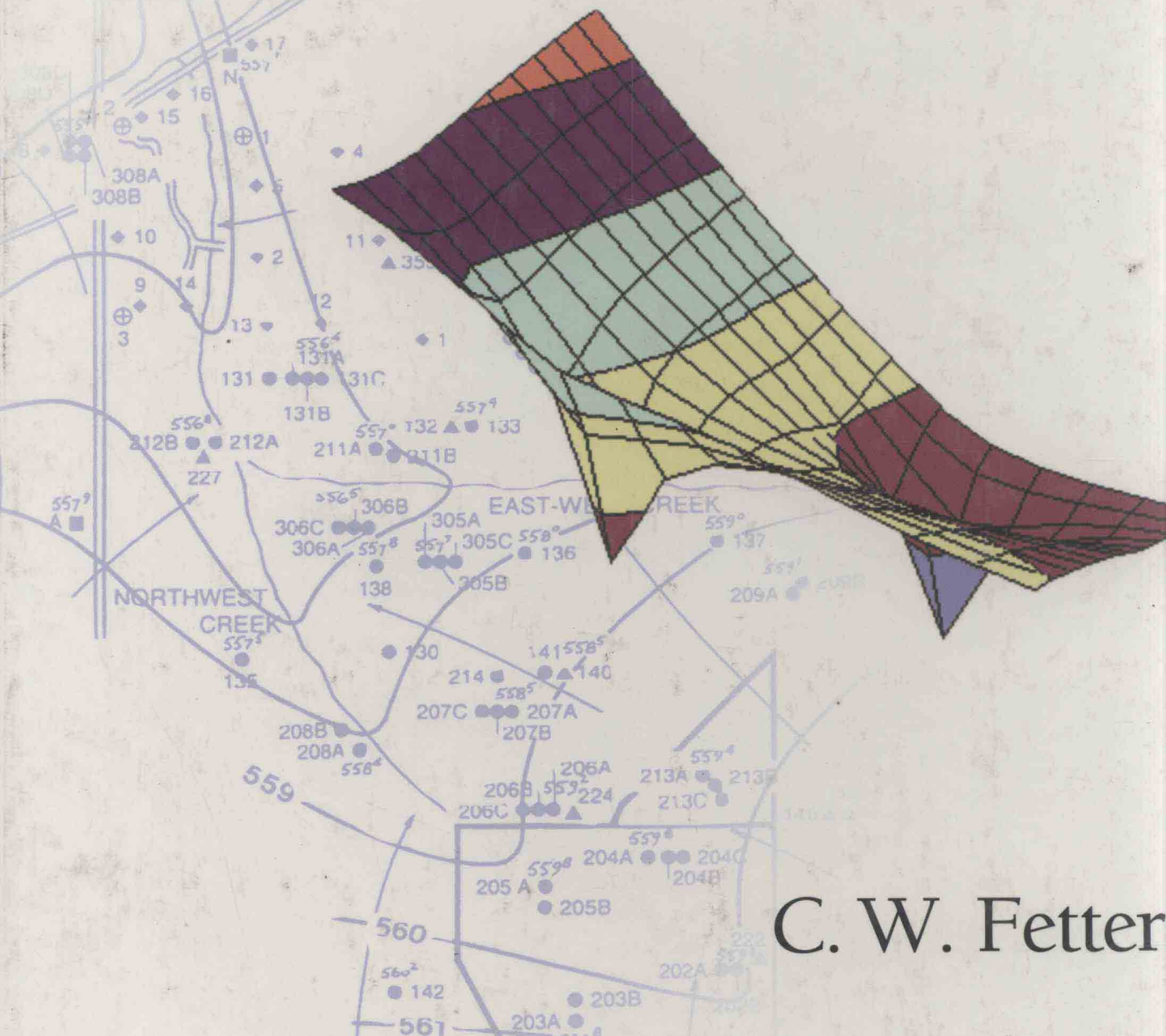
# Applied Hydrogeology

Fourth Edition




C. W. Fetter

C. W. FETTER

UNIVERSITY OF WISCONSIN-OSHKOSH

# Applied Hydrogeology

## Fourth Edition

江苏工业学院图书馆
藏书章

Prentice Hall

Upper Saddle River, New Jersey 07458

**Library of Congress Cataloging-in-Publication Data**

Fetter, C. W. (Charles Willard)
Applied hydrogeology / C.W. Fetter.--4th ed.
p. cm.
Includes bibliographical references.
ISBN 0-13-088239-9
1. Hydrogeology. 2. Water supply. I. Title.

