

Contents

Preface	xiii
1 Introduction	1
1.1 Groundwater Investigations – a Detective Story	1
1.2 Conceptual Models	2
1.3 Computational Models	2
1.4 Case Studies	3
1.5 The Contents of this Book	3
1.6 Units, Notation, Journals	5
 Part I: Basic Principles	 7
2 Background to Groundwater Flow	9
2.1 Introduction	9
2.2 Basic Principles of Groundwater Flow	9
2.2.1 Groundwater head	10
2.2.2 Direction of flow of groundwater	10
2.2.3 Darcy's Law, hydraulic conductivity and permeability	11
2.2.4 Definition of storage coefficients	13
2.2.5 Differential equation describing three-dimensional time-variant groundwater flow	14
2.3 One-dimensional Cartesian Flow	14
2.3.1 Equation for one-dimensional flow	15
2.3.2 Aquifer with constant saturated depth and uniform recharge	16
2.3.3 Definition of transmissivity	17
2.3.4 Aquifer with constant saturated depth and linear variation in recharge	18
2.3.5 Aquifer with constant saturated depth and linear decrease in recharge towards lake	19
2.3.6 Confined aquifer with varying thickness	20
2.3.7 Unconfined aquifer with saturated depth a function of the unknown groundwater head	20
2.3.8 Time-variant one-dimensional flow	22
2.4 Radial Flow	23
2.4.1 Radial flow in a confined aquifer	23
2.4.2 Radial flow in an unconfined aquifer with recharge	24
2.4.3 Radial flow in an unconfined aquifer with varying saturated depth	26
2.4.4 Radial flow in a leaky aquifer	27
2.4.5 Time-variant radial flow	28
2.4.6 Time-variant radial flow including vertical components	28
2.5 Two-dimensional Vertical Section (Profile Model)	28
2.5.1 Steady-state conditions, rectangular dam	28
2.5.2 Time-variant moving water table	31
2.6 Regional Groundwater Flow	32
2.6.1 Analysis of Connerton (1985)	32

2.6.2	Illustrative numerical examples of one-dimensional flow	34
2.6.3	When vertical flows must be included explicitly	35
2.7	Numerical Analysis	36
2.7.1	One-dimensional flow in x -direction	37
2.7.2	Example	38
2.7.3	Radial flow	38
2.7.4	Vertical section	39
2.8	Monitoring and Additional Indirect Evidence	39
2.8.1	Introduction	40
2.8.2	Monitoring groundwater heads	43
2.8.3	Surface water monitoring	46
2.8.4	Monitoring borehole discharge	46
2.8.5	Monitoring groundwater quality	47
2.8.6	Data handling and presentation	49
2.9	Introduction to Quality Issues	49
2.9.1	Introduction	49
2.9.2	Fresh and saline groundwater	51
2.9.3	Conditions at the coast	53
2.9.4	Upconing	54
2.9.5	Monitoring the movement of a saline interface	56
2.9.6	Hydrodynamic dispersion and contaminant transport	58
2.10	Concluding Remarks	60
3	Recharge due to Precipitation or Irrigation	60
3.1	Introduction	60
3.1.1	Representative field situations	61
3.1.2	Symbols used in this chapter	61
3.2	Brief Review of Alternative Methods of Estimating Recharge	62
3.2.1	Methods based on field measurements	62
3.2.2	Estimates using properties of unsaturated soil	64
3.3	Conceptual models for the Soil Moisture Balance Technique	64
3.3.1	Introduction	64
3.3.2	Representation of moisture conditions in the soil	67
3.3.3	Bare soil evaporation	68
3.3.4	Crop transpiration	70
3.3.5	Nature of the soil	70
3.3.6	Runoff	70
3.3.7	Occurrence of recharge	71
3.3.8	Combining crops and bare soil	71
3.3.9	Water storage near the soil surface	74
3.4	Quantified Conceptual and Computational Models for the Soil Moisture Balance Technique	74
3.4.1	Crops and crop coefficients	75
3.4.2	Reduced transpiration when crops are under water stress	76
3.4.3	Reduced evaporation due to limited soil water availability	77
3.4.4	Runoff	78
3.4.5	Combining the influence of crop transpiration and bare soil evaporation	78
3.4.6	Soil moisture balances	81
3.4.7	Soil moisture balances with near surface soil storage	82
3.4.8	Algorithms for soil moisture balance	83
3.4.9	Annual soil moisture balance for a temperate climate	84
3.4.10	Estimating recharge in a semi-arid region of Nigeria	84
3.4.11	Estimating recharge due to precipitation and irrigation in a semi-arid region of India	87

