Ground Water Contamination: Transport and Remediation 2nd ed

GROUND WATER CONTAMINATION

TRANSPORT AND REMEDIATION

Second Edition

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To Cindy, Eric, and Courtney
To my parents for their guidance
To all of my students and colleagues
PBB

To CJ, Imo, Steve and Meaux
To my parents
HSR

To June, Wynne, Mark, Jon, and Phil
To Hanadi, for everything
CJN

PREFACE

The 1970s ushered in a new decade of environmental awareness in response to major air pollution and water quality problems throughout the country. One of the primary missions of the newly formed Environmental Protection Agency (EPA) was to define, maintain, and protect the quality of the nation's surface waters and subsurface aquifers. The field of environmental engineering was in its infancy, but hydrologists, civil and environmental engineers, hydrogeologists and other scientists were needed to provide the necessary expertise and engineering designs for water pollution control of surface waters.

By the late 1970s, the discovery of hazardous wastes at sites such as Love Canal in New York, the Denver Arsenal in Colorado, and a number of chlorinated organics sites in California and Arizona ushered in a new era in hazardous waste site problems. In the early 1980s, a large number of major disposal sites were discovered associated with industrial and military practices. These sites had been in place for decades. As a result, literally thousands of studies of active and abandoned waste sites and spills were conducted, as required by Resource Conservation and Recovery Act (RCRA) and the Superfund legislation administered by EPA, all designed to protect ground water quality (Chapter 14). During this time, hydrogeologists and consulting engineers were collecting samples, characterizing geology, analyzing data, and remediating hazardous waste sites with respect to ground water contamination. More than 1500 hazardous waste sites were eventually placed on the National Priorities List and thousands of other sites still remaining to be cleaned up.

By 1985, leaking underground fuel tanks became one of the most ubiquitous of all subsurface contamination issues. In addition, chlorinated hydrocarbon sites were recognized as some of the most difficult to remediate due to the presence of newly discovered nonaqueous phase liquids (NAPLs). But as these sites and others were being investigated and remediation systems were being designed and installed across the country, it became clear by 1989 that many of these systems were not working to cleanup aquifers to drinking water standards. By the early 1990s, EPA and the National Research Council found that the nation was wasting large sums of money on ineffective remediation systems, such as pump and treat (see Chapter 13).

Along with the maturing of environmental engineering and related ground water fields in the eighties, attention to hazardous waste problems has greatly expanded the scope and emphasis of traditional ground water investigations. Contaminant transport in the subsurface is of paramount importance and encompasses physical, chemical, and biological mechanisms which affect rates of migration, degradation, and ultimate remediation. In the nineties, many of the these complex transport mechanisms were evaluated at actual field sites or in supporting laboratory studies.

After all of the efforts spent on analyzing and remediating soluble contaminant plumes, scientists and engineers in the nineties and beyond 2000 must be prepared to deal with more complex problems. These include source zone areas with non-aqueous phase liquids (NAPLs), residual oils, and vapors in the unsaturated zone. LNAPLs, which float on the water table, and DNAPLs, which sink to the bottom of an aquifer, can leach contamination for decades to shallow ground water aquifers. Specialized remediation schemes, which might involve a variety of methods for a mixture of chemicals, must now be evaluated in complex ground water settings. The old concept of simply pumping out the contaminated ground water does not effectively work to return an aquifer to useful condition. Rather, new and emerging methods and models must be considered in order to address and possibly control complex NAPL source zones.

The second edition of our textbook has been written to better address the scientific and engineering aspects of subsurface contaminant transport and remediation in ground water. This book contains traditional emphasis on site characterization and hydrogeologic evaluation, but with an orientation to the engineering analysis and modeling of complex field problems, compared to other texts written primarily for hydrogeologists. The current text is a departure from past efforts in that it is written from both a theoretical and practical viewpoint with engineering methods and transport theory applied directly to hazardous waste site investigation. Entire chapters are included on biodegradation, soil vapor transport, contaminant transport modeling, and site remediation. A number of new case studies have been added that illustrate the various evaluation schemes and emerging remediation techniques.