GB1003.2 .F47 2001
551.49--dc21 00-48329

Senior editor: *Patrick Lynch*
Editorial assistant: *Sean Hale*
Assistant managing editor: *Beth Sturla*
Art director: *Jayne Conte*
Cover design: *Kiwi Design*
Marketing manager: *Christine Henry*
Manufacturing buyer: *Michael Bell*
Manufacturing manager: *Trudy Pisciotti*
Assistant managing editor, media: *Alison Lorber*
Assistant editor: *Amanda Griffith*
Associate media editor: *Michael Banino*
Composition: *Carlisle Communications*

© 2001, 1994 by Prentice-Hall, Inc.
Upper Saddle River, New Jersey 07458

Earlier editions copyright © 1988, 1980
by Merrill Publishing Company.

All rights reserved. No part of this book may be
reproduced, in any form or by any means,
without the permission in writing from the publisher.

Printed in the United States of America

10 9 8 7 6 5 4 3 2

ISBN 0-13-088239-9

Prentice-Hall International (UK) Limited, *London*
Prentice-Hall of Australia Pty. Limited, *Sydney*
Prentice-Hall Canada Inc., *Toronto*
Prentice-Hall Hispanoamericana, S.A., *Mexico*
Prentice-Hall of India Private Limited, *New Delhi*
Prentice-Hall of Japan, Inc., *Tokyo*
Pearson Education Asia Pte. Ltd.
Editora Prentice-Hall do Brasil, Ltda., *Rio de Janeiro*

*This book is dedicated to my wife, Nancy Blessing Fetter, and to my children and their families:*

*Bill, Barb, Katie and Sarah Fetter*

*Rob and Abby Fetter*

*Elizabeth Fetter*

# PREFACE

Hydrogeology is now considered to be a core course in the curriculum of undergraduate geology programs as well as many fields of engineering. There is ongoing demand for persons with training in hydrogeology by consulting organizations, state and federal regulatory agencies, and industrial firms. Most of the employment in hydrogeology is in the environmental area. This is a book that will help prepare students for either a career in hydrogeology or in other areas of environmental science and engineering where a strong background in hydrogeology is needed.

*Applied Hydrogeology* is intended as a textbook for an introductory course in hydrogeology taught either at the advanced undergraduate level, or as a dual-level undergraduate/graduate course. It is also useful in helping individuals who are preparing to take state examinations for professional registration as a hydrologist or hydrogeologist. It can be found as a reference book in the personal library of many working professionals.

The reader is expected to have a working knowledge of college algebra, and calculus is helpful, but not necessary, for practical understanding of the material. A background in college chemistry is necessary to understand the chapter on water chemistry. The book stresses the application of mathematics to problem-solving rather than the derivation of theory. To this end you will find many example problems with step-by-step solutions. Case studies in many chapters enhance understanding of the occurrence and movement of ground water in a variety of geological settings. A glossary of hydrogeological terms makes this book a valuable reference.

The fourth edition contains new case studies and end-of-chapter problems. In most cases the problems are paired. An odd-numbered problem will have the answer given in a section in the back of the book, followed by an even-numbered problem without the answer. Step-by-step solutions to the odd-numbered problems can also be found at the *Applied Hydrogeology* web page: http://www.appliedhydrogeology.com. Many chapters in the fourth edition also contain a section called Analysis, with non-numerical questions. The use of spreadsheet programs, such as Microsoft® Excel, in hydrogeology is introduced here.

Included with the text are working student versions of three computer programs that are used by ground-water professionals. They have been furnished free of charge by the software publishers. No technical support is furnished for these programs, either by the author or the software publisher. However, they are easy to use and come with tutorials and documentation on the CD-ROM.

