

# Soil Water Dynamics

A. W. WARRICK

# Contents

Symbols and Abbreviations, xix

1. The Soil System, 3
  - 1.1 Introduction, 3
    - Scope, 3
    - Densities, porosities, and water content, 4
  - 1.2 Soil Water in a Static System, 7
    - Soil water potential, 10
    - Units and expressions of potential, 12
    - Water retention—the traditional approach, 13
    - Water retention—the angular pore space model, 19
  - 1.3 Sampling Volumes and the Representative Elementary Volume, 27
  - 1.4 Spatial Variability, 29
    - Expressing variability, 30
    - Sample size, 33
    - Autocorrelated values and variograms, 35
    - Interpolation, 38
    - Nearest neighbor estimates, 40
    - Inverse distance weighting, 40
    - Kriging estimates, 41
  - 1.5 Additional Topics, 42
    - Relationship of relative humidity and osmotic effects to the matric potential  $h_m$ , 42
    - Scaling as a tool to describe soils and address variability, 44
    - Fractal scaling, 46
    - Pedotransfer functions, 49
  - 1.6 Problems, 51
2. Soil Water Flow, 54
  - 2.1 Introduction, 54
    - The Bernoulli and Poiseuille laws, 54
  - 2.2 Darcy's Law—Saturated Flow, 56

- 2.3 Velocities, 59
- 2.4 Simultaneous Flow of Two Fluids and Unsaturated Flow, 60
  - Variably saturated flow, 62
- 2.5 Functional Forms for Hydraulic Properties, 64
  - Flow relationships and unsaturated hydraulic conductivity for the angular pore space model, 68
- 2.6 Richards' Equation, 71
  - Anisotropic soils, 75
  - Source and sink terms, 76
  - Continuity relations for multiphase flow, 76
- 2.7 Boundary Conditions, 76
  - Boundary conditions (time), 77
  - Boundary conditions (space), 77
- 2.8 Coupled Flow Processes, 78
- 2.9 Additional Topics, 79
  - Modeling hysteresis in the soil water retention curve, 79
  - Linear flow laws and analogous systems, 80
  - Simplified derivation of Richards' equation, 82
  - Linear versus nonlinear differential equations, 83
  - Classification of linear, second-order partial differential equations, 84
  - "Best-fitting" retention and conductivity, 84
  - Velocity components and Laplace's equation, 85
- 2.10 Problems, 86
- 3. Saturated Flow, 91
  - 3.1 Introduction, 91
  - 3.2 Subsurface Drainage and Well Discharge (Analytical Approach), 92
    - Line sources and method of images, 92
    - Stream functions and Cauchy-Riemann relationships, 96
    - Complex potential, 99
  - 3.3 Subsurface Drainage and Well-Discharge Solutions (Finite Differences), 100
    - Finite difference approximations, 101
    - Approximation of the Poisson and Laplace equations, 102
    - Ponded drainage solution, 103
  - 3.4 Drainage Example with Travel-Time Calculations, 112
    - Subsurface drains for non-ponded conditions, 112
    - Travel-time calculations, 117
  - 3.5 Three-Dimensional Sources and Sinks, 122

- 3.6 Additional Topics, 123
  - Dupuit–Forchheimer theory and the drainage ellipse, 123
  - Groundwater mounding analyses using Dupuit–Forchheimer theory, 124
  - Image system for parallel drains over an impervious barrier, 129
  - Fourier series, 130
- 3.7 Problems, 130
- 4. One-Dimensional Absorption, 135
  - 4.1 Introduction, 135
  - 4.2 Simplified Analysis for Horizontal Flow, 135
  - 4.3 Linearized Analysis, 138
  - 4.4 The Boltzmann Similarity Transform, 140
    - Evaluation of  $\lambda$  and  $S$ , 142
  - 4.5 An Experimental Test of Darcy's Law, 148
  - 4.6 Evaluation of  $D$  from Absorption Experiments, 151
    - Conventional (graphical) method, 151
    - Additional methods, 152
    - Exfiltration and desorptivity, 155
  - 4.7 Two-Phase Flow and Other Fluids, 155
    - Absorption of other liquids, 155
    - Some results for the unidirectional case, 157
    - Results for countercurrent displacement, 159
  - 4.8 Additional Topics, 159
    - The delta function diffusivity and the Green–Ampt model, 159
    - General solution to the linear equation, 161
  - 4.9 Problems, 162
- 5. One-Dimensional Infiltration and Vertical Flow, 167
  - 5.1 Introduction, 167
  - 5.2 Green–Ampt Solution for Infiltration, 168
  - 5.3 Linearized Solution for Infiltration, 170
  - 5.4 Philip's Solutions for Infiltration, 173
    - Reduced form, 175
    - Solution for small and moderate times, 176
    - Large-times solution, 181
  - 5.5 Finite Difference Approximations, 184
    - An explicit scheme for linear diffusion, 184
    - An explicit scheme for solving Richards' equation, 187
    - An implicit scheme for linear diffusion, 189

