SSSA BOOK SERIES: 5

Methods of Soil Analysis

Part 4—Physical Methods

CONTENTS

FOREWORD xxvii
PREFACE xxix
CONTRIBUTORS xxxi
CONVERSION FACTORS FOR SI AND NON-SI UNITS xxxvii

Chapter 1 Soil Sampling and Statistical Procedures

1.1 Introduction
A.W. WARRICK AND H.M. VAN ES 1
1.2 Soil Variability
H.M. VAN ES 1
1.2.1 Sources and Structure of Variability 1
1.2.1.1 Introduction 1
1.2.1.2 Properties and Processes 2
1.2.1.3 Sources of Variability 3
1.2.1.4 Structure of Variability 4
1.2.2 Variability and Scale 8
1.2.2.1 Scale of Research Domain 8
1.2.2.2 Scale of Observation 9
1.2.3 References 12
1.3 Errors, Variability, and Precision
R.R. ALLMARAS AND OSCAR KEMPTHORNE 15
1.3.1 Introduction 15
1.3.2 Classification of Measurement Errors 16
1.3.3 Scientific Validity of Measurements 17
1.3.4 Characterization of Variability 18
1.3.5 Skewed Frequency Distributions 22
1.3.5.1 Impact of Mathematical Distribution on Imprecision 27
1.3.6 Transformations of a Random Variable or Functions of a Random (Explanatory) Variable 28
1.3.7 The Estimation of Precision 29
1.3.8 Precision of Derived Observations 31
1.3.8.1 Case 1: A Single-Valued Function of an Observation 31
1.3.8.2 Case 2: A Number Derived from Measurements of More Than One Attribute on the Same Sample 33
1.3.8.3 Case 3: A Single Function of Numerous Measurements with Same Attribute 34
1.3.9 Error Propagation in Modeling 35
1.3.10 The Roles of Bias and Precision 36
1.3.11 How to Study Errors of Observation 39
1.3.12 Role of Errors of Observation in the Study of Relationships 40
1.3.13 A Note on Terminology 41

1.3.14 Statistical Problems and Techniques in General 43
1.3.15 References 43
1.4 Sampling
J.J. DE GRUIJTER 45
1.4.1 Designing a Sampling Scheme 45
1.4.1.1 Towards Better Planning 45
1.4.1.2 A Guiding Principle in Designing Sampling Schemes 46
1.4.1.3 Practical Issues 47
1.4.1.4 Scientific Issues 48
1.4.1.5 Statistical Issues 48
1.4.2 Design-Based and Model-Based Approach 50
1.4.3 Design-Based Strategies 52
1.4.3.1 Scope of Design-Based Strategies 53
1.4.3.2 Simple Random Sampling 54
1.4.3.3 Stratified Sampling 58
1.4.3.4 Two-Stage Sampling 60
1.4.3.5 Cluster Sampling 62
1.4.3.6 Systematic Sampling 63
1.4.3.7 Advanced Design-Based Strategies 65
1.4.4 Model-Based Strategies 67
1.4.5 Composite Sampling 70
1.4.6 Sampling in Dimensions Other Than Two-Dimensional Space 71
1.4.6.1 Sampling in Three-Dimensional Space and at Depth. 72
1.4.6.2 Sampling in Time 72
1.4.6.3 Sampling in Space–Time 74
1.4.7 References 77
1.5 Geostatistics
S.R. YATES AND A.W. WARRICK 81
1.5.1 Introduction 81
1.5.1.1 Geostatistical Investigations 82
1.5.2 Using Geostatistical Methods 83
1.5.2.1 Sampling 83
1.5.2.2 Spatial Autocorrelation 84
1.5.2.3 Geostatistics and Estimation 94
1.5.2.4 Geostatistics and Uncertainty 107
1.5.3 Appendices 114
1.5.3.1 Selected Windows-Based Geostatistical Software ... 114
1.5.3.2 Simulating Random Fields 115
1.5.4 References 116
1.6 Time and Space Series
O. WENDROTH AND D.R. NIELSEN 119
1.6.1 General Information 119
1.6.2 Auto- and Cross-Correlation 119
1.6.3 Spectral Analysis 123
1.6.4 State–Space Analysis 128
1.6.4.1 Autoregressive State–Space Model for Spatial Processes 131