The following reviewers of the Third Edition provided helpful suggestions for the Fourth Edition: Gary S. Johnson, University of Idaho; Larry Murdoch, Clemson University; Claude Epstein, Richard Stockton College of New Jersey; David L. Brown, California State University at Chico; F. Edwin Harvey, University of Nebraska at Lincoln; Edward L. Shuster, Rensselaer Polytechnic Institute; Willis D. Weight, Montana Tech. of the University of Montana; Larry D. McKay, University of Tennessee at Knoxville; Laura L. Sanders, Northwestern Illinois University; Jean Hoff, St. Cloud State University; and Jim Butler,



此为试读,需要完整PDF请访问: www.ertongbook.com

Kansas Geological Survey. Dr. Carl Mendoza of the University of Alberta peer reviewed the Fourth Edition and made many helpful suggestions and corrections.

I am grateful to Larry Murdoch and Rex Hodges of Clemson University for introducing me to the use of spreadsheet ground-water flow models. I would especially like to thank Glenn Duffield of Hydrosolve, Inc. for furnishing the student version of AQTESOLV, Pat Delaney of Waterloo Hydrogeologic Inc. for furnishing the student version of Visual MODFLOW, and Kirk Hemker for the use of FLOWNETLT. Todd Rayne of Hamilton College has prepared the solution manual for the problems, which course instructors can request from their Prentice Hall sales representative. Patrick Lynch, Senior Editor for Geology at Prentice Hall, has been very supportive through the course of my preparation of this revision.

C. W. Fetter
*C. W. Fetter, Jr. Associates and*
*Emeritus Professor of Hydrogeology*
*University of Wisconsin Oshkosh*

# ABOUT THE AUTHOR

C. W. Fetter received a B.A. degree in chemistry from DePauw University, an M.A. in geology and a Ph.D. in hydrogeology from Indiana University. He has practiced as a professional hydrogeologist since 1966, and is registered as both a professional geologist and professional engineer.

He was on the faculty of the University of Wisconsin–Oshkosh for 25 years, where he was department chair for 15 years. Since his retirement from UW–Oshkosh in 1996 he has been a full time consultant in environmental hydrogeology. His clients have included the United States Environmental Protection Agency, the Wisconsin Department of Justice, the United States Department of Justice, Fortune 500 corporations, insurance companies, municipal government, and attorneys at law. Dr. Fetter has been an expert witness in legal proceedings on numerous occasions.

In 1996 he received the Excellence in Science and Engineering Award from the Association of Ground Water Scientists and Engineers in recognition of his two books about hydrogeology. In 1998 he received the Hydrogeologist of the Year award from the Wisconsin Ground Water Association.

# CONTENTS

Preface xvi
About the Author xviii

## CHAPTER 1 Water

1.1 Water 1
1.2 Hydrology and Hydrogeology 3
1.3 The Hydrologic Cycle 4
1.4 Energy Transformations 5
1.5 The Hydrologic Equation 8
Case Study: Mono Lake 9
1.6 Hydrogeologists 11
1.7 Applied Hydrogeology 11
1.8 The Business of Hydrogeology (What Do Hydrogeologists Do All Day?) 12
1.8.1 Application of Hydrogeology to Human Concerns 12
1.8.2 Business Aspects of Hydrogeology 14
1.8.3 Ethical Aspects of Hydrogeology 15
1.9 Sources of Hydrogeological Information 16
1.10 American Society of Testing and Materials Standards 18
1.11 Working the Problems 18
1.12 Solving Problems Using Spreadsheets 20

Notation 22 • Analysis 22 • Problems 22

## CHAPTER 2 Elements of the Hydrologic Cycle

2.1 Evaporation 24
2.2 Transpiration 27
2.3 Evapotranspiration 28
2.4 Condensation 32
2.5 Formation of Precipitation 32
2.6 Measurement of Precipitation and Snow 32
2.7 Effective Depth of Precipitation 33
2.8 Events During Precipitation 37
2.9 Stream Hydrographs 42
2.9.1 Baseflow Recessions 42
2.9.2 Storm Hydrograph 44
2.9.3 Gaining and Losing Streams 46
2.10 Rainfall-Runoff Relationships 48
2.11 Duration Curves 50

