

Contents

1	Basic Concepts	1
1.1	Water and its Properties	2
1.2	Groundwater	5
1.2.1	Gravitational Water	5
1.2.2	Pendular Water	5
1.3	Aquifer Types and Classification Criteria	8
1.4	Hydraulic Head	9
1.4.1	Field Measurements of the Hydraulic Head	11
1.5	Storage and Release Capacity	12
1.5.1	Storage in Unconfined Aquifers: Specific Yield and Retention	14
1.5.2	Storage in Confined Aquifers	16
1.6	Flow Capacity	17
1.6.1	Darcy's Law	17
1.6.2	Hydraulic Conductivity and Permability	18
1.6.3	Transmissivity	21
1.7	Leakage Between Different Aquifers	22
1.8	Field Applications of Darcy's Law	22
1.8.1	Potentiometric Surface and Flow Field Mapping	22
	References	25
2	The Groundwater Flow Equation	27
2.1	Derivation of the Equation of Continuity	27
2.2	The Groundwater Flow Equation	30
	References	32
3	Analytical Solutions of the Groundwater Flow Equation	33
3.1	Confined Aquifers	34
3.1.1	Unsteady (or Transient) State	34
3.1.2	Steady State Flow	37

3.2	Leaky Aquifers	38
3.2.1	Unsteady or Transient State	39
3.2.2	Steady State Flow	42
3.3	Unconfined Aquifers	42
3.3.1	Unsteady or Transient State	44
3.3.2	Steady State Flow	50
3.4	Radius of Investigation and Radius of Influence	51
	References	52
4	Aquifer Characterization	55
4.1	Aquifer Test Classification and Planning	56
4.2	Aquifer Tests	61
4.2.1	Hydraulic Behavior Identification	61
4.2.2	Interpretation Procedure	64
4.3	Recovery Tests	81
4.4	Slug Test	83
4.4.1	Interpretation Models	84
4.4.2	Bouwer and Rice's Method	85
4.4.3	Cooper, Bredehoeft and Papadopoulos' Method	90
4.4.4	The KGS Method	93
4.5	Other Methods for the Determination of Parameters Characterizing an Aquifer	96
4.5.1	Determination of Hydraulic Conductivity or Transmissivity	96
4.5.2	Determination of the Storativity	106
4.5.3	Determination of the Specific Yield	107
4.5.4	Determination of the Effective Porosity	108
	References	111
5	Well Testing	113
5.1	Operating Conditions of a Well Test	114
5.2	Theoretical Foundations and Interpretation of Step-Drawdown Tests	114
5.3	Well Productivity and Efficiency	117
5.4	Estimation of the Coefficients B_2 and B_3	120
5.4.1	Estimation of the Coefficient B_2	120
5.4.2	Estimation of the Coefficient B_3	122
5.4.3	Calculation of B_2 and B_3	123
5.4.4	Correlation Between Specific Capacity and Transmissivity	124
5.5	Recent Developments in the Interpretation of Step-Drawdown Tests	124
	References	125

- 6 **Optimization of a Water Supply System** 127
 - 6.1 Water Supply System Description 128
 - 6.2 Assessment of Head Losses in the System 129
 - 6.3 Head Losses in the Well-Aquifer Sub-system 129
 - 6.4 Head Losses in the Pipe Network 129
 - 6.4.1 Distributed Head Losses 129
 - 6.4.2 Local Head Losses 130
 - 6.5 Optimization of the Productive Capacity of the System 134
 - 6.6 Changes Over Time 134
 - References 136

- 7 **Aquifer Vulnerability and Contamination Risk** 137
 - 7.1 Vulnerability Assessment Methods 138
 - 7.1.1 Overlay Methods 139
 - 7.1.2 Index Methods 141
 - 7.2 Comparison of Different Vulnerability Assessment Methods 151
 - 7.3 Contamination Risk 151
 - 7.4 An Example of Contamination Risk Reduction 153
 - 7.4.1 Reduction of the Probability of Occurrence of the Event 153
 - 7.4.2 Reducing the Intensity of the Event 154
 - 7.4.3 Reducing Potential Damage 156
 - References 158