3.4.12 Bypass recharge	90
3.4.13 Estimating catchment-wide recharge distributions	90
3.5 Estimating Recharge when Drift is Present	90
3.5.1 Introduction	90
3.5.2 Recharge factors	91
3.5.3 Recharge through Drift estimated using Darcy's Law	92
3.5.4 Delay in recharge reaching the water table	93
3.6 Delayed Runoff and Runoff Recharge	95
3.6.1 Delayed runoff from minor aquifers in the Drift	95
3.6.2 Runoff recharge	97
3.6.3 Incorporating several recharge processes	98
3.7 Concluding Remarks	98
4 Interaction between Surface Water and Groundwater	100
4.1 Introduction	100
4.2 Canals	101
4.2.1 Introduction	101
4.2.2 Classification of interaction of canals with groundwater	101
4.2.3 More detailed consideration of boundary conditions and canal dimensions	103
4.2.4 Effect of lining of canals	106
4.2.5 Perched canals	108
4.2.6 Estimation of losses from canals	111
4.2.7 Artificial recharge using spreading techniques	111
4.3 Springs, Rivers, Lakes and Wetlands	112
4.3.1 Introduction	112
4.3.2 Spring-aquifer interaction	113
4.3.3 River-aquifer interaction: basic theory and modelling	115
4.3.4 River-aquifer interaction in practice	116
4.3.5 Lakes and wetlands	121
4.3.6 Impact of groundwater abstraction on springs, rivers, lakes and wetlands	125
4.4 Drains	126
4.4.1 Introduction	126
4.4.2 Field evidence	126
4.4.3 Formulation of drainage problems	127
4.4.4 Approximate methods of analysis for steady-state problems	129
4.4.5 Numerical solutions	131
4.4.6 Representative time-variant analysis	134
4.4.7 Interceptor drains	135
4.5 Irrigated Ricefields	138
4.5.1 Introduction	138
4.5.2 Formulation of flow processes in ricefields	139
4.5.3 Representative results	140
4.5.4 Ricefields with different geometry and water levels	141
4.6 Concluding Remarks	142
Part II: Radial Flow	145
5 Radial Flow to Pumped Boreholes – Fundamental Issues	147
5.1 Aquifer Response due to Pumping from a Borehole	147
5.1.1 Introduction	147
5.1.2 Details of field study	147

