Contents

Preface

1. The Atmosphere-Vegetation-Soil System
   1.1. Introduction
   1.2. Conservation of Energy and Mass
      1.2.1. Water Balance
      1.2.2. Energy Balance
      1.2.3. The Link: Evapotranspiration
      1.2.4. Simplified Balances
   1.3. Modes of Transport of Energy and Mass
   1.4. Setup of the Book

   2.1. Introduction
   2.2. Net Radiation
      2.2.1. Interaction between Radiation and the Atmosphere
      2.2.2. Downwelling Shortwave Radiation
      2.2.3. Reflected Shortwave Radiation
      2.2.4. Downwelling Longwave Radiation
      2.2.5. Emitted (and Reflected) Longwave Radiation
      2.2.6. Net Radiation: Sum of Components
      2.2.7. Measurement of Net Radiation
   2.3. Soil Heat Flux
      2.3.1. Bare Soil
      2.3.2. Heat Transport in Soils
      2.3.3. Thermal Properties of Soils
      2.3.4. Semi-infinite Homogeneous Soil with Sine-Wave at the Surface
      2.3.5. Force-Restore Method
      2.3.6. Vegetated Surfaces
      2.3.7. Measurement of Soil Heat Flux
      2.3.8. Snow and Ice
   2.4. Summary
### Contents

3. Turbulent Transport in the Atmospheric Surface Layer 69
   3.1. Introduction 69
   3.2. Characteristics of Turbulent Diffusivities 71
   3.3. Turbulence
      3.3.1. Qualitative Description 74
      3.3.2. Intermezzo: Conserved Quantities, Scalars and Vectors 76
      3.3.3. Statistical Description of Turbulence 77
      3.3.4. Buoyancy 82
      3.3.5. Turbulent Kinetic Energy 84
   3.4. Turbulent Transport
      3.4.1. Mean Vertical Flux Density 87
      3.4.2. Eddy-Covariance Method 89
      3.4.3. The Atmospheric Surface-Layer and the Roughness Sublayer 95
   3.5. Similarity Theory
      3.5.1. Dimensionless Gradients: Relevant Variables in MOST 99
      3.5.2. Physical Interpretation of $z/L$ and Its Relationship to the Richardson Number 102
      3.5.3. Similarity Relationships for Gradients 104
      3.5.4. Gradients and Profiles Under Neutral Conditions 106
      3.5.5. Gradients and Profiles Under Conditions Affected by Buoyancy 108
      3.5.6. Similarity Theory: Final Remarks 111
   3.6. Practical Applications of Similarity Relationships 117
      3.6.1. Fluxes from Observations at Two Levels 117
      3.6.2. Fluxes from Observations at a Single Level in the Air and One at the Surface 118
      3.6.3. Analytical Solutions for the Integrated Flux–Gradient Relationships 125
      3.6.4. Feedback Between Stability and the Sensible Heat Flux for Stable Conditions 127
      3.6.5. The Schmidt Paradox 128
   3.7. Summary 130

4. Soil Water Flow 133
   4.1. Introduction 133
   4.2. Field Water Balance 136
   4.3. Hydraulic Head
      4.3.1. Hydraulic Head of Groundwater 140
      4.3.2. Hydraulic Head of Soil Water 141
      4.3.3. Hydraulic Head of Water Vapour 145
   4.4. The Soil Water Characteristic 145
   4.5. Darcy’s Law 149
      4.5.1. Saturated Soil 149
      4.5.2. Unsaturated Soil 152
   4.7. Soil Hydraulic Functions 155
   4.8. Infiltration
      4.8.1. Horton Infiltration Model 158
      4.8.2. Green–Ampt Infiltration Model 159
4.9. Capillary Rise 163
4.10. Measurement of Soil Water Pressure Head 164
  4.10.1. Piezometer 164
  4.10.2. Tensiometer 165
4.11. Measurement of Soil Water Content 168
  4.11.1. Gravimetric and Volumetric Soil Water Content 168
  4.11.2. Measurement by Oven Drying 169
  4.11.3. Measurement by Time Domain Reflectometry 169
4.14. Summary 175

5. Solute Transport in Soil 177
  5.1. Introduction 177
  5.2. Solute Flux through Soil 178
  5.3. Convection–Dispersion Equation 181
  5.4. Transport of Inert, Nonadsorbing Solutes 182
  5.5. Transport of Inert, Adsorbing Chemicals 185
  5.6. Reactions of Chemicals in Soil 188
  5.7. Salinization of Root Zones 190
  5.8. Pesticide Pollution of Groundwater 192
  5.9. Residence Time in Groundwater 193
  5.10. Simulation of Solute Transport 197
  5.11. Summary 198