2.12 Determining Ground-Water Recharge from Baseflow 51
2.12.1 Seasonal Recession Method (Meyboom Method) 51
2.12.2 Recession Curve Displacement Method (Rorabaugh Method) 53
2.13 Measurement of Streamflow 55
2.13.1 Stream Gauging 55
2.13.2 Weirs 57
2.14 Manning Equation 58

Notation 60 • Analysis 61 • Problems 61

CHAPTER 3

Properties of Aquifers

3.1 Matter and Energy (A Brief Review of Physics) 66
3.2 Porosity of Earth Materials 69
3.2.1 Definition of Porosity 69
3.2.2 Porosity and Classification of Sediments 70
3.2.3 Porosity of Sedimentary Rocks 75
3.2.4 Porosity of Plutonic and Metamorphic Rocks 77
3.2.5 Porosity of Volcanic Rocks 78
3.3 Specific Yield 78
3.4 Hydraulic Conductivity of Earth Materials 81
3.4.1 Darcy's Experiment 81
3.4.2 Hydraulic Conductivity 82
3.4.3 Permeability of Sediments 84
Case Study: Hydraulic Conductivity Estimates in Glacial Outwash 88
3.4.4 Permeability of Rocks 89
3.5 Permeameters 90
3.6 Water Table 93
3.7 Aquifers 95
3.8 Water-Table and Potentiometric Surface Maps 98
3.9 Aquifer Characteristics 100
3.10 Compressibility and Effective Stress 102
3.11 Homogeneity and Isotropy 104
3.12 Gradient of the Potentiometric Surface 107

Notation 109 • Analysis 109 • Problems 109

CHAPTER 4

Principles of Ground-Water Flow

4.1 Introduction 113
4.2 Mechanical Energy 114
4.3 Hydraulic Head 115
4.4 Head in Water of Variable Density 118
4.5 Force Potential and Hydraulic Head 121
4.6 Darcy's Law 122

4.6.1 Darcy's Law in Terms of Head and Potential 122
4.6.2 The Applicability of Darcy's Law 123
4.6.3 Specific Discharge and Average Linear Velocity 124
4.7 Equations of Ground-Water Flow 125
4.7.1 Confined Aquifers 125
4.7.2 Unconfined Aquifers 129
4.8 Solution of Flow Equations 129
4.9 Gradient of Hydraulic Head 129
4.10 Relationship of Ground-Water-Flow Direction to Grad $h$ 131
4.11 Flow Lines and Flow Nets 132
4.12 Refraction of Flow Lines 136
4.13 Steady Flow in a Confined Aquifer 138
4.14 Steady Flow in an Unconfined Aquifer 140

Notation 146 • Analysis 147 • Problems 148

CHAPTER 5

Ground-Water Flow to Wells

5.1 Introduction 150
5.2 Basic Assumptions 151
5.3 Radial Flow 151
5.4 Computing Drawdown Caused by a Pumping Well 153
5.4.1 Flow in a Completely Confined Aquifer 153
5.4.2 Flow in a Leaky, Confined Aquifer 156
5.4.3 Flow in an Unconfined Aquifer 164
5.5 Determining Aquifer Parameters from Time-Drawdown Data 166
5.5.1 Introduction 166
5.5.2 Steady-State Conditions 166
5.5.3 Nonequilibrium Flow Conditions 169
5.5.4 Nonequilibrium Radial Flow in a Leaky Aquifer with Storage in the Aquitard 183
5.5.5 Nonequilibrium Radial Flow in an Unconfined Aquifer 184
5.5.6 Effect of Partial Penetration of Wells 188
5.6 Slug Tests 190
5.6.1 Determination of Aquifer Parameters with Slug Tests 190
5.6.2 Overdamped Response Slug Tests 190
5.6.3 Underdamped Response Slug Test 200
5.6.4 General Observations on Slug-Test Analysis 204
5.7 Estimating Aquifer Transmissivity from Specific Capacity Data 205
5.8 Intersecting Pumping Cones and Well Interference 207
5.9 Effect of Hydrogeologic Boundaries 208
5.10 Aquifer-Test Design 210
5.10.1 Single-Well Aquifer Tests 210
5.10.2 Aquifer Tests with Observation Wells 212

