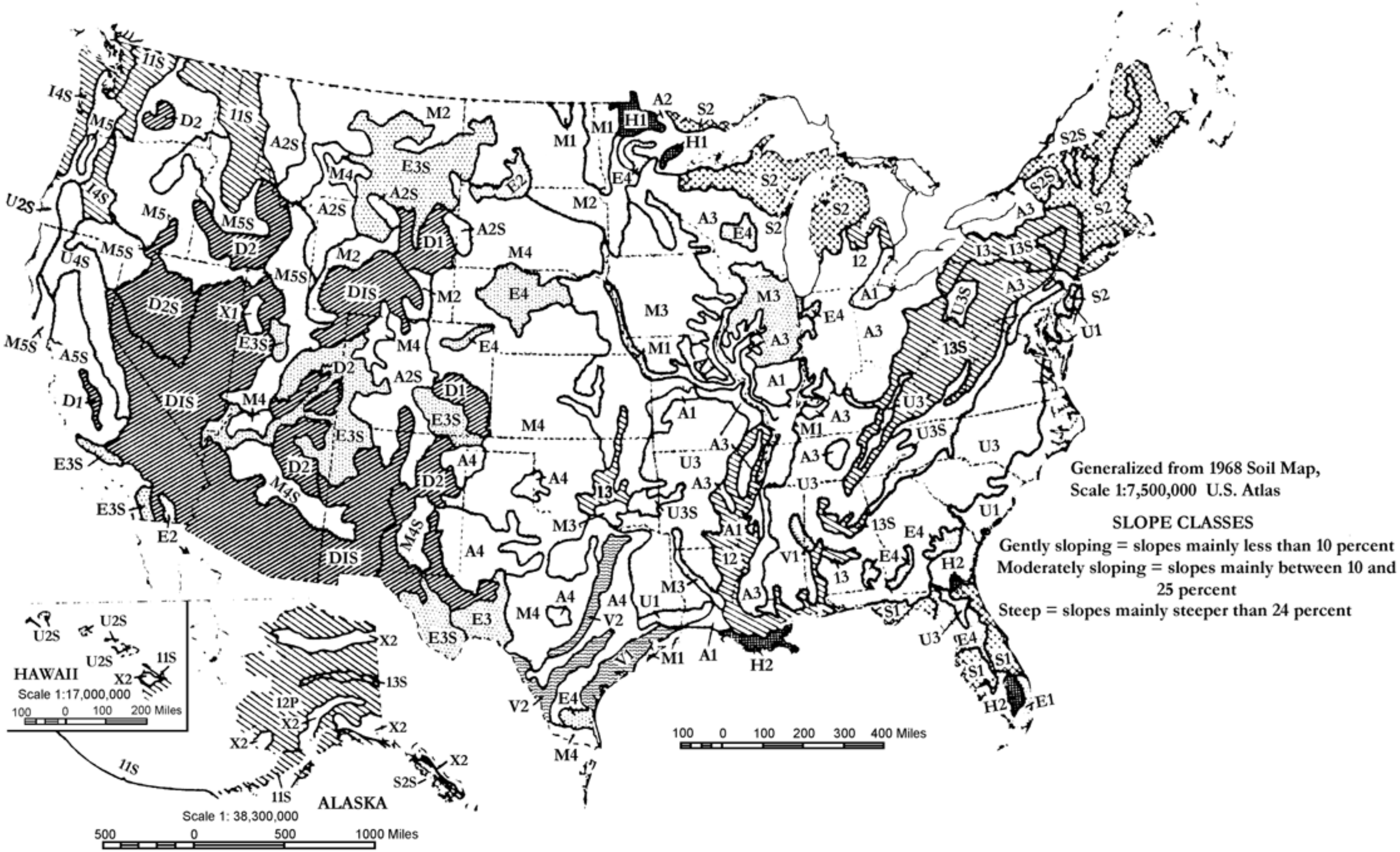

Figure 1.7 Patterns of soil orders and suborders of the U.S. (Birkeland, 1984).

Continued.

LEGEND

Only the dominant orders and suborders are shown. Each delineation has many inclusions of other kinds of soil. General definitions for the orders and suborders follow. For complete definitions, see Soil Survey Staff.[12] Approximate equivalents in the modified 1938 soil classification system are indicated for each suborder.

ALFISOLS . . . Soils with gray to brown surface horizons, medium to high base supply, and subsurface horizons of clay accumulation; usually moist but may be dry during warm season

A1 AQUALFS (seasonally saturated with water) gently sloping; general crops if drained, pasture and woodland if undrained (Some Low-Humic Gley soils and Planosols)

A2 BORALFS (cool or cold) gently sloping; mostly woodland, pasture, and some small grain (Gray Wooded soils)

A2S BORALFS steep; mostly woodland

A3 UDALFS (temperate, or warm, and moist) gently or moderately sloping; mostly farmed, corn, soybeans, small grain, and pasture (Gray-Brown Podzolic soils)

A4 USTALFS (warm and intermittently dry for long periods) gently or moderately sloping; range, small grain, and irrigated crops (Some Reddish Chestnut and Red-Yellow Podzolic soils)

A5S XERALFS (warm and continuously dry in summer for long periods, moist in winter) gently sloping to steep; mostly range, small grain, and irrigated crops (Noncalcic Brown soils)

ARIDISOLS . . . Soils with pedogenic horizons, low in organic matter, and dry more than 6 months of the year in all horizons

D1 ARGIDS (with horizon of clay accumulation) gently or moderately sloping; mostly range, some irrigated crops (Some Desert, Reddish Desert, Reddish Brown, and Brown soils and associated Solonetz soils)

D1S ARGIDS gently sloping to steep

D2 ORTHIDS (without horizon of clay accumulation) gently or moderately sloping; mostly range and some irrigated crops (Some Desert, Reddish Desert, Sierozem, and Brown soils, and some Calcisols and Solonchak soils)

D2S ORTHIDS gently sloping to steep

ENTISOLS . . . Soils without pedogenic horizons

E1 AQUENTS (seasonally saturated with water) gently sloping; some grazing

E2 ORTHENTS (loamy or clayey textures) deep to hard rock; gently to moderately sloping; range or irrigated farming (Regosols)

E3 ORTHENTS shallow to hard rock; gently to moderately sloping; mostly range (Lithosols)

E3S ORTHENTS shallow to rock; steep; mostly range

E4 PSAMMENTS (sand or loamy sand textures) gently to moderately sloping; mostly range in dry climates, woodland or cropland in humid climates (Regosols)

HISTOSOLS . . . Organic soils

H1 FIBRISTS (fibrous or woody peats, largely undecomposed) mostly wooded or idle (Peats)

H2 SAPRISTS (decomposed mucks) truck crops if drained, idle if undrained (Mucks)

INCEPTISOLS . . . Soils that are usually moist, with pedogenic horizons of alteration of parent materials but not of accumulation

I1S ANDEPTS (with amorphous clay or vitric volcanic ash and pumice) gently sloping to steep; mostly woodland; in Hawaii mostly sugar cane, pineapple, and range (Ando soils, some Tundra soils)

I2 AQUEPTS (seasonally saturated with water) gently sloping; if drained, mostly row crops, corn, soybeans, and cotton; if undrained, mostly woodland or pasture (Some Low-Humic Gley soils and Alluvial soils)

(continued)

Figure 1.7 Legend.

I2P AQUEPTS (with continuous or sporadic permafrost) gently sloping to steep; woodland or idle (Tundra soils)

I3 OCHREPTS (with thin or light-colored surface horizons and little organic matter) gently to moderately sloping; mostly pasture, small grain, and hay (Sols Bruns Acides and some Alluvial soils)

I3S OCHREPTS gently sloping to steep; woodland, pasture, small grains

I4S UMBREPTS (with thick dark-colored surface horizons rich in organic matter) moderately sloping to steep; mostly woodland (Some Regosols)

MOLLISOLS . . . Soils with nearly black, organic-rich surface horizons and high base supply

M1 AQUOLLS (seasonally saturated with water) gently sloping; mostly drained and farmed (Humic Gley soils)

M2 BOROLLS (cool or cold) gently or moderately sloping, some steep slopes in Utah; mostly small grain in North Central States, range and woodland in Western States (Some Chernozems)

M3 UDOLLS (temperate or warm, and moist) gently or moderately sloping; mostly corn, soybeans, and small grains (Some Brunizems)

M4 USTOLLS (intermittently dry for long periods during summer) gently to moderately sloping; mostly wheat and range in western part, wheat and corn or sorghum in eastern part, some irrigated crops (Chestnut soils and some Chernozems and Brown soils)

M4S USTOLLS moderately sloping to steep; mostly range or woodland

M5 XEROLLS (continuously dry in summer for long periods, moist in winter) gently to moderately sloping; mostly wheat, range, and irrigated crops (Some Brunizems, Chestnut, and Brown soils)

M5S XEROLLS moderately sloping to steep; mostly range

SPODOSOLS . . . Soils with accumulations of amorphous materials in subsurface horizons

S1 AQUODS (seasonally saturated with water) gently sloping; mostly range or woodland; where drained in Florida, citrus and special crops (Ground - Water Podzols)

