

Contents

Preface

xi

Chapter One

Introduction

1

1.1	Ground Water as a Resource	1
1.2	Types of Ground-Water Contaminants	2
1.3	Drinking-Water Standards	11
1.4	Risk and Drinking Water	13
1.5	Sources of Ground-Water Contamination	18
1.5.1	Category I: Sources Designed to Discharge Substances	19
1.5.2	Category II: Sources Designed to Store, Treat and/or Dispose of Substances	21
1.5.3	Category III: Sources Designed to Retain Substances During Transport	27
1.5.4	Category IV: Sources Discharging Substances as a Consequence of Other Planned Activities	27
1.5.5	Category V: Sources Providing a Conduit for Contaminated Water to Enter Aquifers	30
1.5.6	Category VI: Naturally Occurring Sources Whose Discharge is Created and/or Exacerbated by Human Activity	30
1.6	Relative Ranking of Ground-Water-Contamination Sources	31
1.7	Ground-Water Contamination as a Long-Term Problem	33
1.8	Review of Mathematics and the Flow Equation	34
1.8.1	Derivatives	34
1.8.2	Darcy's Law	37
1.8.3	Scalar, Vector, and Tensor Properties of Hydraulic Head and Hydraulic Conductivity	37
1.8.4	Derivation of the Flow Equation in a Deforming Medium	39
1.8.5	Mathematical Notation	42
	References	43
	Problems	44

Chapter Two

Mass Transport in Saturated Media

45

2.1	Introduction	45
2.2	Transport by Concentration Gradients	45
2.3	Transport by Advection	50
2.4	Mechanical Dispersion	52
2.5	Hydrodynamic Dispersion	53
2.6	Derivation of the Advection-Dispersion Equation for Solute Transport	55
2.7	Diffusion versus Dispersion	57
2.8	Analytical Solutions of the Advection-Dispersion Equation	58
2.8.1	Methods of Solution	58

4.12	Summary	204
	Chapter Notation	205
	References	206
	Problems	207

Chapter Five

Multiphase Flow 208

5.1	Introduction	208
5.2	Basic Concepts	209
	5.2.1 Saturation Ratio	209
	5.2.2 Interfacial Tension and Wettability	209
	5.2.3 Capillary Pressure	210
	5.2.4 Relative Permeability	212
	5.2.5 Darcy's Law For Two-Phase Flow	217
	5.2.6 Fluid Potential and Head	217
5.3	Migration of Light Nonaqueous Phase Liquids (LNAPLs)	221
5.4	Volitilization of NAPLs	225
5.5	Measurement of the Thickness of a Floating Product	231
5.6	Effect of the Rise and Fall of the Water Table on the Distribution of LNAPLs	239
	Case Study: Spill of Jet Fuel — Effect of Water Table Decline on Product Recovery	
5.7	Migration of Dense Nonaqueous Phase Liquids (DNAPLs)	242
	5.7.1 Relative Mobility	242
	5.7.2 Vadose Zone Migration	245
	5.7.3 Vertical Movement in the Saturated Zone	245
	5.7.4 Horizontal Movement in the Saturated Zone	247
	Case Study: Movement of Tetrachloroethene From a Controlled Release below the Water Table	
	5.7.5 DNAPL Flow in Fracture Systems	253
	5.7.6 Dissolution of DNAPL	256
5.8	Monitoring for LNAPLs and DNAPLs	257
5.9	Summary	260
	Chapter Notation	260
	References	261
	Problems	263

Chapter Six

Inorganic Chemicals in Ground Water 264

6.1	Introduction	264
6.2	Units of Measurement and Concentration	264
6.3	Chemical Equilibrium and the Law of Mass Action	265

6.4	Oxidation-Reduction Reactions	268
6.5	Relationship between pH and Eh	271
6.5.1	pH	271
6.5.2	Relationship of Eh and pH	273
6.5.3	Eh-pH Diagrams	274
6.5.4	Calculating Eh-pH Stability Fields	276
6.6	Metal Complexes	285
6.6.1	Hydration of Cations	285
6.6.2	Complexation	286
6.6.3	Organic Complexing Agents	287
6.7	Chemistry of Nonmetallic Inorganic Contaminants	288
6.7.1	Fluoride	288
6.7.2	Chlorine and Bromine	290
6.7.3	Sulfur	290
6.7.4	Nitrogen	292
6.7.5	Arsenic	293
6.7.6	Selenium	293
6.7.7	Phosphorus	294
6.8	Chemistry of Metals	295
6.8.1	Beryllium	295
6.8.2	Strontium	295
6.8.3	Barium	295
6.8.4	Vanadium	295
6.8.5	Chromium	295
	Case History: Hexavalent Chromium Contamination of Groundwater—Odessa, Texas	
6.8.6	Cobalt	297
6.8.7	Nickel	297
6.8.8	Molybdenum	298
6.8.9	Copper	298
6.8.10	Silver	300
6.8.11	Zinc	300
6.8.12	Cadmium	300
6.8.13	Mercury	300
6.8.14	Lead	301
6.9	Radioactive Isotopes	302
6.9.1	Introduction	302
6.9.2	Adsorption of Cationic Radionuclides	303
6.9.3	Uranium	304
	Case History: Uranium Contamination of Groundwater—Fernald, Ohio	
6.9.4	Thorium	307
6.9.5	Radium	307
6.9.6	Radon	310
6.9.7	Tritium	311
6.10	Geochemical Zonation	311
6.11	Summary	314
	Chapter Notation	315
	References	315
	Problems	317