Notation 214 • Computer Notes 214 • Analysis 215 • Problems 215

## CHAPTER 6

## Soil Moisture and Ground-Water Recharge

6.1 Introduction 219
6.2 Porosity and Water Content of Soil 220
6.3 Capillarity and the Capillary Fringe 223
6.4 Pore-Water Tension in the Vadose Zone 225
6.5 Soil Water 225
6.6 Theory of Unsaturated Flow 228
6.7 Water-Table Recharge 231

Notation 234 • Analysis 235 • Problems 235

## CHAPTER 7

## Regional Ground-Water Flow

7.1 Introduction 236
7.2 Steady Regional Ground-Water Flow in Unconfined Aquifers 237
7.2.1 Recharge and Discharge Areas 237
7.2.2 Ground-Water Flow Patterns in Homogeneous Aquifers 237
7.2.3 Effect of Buried Lenses 243
7.2.4 Nonhomogeneous and Anisotropic Aquifers 244
7.3 Transient Flow in Regional Ground-Water Systems 247
7.4 Noncyclical Ground Water 248
7.5 Springs 248
7.6 Geology of Regional Flow Systems 250
Case Study: Regional Flow Systems in the Great Basin 250
Case Study: Regional Flow Systems in the Coastal Zone of the Southeastern United States 255
Case Study: Regional Flow System of the High Plains Aquifer 263
Case Study: The Dakota Aquifer 268
7.7 Interactions of Ground Water and Lakes or Wetlands and Streams 272

Computer Notes 279 • Notation 280 • Analysis 280 • Problems 280

## CHAPTER 8

## Geology of Ground-Water Occurrence

8.1 Introduction 283
8.2 Unconsolidated Aquifers 284
8.2.1 Glaciated Terrane 285
Case Study: Hydrogeology of a Buried Valley Aquifer at Dayton, Ohio 289

此为试读,需要完整PDF请访问: www.ertongbook.com

8.2.2 Alluvial Valleys 289
8.2.3 Alluvium in Tectonic Valleys 291
Case Study: Tectonic Valleys—San Bernardino Area 294
8.3 Lithified Sedimentary Rocks 297
Case Study: Sandstone Aquifer of Northeastern Illinois–Southeastern Wisconsin 297
8.3.1 Complex Stratigraphy 300
8.3.2 Folds and Faults 302
Case Study: Faults as Aquifer Boundaries 303
8.3.3 Clastic Sedimentary Rocks 307
Case Study: Newark Basin Hydrogeology 309
8.3.4 Carbonate Rocks 310
8.3.5 Coal and Lignite 319
8.4 Igneous and Metamorphic Rocks 319
8.4.1 Intrusive Igneous and Metamorphic Rocks 319
8.4.2 Volcanic Rocks 321
Case Study: Volcanic Plateaus—Columbia River Basalts 321
Case Study: Volcanic Domes—Hawaiian Islands 322
8.5 Ground Water in Permafrost Regions 323
Case Study: Alluvial Aquifers—Fairbanks, Alaska 326
8.6 Ground Water in Desert Areas 326
Case Study: Desert Hydrology—Azraq Basin, Jordan 327
8.7 Coastal-Plain Aquifers 327
8.8 Fresh-Water–Saline-Water Relations 331
8.8.1 Coastal Aquifers 331
8.8.2 Oceanic Islands 335
8.9 Tidal Effects 337
8.10 Ground-Water Regions of the United States 338
8.10.1 Western Mountain Ranges 338
8.10.2 Alluvial Basins 340
8.10.3 Columbia Lava Plateau 341
8.10.4 Colorado Plateau and Wyoming Basin 341
8.10.5 High Plains 341
8.10.6 Nonglaciated Central Region 342
8.10.7 Glaciated Central Region 342
8.10.8 Piedmont—Blue Ridge Region 343
8.10.9 Northeast and Superior Uplands 343
8.10.10 Atlantic and Gulf Coastal Plain 343
8.10.11 Southeast Coastal Plain 344
8.10.12 Alluvial Valleys 344
8.10.13 Hawaiian Islands 344
8.10.14 Alaska 344
8.10.15 Puerto Rico 344