S2 ORTHODS (with subsurface accumulations of iron, aluminum, and organic matter) gently to moderately sloping; woodland, posture, small grains, special crops (Podzols, Brown Podzolic soils)

S2S ORTHODS steep; mostly woodland

ULTISOLS . . . Soils that are usually moist, with horizon of clay accumulation and a low base supply

U1 AQUULTS (seasonally saturated with water) gently sloping; woodland and pasture if undrained, feed and truck crops if drained (Some Low - Humic Gley soils)

U2S HUMULTS (with high or very high organic matter content) moderately sloping to steep; woodland and pasture if steep, sugar cane and pineapple in Hawaii, truck and seed crops in Western States (Some Reddish-Brown Lateritic soils)

U3 UDULTS (with low organic-matter content; temperate or warm, and moist) gently to moderately sloping; woodland, pasture, feed crops, tobacco, and cotton (Red-Yellow Podzolic soils, some Reddish-Brown Lateritic soils)

U3S UDULTS moderately sloping to steep, woodland, pasture

U4S XERULTS (with low to moderate organic-matter content, continuously dry for long periods in summer) range and woodland (Some Reddish-Brown Lateritic soils)

VERTISOLS. . . Soils with high content of swelling clays and wide deep cracks at some season

V1 UDERTS (cracks open for only short periods, less than 3 months in a year) gently sloping; cotton, corn, pasture, and some rice (Some Grumusols)

V2 USTERTS (cracks open and close twice a year and remain open more than 3 months); general crops, range, and some irrigated crops (Some Grumusols)

Figure 1.7 Legend.

☐ AREAS with little soil . . .

X1 Salt flats X2

X2 Rock land (plus ice fields in Alaska)

NOMENCLATURE

The nomenclature is systematic. Names of soil orders end in *sol* (L. *solum*, soil), e.g., ALFISOL, and contain a formative element used as the final syllable in names of taxa in suborders, great groups, and subgroups.

Names of suborders consist of two syllables, e.g., AQUALF. Formative elements in the legend for this map and their connotations are as follows:

and	— Modified from Ando soils; soils from vitreous parent materials
aqu	— L. *aqua*, water; soils that are wet for long periods
arg	— Modified from L. *argilla*, clay; soils with a horizon of clay accumulation
bor	— Gr. *boreas*, northern; cool
fibr	— L. *fibra*, fiber; least decomposed
hum	— L. *humus*, earth; presence of organic matter
ochr	— Gr. base of ochros, pale; soils with little organic matter
orth	— Gr. *orthos*, true; the common or typical
psamm	— Gr. *psammos*, sand; sandy soils
sapr	— Gr. *sapros*, rotten; most decomposed
ud	— L. *udus*, humid; of humid climates
umbr	— L. *umbra*, shade; dark colors reflecting much organic matter
ust	— L. *ustus*, burnt; of dry climates with summer rains
xer	— Gr. *xeros*, dry; of dry climates with winter rains

Figure 1.7 Legend.

et al. (1981)[3] used micromorphological methods to evaluate the effect of sewage sludges applied to soil on pore size and density.

1.4.4 Soil Chemical Properties

Minerals in the soil are the chemical signature of the bedrock from which they originated. Rainfall and temperature are two significant factors that dictate the rate and extent to which mineral solids in the soil react with water. As water passes through soil horizons, it dissolves the chemical remnants of the parent material. In arid and semiarid climates dissolved constituents often precipitate in a lower horizon when plants transpire soil water to the atmosphere. In humid climates, soil water that is not taken up by plant roots carries the dissolved minerals to the ground water. The more water that flows through the soil, the more solids react with the undersaturated solvent.

Organic matter and clay content are major parameters of importance in studying the transport and fate of contaminants in soil. The geochemical properties of clay have been described in Section 1.1.1, and the importance of organic matter in adsorption of organic chemicals covered in Section 3.4.4. Chapter 3 covers basic concepts related to soil chemistry.

1.5 GEOMORPHOLOGY AND GROUND WATER

Geomorphology is the study of the evolution of surface landforms. Careful observation of surface features at a site (landforms, streams and stream patterns, locations of springs, seeps, and lakes, as well as vegetation) may reveal considerable information about both geology and ground water. Landforms are controlled by the geology, and many hills are capped by resistant strata, such as sandstone, while valleys are usually carved into soft, less resistant material, such as shale.

[3] Paglai, M., M. LaMarca, and G. Lucamante. 1981. Micromorphological investigation of the effect of sewage sludges applied to soil in *Soil Micromorphology, Vol. 1. Techniques and Applications,* P. Bullock and C.P. Murphy, Eds., Academic Publishers, New York, pp. 219–225.

Likewise, many changes in topographic slope are related to differences in rock type. These, in turn, provide a general impression of the types of rocks present, their areal extent, and composition. Rock exposures in stream channels and road cuts are very useful also when attempting to understand the local geology. Large-scale fracture systems can be mapped as linear features on aerial photographs. Lineations on aerial photographs may also serve as indicators of changes in lithology and geologic structure. At a smaller scale, joint and fracture systems, their directional trends, density, and size can all be measured on rock outcrops. Fluid movement through joints and other fractures may be the controlling factor for migration of contaminants.

Geomorphology is a logical starting point for site investigations, because it allows preliminary interpretations of subsurface conditions without the cost of drilling or other subsurface investigation methods. For example, Hatheway and Bliss (1980)[4] used surficial geologic maps to develop geomorphic units of similar engineering and hydrogeologic properties as a starting point for evaluating siting options for hazardous waste facilities.

1.5.1 Hydrogeomorphology

A lot can be inferred about subsurface flow of water from examination of a topographic map, because slope steepness and shape strongly influence how much precipitation enters the ground. Figure 1.8 illustrates a number of geomorphic and hillslope components. Refer to this figure for help in visualizing the following common relationships between surface runoff or infiltration (the entry of water into the soil) and geomorphic and hillslope features:

- *Headslopes* concentrate surface runoff; *noseslopes* disperse surface runoff.
- Infiltration is usually highest on *footslopes* and *toeslopes*, followed by interfluves/hill summits, and lowest on shoulders and backslopes. At all topographic situations, infiltration is highest in dry soils and slows as the soil gets wetter.
- Surface runoff is usually greatest on steep surfaces such as *headslopes/sideslopes* and *shoulders/backslopes*, and lowest on flat surfaces (broad interfluvs and alluvial fill). At all topographic positions surface runoff is at a maximum when the soil is saturated.
- A *concave* sideslope will concentrate water in the soil more than a *convex* sideslope (this is not explicitly illustrated in Figure 1.8, but the principle is the same as the headslope/hillslope relationship).
- Alluvial fill will usually have more ground water than interfluvs.

The above relationships can be useful in developing a preliminary conceptual model of how water is flowing in the subsurface. Very subtle changes in surface topography may affect the distribution of water between the surface and ground. These are often evident in vegetation, with relative greenness marking differences in the availability of ground water. Vegetation can sometimes also be used to map certain rock types. For example, cedar trees can be an indicator of limestone bedrock. Springs and seeps are zones of ground-water discharge. They develop in the vicinity of strata of low permeability that are overlain by a unit of greater permeability.

Stream patterns also are related to the geology, especially geologic structure and fracture or joint systems. Regional stream patterns provide an idea of the relative difference in discharge from one stream to another. Surface streams can also provide useful information on basin permeability, shallow ground-water quality, and local sites where the ground water is contaminated (Section 2.3).

1.5.2 Karst Geomorphology and Hydrology

The term *karst*, named after the Dinaric karst limestone region of the former Yugoslavia, refers to a distinctive set of geomorphic landforms resulting from the development of extensive subsurface

[4] Hathaway, A.W. and Z.F. Bliss. 1980. Geomorphology as an aid to hazardous waste facility siting, Northeast United States, in *Applied Geomorphology,* R.G. Craig and J.L. Craft, Eds., George Allen & Unwin, Boston, MA, pp. 55–71.

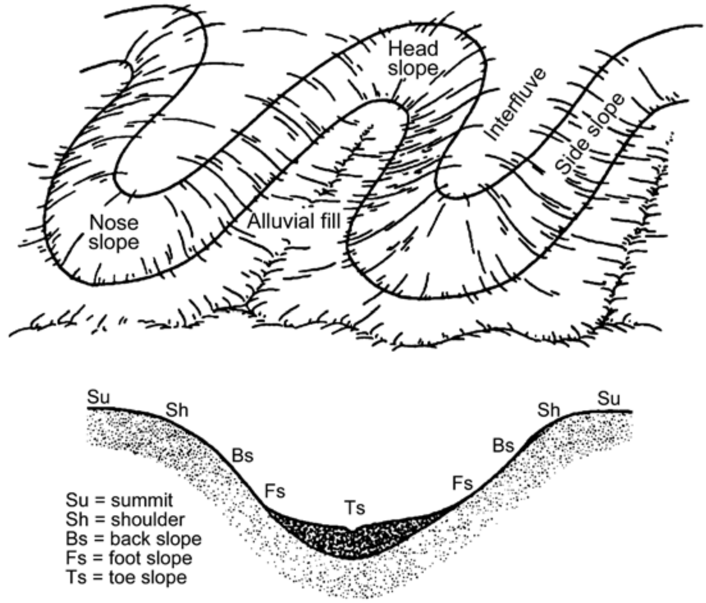

Figure 1.8 Geomorphic and hill slope components (Mausbach and Nielsen, 1991, after Ruhe and Walker, 1968).

solution channels and caves in carbonate rocks. These channels form where circulating ground water has dissolved carbonates along fractures and bedding planes (see Figure 1.9). Karst terrane (also spelled terrain in the karst literature) is usually characterized by sinkholes and general absence of perennial surface streams. Springs are abundant where impermeable rock below the cavernous limestone crops out at the surface.