5.1.3 Measurements in pumped borehole and observation piezometers	148
5.1.4 Conceptual models of flows for different times	149
5.1.5 Recovery phase	151
5.1.6 Results for open borehole instead of individual piezometers	152
5.1.7 Analysis of pumping test results	153
5.1.8 Summary	154
5.2 Classification of Radial Flow Problems	157
5.3 Steady Radial Flow in Confined Aquifers	158
5.4 Analytical Solutions for Unsteady Radial Flow in Confined Aquifers	158
5.4.1 Analytical solutions	159
5.4.2 Theis method using log-log graphs	160
5.4.3 Cooper–Jacob technique	161
5.4.4 Transmissivity and storage coefficient varying with radius	162
5.5 Numerical Solution for Unsteady Radial Flow	162
5.5.1 Theoretical basis of the numerical model	163
5.5.2 Comparison of analytical and numerical solutions	163
5.5.3 Example of the use of the numerical model	164
5.5.4 Representation of well losses	164
5.6 Analysis of the Recovery Phase for Unsteady Radial Flow in Confined Aquifers	165
5.7 Comparison of Analytical and Numerical Techniques of Pumping Test Analysis	167
5.8 Analysis of Leaky Aquifers Without Storage in the Aquitard	168
5.9 Further Consideration of Single-Layer Aquifers	169
5.10 Aquifer with Restricted Dimensions (Boundary Effects)	170
5.11 Change in Transmissivity or Storage Coefficient with Radius	173
5.12 Changing Saturated Depth and Changing Permeabilities in Unconfined Aquifers	174
5.13 Varying Abstraction Rates	174
5.14 Overflowing Artesian Boreholes	176
5.15 Interfering Boreholes	176
5.15.1 Introduction to interference	177
5.15.2 Theoretical analysis of interfering boreholes	178
5.15.3 Practical example of the significance of interfering boreholes	180
5.16 Conditions Changing between Confined and Unconfined	183
5.17 Delayed Yield	183
5.17.1 Background	184
5.17.2 Inclusion of delayed yield in radial flow numerical model	184
5.17.3 Comparison of analytical and numerical solutions of a field example with delayed yield	185
5.18 Concluding Remarks	185
6 Large Diameter Wells	187
6.1 Introduction	187
6.2 Description of Flow Processes for Large Diameter Wells	189
6.3 Analytical Solutions for Large Diameter Wells	189
6.3.1 Conventional analyses	189
6.3.2 Drawdown ratio method	191
6.3.3 Alternative methods including Kernel function techniques	193
6.4 Numerical Analysis of Large Diameter Well Tests using Observation Well Data	194
6.5 Analysis with Varying Abstraction Rates	195
6.6 Use of Large Diameter Wells for Agriculture	196
6.6.1 Representative problem	196
6.6.2 Agrowells in Sri Lanka	198

6.6.3	Case study of a Miliolite limestone aquifer	199
6.7	Concluding Remarks	200
7	Radial Flow where Vertical Components of Flow are Significant	201
7.1	Introduction	201
7.2	Radial-Vertical Time-variant Flow $[r, z, t]$	203
7.2.1	Mathematical formulation	203
7.2.2	Analytical solutions	204
7.2.3	Numerical methods	206
7.2.4	Examples of numerical solutions in $[r, z, t]$	206
7.3	Radial-Vertical Time-instant $[r, z]$	209
7.3.1	Principles of the approach	209
7.3.2	Case study: reduction of discharge due to partial penetration of borehole	209
7.3.3	Case study: effectiveness of water table control using tubewells	210
7.4	Two-zone Approximation $[r, t, v_r]$	213
7.4.1	Introduction	213
7.4.2	Examples of formulation using the two-zone model	213
7.4.3	Details of the two-zone model	214
7.4.4	Discrete space-discrete time equations for the two-zone model	216
7.4.5	Solution of simultaneous equations	218
7.4.6	Examples of the use of the two-zone model	218
7.5	Inclusion of Storage in Aquitards $[r, t; z, t]$	223
7.5.1	Introduction	223
7.5.2	Analytical solutions	223
7.5.3	Case study: influence of aquitard storage on an aquifer system; increase and subsequent decrease in flows from the aquitard	224
7.5.4	Influence on aquitard storage of pumping from sandstone aquifers	226
7.6	Concluding Remarks	227
8	Practical Issues of Interpreting and Assessing Resources	228
8.1	Introduction	228
8.2	Step Drawdown Tests and Well Losses	228
8.2.1	Introduction	228
8.2.2	Confined, leaky or unconfined conditions	230
8.2.3	Estimating the coefficients B and C	230
8.2.4	Exploring well losses	231
8.2.5	Causes of well loss	231
8.2.6	Field examples of well losses	235
8.3	Packer Testing to Identify variations in Hydraulic Conductivity with Depth	236
8.3.1	Conducting packer tests	236
8.3.2	Interpretation of packer tests using analytical expressions	237
8.3.3	Do the analytical solutions provide a reasonable approximation to hydraulic conductivity variations?	238
8.3.4	Effectiveness of fissures in collecting water from the aquifer	240
8.3.5	Comparison of properties of sandstone aquifers based on cores, packer testing and pumping tests	241
8.3.6	Slug tests	241
8.4	Information about Groundwater Heads in the Vicinity of Production Boreholes	242
8.4.1	Background	242
8.4.2	Case Study: identifying the water table elevation	243
8.5	Realistic Yield from Aquifer Systems	245
8.5.1	Introduction	245