Notation 345 • Problems 345

## CHAPTER 9

## Water Chemistry

9.1 Introduction 346
9.2 Units of Measurement 347
9.3 Types of Chemical Reactions in Water 348
9.4 Law of Mass Action 348
9.5 Common-Ion Effect 350
9.6 Chemical Activities 350
9.7 Ionization Constant of Water and Weak Acids 353
9.8 Carbonate Equilibrium 355
9.8.1 Carbonate Reactions 356
9.8.2 Carbonate Equilibrium in Water with Fixed Partial Pressure of $CO_2$ 358
9.8.3 Carbonate Equilibrium with External pH Control 359
9.9 Thermodynamic Relationships 361
9.10 Oxidation Potential 362
9.11 Ion Exchange 366
9.12 Isotope Hydrology 368
9.12.1 Stable Isotopes 368
9.12.2 Radioactive Isotopes Used in Age Dating 371
9.13 Major Ion Chemistry 373
9.14 Presentation of Results of Chemical Analyses 374
9.14.1 Piper Diagram 374
9.14.2 Stiff Pattern 376
9.14.3 Schoeller Semilogarithmic Diagram 377
Case Study: Chemical Geohydrology of the Floridan Aquifer System 377

Notation 381 • Analysis 382 • Problems 383

## CHAPTER 10

## Water Quality and Ground-Water Contamination

10.1 Introduction 385
10.2 Water-Quality Standards 388
10.3 Collection of Water Samples 389
10.4 Ground-Water Monitoring 391
10.4.1 Planning a Ground-Water Monitoring Program 391
10.4.2 Installing Ground-Water Monitoring Wells 391
10.4.3 Withdrawing Water Samples from Monitoring Wells 396
10.5 Vadose-Zone Monitoring 397
10.6 Mass Transport of Solutes 400
10.6.1 Introduction 400
10.6.2 Diffusion 400
10.6.3 Advection 401
10.6.4 Mechanical Dispersion 401
10.6.5 Hydrodynamic Dispersion 402

10.6.6 Retardation 407
10.6.7 Degradation of Organic Compounds 415
10.7 Ground-Water Contamination 415
10.7.1 Introduction 415
10.7.2 Septic Tanks and Cesspools 416
10.7.3 Landfills 418
10.7.4 Chemical Spills and Leaking Underground Tanks 420
10.7.5 Mining 423
Case Study: Contamination from Uranium Tailings Ponds 424
10.7.6 Other Sources of Ground-Water Contamination 425
10.8 Ground-Water Restoration 426
10.8.1 Risk-Based Corrective Action 426
10.8.2 Source-Control Measures 426
10.8.3 Plume Treatment 427
10.8.4 Natural and Enhanced Bioremediation 428
10.9 Case History: Ground-Water Contamination at a Superfund Site 428
10.9.1 Background 428
10.9.2 Geology 430
10.9.3 Hydrogeology 431
10.9.4 Ground-Water Contamination 432
10.9.5 Site Remediation 434
10.10 Capture-Zone Analysis 436
Notation 439 • Analysis 440 • Problems 440

## CHAPTER 11

## Ground-Water Development and Management

11.1 Introduction 441
11.2 Dynamic Equilibrium in Natural Aquifers 442
Case Study: Deep Sandstone Aquifer of Northeastern Illinois 443
11.3 Ground-Water Budgets 443
11.4 Management Potential of Aquifers 445
11.5 Paradox of Safe Yield 447
11.6 Water Law 449
11.6.1 Legal Concepts 449
11.6.2 Laws Regulating Quantity of Surface Water 449
11.6.3 Laws Regulating Quantity of Ground Water 452
Case Study: Arizona's Ground-Water Code 454
11.6.4 Laws Regulating the Quality of Water 455
Case Study: Wisconsin's Ground-Water Protection Law 458
11.7 Artificial Recharge 459
11.8 Protection of Water Quality in Aquifers 460
11.9 Ground-Water Mining and Cyclic Storage 463
11.10 Conjunctive Use of Ground and Surface Water 464
11.11 Global Water Issues 465
Analysis 467