Conduit flow, which does not obey Darcy's law (Section 2.6.3), is a salient characteristic of karst aquifers. As the term implies, flow in solution channels is rapid, more like flow in a pipe or open channel. This feature of karst aquifers makes them characteristically idiosyncratic in behavior, and surface water entering such a system may reappear at unexpected locations and at different locations depending on whether low- or high-flow conditions exist. As shown in Figure 1.9, large fluctuations can result in seasonal artesian conditions. Ground-water tracing experiments are the only way that karst ground-water flow patterns can be accurately characterized (Section 8.4).

Karst areas are troublesome water sources even though they can provide large quantities of water to wells and springs. Rapid infiltration rates limit filtering action to retard contaminants; pollutants move rapidly once they reach a karst conduit and are less attenuated by adsorption compared to porous aquifers (Field, 1989).[5] Consequently, karst terrane is generally unsuitable for the disposal of polluting wastes.

Figure 1.10 shows the distribution of karst areas in the U.S. Near-surface karst areas are shaded, and other areas with carbonate or sulfate rocks near the surface are stippled. Karst areas in this figure are divided into four major regions: A = Atlantic and Gulf Coastal Plain; B = east-central region of Paleozoic and other old rock; C = Great Plains; and D = western mountain region. The distinctive geomorphic and hydrogeologic features of karst terrane have resulted in a scientific literature that is probably out of proportion to its actual distribution on the face of the earth (see next section).

[5] Field, M.S. 1989. The Vulnerability of Karst Aquifers to Chemical Contamination. In: Recent Advances in Ground-Water Hydrology, J.E. Moore et al. (eds.), American Institute of Hydrology, Minneapolis, pp. 130–142.

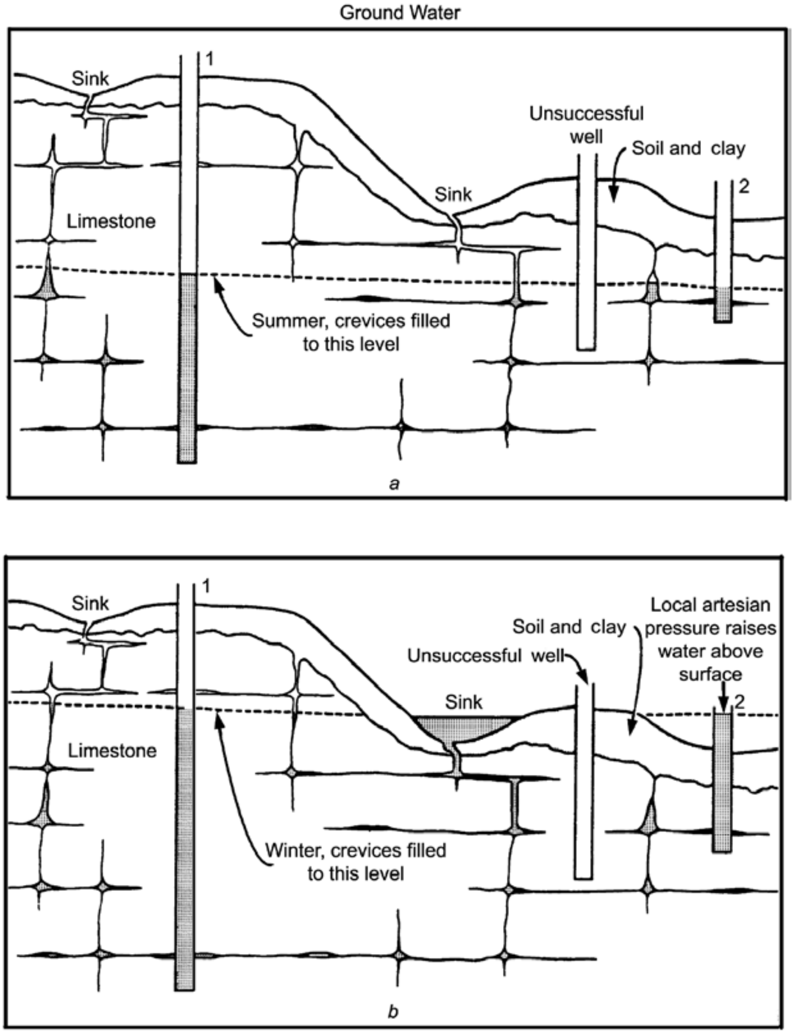

Figure 1.9 Diagram of a karst aquifer showing seasonal artesian conditions (Walker, 1956).

1.6 GEOLOGIC SETTINGS OF GROUND WATER OCCURRENCE AND QUALITY

The occurrence of ground water is intimately related to its geologic setting. Heath (1982)[6] describes 12 major ground-water regions in the continental U.S. based on geologic setting: (1) Western mountain ranges, (2) alluvial basins, (3) Columbia lava plateau, (4) Colorado Plateau and Wyoming, (5) high plains, (6) nonglaciated central region, (7) glaciated central region (Figure 1.3), (8) Piedmont Blue Ridge region, (9) northeast and superior uplands, (10) Atlantic and Gulf Coastal Plain, (11) southeast coastal plain, and (12) alluvial valleys. Figure 1.11 shows the boundaries of the first 11 regions. The alluvial valleys region consists mainly of the floodplains of the Mississippi, Missouri, and Ohio Rivers. Aller et al. (1987/T11.10) have further subdivided Heath's major regions into 85 subregions for purposes of evaluating ground-water pollution potential. Section 11.2.3 discusses ground-water vulnerability mapping further.

[6] Heath, R.C. 1982. Classification of Ground-Water Systems of the United States. Ground Water 20(4):393–401. Additional information on Heath's ground water regions can be found in U.S. Geological Professional Paper 2242, published in 1984.

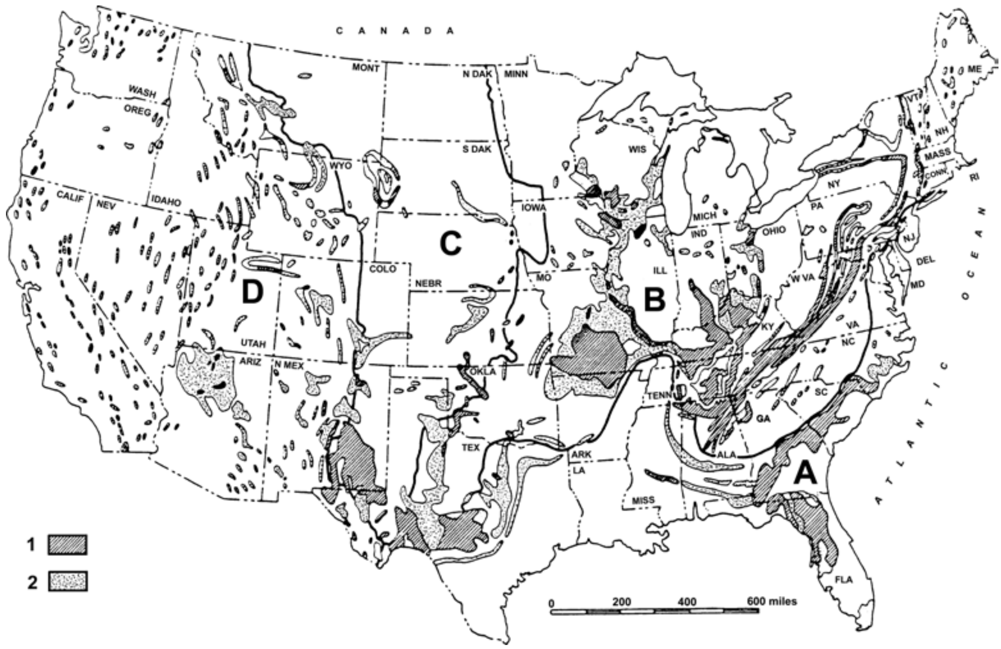

Figure 1.10 Distribution of karst areas in relation to carbonate and sulfate rocks in the U.S. (Davies and LeGrand, 1972). 1 = Karst areas; 2 = carbonate and sulfate rocks at or near the surface.