- 8 **Well Head Protection Areas** 161
 - 8.1 Approaches for the Definition of Protection Areas 162
 - 8.1.1 Analytical Definition of the Protection Area of a Single Well in a Confined Aquifer 162
 - 8.1.2 General Application of the Time of Travel Criterion 163
 - 8.2 Dynamic Protection 166
 - References 168

- 9 **Groundwater Contaminants** 169
 - 9.1 Chemical Classification 171
 - 9.1.1 Inorganic Contaminants 171
 - 9.1.2 Organic Contaminants 171
 - 9.2 Physical Characteristics 182
 - 9.2.1 Physical State 182
 - 9.2.2 Miscibility 182
 - 9.2.3 Density 183
 - 9.2.4 Solubility 183
 - 9.2.5 Octanol-Water Partition Coefficient 184

9.2.6	Vapor Pressure	184
9.2.7	Henry's Constant	185
9.3	Contaminant Toxicity and Regulatory Framework	187
9.3.1	Toxicological Classification	187
9.3.2	Regulation of Contaminants in Groundwater	190
	References	191
10	Mechanisms of Contaminant Transport in Aquifers	193
10.1	Hydrological Phenomena	194
10.1.1	Advection	194
10.1.2	Molecular Diffusion	195
10.1.3	Mechanical Dispersion	197
10.1.4	Hydrodynamic Dispersion	199
10.2	Chemical Phenomena	203
10.2.1	Reaction Models	203
10.2.2	Chemical Reactions	205
10.3	Biological Processes: Biodegradation	208
10.4	Physico-Chemical Processes: Sorption	210
10.5	Concomitant Processes	215
	References	216
11	The Mass Transport Equations	219
11.1	Contaminant Mass Balance	219
11.2	Conservative Solutes	220
11.3	Reactive Solutes	222
11.4	Initial and Boundary Conditions	223
12	Analytical Solutions to the Differential Equation of Mass Transport for Conservative Solutes	225
12.1	One-Dimensional Geometry	226
12.1.1	Continuous Input	226
12.1.2	Pulse (or Instantaneous) Input	229
12.2	Two-Dimensional Geometry	230
12.2.1	Vertical Line Source, Pulse Input	231
12.2.2	Vertical Line Source, Continuous Input	231
12.3	Three-Dimensional Geometry	233
12.3.1	Point Source, Pulse Input	233
12.3.2	Plane Source, Continuous Input	234
	References	236
13	Analytical Solutions of the Differential Equation of Mass Transport for Reactive Solutes	239
13.1	One-Dimensional Geometry	239
13.1.1	Continuous Input	240
13.1.2	Pulse Input	242

13.2	Two-Dimensional Geometry	244
13.2.1	Line Source, Pulse Input	244
13.2.2	Line Source, Continuous Input	244
13.3	Three-Dimensional Geometry	245
13.3.1	Point Source, Pulse Input	246
13.3.2	Plane Source, Continuous Input	246
	References	247
14	Transport of Immiscible Fluids	249
14.1	Properties of a Solid–Liquid Multiphase System	249
14.1.1	Wettability	250
14.1.2	Interfacial Tension and Capillary Pressure	251
14.1.3	Effective and Relative Permeability	251
14.1.4	Imbibition and Draining	253
14.2	Qualitative Models of NAPL Behavior in the Ground	255
14.2.1	Behavior of LNAPLs	255
14.2.2	Behavior of DNAPLs	256
14.3	Secondary Contamination Due to NAPLs	257
14.4	Quantitative Approach	258
14.4.1	Geometrical and Temporal Characterization	259
14.4.2	NAPL Mass Distribution	259
14.5	Concluding Remarks	261
	References	262
15	Characterization of a Contamination Event	263
15.1	Sampling Design	264
15.2	Sampling the Unsaturated Medium	268
15.2.1	Minimum Number of Sampling Points	268
15.2.2	Soil Sampling	268
15.2.3	Rotary Techniques	269
15.2.4	Direct Push or Drive Drilling Methods	269
15.2.5	Soil Sampling for Volatile Compound Analysis	270
15.2.6	Soil Gas Sampling	271
15.2.7	Pore Water Sampling	273
15.3	Sampling the Saturated Medium	277
15.3.1	Vertical Sampling	278
15.3.2	Multilevel Monitoring Wells	278
15.3.3	Direct Push Techniques	279
15.4	Purging	280
15.4.1	Well Volume Based Criterion	281
15.4.2	Criterion Based on Physico-Chemical Parameters Stabilization	281
15.4.3	Well Storage and Hydrodynamic Parameters Based Criterion	281