This second edition is designed for hydrologists, civil, environmental, and chemical engineers, hydrogeologists, and other decision makers in the ground water field who are or will be involved in the evaluation and remediation of the nation's ground water. However, the field of ground water contamination has changed rapidly in recent years (since 1994) as new remediation techniques are being researched in laboratories and at many field sites nationwide. Any modern student of the topic must keep a watchful eye on the literature, which reports both results and breakthroughs on a monthly basis. We hope this text will provide the fundamentals for understanding and incorporating new approaches into the more traditional methods developed in site investigations of the past two decades.

The legal framework of ground water legislation under RCRA and Superfund has provided significant guidance and funding for many of the ground water studies which have been performed to date. These comprehensive legal instruments set into motion an entire industry devoted to the identification, characterization, and remediation of hazardous waste sites throughout the U.S. As a result of billions of dollars allocated for remedial investigations and studies in the past 20 years, thousands of engineers and scientists now form the core of the ground water and remediation industry. During this time, college and university programs quickly added ground water flow and transport courses to their traditional fields of civil and environmental engineering and geology. And professional groups, such as the Assn. of Ground Water Scientists and Engineers, saw their memberships grow in response to the challenge of education and technology transfer.

Our new revision was written in response to the tremendous demand in the college classroom and in the environmental industry for a modern engineering approach to ground water contamination problems of the nineties and beyond. Any practicing hydrologist or engineer today must understand mechanisms of ground water flow (Chapters 2 and 3), sources of contamination (Chapter 4), site investigations (Chapter 5), and contaminant transport (Chapters 6 and 7). In addition, biodegradation (Chapters 7 and 8), modeling approaches (Chapter 10), NAPL impacts in source areas and plumes (Chapters 11), natural attenuation (Chapter 12), and emerging remediation schemes (Chapter 13) are covered. In the second edition, Chapters 4, 7, 8, 9, 11, 12, and 13 have been completely rewritten to better reflect current trends and ideas. Many new examples and case studies have been added based on emerging methods from the current literature. A new chapter on natural attenuation and risk assessment has been added, along with detailed discussions of emerging remediation methods such as surfactant and co-solvent soil flushing for sites contaminated with residual oils. The organization is described in more detail in Chapter 1.

For more information about software that relates to the book, updates, or to communicate with the primary author, please visit Prentice-Hall's website at http://www.prenhall.com or http://www.rice.edu/envi.

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Many Rice University staff and students contributed significantly to the new edition of the text. Joseph Hughes, Manar El-Beshry, Robert Lee, and Anthony Holder contributed important new sections to the second edition. Emily Hall, AnnMarie Spexet, Michelle Truesdale, and Jude Benavides contributed to final editing. Susan Hickman and Michelle Truesdale handled new figure designs, and Christina Walsh organized the revised figures and final layout for the second edition. AnnMarie Spexet did a great job with figure design, indexing, revised homework problems, and helped develop the solutions manual. Anthony Holder did a superb job of final text and figure editing, placement, and computer linkage. Cory Deveney was responsible for the revised cover for the new edition. Finally, the authors are deeply indebted to Emily Hall for taking on the enormous challenge of typing, format layout, and editing the newly revised manuscript. Without her daily commitment to the overall success of the project, the revision would not have been completed on time and with such style.

CONTENTS

CHAPTER 1

INTRODUCTION TO GROUND WATER CONTAMINATION

1 THE HYDROLOGIC CYCLE

The definition of **hydrology** includes the study of storage and movement of water in streams and lakes on the surface of the earth, as well as in ground water aquifers in the subsurface. An **aquifer** represents a geological unit, which can store and supply significant quantities of water for a variety of uses. Many shallow and deep aquifers have been investigated and identified as having elevated levels of contaminants from releases that may have occurred decades ago. Modern hydrology encompasses both flow and water quality transport aspects of the water cycle.

Figure 1.1 shows the various components of the hydrologic cycle, including both natural processes and manmade or engineered processes and transport pathways. These concepts are covered in detail in modern texts on hydrology (Bedient and Huber, 1992; Gupta,