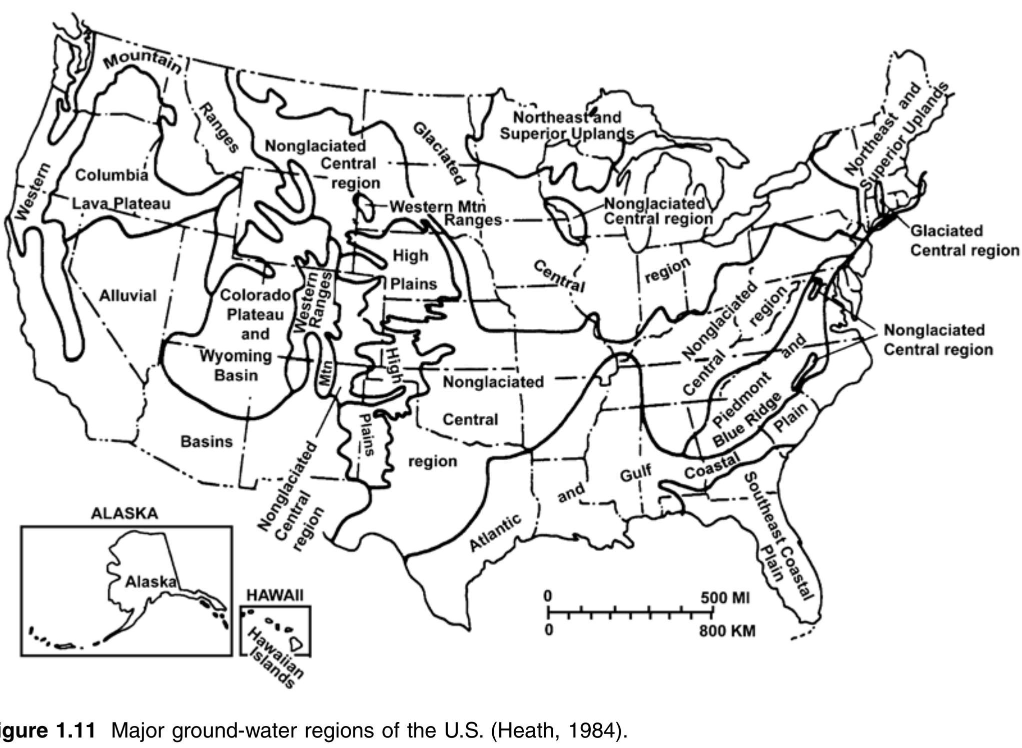

Figure 1.11 Major ground-water regions of the U.S. (Heath, 1984).

1.6.1 Ground Water in Igneous and Metamorphic Rocks

Nearly all of the porosity and permeability of igneous and metamorphic rocks are the result of secondary openings such as fractures and faults and the dissolution of certain minerals. A few notable exceptions include large lava tunnels present in some flows, interflow or coarse sedimentary layers between individual lava flows, and deposits of selected pyroclastic materials.

Because the openings in igneous and metamorphic rocks are quite small volumetrically, rocks of this type are poor suppliers of ground water. The supplies that are available commonly drain rapidly after a period of recharge by infiltration of precipitation. In addition, they are subject to contamination from the surface where these rocks outcrop.

Evaluating water and contaminant movement in fractured rocks is difficult, because the actual direction of movement may not be in the direction of decreasing head, but rather in some different though related direction. The problem is further compounded by the difficulty in locating the fractures. Because of these characteristics, evaluating water availability, direction of movement, and velocity is exceedingly difficult.

Unless some special circumstance exists, such as where rocks crop out at the surface, water obtained from igneous and metamorphic rocks is nearly always of excellent chemical quality. Dissolved solids are present in crystalline rocks; however, they are commonly in concentrations of less than 100 mg/l. In the case of water from metamorphosed carbonate rocks, moderate to high concentrations of hardness may be found.

1.6.2 Ground Water in Sedimentary Rocks

Usable supplies of ground water can be obtained from all types of sedimentary rocks, but the fine-grained strata such as shale and siltstone may only provide a few gallons per day, and even this can be highly mineralized. Even though fine-grained rocks may have relatively high porosities, their primary permeabilities are usually low. On the other hand, shale is likely to contain a great number of joints that are closely spaced and extend to considerable depths. Therefore, in this case, rather than being impermeable, they can be quite transmissive. This is of considerable importance in waste disposal schemes because of the potential for flow through fractures. In addition, leachate formed as water infiltrates through waste might be small in quantity but highly mineralized. Because of the low bulk permeability, it would be difficult to pump out the contaminated water or even to properly locate monitoring wells.

From another perspective, fine-grained sedimentary rocks, owing to their high porosity, can store huge quantities of water. Some of this water can be released to adjacent aquifers when a head difference is developed due to pumping. On a regional scale, fine-grained confining units provide a great deal of water to aquifer systems. The porosity, however, decreases with depth because of compaction brought about by the weight of overlying sediments.

The porosity of sandstones ranges from less than 1% to a maximum of about 30%. This is a function of sorting, grain shape, and cementation. Cementation can vary both in space and time, and on outcrops, cementation can differ greatly from that in the subsurface.

As is the case in igneous and metamorphic rocks, fractures also play an important role in the movement of fluids through sandstones. Transmissivities may be as much as two orders of magnitude greater in a fractured rock than in an unfractured part of the same geologic formation.

Sandstone units that were deposited in a marine or near-marine environment can be very widespread, covering tens of thousands of square miles, such as the St. Peter Sandstone of the Cambrian age. Those representing ancient alluvial channel fills, deltas, and related environments of deposition are more likely to be discontinuous and erratic in thickness. Individual units are exceedingly difficult to trace in the subsurface. Regional ground-water flow and storage may be strongly influenced by the geologic structure.

Carbonate rocks are formed in many different environments, and the original porosity and permeability are modified rapidly after burial. Some special carbonate rocks, such as coquina and some breccias, which tend to have a coarse texture, may remain very porous and permeable, but these are exceptions. When calcite changes to dolomite ($CaMg(CO_3)_2$), the resulting 13% reduction in volume creates considerable pore space. High-yielding aquifers develop from fractures and other secondary openings in carbonate formations (see discussion of karst in Section 1.5.2).

1.6.3 Ground Water in Unconsolidated Sediments

Unconsolidated sediments accumulate in many different environments, all of which leave their mark on the characteristics of the deposit. Some are thick and areally extensive, as the alluvial fill in the Basin and Range Province; others are exceedingly long and narrow, such as the alluvial deposits along streams and rivers; and others may cover only a few hundred square feet, for example, some glacial forms. In addition to serving as major aquifers, unconsolidated sediments are also important as sources of raw materials for construction.

Closely related to sorting, the porosities of unconsolidated materials range from less than 1% to more than 90%, the latter representing the porosity of uncompacted mud. Permeabilities also range widely. Cementing of some type and degree is probably universal, but not obvious, with silt and clay being the predominant form.

Most unconsolidated sediments owe their emplacement and texture (sorting, grain size, etc.) to running water. Water as an agent of transport varies in both volume and velocity, which are climate dependent, and this variation leaves an imprint on the sediments. Stream-related, unconsolidated material varies in extent, thickness, and grain size. The water-bearing properties of glacial drift are highly variable, but stratified drift is more uniform and better sorted than glacial till. Some knowledge of the stratigraphy of the most common depositional environments is essential for adequate characterization.

1.6.4 Regional Relationships in Ground-Water Quality

As water infiltrates in a recharge area, the mineral content is relatively low. The quality changes, however, along the flow path and dissolved solids as well as other constituents increase with increasing distances traveled in the ground. The water eventually flows into a stream or body of surface water, and due to the different lengths of flow paths and rock solubility, even streams and small lakes in close proximity may differ greatly in both flow and quality.

The availability of ground-water supplies and their chemical quality are closely related to precipitation. As a general rule, the least mineralized water, both in streams and underground, occurs in areas of the greatest amount of rainfall. Inland, precipitation decreases, water supplies diminish, and quality deteriorates. Because water-bearing rocks exert a strong influence on ground-water quality, however, the solubility of the rocks may override the role of precipitation.

Where precipitation exceeds 40 in. per year, shallow ground water usually contains less than 500 mg/l and commonly less than 250 mg/l of dissolved solids. Where precipitation ranges between 20 and 40 in., dissolved solids may range between 400 and 1000 mg/l, and in drier regions, dissolved solids commonly exceed 1000 mg/l.

The dissolved solids concentration of ground water increases toward the interior of the continent. The increase is closely related to precipitation and the solubility of the aquifer framework. The least mineralized ground water is found in a broad belt that extends southward from the New England states along the Atlantic Coast to Florida, and then continues to parallel much of the Gulf Coast. Similarly, along the Pacific Coast from Washington to central California the mineral content is also very low. Throughout this belt, dissolved solids concentrations are generally less than 250 mg/l and commonly less than 100 mg/l (Figure 1.12).