8.5.2	Weathered-fractured aquifers	246
8.5.3	Alluvial aquifers with an uppermost layer of low hydraulic conductivity	247
8.5.4	Response of an alluvium-sandstone aquifer system	252
8.6	Injection Wells and Well Clogging	254
8.6.1	Introduction	254
8.6.2	Alluvial aquifer in India	256
8.6.3	Initial pumping test	257
8.6.4	Artificial recharge results and interpretation	258
8.6.5	North London Artificial Recharge Scheme	259
8.7	Variable Hydraulic Conductivity with Depth in Chalk and Limestone	259
8.7.1	Introduction	259
8.7.2	Case study in Berkshire Downs, the UK	261
8.7.3	Consequences of variation in hydraulic conductivity	262
8.8	Horizontal Wells	262
8.8.1	Collector wells	263
8.8.2	Mathematical expressions for horizontal wells	264
8.8.3	Horizontal well in a shallow coastal aquifer	267
8.9	Concluding Remarks	269
Part III: Regional Groundwater Flow		
9 Regional Groundwater Studies in which Transmissivity is Effectively Constant		271
9.1	Introduction	271
9.2	Nottinghamshire Sherwood Sandstone Aquifer	271
9.2.1	Identifying the conceptual model, focus on recharge components	274
9.2.2	Idealisations introduced in the regional groundwater model	274
9.2.3	Quantifying the parameters of the conceptual model	276
9.2.4	Numerical groundwater model	276
9.2.5	Adequacy of model	278
9.2.6	Flow balances	279
9.3	Northern Extension of Nottinghamshire Sherwood Sandstone Aquifer	280
9.3.1	Brief description of groundwater catchment	281
9.3.2	Conceptual models	282
9.3.3	Numerical groundwater model and flow balances	284
9.4	Lower Mersey Sandstone Aquifer	284
9.4.1	Conceptual model	286
9.4.2	Recharge through drift	287
9.4.3	Saline water	289
9.4.4	Numerical groundwater model	291
9.4.5	Flow balances and predictions	292
9.5	Barind Aquifer in Bangladesh	293
9.5.1	Background	293
9.5.2	Development of conceptual models	296
9.5.3	Can this rate of abstraction be maintained?	297
9.5.4	Possible provision of a regional groundwater model	298
9.6	Concluding Remarks	299
10 Regional Groundwater Flow in Multi-Aquifer Systems		299
10.1	Introduction	299
10.2	Mehsana Alluvial Aquifer, India	300
10.2.1	Introduction	