1.6.4.2 State–Space Analysis for Time Series 133
1.6.5 References 136
1.7 Parameter Optimization and Nonlinear Fitting
JIŘÍ ŠIMŮNEK AND JAN W. HOPMANS 139
1.7.1 Introduction 139
1.7.2 Maximum-Likelihood and Weighted Least-Squares Estimator 140
1.7.3 Methods of Solution 143
1.7.4 Correlation and Confidence Intervals 146
1.7.5 Goodness of Fit 148
1.7.6 Examples and Optimization Programs 149
1.7.7 Discussion 155
1.7.8 References 156
1.8 Newer Application Techniques
ALEX. B. McBRATNEY, ALISON N. ANDERSON,
R. MURRAY LARK, AND INAKWU O. ODEH 159
1.8.1 Fractal Dimensions
A.N. ANDERSON AND A.B. McBRATNEY 159
1.8.1.1 Theory 160
1.8.1.2 Quantifying Soil Structure Using Fractal Geometry . 163
1.8.1.3 Applications of Fractal Geometry to Soil Physics ... 168
1.8.1.4 Characterizing Soil Spatial Variability Using Fractal Geometry 170
1.8.1.5 Future Prospects 171
1.8.2 Fuzzy Sets
I.O. ODEH AND A.B. McBRATNEY 171
1.8.2.1 The Concept of Fuzzy Sets 172
1.8.2.2 Some Definitions and Examples Related to Fuzzy Sets 172
1.8.2.3 Fuzzy Models of Soil Physical Processes: Example . 178
1.8.2.4 Application to Soil Classification, Mapping, and Land Evaluation 181
1.8.3 Wavelet Analysis
R.M. LARK AND A.B. McBRATNEY 184
1.8.3.1 The Continuous Wavelet Transform 187
1.8.3.2 The Discrete Wavelet Transform 189
1.8.3.3 Prospects for Wavelet Analysis 192
1.8.4 References 195

Chapter 2 The Solid Phase

2.1 Bulk Density and Linear Extensibility
R.B. GROSSMAN AND T.G. REINSCH 201
2.1.1 Introduction 201
2.1.1.1 Principles 201
2.1.1.2 Variability 202
2.1.1.3 Application 203
2.1.1.4 Dealing with Rock Fragments 205

2.1.2 Core Method 207
2.1.2.1 Introduction 207
2.1.2.2 Method 207
2.1.2.3 Comments 210
2.1.3 Excavation Method 211
2.1.3.1 Introduction 211
2.1.3.2 Method 211
2.1.3.3 Comments 216
2.1.4 Clod Method 218
2.1.4.1 Introduction 218
2.1.4.2 Equipment and Supplies 218
2.1.4.3 Procedure 219
2.1.4.4 Comments 222
2.1.5 Radiation Methods 222
2.1.5.1 Introduction 222
2.1.5.2 Equipment and Procedures 223
2.1.5.3 Comments 223
2.1.6 Linear Extensibility 223
2.1.6.1 Introduction 223
2.1.6.2 Calculations 224
2.1.6.3 Comments 225
2.1.7 References 225
2.2 Particle Density
ALAN L. FLINT AND LORRAINE E. FLINT 229
2.2.1 Introduction 229
2.2.2 Principles 229
2.2.3 Methods 230
2.2.3.1 Calculation from Porosity and Bulk Density 230
2.2.3.2 Liquid Displacement 230
2.2.3.3 Gas Displacement 235
2.2.3.4 Estimation from Constituent Properties 237
2.2.4 Comments 239
2.2.5 References 240
2.3 Porosity
LORRAINE E. FLINT AND ALAN L. FLINT 241
2.3.1 Introduction 241
2.3.2 Total Porosity 242
2.3.2.1 Calculation from Particle and Bulk Densities 242
2.3.2.2 Gravimetric Method with Water Saturation 243
2.3.2.3 Volumetric Method with Gas Pycnometry 245
2.3.3 Pore-Size Distribution 246
2.3.3.1 Water-Desorption Method 246
2.3.3.2 Visualization Method Using Impregnation 249
2.3.3.3 Mercury-Porosimetry Method 251
2.3.4 References 253
2.4 Particle-Size Analysis
GLENDON W. GEE AND DANI OR 255
2.4.1 Introduction 255