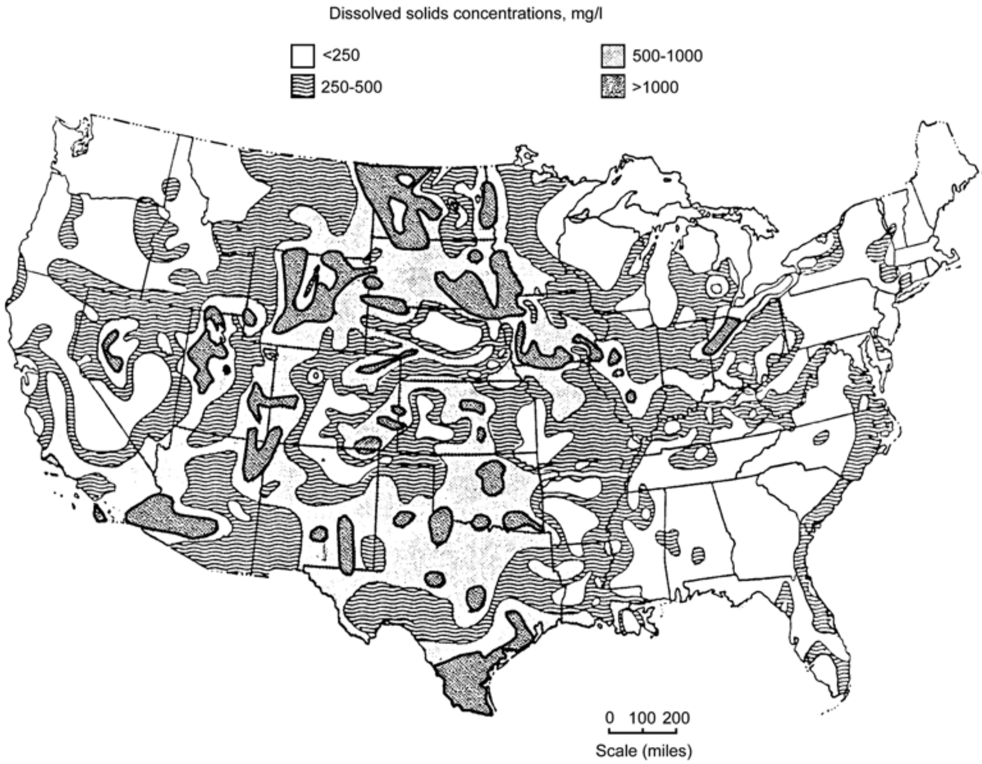

Figure 1.12 Dissolved solids concentrations in ground water used for drinking in the U.S. (U.S. EPA, 1987a, after Pettyjohn et al., 1979).

The Appalachian region consists of a sequence of strata that range from nearly horizontal to complexly folded and faulted. Likewise, ground-water quality in this region is also highly variable, being generally harder and containing more dissolved minerals than water along the coastal belt. Much of the difference in quality, however, is related to the abundance of carbonate aquifers, which provide waters rich in calcium and magnesium.

Westward from the Appalachian Mountains to about the position of the 20-in. precipitation line (eastern North Dakota to Texas), dissolved solids in ground water progressively increase. They are generally less than 1000 mg/l and are most commonly in the 250 to 750 mg/l range. The water is moderately to very hard, and in some areas concentrations of sulfate and chloride are excessive.

From the 20-in. precipitation line westward to the northern Rocky Mountains, dissolved solids are in the 500 to 1500 mg/l range. Much of the water from glacial drift and bedrock formations is very hard and contains significant concentrations of calcium sulfate. Other bedrock formations may contain soft sodium bicarbonate, sodium sulfate, or sodium chloride water.

Throughout much of the Rocky Mountains, ground-water quality is variable, although the dissolved solids concentrations commonly range between 250 and 750 mg/l. Stretching southward from Washington to southern California, Arizona, and New Mexico is a vast desert region. Here the difference in ground-water quality is wide and dissolved solids generally exceed 750 mg/l. In the central parts of some desert basins, the ground water is highly mineralized, but along the mountain flanks the mineral content may be quite low.

Extremely hard water is found over much of the interior lowlands, Great Plains, Colorado Plateau, and Great Basin. Isolated areas of high hardness are present in northwestern New York, eastern North Carolina, the southern tip of Florida, northern Ohio, and parts of southern California. In general, the hardness is of the carbonate type.

On a regional level, chloride does not appear to be a significant problem, although it is troublesome locally due largely to industrial activities, the intrusion of seawater caused by over-pumping coastal aquifers, or interaquifer leakage related to pressure declines brought about by withdrawals.

In many locations, sulfate levels exceed the federal recommended limit of 250 mg/l; regionally, sulfate may be a problem only in the Great Plains, eastern Colorado Plateau, Ohio, and Indiana. Iron problems are ubiquitous; concentrations exceeding only 0.3 mg/l will cause staining of clothing and fixtures. Fluoride is abnormally high in several areas, particularly parts of western Texas, Iowa, Illinois, Indiana, Ohio, New Mexico, Wyoming, Utah, Nevada, Kansas, New Hampshire, Arizona, Colorado, North and South Dakota, and Louisiana.

1.7 GUIDE TO MAJOR REFERENCES

Table 1.3 identifies major text references in five major areas: (1) geology, (2) soils, (3) geomorphology, (4) interfaces between geology, soils, and geomorphology, and (5) engineering applications. The last category, soils and geologic engineering, has not been discussed in any detail in this chapter, but is an essential element in planning and design for remediation of contaminated soils and ground water.

Almost any text on physical geology, stratigraphy, and structural geology, general soils, and geomorphology will provide more in-depth coverage of topics covered in this chapter, but generally will not emphasize principles as they relate to soil and ground-water contamination. This chapter has emphasized the value of USDA Soil Conservation Service (now called the Natural Resources Conservation Service) soil description and survey methods for contaminant investigations, and more needs to be said about key reference sources in this area.

For years the standard reference for soil horizon nomenclature was the 1962 supplement to the *Soil Survey Manual* (Soil Survey Staff, 1951, 1962), and it was elaborated further in *Soil Taxonomy* (Soil Survey Staff, 1975, 1999).[7] In 1981 conventions for describing soil horizons and subordinate distinctions within master horizons were significantly changed as part of a comprehensive revision of the 1951 *Soil Survey Manual*, which was published in 1994 (Soil Survey Staff, 1994). The best up-to-date source of official SCS horizon designations and naming conventions can be found in *Keys to Soil Taxonomy* (Soil Survey Staff, 2002), which is updated biannually.

None of the above documents are specifically oriented toward use of SCS soil description at contaminated sites. In 1991 U.S. EPA's Center for Environmental Research Information published *Description and Sampling of Contaminated Soils: A Field Pocket Guide* (Boulding, 1991), which presented a detailed, field-oriented adaptation of SCS soil description procedures for use with EPA's *Environmental Sampling Expert Systems* (Cameron, 1991). A second edition of the 1991 guide was published three years later (Boulding, 1994), which incorporated new SCS procedures for describing soil wetness conditions. These were adopted in 1992 and represent a significant improvement in the ability to characterize soil hydrology based on soil morphology. Burden and Sims (1999/T1.3) provide guidance on use of both the USDA and the more engineering-oriented ASTM Unified Soil Classification System at hazardous waste sites.

Table 1.4 provides an index of major references on karst in the following categories: (1) hydrology and ground water, (2) karst tracing, (3) geomorphology and geology, (4) geochemistry, (5) engineering applications, (6) environmental applications, and (7) major symposia. Ford and Williams (1989) is probably the best single text that covers both karst geomorphology and hydrology with a strong U.S. focus. Balkema Publishers (Old Post Road, Brookfield, VT 05036) is the major publisher of conference proceedings related to karst hydrogeology.

[7] Citations are to references included in Table 1.3.