Chapter Seven

Organic Compounds in Ground Water	318	
7.1	Introduction	318
7.2	Physical Properties of Organic Compounds	318
7.3	Organic Structure and Nomenclature	320
7.3.1	Hydrocarbon Classes	320
7.3.2	Aromatic Hydrocarbons	324
7.4	Petroleum and Coal Tar	325
7.4.1	Petroleum Distillates	325
7.4.2	Coal Tar	329
7.4.3	Ground-Water Contamination Associated with Petroleum Products and Coal Tar	329
7.5	Functional Groups	332
7.5.1	Organic Halides	332
7.5.2	Alcohols	332
7.5.3	Ethers	336
7.5.4	Aldehydes and Ketones	336
7.5.5	Carboxylic Acids	337
7.5.6	Esters	338
7.5.7	Phenols	338
7.5.8	Organic Compounds Containing Nitrogen	339
7.5.9	Organic Compounds Containing Sulfur and Phosphorus	341
7.6	Degradation of Organic Compounds	342
7.6.1	Introduction	342
7.6.2	Degradation of Hydrocarbons	342
7.6.3	Degradation of Chlorinated Hydrocarbons	346
7.6.4	Degradation of Organic Pesticides	349
7.7	Field Examples of Biological Degradation of Organic Molecules	352
7.7.1	Introduction	352
7.7.2	Chlorinated Ethanes and Ethenes	352
7.7.3	Aromatic Compounds	354
7.8	Analysis of Organic Compounds in Ground Water	355
7.9	Fingerprinting Petroleum Distillates and Coal Tar	361
7.10	Summary	369
	References	369
	Problems	371

Chapter Eight

Ground-Water and Soil Monitoring	374	
8.1	Introduction	374
8.2	Monitoring-Well Design	374
8.2.1	General Information	374
8.2.2	Monitoring-Well Casing	375
8.2.3	Monitoring-Well Screens	381

8.2.4	Naturally-Developed and Filter-Packed Wells	382
8.2.5	Annular Seal	383
8.2.6	Protective Casing	384
8.2.7	Screen Length and Setting	385
8.2.8	Summary of Monitoring-Well Design	388
8.3	Installation of Monitoring Wells	389
8.3.1	Decontamination Procedures	389
8.3.2	Methods of Drilling	390
8.3.3	Drilling in Contaminated Soil	395
8.4	Sample Collection	396
8.5	Installation of Monitoring Wells	399
8.6	Monitoring-Well Development	404
8.7	Record Keeping During Monitoring-Well Construction	407
8.8	Monitoring Well and Borehole Abandonment	409
8.9	Multiple-level Devices for Ground-Water Monitoring	409
8.10	Methods of Collecting a Ground-Water Sample Without Drilling a Well	412
8.11	Well Sampling	415
8.11.1	Introduction	415
8.11.2	Well Purging	415
8.11.3	Well-Sampling Devices	416
8.12	Low Flow Purging of Monitoring Wells	420
8.13	Soil-Gas Monitoring	421
8.13.1	Introduction	421
8.13.2	Methods of Soil-Gas Monitoring	422
8.14	Soil-Water Sampling	423
8.14.1	Introduction	423
8.14.2	Suction Lysimeters	423
8.14.3	Installation of Suction Lysimeters	424
8.15	Summary	426
	References	427

Chapter Nine

Site Remediation	429	
9.1	Introduction	429
9.2	Source-Control Measures	430
9.2.1	Solid Waste	430
9.2.2	Removal and Disposal	430
9.2.3	Containment	431
9.2.4	Hydrodynamic Isolation	436
9.3	Pump-and-Treat Systems	438
9.3.1	Overview	438
9.3.2	Capture Zones	441
9.3.3	Computation of Capture Zones	442
9.3.4	Optimizing Withdrawal-Injection Systems	451
9.3.5	Permanent Plume Stabilization	452

9.4	Treatment of Extracted Ground Water	453
9.4.1	Overview	453
9.4.2	Treatment of Inorganic Contaminants	453
9.4.3	Treatment of Dissolved Organic Contaminants	454
9.5	Recovery of Nonaqueous Phase Liquids	455
9.6	Removal of Leaking Underground Storage Tanks	459
9.7	Soil Vapor Extraction	462
9.8	Air Sparging and Bioslurping	466
9.9	Bioremediation	467
9.9.1	Introduction	467
9.9.2	Intrinsic Biodegradation of Hydrocarbons	468
9.9.3	Enhanced Bioremediation of Hydrocarbons	469
9.9.4	Bioremediation of chlorinated Organic Compounds	471
9.10	Combination Methods	473
	Case Study: Effectiveness of Pump and Treat Remediation in a Ground Water Basin	
	Case Study: Recovery of DNAPL Pooled Below the Water Table	
	Case Study: Remediation of Soil and Ground Water at the Site of an Automotive Manufacturer's Plant	
9.11	Summary	482
	Chapter Notation	484
	References	484
Appendix A		
Error Function Values		487
Appendix B		
Bessel Functions		488
Appendix C		
$W(t_D, B)$ Values		491
Appendix D		
Exponential Integral		493
Appendix E		
Unit Abbreviations		494
Appendix F		
Visual MODFLOW Instructions (from Schlumberger Water Services)		495
Index		497