## CHAPTER 12

## Field Methods

12.1 Introduction 468
12.2 Fracture-Trace Analysis 469
12.3 Surficial Methods of Geophysical Investigations 474
12.3.1 Direct-Current Electrical Resistivity 474
12.3.2 Electromagnetic Conductivity 479
12.3.3 Seismic Methods 483
12.3.4 Ground-Penetrating Radar and Magnetometer Surveys 490
12.3.5 Gravity and Aeromagnetic Methods 491
12.4 Geophysical Well Logging 492
12.4.1 Caliper Logs 495
12.4.2 Temperature Logs 495
12.4.3 Single-Point Resistance 495
12.4.4 Resistivity 498
12.4.5 Spontaneous Potential 498
12.4.6 Nuclear Logging 499
Case Study: Use of Multiple Geophysical Methods to Determine the Extent and Thickness of a Critical Confining Layer 502
12.5 Hydrogeologic Site Evaluations 505
12.6 Responsibilities of the Field Hydrogeologist 508
12.7 Project Reports 510
Notation 512 • Problems 512

## CHAPTER 13

## Ground-Water Models

13.1 Introduction 514
13.2 Applications of Ground-Water Models 516
13.3 Data Requirements for Models 517
13.4 Finite-Difference Models 519
13.4.1 Finite-Difference Grids 519
13.4.2 Finite-Difference Notation 519
13.4.3 Boundary Conditions 520
13.4.4 Methods of Solution for Steady-State Case for Square Grid Spacing 521
13.4.5 Methods of Solution for the Transient Case 523
13.5 Finite-Element Models 524
13.6 Use of Published Models 525
13.7 MODFLOW Basics 528
13.8 Visual MODFLOW 530
13.9 Geographical Information Systems 530
Analysis 531

Appendices 534
1. Values of the function $W(u)$ for various values of $u$ 535
2. Values of the function $F(\eta,\mu)$ for various values of $\eta$ and $\mu$ 536
3. Values of the functions $W(\mu, r/B)$ for various values of $\mu$ 537
4. Values of the function $H(\mu, \beta)$ 538
5. Values of the functions $K_0(x)$ and $\exp(x)K_0(x)$ 539
6. Values of the functions $W(u_A,\Gamma)$, and $W(u_B, \Gamma)$ for water-table aquifers 540
7. Table for length conversion 542
8. Table for area conversion 542
9. Table for volume conversion 543
10. Table for time conversion 543
11. Solubility products for selected minerals and compounds 544
12. Atomic weights and numbers of naturally occurring elements 545
13. Table of values of erf $(x)$ and erfc $(x)$ 547
14. Absolute density and absolute viscosity of water 548
15. Loading and running computer programs 549

Glossary 552
Answers 562
References 567
Index 588

# CHAPTER 1

# Water

*In the winter of wet years the streams ran full-freshet, and they swelled the river until it sometimes raged and boiled bank full, and then it was a destroyer. The river tore the edges of the farm lands and washed whole acres down; it toppled barns and houses into itself, to go floating and bobbing away. It trapped cows and pigs and sheep and drowned them in its muddy brown water and carried them to the sea. Then when the late spring came the river drew in from its edges and the sand banks appeared. And in the summer the river didn't at all run above ground.*

*There were dry years too . . . The water came in a thirty-year cycle. There would be five or six wet and wonderful years when there might be nineteen to twenty-five inches of rain, and the land would shout with grass. Then would come six or seven pretty good years of twelve to sixteen inches of rain. And then the dry years would come, and sometimes there would be only seven or eight inches of rain. The land dried up . . . And it never failed that during the dry years the people forgot the rich years, and during the wet years they lost all memory of the dry years. It was always that way.*

*East of Eden,* John Steinbeck, 1952

## 1.1 Water

John Steinbeck wrote the above words 50 years ago to describe the hydrology of the Salinas Valley in northern California. In doing so he revealed an attitude toward water that was held by many in the early part of the twentieth century. Water was always assumed to be available and no one worried about its longevity until it seemed threatened. We perhaps have a more realistic attitude today and know that we must preserve and protect our precious and limited natural resources, including water.

Although our intentions toward preserving the environment may be good, we sometimes act without full consideration of all possible



此为试读,需要完整PDF请访问: www.ertongbook.com