Table 1.3 Index to Major References on Geology, Soils, and Geomorphology

Topic	References
	Geology
Terminology	Allaby and Allaby (1990), Bates and Jackson (1984), Michel and Fairbridge (1992), SCS (1977), Weller (1960a), Whitten and Brooks (1972)
Physical Geology	Birkeland and Larson (1989), Dercourt and Pacquet (1985), Flint and Skinner (1977), Foster (1983), Gilluly et al. (1975), Hamblin (1978), Mears (1977), Press and Siever (1986), Sawkins et al. (1978), Strahler (1976), Tarbuck and Lutgens (1984), Verhoogen et al. (1979)
Stratigraphy	Adams and Mackenzie (1999), Blatt et al. (1980), Bouma (1969), Chakraboty and Bhattacharyya (2000), Folk (1968), Garrels and Mackenzie (1971), Krumbein and Sloss (1963), Lucchi (1995), Matthews (1984), Pettijohn (1975), Pettijohn et al. (1987), Trask (1950), Weller (1960b)
Structural Geology	Billings (1972), Hills (1972), Ragan (1973), Ramsay and Huber (1983, 1987), Spencer (1977)
Field Geology	Bishop (1960), Compton (1962, 1985), Dietrich et al. (1990), Kempton (1981), Lahee (1961), LeRoy et al. (1987), Low (1957); Field Rock Description: Fry (1984), Thorpe and Brown (1985), Tucker (1982)
	Soils
General	Brady and Weil (1999), Charman and Murphy (2000), Courtney and Trudgill (1984), Fairbridge and Finkl (1979), Fitzpatrick (1980, 1986), Foth (1971), Harpstead and Hole (1980), Hausenbuiller (1972), Jenny (1980), Singer and Munns (1999), Stefferud (1957), Sumner (2000), Van Breeman and Buurman (2001), Windegardner (1996); Bedrock Soils: Cremeens et al. (1994); Forest Soils: Armson (1979), Burns (1959), Lutz and Chandler (1947), Pritchett (1979), Valentine (1986), Wilde (1958); Soil and Vegetation: Trudgill (1988); Wet Soils: Rabenhorst et al. (1998), Richardson and Vepraskas (2000), Vepraskas and Sprecher (1997); Terminology: ASAE (1967), Gregorich et al. (2001), Soil Science Society of America (1996)
Classification and Mapping	Amundson et al. (1994), Bailey (1987 — bibliography), Buol et al. (1989), Butler (1980), Fanning and Fanning (1989), Finkl (1982), Forest Service (1961, 1963), McRae (1988), Milne et al. (1991), Olson (1981, 1984), Soil Survey Staff (1951, 1962, 1992, 1994, 1999, 2002), Webster (1977); Contaminated Sites: Boulding (1991, 1994), Burden and Sims (1999), Cameron (1991)
Micromorphology and Fabric Analysis	Brewer (1976), Brewer and Sleeman (1988), Bullock and Murphy (1983), Bullock et al. (1985), Douglas (1990), Douglas and Thompson (1985), Fitzpatrick (1984, 1993), Hartge and Stewart (1995-soil structure), Miedema and Mermut (1990), Stoops and Eswarin (1986), Thompson et al. (1993)
	Geomorphology
General	Chorley et al. (1984), Dury (1960), Lobeck (1939), Pitty (1971), Ritter (1986), Ruhe (1975), Selby (1985), Sparks (1986), Thornbury (1969); Terminology: SCS (1977)
Geomorphic Regions	Austin (1972), Fenneman (1931, 1938), Fenneman et al. (1946), Hunt (1967), Snead (1980), Thornbury (1965), USDA (1981)
Specific Topics	Environmental: Cook and Doornkamp (1990); Coasts: Trenhaile (1987); Deserts: Cook et al. (1993); Fluvial: Heede (1992), Leopold et al. (1964), Morisawa (1985), Richards (1982); Ground Water: Higgings and Coates (1990); Hillslope: Selby (1993); Phytogeomorphology: Howard and Mitchell (1985)
	Interfaces between Geology, Soils, and Geomorphology
Soils/Geomorphology	Birkeland (1999), Cruikshank (1972), Daniels and Hammer (1992), Foth and Shafer (1980), Gerrard (1981, 1992), Hole and Campbell (1981), Richards et al. (1985)
Glacial and Quaternary Soils/Geology/Geomorphology	Bell and Walker (1992), Catt (1986, 1988), Embleton and King (1968), Eyles (1983), Flint (1971), Ruhe (1965)

Table 1.3 Index to Major References on Geology, Soils, and Geomorphology (*Continued*)

Topic	References
	Engineering Applications
Soil	Asphalt Institute (1969), Bureau of Reclamation (1969, 1974, 1990), Chen (1999), Droshevska (1962), Hough (1969), Kezdi (1980), Portland Cement Association (1992), SCS (1990), Sowers (1979), Terghazi and Peck (1967); Unified Soil Classification System: Howard (1986)
Soil Engineering Properties	Bell (1992), Bowles (1978, 1984), Lamb and Whitman (1969), Means and Parcher (1963), Mitchell (1976), Obert and Duvall (1967), Spengler and Handy (1982), Taylor (1948), U.S. Navy Facilities Command (1971), Yong and Wartentin (1975); Foundation Engineering: Bowles (1982), Leonards (1962), Peck et al. (1974)
Engineering Geology/Rock Mechanics	Attewell and Farmer (1976), Bell (1992), Bureau of Reclamation (1988, 1989), Dennen and Moore (1986), Heley and McIver (1971), Holtz and Kovacs (1981), Hunt (1972), Institution of Civil Engineers (1976), Legget and Hatheway (1988), Rahn (1986), Stagg and Zienkiewicz (1968); Terminology: International Society for Rock Mechanics (1972)

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* See Preface for information on how to obtain documents from CERI and NTIS.

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Topic	References
Glossary	Monroe (1970)
Hydrology/Ground Water	Bibliographies: LaMoreaux (1986), LaMoreaux et al. (1970, 1989, 1993), Warren and Moore (1975); Texts: Back et al. (1990), Bögli (1980), Bonacci (1987), Burger and Dubertret (1975), Ford and Williams (1989), LaMoreaux (1986), LaMoreaux et al. (1975, 1984), Milanović (1981), Stringfield et al. (1974), White (1988); Review Papers: Field (1989), Kresic (1993), LeGrand and Stringfield (1973); Case Histories: Burger and Dubertret (1984), White and White (1989); Proceedings: AGWSE (1991), Beck and Wilson (1987), Beck et al. (1999), Drew and Hötzl (1999), Doaxin (1988), Günay and Johnson (1986), IASH (1967), Rauch and Werner (1974), Saslowky and Wicks (2000), Tolson and Doyle (1977), Yevjevich (1976)
Karst Tracing	Aley and Fletcher (1976), Back and Zoetl (1975), Bögli (1980), Brown (1972), Ford and Williams (1989), Gospodaric and Habic (1976), Gunn (1982), Jones (1984), LaMoreaux (1984, 1989), Milanović (1981), Mull et al. (1988), Quinlan (1986, 1989), Sweeting (1973), SUWT (1966, 1970, 1976, 1981, 1986), Thrailkill et al. (1983)
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Environmental Aspects	AGWSE (1991), Beck (1984, 1990), Beck and Wilson (1987), Doaxin (1988), NWWA (1986, 1988)
Conference Proceedings	AGWSE (1991), Beck (1984, 1990), Beck and Wilson (1987), Beck et al. (1999), Doaxin (1988), Drew and Hötzl (1999), Günay and Johnson (1986), IASH (1967), NWWA (1986, 1988), Rauch and Werner (1974), Saslowsky and Wicks (2000), Tolson and Doyle (1977), Yevjevich (1976)

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CHAPTER 2

Ground Water and Vadose Zone Hydrology

Hydrogeology is the study of ground water — its origin, occurrence, movement, and quality. Modern hydrogeology in the past century has developed along three more or less separate lines:[1] (1) elaboration of the relation between geology and ground-water occurrences (Section 1.6), (2) development of mathematical equations to describe the movement of water through rocks and unconsolidated sediments (this chapter), and (3) the study of the chemistry of ground water (Chapter 3). Another line of study, movement of water in the *vadose*, or unsaturated zone, has been mainly studied by agronomists and soil physicists. Only in the last 10 years or so has the importance of the vadose zone in the study of the movement and fate of contaminants in the subsurface been recognized; this part of the ground-water system is still often overlooked.

2.1 GROUND WATER IN THE HYDROLOGIC CYCLE

The hydrologic cycle involves the continual movement of water between the atmosphere, surface water, and the ground (Figure 2.1). The ground-water system must be understood in relation to both surface water and moisture in the atmosphere. Most additions (recharge) to ground water come from the atmosphere in the form of precipitation, but surface water in streams, rivers, ponds, lakes, and artificial impoundments will move into the ground-water system wherever the hydraulic head of the water surface is higher than the water table (Section 2.5.1). Most water entering the ground as precipitation returns to the atmosphere by evapotranspiration before reaching the saturated zone. Most water that reaches the saturated zone eventually returns to the surface again by flowing to a point of discharge at the ground surface. Typically, these points of surface discharge are rivers, lakes, or the ocean; locally, they may also take the form of springs or soil seeps. Soil, geology, and climate will in large measure determine the amounts and rates of flow among the atmospheric, surface, and ground-water systems.

Ground water is the most difficult part of the hydrologic cycle to study because it is hidden from view and occurs in a complex environment of soil and geologic materials. The movement of water in the atmosphere and surface water can be directly observed, and boundary conditions (air–ground, air–surface water, and surface water–ground) are readily defined. Inferences concerning the movement of ground water rely largely on indirect observations supplemented by a limited number of direct observations (monitoring wells). Even data from direct observations may have large margins of error as a result of variability in the materials through which the ground water is flowing.

[1] Davis, S.N. and R.J.M. DeWiest. 1966. Hydrogeology. John Wiley & Sons, New York, 463 pp.

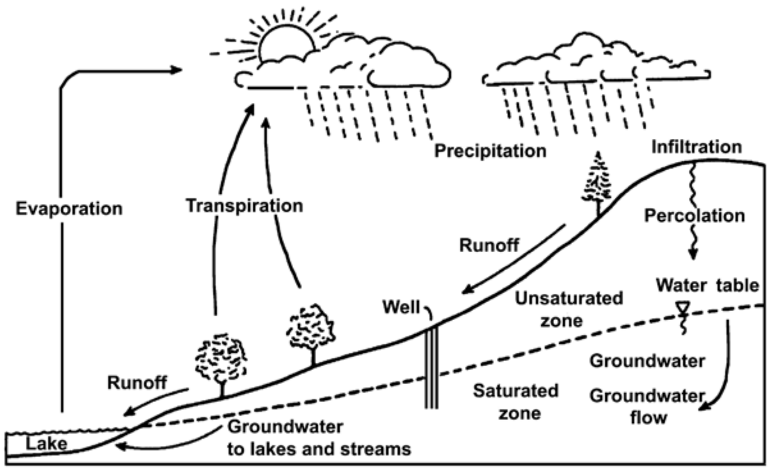

Figure 2.1 The hydrologic cycle (Muldoon and Payton, 1993).