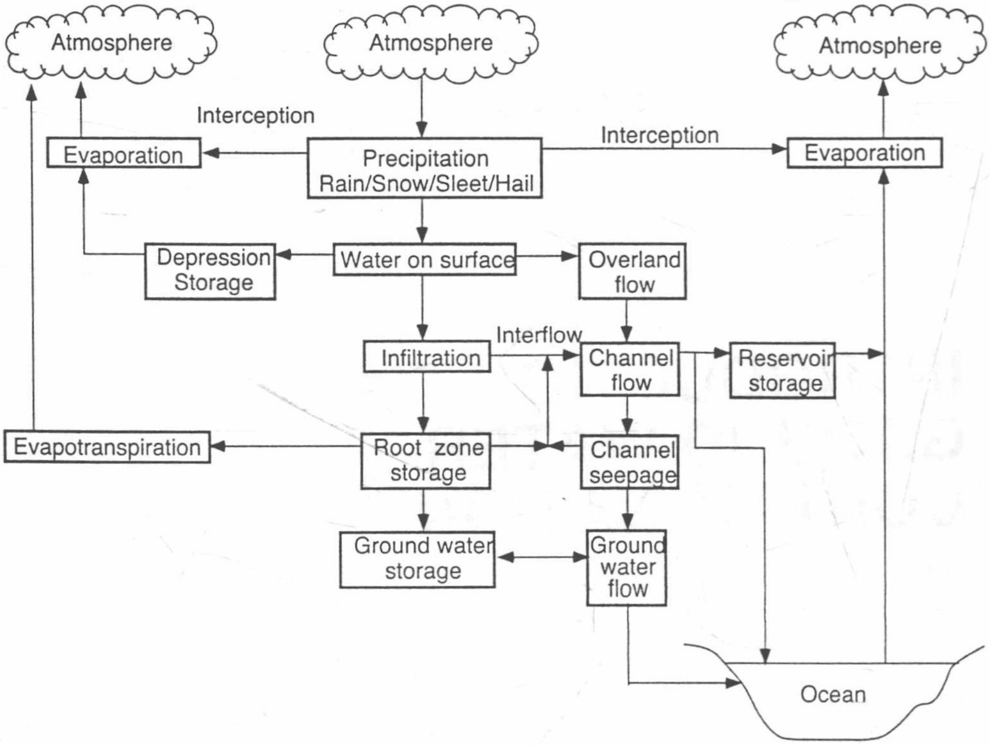

Figure 1.1 Components of the hydrologic cycle.

1989, Chow et al., 1988). Atmospheric water and solar energy provide the main inputs for the generation of precipitation, which falls over the land and oceans. Rainfall can infiltrate into the soil system, percolate to deeper ground water, evaporate from detention areas, transpire through vegetation back to the atmosphere, or runoff to the nearest stream or river. Infiltrating water is the main source of recharge to the root zone and ground water aquifers below. Rivers can also recharge aquifers or can act as discharge points for aquifer outflows. The ocean is the ultimate receptor of surface and ground water contributions from surrounding land areas, and provides the main source of water for evaporation back to the atmosphere.

Manmade changes to the cycle have been recorded since the beginning of civilization. They include changes in infiltration patterns and evaporation due to land development, changes in runoff and evaporation patterns due to reservoir storage, increases in streamflow due to channelization and piping, and changes in ground water levels due to pumping of aquifers. Since the 1930s, hydrologists traditionally have spent much time and effort designing alterations to the natural hydrologic cycle for man's use. Such alterations include providing surface or ground water supplies for industrial, agricultural, and municipal needs; providing water treatment for drinking water and the disposal of wastewater; meeting water supply needs through building of dams and reservoirs or drilling of water supply well fields; providing drainage and flood control via channelization and dams; and providing water quality and recreational benefits through development and maintenance of reservoirs and stream corridors.

Due to the complexity of the hydrologic cycle shown in Figure 1.1, not all of the transport pathways and storage elements can be measured easily, and some components can be determined only indirectly as unknowns in the overall hydrologic water balance equation. Infiltration and evaporation are often computed as losses from the system and are not usually measured directly. Precipitation rates and stream levels can be directly measured by rainfall and stream gages that have been located within a particular watershed being studied. Ground water levels and flow rates are measured from wells installed into aquifers with screens across the permeable zones. In complex geological settings, multiple layers are monitored for water and contaminant levels. Methods include use of flow meters within the well casing and electronic water level meters. Pumps and individual bailers are used to collect water samples for the analysis of water quality levels in wells.

Overall water balances for a watershed or ground water basin can be computed if the above hydrologic data is available. Computer methods have been developed beginning in the 1970s to assist the hydrologist in watershed analysis, ground water assessment, and hydrologic design. Surface water aspects of the hydrologic cycle are usually covered in modern hydrology texts such as Viessman et al. (1989), Chow et al. (1988), and Bedient and Huber (1992).