2.4.2 Pretreatment and Dispersion Techniques 257
2.4.2.1 General Principles 257
2.4.2.2 Organic Matter Removal 259
2.4.2.3 Iron Oxide Removal 261
2.4.2.4 Carbonate Removal 262
2.4.2.5 Soluble Salts Removal 262
2.4.2.6 Sample Dispersion 262
2.4.3 Specific Methods of Particle-Size Analysis 264
2.4.3.1 Introduction 264
2.4.3.2 Analysis by Sieving 265
2.4.3.3 Analysis by Gravitational Sedimentation 269
2.4.3.4 Pipette Method 272
2.4.3.5 Hydrometer Method 278
2.4.3.6 Modern Methods for Particle-Size Measurement 283
2.4.4 References 289
2.5 Specific Surface Area
K.D. PENNELL 295
2.5.1 Introduction 295
2.5.2 Liquid-Phase Adsorption Methods 298
2.5.2.1 Principles 298
2.5.2.2 Equipment and Supplies 299
2.5.2.3 Experimental Procedure 300
2.5.2.4 Comments 302
2.5.3 Gas-Phase Adsorption Methods 303
2.5.3.1 Principles 303
2.5.3.2 Equipment and Supplies 305
2.5.3.3 Experimental Procedure 306
2.5.3.4 Comments 307
2.5.4 Retention of Polar Liquids 308
2.5.4.1 Principles 308
2.5.4.2 Equipment and Supplies 309
2.5.4.3 Experimental Procedure 309
2.5.4.4 Comments 311
2.5.5 Comparison of Surface Area Methods 312
2.5.6 References 313
2.6 Aggregate Stability and Size Distribution
JOHN R. NIMMO AND KIM S. PERKINS 317
2.6.1 Principles 317
2.6.2 Apparatus and Procedures 320
2.6.2.1 General Sample Preparation 320
2.6.2.2 Modifications of Informally Standardized Methods and Apparatus 323
2.6.2.3 Representation of Data 324
2.6.3 Comments 326
2.6.4 References 327
2.7 Shear Strength of Unsaturated Soils
D.G. FREDLUND AND S.K. VANAPALLI 329
2.7.1 Introduction 329

2.7.2 Shear Strength Equation for Unsaturated Soils 331
2.7.3 Triaxial Shear Tests for Unsaturated Soils 332
2.7.3.1 Test Procedures for Triaxial Tests 333
2.7.4 Direct Shear Tests for Unsaturated Soils 343
2.7.5 Failure Criteria for Unsaturated Soils 347
2.7.5.1 Strain Rates for Triaxial and Direct Shear Tests 347
2.7.6 Interpretation of Drained Test Results Using Multistage Testing Procedures 349
2.7.7 Nonlinearity of Failure Envelope 351
2.7.8 Interpretation of Undrained Test Results 351
2.7.8.1 Confined Compression Tests 353
2.7.8.2 Unconfined Compression Tests 354
2.7.9 Relationship Between the Soil Water Characteristic Curve and the Shear Strength of Unsaturated Soils 354
2.7.10 Procedure for Predicting the Shear Strength of Unsaturated Soils 357
2.7.11 Summary 360
2.7.12 References 360
2.8 Soil Penetrometers and Penetrability
BIRL LOWERY AND JOHN E. MORRISON, JR. 363
2.8.1 Introduction 363
2.8.2 Principles 366
2.8.2.1 Soil Mechanics Associated with Penetrometers 367
2.8.3 Equipment, Software, and Supplies 375
2.8.3.1 Penetrometer Rod or Shaft and Active Element 375
2.8.3.2 Force-Sensing Apparatus 375
2.8.3.3 Depth-Sensing Apparatus 376
2.8.3.4 Structure of Penetrometer 377
2.8.3.5 Data Logging 378
2.8.4 Data Logging Operational Details for Specific Penetrometers . 378
2.8.4.1 Pocket Penetrometer 378
2.8.4.2 Cone Penetrometer 379
2.8.4.3 Friction-Sleeve Cone Penetrometer 383
2.8.5 Summary 385
2.8.6 References 385
2.9 Atterberg Limits
R.A. MCBRIDE 389
2.9.1 Introduction 389
2.9.2 Liquid Limit 390
2.9.2.1 Casagrande Method 391
2.9.2.2 One-Point Casagrande Method 393
2.9.2.3 Drop-Cone Penetrometer Method 394
2.9.3 Plastic Limit 395
2.9.3.1 Casagrande Method 396
2.9.4 References 398
2.10 Soil Compressibility
S.C. GUPTA, J.M. BRADFORD, AND A. DRESCHER 399
2.10.1 Introduction 399

2.10.2 Principles 400
2.10.3 Methods 409
2.10.3.1 Apparatus 409
2.10.3.2 Procedure 410
2.10.4 Comments 413
2.10.5 References 414