Hydrogeology is not an exact science, but the fundamental principles of ground-water flow are well enough understood that a reasonably good characterization of a particular system is possible. In fact, at the site-specific level, the ground-water system is more predictable than either atmospheric or surface water systems that have large stochastic (random) elements. Provided that the subsurface system is adequately characterized, greater confidence can be placed in what direction and how far a contaminant will travel in a specified time period than in how much rain will fall or how much water will flow through a cross section of a stream during the same period of time.

2.2 GROUND WATER–ATMOSPHERIC RELATIONSHIPS

Precipitation, infiltration, and evapotranspiration are the key elements governing the flow of water between the atmosphere and the ground.

2.2.1 Precipitation

Precipitation (rain, snow, sleet, etc.) is usually the starting point of any mass balance analysis of the flow of water in the hydrologic cycle. Properties of precipitation that affect how much reaches the ground surface include:

- *Amount*. The total amount of precipitation falling on the surface is the first parameter required in any water budget calculation. There is likely to be more ground water, and it will tend to be nearer the surface, in an area of high precipitation rather than in one with low precipitation. Figure 2.2 shows average annual precipitation in the continental U.S.
- *Form*. Whether precipitation reaches the ground as rain or snow will influence how much is likely to reach the ground-water system. In humid areas rain will more readily enter the soil than snow, although snow and ice may be significant sources of ground-water recharge in the spring once the ground has thawed. In arid, semiarid, and alpine areas snowmelt may be the dominant form of recharge to ground water.
- *Seasonal Distribution*. Equal amounts of precipitation during different seasons will result in different amounts of ground-water recharge. When the ground is frozen, ground-water recharge is low because snow returns to the atmosphere through evaporation or runs off the surface when it melts. In spring and early summer, when the ground is saturated or has a high moisture content, recharge will be the greatest. In late summer and fall, when soils tend to be drier, recharge will be less because precipitation goes to replenish soil moisture. Conversely, when plants are dormant

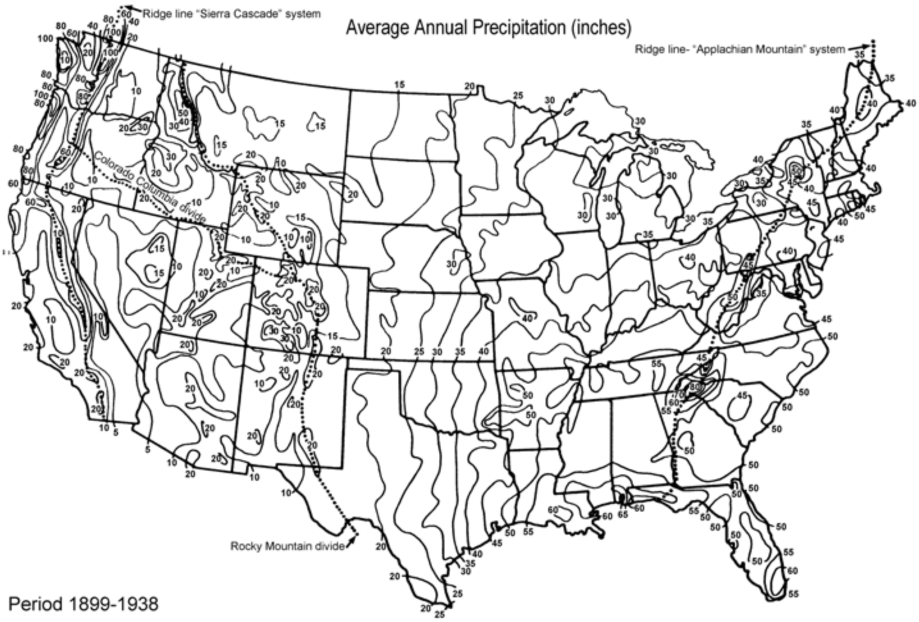

Figure 2.2 Mean annual precipitation (Viessman et al., 1972, after USDA Soil Conservation Service).

(i.e., after freeze in the fall, or in early spring before plants start their normal growth) recharge will be greater.

- *Intensity and Duration.* Precipitation events can be characterized by intensity (inches per hour) and duration (length of time over which the precipitation falls). *Convectional* precipitation (thunderstorms with high intensity and short duration) is common during the summer and results in less ground-water recharge than *cyclonic* precipitation (low-intensity, long-duration events caused by large low-pressure systems that cross the U.S. from the northwest of the Gulf of Mexico). *Orographic* precipitation (caused by topographic barriers that force moisture-laden air to rise and cool) also tends to be of low intensity and long duration.

2.2.2 Infiltration

Not all precipitation reaches the ground; some is *intercepted* by buildings and trees and evaporates. The amount of water reaching the ground that then enters the soil is determined by the *infiltration capacity*. The infiltration capacity of a given soil is controlled by several factors:

- *Antecedent precipitation and soil moisture conditions*. Soil moisture fluctuates seasonally; it is usually high during winter and spring and low during the summer and fall. If the soil is dry, wetting the top of it will create a strong capillary potential just under the surface, supplementing gravity. When wetted, some clayey soils swell, closing pore spaces, thereby reducing the infiltration capacity shortly after a rain starts.
- *Compaction of the soil due to rain*. The impact of raindrops on the soil surface during an intense rainfall is more likely to reduce infiltration than a gentle rain.
- *Inwash of fine material* into soil openings reduces infiltration capacity. This is especially important if the soil is dry.
- *Compaction of the soil* due to animals, roads, trails, urban development, etc., reduces infiltration.
- Certain *microstructures* in the soil will promote infiltration, such as channels created by the interface between soil structural units; openings caused by burrowing animals, insects, decaying roots, and other vegetative matter; frost heaving; desiccation cracks; and other macropores.
- *Vegetative cover* tends to increase infiltration because it promotes populations of burrowing organisms and retards surface runoff, erosion, and compaction by raindrops.

- *Decreasing temperature*, which increases water viscosity, reduces infiltration.
- *Entrapped air* in the unsaturated zone tends to reduce infiltration.
- *Surface gradient*. Flat topography favors infiltration because any surface water will move more slowly than it will on sloping topography.

Infiltration capacity is usually greater at the start of a rain that follows a dry period, but it decreases rapidly. As the duration of rainfall increases, infiltration is determined by the saturated hydraulic conductivity of the soil and becomes nearly constant. In fine-grained soil, infiltration may be lower than the hydraulic conductivity immediately below the surface as a result of clogging by particles. If precipitation is greater than the infiltration capacity, surface runoff occurs. If it is less than the infiltration capacity, all the moisture enters the subsurface. The amount of infiltrating water that actually enters the ground-water system as recharge will depend on the amount of evapotranspiration.

2.2.3 Evapotranspiration

Water moves from the ground to the atmosphere by direct evaporation and by plant transpiration. During the growing season, water intercepted by vegetation before reaching the ground, which then evaporates, typically amounts to 10 to 20% of total precipitation in humid areas. Water removal from the soil by transpiration occurs to whatever depth plant roots are able to penetrate. Depending on the type of vegetation and soil conditions, this depth is typically 3 to 4 ft for grains and pasture grasses (although under favorable conditions, alfalfa roots will penetrate as deep as 10 ft). Deciduous trees have deeper roots and consequently remove soil moisture from greater depths (6 to 12 ft or more); desert plants may extend roots tens of feet below the surface to obtain moisture. Obviously, these rooting depths will be shallower where soil or geologic conditions limit rooting.

The relationship between evapotranspiration and precipitation determines whether soluble salts in soil will leach (precipitation > evapotranspiration) or accumulate (precipitation < evapotranspiration). This has important implications for contaminant transport, because a leaching environment will tend to move soluble contaminants into the saturated zone (generally in the humid East, Midwest, and coastal areas of the Pacific Northwest), whereas contaminants will tend to stay in the soil in a salt-accumulating environment (the semiarid plains and deserts of the West).

2.2.4 Distribution of Precipitation in the Hydrologic Cycle

Very little precipitation that reaches the ground surface actually reaches the saturated zone. The mass balance for precipitation at a site in southwestern Indiana might look something like this:

$$P = E + T + G + S \tag{2.1}$$

where:
P = precipitation = 41 in.
E = evaporation (interception) = 4 in.
T = transpiration = 24 in.
G = ground-water recharge = 1 in.
S = surface runoff = 12 in.

This example shows that about 10% of the precipitation is intercepted and returns to the atmosphere by evaporation, about 30% runs off the surface to enter streams, and about 60% of the precipitation enters the soil. However, of the water entering the soil by infiltration, the amount actually reaching the water table represents only about 2% of total precipitation, while transpiration returns the rest to the atmosphere (58% of total precipitation).

2.3 GROUND WATER–SURFACE WATER RELATIONSHIPS

Surface and near-surface ground water are intimately connected. Ground water that reaches the surface becomes surface water and vice versa. The direction(s) of flow between these two systems must be understood because contaminated ground water may contaminate surface water (ground water flows to the surface), or contaminated surface water may contaminate ground water (surface water flows to the ground).