10.2.2 Description of the aquifer system	301
10.2.3 Field records of groundwater head	301
10.2.4 Flow processes in aquifer system	304
10.2.5 Mathematical model of a vertical section	305
10.2.6 Origin of flows as determined from vertical section model	307
10.2.7 More detailed study of smaller area	308
10.2.8 Concluding discussion	310
10.3 Vanathavillu Aquifer System, Sri Lanka	311
10.3.1 Introduction	311
10.3.2 Aquifer parameters	312
10.3.3 Groundwater head variations and estimates of aquifer resources	313
10.4 San Luis Potosi Aquifer System, Mexico	315
10.4.1 Shallow aquifer system	316
10.4.2 Deeper aquifer system	316
10.4.3 Input of deep thermal water:	318
10.4.4 Further considerations	319
10.5 Bromsgrove Sandstone Aquifer, UK	319
10.5.1 Summary of field information	320
10.5.2 Conceptual model	322
10.5.3 Mathematical model	322
10.5.4 Presentation of model outputs	323
10.5.5 Management issues	325
10.6 Further examples where vertical components of flow are significant	326
10.6.1 Madras aquifer	326
10.6.2 Waterlogging in Riyadh, Saudi Arabia	327
10.6.3 SCARPS: Saline Control and Reclamation Projects in Pakistan	328
10.6.4 Fylde aquifer, UK	329
10.7 Concluding Remarks	331
11 Regional Groundwater Flow with Hydraulic Conductivity Varying with Saturated Thickness	332
11.1 Introduction	332
11.2 Chalk Aquifer of the Berkshire Downs	333
11.2.1 Changing estimates of yields of the Lambourn Valley catchment	334
11.2.2 Conceptual and mathematical modelling	335
11.3 Southern Lincolnshire Limestone	337
11.3.1 General description of Southern Lincolnshire Limestone catchment	337
11.3.2 Recharge including runoff-recharge	338
11.3.3 Surface water-groundwater interaction	341
11.3.4 Wild boreholes	343
11.3.5 Variable hydraulic conductivity with depth	343
11.3.6 Résumé of conceptual models	345
11.3.7 Brief description of the total catchment models	346
11.3.8 Selected results and insights from the numerical model	347
11.4 Miliolite Limestone Aquifer in Western India	350
11.5 Gipping Chalk Catchment, Eastern England	351
11.5.1 Conceptual model	351
11.5.2 Quantified conceptual model	353
11.6 Further Examples	354
11.6.1 South Humbershire Chalk	354
11.6.2 Candover Augmentation Scheme	354
11.6.3 Hesbaye aquifer, Belgium	357
11.7 Concluding Remarks	358

12 Numerical Modelling Insights	360
12.1 Introduction	360
12.2 Representation of Rivers	360
12.2.1 Intermittent rivers	361
12.2.2. Rivers with significant seasonal changes in stage and wetted perimeter	364
12.3 Representing Boreholes Pumping Water from Multi-layered Aquifers	366
12.4 Time-Instant Conditions	366
12.4.1 Introduction	367
12.4.2 Basis of <i>time-instant</i> approach	367
12.4.3 Examples of sandstone and limestone aquifers	368
12.4.4 Time-instant solutions	368
12.5 Initial Conditions	368
12.5.1 Specified heads or specified flows	369
12.5.2 Initial conditions for Sandstone and other high storage aquifers	370
12.5.3 Initial conditions for aquifers with seasonal changes in transmissivity	372
12.6 Dimensions and Detail of Numerical Models	372
12.6.1 Identification of the area to be represented by a numerical model	374
12.6.2 Identification of the duration of a numerical model simulation	376
12.6.3 External boundary conditions	377
12.6.4 Estimating parameter values for a numerical model	378
12.6.5 Refinement of numerical groundwater models	379
12.6.6 Sensitivity analysis	379
12.6.7 Preparing exploratory groundwater models with limited field information	381
12.7 Predictive Simulations	381
12.7.1 Issues to be considered	382
12.7.2 Representative example	384
12.8 Evaluation of Conceptual and Computational Models	384
12.8.1 Approach to groundwater modelling	384
12.8.2 Monitoring	385
12.8.3 Recharge	385
12.8.4 Model calibration and refinement	386
12.8.5 Sustainability, legislation and social implications	387
12.8.6 Climate change	387
12.8.7 Substantive issues requiring further investigation	387
Appendix: Computer Program for Two-zone Model	389
List of Symbols	399
References	408
Index	