15.4.4	Low-Flow Purging and Physico-Chemical Parameters Stabilization	282
15.5	Sampling	283
15.5.1	Sampling Rate	283
15.5.2	Sample Collection	284
15.6	Sampling and Purging Mechanisms	285
15.6.1	Bailers	286
15.6.2	Submersible Centrifugal Pumps	287
15.6.3	Bladder Pumps	289
15.6.4	Peristaltic Pumps	290
15.6.5	Inertial Lift Pumps	291
15.7	On Site Measurement of Water Quality Parameters	292
15.8	Sample Filtration	293
15.9	Quality Control	294
15.10	Equipment Cleaning and Decontamination	295
15.11	Sample Storage	296
15.12	Blanks and Replicates	297
15.13	Materials	298
	References	298
16	Human Health Risk Assessment	301
16.1	Definition of Human Health Risk	302
16.2	Features of Risk Assessment	303
16.2.1	Phases	303
16.2.2	Risk Assessment Tiers	305
16.3	Risk Assessment Development	307
16.3.1	Characterization Plan	307
16.3.2	Calculation of the Concentration at the Point of Exposure	308
16.4	Toxicological Models and Parameters	319
16.5	Risk Assessment	320
16.5.1	Determination of the Concentration at the Point of Exposure	320
16.5.2	Rate of Exposure	321
16.5.3	Risk Calculation	322
16.5.4	Acceptability Criteria	325
16.6	Risk Management	326
16.7	Concluding Remarks	327
	References	328
17	Remediation of Contaminated Groundwater	331
17.1	Free Product Recovery	332
17.1.1	Free Product Removal with Skimming Systems	333
17.1.2	Free Product Recovery with Water Table Depression	333

17.1.3	Vacuum Enhanced Extraction	336
17.2	Subsurface Containment	336
17.3	Pump and Treat	338
17.3.1	Design of a P&T System	338
17.3.2	Flushing Water Volume	348
17.3.3	Performance of a P&T System	351
17.3.4	Potential P&T Limitations	353
17.3.5	Extracted Water Treatment Technology	354
17.4	Air Sparging and Biosparging	355
17.4.1	Design and Aim	356
17.4.2	Applicability	357
17.4.3	Dynamics of the Process	359
17.4.4	Air Sparging System Design	360
17.5	Permeable Reactive Barriers	361
17.5.1	Laboratory Tests	365
17.5.2	Design of a PRB	368
17.5.3	Technical Solutions for Constructing a Permeable Reactive Barrier	371
17.5.4	Monitoring Network	376
17.5.5	Iron Microparticles and Nanoparticles	377
17.5.6	A Case Study: The Permeable Reactive Barrier in Avigliana	379
17.6	In Situ Flushing	385
17.7	In Situ Oxidation	388
17.8	In Situ Bioremediation	391
17.8.1	Factors Contributing to Biodegradation	392
17.8.2	Biodegradation of Organic Contaminants	397
17.8.3	Biodegradation of Petroleum Products	397
17.8.4	Biodegradation of Chlorinated Organic Compounds	398
17.8.5	Enhanced in Situ Bioremediation	402
	References	405
	Appendix A: Exponential Integral or Well Function	411
	Appendix B: Hantush and Jacob Function	415
	Appendix C: Function K_0	421
	Appendix D: Dimensionless Neuman's Function $s_D(t_s, \beta)$ Valid for Short Times	423
	Appendix E: Dimensionless Neuman's Function $s_D(t_s, \beta)$ Valid for Extended Periods of Times	427
	Index	433