2.3.1 Characteristics of Surface Water Flow

Channel storage refers to all of the water contained at any instant within the permanent stream channel. Runoff includes all of the water in a stream channel flowing past a cross section; this water may consist of precipitation that falls directly into the channel, surface runoff, ground-water runoff (also called *base flow*), and effluent. Stream flow, runoff, discharge, and yield of drainage basin are all nearly synonymous terms. Bank storage (Section 2.3.3) will also move into channel storage after flow in a stream channel drop from high-flow to intermediate and low-flow conditions.

Rates of flow are generally reported as cubic feet per second (cfs); millions of gallons per day (mgd); acre-feet per day, month, or year; cubic feet per second per square mile of drainage basin (cfs/mi^2); or inches depth on drainage basin per day, month, or year. In the U.S., the most common unit of measurement for rate of flow is cubic feet per second.

Surface water discharge (Q) is determined by measuring the cross-sectional area of the channel (A), in square feet, and the average velocity of the water (v), in feet per second, so that

$$Q = Av \tag{2.2}$$

The cross-sectional area generally shows little change with time, so velocity is the main variable that must be measured to calculate stream flow. Typically, stream flow is measured by developing rating curves, in which accurate discharge measurements are made at low, intermediate, and high flows, and plotted against a gauge that measures the height of the stream at each discharge measurement. Once the rating curve has been fitted to the initial measurements, the flow at any gauge height can be estimated (provided that the channel geometry remains stable).

Surface water flow generally shows short-term fluctuations in response to individual precipitation events, and longer-term seasonal fluctuations. *Stream hydrographs* (plots of discharge as a function of time) are a useful way of viewing these fluctuations. Figure 2.3 shows a hydrograph in which individual peaks represent stream flow response to specific precipitation events. Seasonal fluctuations are also evident in this hydrograph, with lowest flow occurring in the fall. Another useful way to describe stream flow is the *flow-duration curve*, which shows the percentage of time discharge for the period of record equaled or exceeded various rates of discharge. *Base flow* (labeled as ground-water runoff in Figure 2.3) is the contribution of ground-water flow to a stream after all other contributions to stream flow have been subtracted out. Figure 2.3 shows that base flow fluctuates seasonally with a maximum in the spring and a minimum in the fall.

2.3.2 Drainage Basins

The drainage basin or *watershed* is the basic geographic unit for studying surface water. The watershed is the area that contributes water to a particular channel or set of channels. When the ground surface is saturated or precipitation exceeds the infiltration rate, surface runoff moves downhill until it reaches a stream. When several streams come together, the flows from their separate watersheds combine to form a larger watershed. Surface drainage basins are readily defined by topographic maps on which *drainage divides* mark the boundaries between watersheds.

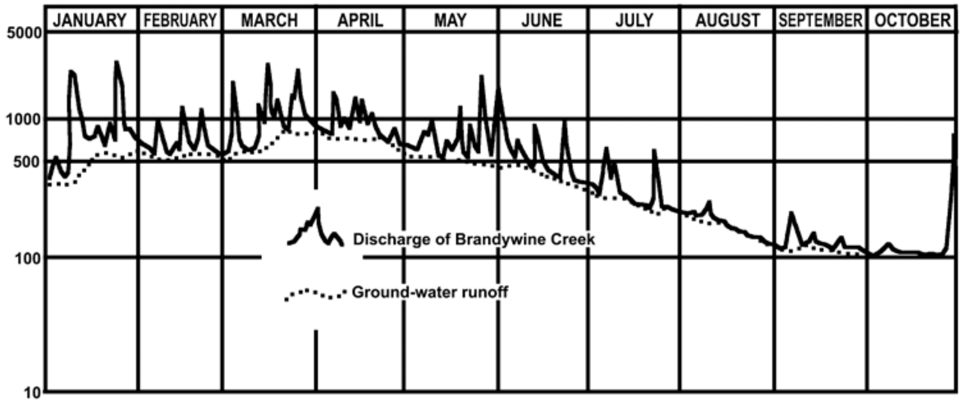

Figure 2.3 Hydrograph of Brandywine Creek, Chadd's Ford, PA, 1952–1953 (U.S. EPA, 1987a, after Olmsted and Hely, 1962).

Surface drainage patterns can be classified according to type of pattern and density. Figure 2.4a illustrates six basic drainage patterns, and Figure 2.4b shows coarse, medium, and fine densities. Stream segments can also be classified according to the number of tributaries. *First-order* streams have no tributaries and tend to be located in the upper reaches of a watershed. *Second-order* streams have as tributaries only first-order channels, *third-order* streams receive as tributaries only first- and second-order channels, and so on. Figure 2.4b shows stream orders for the coarse drainage density. Preliminary interpretation concerning geology and hydrogeology can be made by examining drainage patterns on aerial photographs or topographic maps. Table 2.1 summarizes preliminary geologic and hydrogeologic interpretations that can be made based on drainage patterns illustrated in Figure 2.4a.

Surface and ground-water drainage basins commonly coincide, but a perfect match should never be assumed. Situations where near-surface ground water and surface water watersheds may not include:

- Karst limestone terrane where subsurface drainage may have developed independently of surface drainage
- Sedimentary formations where the regional dip is in the opposite direction of surface water flow
- Areas where pumping of ground water has created disturbed normal ground-water flow patterns
- Areas where underground mining has altered subsurface flow patterns
- Heterogeneities in the subsurface near drainage divides, which may result in ground-water divides that differ from the topographic divide

2.3.3 Stream Types

From a hydrogeologic point of view, there are three major stream types: ephemeral, intermittent, and perennial. Stream type is determined by the relation between the water table and the stream channel.

An *ephemeral* stream owes its entire flow to surface runoff. It may have no well-defined channel, and the water table consistently remains below the bottom of the channel (Figure 2.5, A-A′). Water leaks from the channel into the ground, recharging the underlying strata.

Intermittent streams flow only part of the year, generally from spring to midsummer, as well as during wet periods. During dry weather, these streams flow only because of ground water that discharges into them when the water table rises above the base of the channel (Figure 2.5, B-B′). Eventually sufficient ground water discharges throughout the basin to lower the water table below the channel, which then becomes dry. This reflects a decrease in the quantity of ground water in

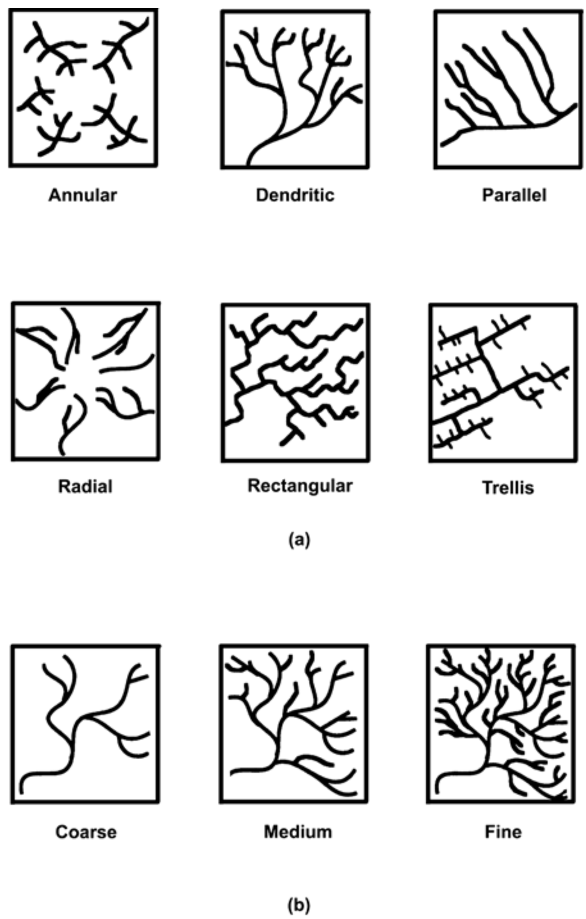

Figure 2.4 Drainage patterns: (a) six basic patterns; (b) drainage density variations (Kolm, 1993, after Way, 1973).

storage. During late summer or fall, a wet period may temporarily raise the water table enough for ground water to again discharge into the stream. Thus, during part of the year the floodplain materials are full to overflowing, causing the discharge to increase in a downstream direction; at other times, water will leak into the ground, reducing the discharge.

Perennial streams flow year-round. Typically, the water table is always above the stream bottom; hence, ground water is discharged to the surface, and stream flow increases downstream (Figure 2.5, C-C′). A stream in which the discharge increases downstream is called a *gaining stream*. When the discharge of a stream decreases downstream due to leakage, it is called a *losing stream*. In a losing stream, the water table is below the bottom of the stream, but the amount discharged to the subsurface is not enough to eliminate surface flow during periods of low flow. During wet periods, surface flow in perennial streams comes from a mixture of surface runoff and ground-water inflow. During dry periods, the flow of perennial streams comes primarily from ground-water discharge, and is called the *base flow*. Figure 2.3 shows the ground-water base flow component of Brandywine Creek. In this figure most of the flow in the months of August through October is ground-water base flow.

Normally, ground water flows into a gaining stream. However, short-term reversals in the direction of flow may occur in response to precipitation events. When the crest of runoff from a precipitation event passes a particular stream cross section, the stream level may rise higher than the water table, resulting in stream flow into the unsaturated portion of the stream bank. This