6. Vegetation: Transport Processes Inside and Outside of Plants 200
  6.1. Functions of Water in the Plant 200
  6.2. Root Water Uptake 201
    6.2.1. Functions of Roots 201
    6.2.2. Structure of the Root Tip 202
    6.2.3. Physiology of Root Water Uptake 204
    6.2.4. Modelling of Root Water Uptake 206
  6.3. Water Flow within the Plant 215
  6.4. Transpiration, Photosynthesis and Stomatal Control 219
    6.4.1. Transpiration 219
    6.4.2. Photosynthesis 222
    6.4.3. Stomatal Behaviour 226
    6.4.4. CO₂ Exchange at the Ecosystem Level 230
  6.5. Dry Matter Production 232
  6.6. Microclimate 236
    6.6.1. Radiation 238
    6.6.2. Air Temperature 241
    6.6.3. Wind Speed 241
    6.6.4. Leaf Temperature 242
    6.6.5. Dew 244
  6.7. Rainfall Interception 246
  6.8. Summary 250
7. Combination Methods for Turbulent Fluxes 252
   7.1. Bowen Ratio Method 252
      7.1.1. Sensible and Latent Heat Flux 252
      7.1.2. Trace Gases 254
   7.2. Penman–Monteith Equation 255
      7.2.1. Penman Derivation 256
      7.2.2. Penman–Monteith Derivation 260
      7.2.3. Canopy Resistance 265
      7.2.4. Analysis of Evapotranspiration from Different Surface Types 267
   7.3. Derived Evapotranspiration Models 269
      7.3.1. Equilibrium Evaporation 269
      7.3.2. Priestley–Taylor Equation 272
      7.3.3. Makkink Equation 273
   7.4. Dewfall 274
   7.5. Summary 276

8. Integrated Applications 278
   8.1. Crop Water Requirements 278
      8.1.1. Definitions of Terms and Units 278
      8.1.2. Factors Affecting Evapotranspiration 280
      8.1.3. Crop Factor Method: General Structure 280
      8.1.4. Crop Factor Method: Penman–Monteith Equation for $E_{\text{ref}}$ 282
      8.1.5. Crop Factor Method: Makkink Equation for $E_{\text{ref}}$ 285
   8.2. Evapotranspiration Measurement: Lysimeters 286
   8.3. Water Productivity at Field and Regional Scale 288
      8.3.1. Introduction 288
      8.3.2. Sirsa District 289
      8.3.3. Modelling Tools 290
      8.3.4. Measurements 291
      8.3.5. Yield Gap 291
      8.3.6. Crop Yields at Field Scale 292
      8.3.7. Water Productivity at a Regional Scale 292
      8.3.8. Scenario Analysis 292
      8.3.9. Satellite Data Assimilation 294
      8.4.1. Data 295
      8.4.2. Energy Balance during Normal Summers 296
      8.4.3. Energy Balance during Heat Wave Conditions 297
      8.4.4. Temporal Development of the Energy and Water Balance 299

9. Integrated Models in Hydrology and Meteorology 302
   9.1. SWAP 302
      9.1.1. Introduction 302
      9.1.2. Soil Water Flow 303
      9.1.3. Top Boundary Condition Hydrology 309
      9.1.4. Bottom Boundary Condition Hydrology 311
      9.1.5. Lateral Drainage 312
      9.1.6. Solute Transport 315
Contents

9.1.7. Heat Flow 316
9.1.8. Crop Growth 320

9.2. The Land-Surface in Atmospheric Models 323
9.2.1. The Role of LSMs in Atmospheric Models 323
9.2.2. General Structure of a LSM 326
9.2.3. Modelling of Vegetation 328
9.2.4. Canopy Resistance 332
9.2.5. Surface Heterogeneity 338
9.2.6. Coupling to the Atmosphere and the Soil 341
9.2.7. The Role of Observations 343

Appendix A: Radiation 345
A.1. Radiation Laws 345
A.2. Solar Radiation: Instantaneous 346

Appendix B: Thermodynamics and Water Vapour 348
B.1. Some Basic Thermodynamics 348
B.2. Hydrostatic Equilibrium 350
B.3. Potential Temperature 351
B.4. Measures of Water Vapour Content 351
B.5. Latent Heat of Vaporization 354

Appendix C: Dimensional Analysis 356
C.1. Choose Relevant Physical Quantities 356
C.2. Make Dimensionless Groups 357
C.3. Do an Experiment 358
C.4. Find the Relationship between Dimensionless Groups 358

Appendix D: Microscopic Root Water Uptake 359
D.1. Mass Balance Equation 359
D.2. General Solution of Matrix Flux Potential Differential Equation 361

Appendix E: Crop Factors for Use with Makkink Reference Evapotranspiration 362

Answers 363
List of Main Symbols 403
References 409
Index 431