- An implicit scheme for Richards' equation, 192
- 5.6 Plant Water Extraction, 197
  - One-dimensional linearized water flow with plant extraction, 199
- 5.7 Steady Vertical Flow Above a Water Table, 201
  - Layered profiles, 202
  - Evaporation from a shallow water table, 203
- 5.8 Preferential Flow, 207
  - Dual porosity model, 207
- 5.9 Additional Topics, 210
  - Burgers' equation, 210
  - Simplified drainage using characteristics, 211
  - Infiltration with air resistance, 213
  - "AUSTERE," an explicit finite difference scheme, 214
  - "AUSTERE-LAYERED" (AL), an implicit finite difference scheme, 217
  - "HYDRUS" and "HYDRUS-1D," 220
- 5.10 Problems, 220
- 6. Multidimensional Water Flow in Variably Saturated Soils, 230
  - 6.1 Introduction, 230
  - 6.2 Absorption, 232
    - Green and Ampt analysis, 232
    - Linearized analysis, 237
    - Flux-concentration relationship, 240
    - Steady absorption from a point or sphere, 245
    - Steady absorption from a line, 246
  - 6.3 Analytical Solutions Using Quasi-Linear Forms, 247
    - Point sources (three dimensions), 247
    - Evaporation from buried sources, 251
    - Stream functions for two- and three-dimensional steady flow, 251
    - Wooding's solution and the disc tension infiltrometer, 254
    - Suction samplers, 256
    - Time-dependent quasi-linear solutions, 257
    - Some further applications of the quasi-linear analysis, 258
  - 6.4 Numerical Solutions, 258
    - Boundary conditions and source terms, 260
    - Solution for  $h$ , 262
    - Flux updating, 263
    - Two- and three-dimensional examples, 264

- 6.5 Additional Topics, 274
  - Images and solutions near planar boundaries for unsaturated flow, 274
  - Capillary diversions and barriers, 278
  - “AUSTERE Two and Three Dimensions” (a2&3.for), 280
- 6.6 Problems, 292
- 7. Solute and Contaminant Transport, 298
  - 7.1 Introduction, 298
  - 7.2 Solute Concentrations, 299
    - Resident concentrations, 299
    - Flux concentration, 300
  - 7.3 Convective–Dispersive (Fickian) Processes, 302
    - Apparent diffusion, 303
    - Examples of breakthrough patterns, 305
    - Derivation of the convective-dispersion equation, 306
    - Analytical solutions, 308
    - Further examples, 320
  - 7.4 Transfer Functions, 329
    - Travel-time probability, 331
    - Travel-time moments, 332
    - The log normal travel-time probability distribution function, 333
    - Adaptation of travel-time distributions to alternative flow rates, 334
    - Adaptation of travel-time probability distribution function from a reference to unknown depth, 335
    - Residence probability functions, 339
    - Calculation of spatial moments for a pulse, 341
    - Calculation of travel-time probability distribution functions from time domain reflectometry data, 343
  - 7.5 Stream Tube Models, 346
    - Stream tube results for piston flow and a step input, 346
    - A stratified aquifer, 350
    - More general cases, 351
  - 7.6 Mobile–Immobile Systems, 352
    - Transport through undisturbed and disturbed soils, 353
  - 7.7 Reactive and Adsorbed Chemicals, 354
    - Instantaneous adsorption, 354
    - First-order reactions, 356
    - First-order decay for convective-dispersion processes, 356
  - 7.8 Nonideal Transport, 358

7.9 Additional Topic, 359

Numerical dispersion, 359

7.10 Problems, 364

References, 369

Index, 383