2 GROUND WATER HYDROLOGY

Ground water is an important source of water supply for municipalities, agriculture, and industry. Figure 1.2 indicates the percentage of various types of ground water use in the United States through 1995. Primary users are agriculture, municipalities, industry, and rural areas where alternate surface supplies are inadequate. Agricultural irrigation use is clearly the largest category. Figure 1.3 depicts ground water use relative to total water use for each state in the continental United States, indicating that western and midwestern areas are more dependent on ground water aquifers than are states in the east and northeast.

Ground water hydrology has traditionally included the characterization of aquifers, application of Darcy's law for ground water flow through porous media, infiltration into soils, and flow in shallow and deep aquifer systems. More advanced topics include the mechanics of well flow in radial coordinates for single or multiple well systems. Techniques for the analysis of aquifer characteristics using slug tests, pump tests, or tracer tests are a major part of ground water investigations. The prediction of flow rates and directions in confined (under pressure) and unconfined (water table) aquifers is the starting point for understanding ground water contamination issues. The **water table** in a shallow aquifer is defined as the level to which water will rise in a dug well under atmospheric conditions. The **piezometric** surface is the level to which water rises in a confined aquifer under pressure (see Chapter 2).

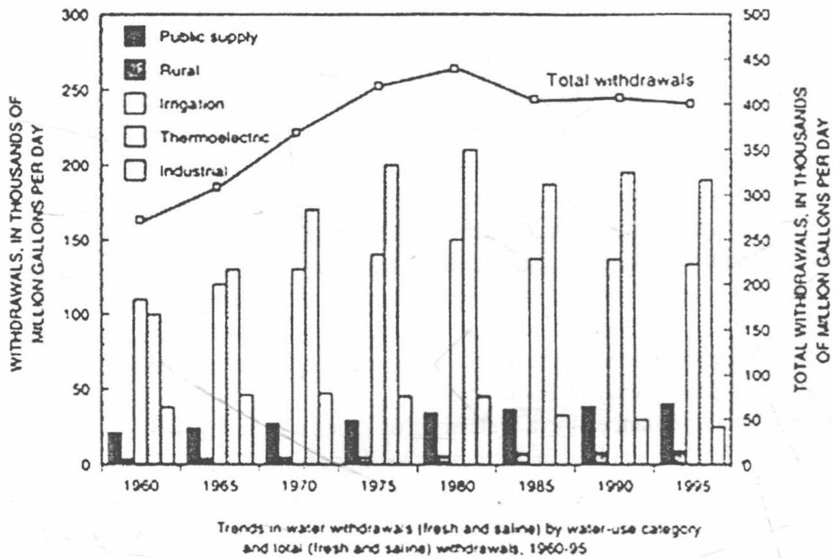

Figure 1.2 Trends in water withdrawals (fresh and saline) by water use category and total (fresh and saline) withdrawals, 1960-95. Source USGS, 1995.

Ground water hydrology is of great importance because of the use of aquifer systems for water supply and because of the threat of contamination from leaking hazardous waste sites, which occur at or below the ground surface. Recently, more attention has been given to the connection between the unsaturated zone and shallow aquifers just below the water table as it relates to migration of contaminants from the surface or from buried tanks, pipes, or waste ponds. Properties of the porous media and subsurface geology govern both the rate and direction of ground water flow in any aquifer system. The injection or accidental spill of hazardous wastes into an aquifer or the pumping of the aquifer for water supply may alter the natural hydrologic flow patterns. In order for the hydrologist, hydrogeologist, civil engineer, or environmental engineer to obtain a full understanding of the mechanisms that lead to ground water contamination from spills or continuous leaks, it is necessary to address first the properties of ground water flow and well mechanics, as covered in Chapters 2 and 3.

Geological aspects of ground water, sometimes referred to as hydrogeology, are of importance to understanding ground water flow and the fate and transport of contaminants in the subsurface. Regional geological aspects have been covered in detail in books by Freeze and Cherry (1979), Fetter (1994), and Domenico and Schwartz (1998) and will be addressed in this text only to a limited basis. One useful generalization is the concept of ground water regions, which are geographical areas of similar occurrence of ground water. Meinzer (1923), considered the father of modern hydrogeology in the United States, proposed a classification