Chapter 3 The Soil Solution Phase

3.1 Water Content 417
3.1.1 General Information
G. CLARKE TOPP AND P.A. (TY) FERRÉ 417
3.1.2 Scope of Methods and Brief Description
G. CLARKE TOPP AND P.A. (TY) FERRÉ 419
3.1.2.1 Thermogravimetric Method Using Convective Oven-Drying 419
3.1.2.2 Gravimetric Method Using Microwave Oven-Drying 419
3.1.2.3 Time Domain Reflectometry 419
3.1.2.4 Ground Penetrating Radar 420
3.1.2.5 Capacitance Devices 420
3.1.2.6 Radar Scatterometry or Active Microwave 420
3.1.2.7 Passive Microwave 420
3.1.2.8 Electromagnetic Induction 421
3.1.2.9 Neutron Thermalization 421
3.1.2.10 Nuclear Magnetic Resonance 421
3.1.2.11 Gamma Ray Attenuation 421
3.1.3 Methods for Measurement of Soil Water Content 422
3.1.3.1 Thermogravimetric Method Using Convective Oven-Drying
G. CLARKE TOPP AND P.A. (TY) FERRÉ 422
3.1.3.2 Gravimetric Method Using Microwave Oven-Drying
G. CLARKE TOPP AND P.A. (TY) FERRÉ 425
3.1.3.3 The Basis of Electromagnetic Methods: A Wave Equation Framework 428
3.1.3.4 Time Domain Reflectometry
P.A. (TY) FERRÉ AND G. CLARKE TOPP 434
3.1.3.5 Ground Penetrating Radar to Measure Soil Water Content
J.L. DAVIS AND A.P. ANNAN 446
3.1.3.6 Capacitance Devices
JAMES L. STARR AND IOAN C. PALTINEANU 463
3.1.3.7 Active Microwave Remote Sensing Methods
H. MCNAIRN, T.J. PULTZ, AND J.B. BOISVERT 475
3.1.3.8 Passive Microwave Remote Sensing Methods
THOMAS J. JACKSON 488

3.1.3.9 Electromagnetic Induction
R.G. KACHANOSKI, J.M.H. HENDRICKX, AND E. DE JONG 497
3.1.3.10 Neutron Thermalization
CLIFF HIGNETT AND STEVEN R. EVETT 501
3.1.3.11 Nuclear Magnetic Resonance
CAROLINE M. PRESTON 521
3.1.4 References 534
3.2 Water Potential 547
3.2.1 Piezometry
MICHAEL H. YOUNG 547
3.2.1.1 Introduction 547
3.2.1.2 Principles 548
3.2.1.3 Drilling Methods 552
3.2.1.4 Installation 555
3.2.1.5 Monitoring 562
3.2.1.6 Technical Considerations 567
3.2.1.7 References 571
3.2.2 Tensiometry
MICHAEL H. YOUNG AND JAMES B. SISSON 575
3.2.2.1 Introduction 575
3.2.2.2 Soil Water Matric Potential 575
3.2.2.3 Principles 577
3.2.2.4 Essential Components of Tensiometers 579
3.2.2.5 Alternative Types of Tensiometers 586
3.2.2.6 Field and Laboratory Applications 587
3.2.2.7 Field Measurements 589
3.2.2.8 Laboratory Measurements 599
3.2.2.9 Interpretation of Tensiometric Readings 602
3.2.2.10 Gauge Calibration 605
3.2.2.11 References 606
3.2.3 Thermocouple Psychrometry
BRIAN J. ANDRASKI AND BRIDGET R. SCANLON 609
3.2.3.1 Principles 609
3.2.3.2 Equipment 612
3.2.3.3 Procedures 620
3.2.3.4 Comments 637
3.2.3.5 Commercial Sources 638
3.2.3.6 References 639
3.2.4 Miscellaneous Methods for Measuring Matric or Water Potential
BRIDGET R. SCANLON, BRIAN J. ANDRASKI, AND JIM BILSKIE 643
3.2.4.1 Introduction 643
3.2.4.2 Heat Dissipation Sensors 644
3.2.4.3 Electrical Resistance Sensors 654
3.2.4.4 Frequency Domain and Time Domain Matric Potential Sensors 660
3.2.4.5 Electro-Optical Switches 661

3.2.4.6 Dew Point Potentiameter 662
3.2.4.7 Filter Paper Technique 665
3.2.4.8 Vapor Equilibration 668
3.2.4.9 References 669
3.3 Water Retention and Storage 671
3.3.1 Introduction
J.H. DANE AND JAN W. HOPMANS 671
3.3.1.1 References 673
3.3.2 Laboratory 675
3.3.2.1 Introduction
J.H. DANE AND JAN W. HOPMANS 675
3.3.2.2 Hanging Water Column
J.H. DANE AND JAN W. HOPMANS 680
3.3.2.3 Pressure Cell
J.H. DANE AND JAN W. HOPMANS 684
3.3.2.4 Pressure Plate Extractor
J.H. DANE AND JAN W. HOPMANS 688
3.3.2.5 Long Column
J.H. DANE AND JAN W. HOPMANS 690
3.3.2.6 Suction Table
N. ROMANO, JAN W. HOPMANS, AND J.H. DANE 692
3.3.2.7 Controlled Liquid Volume
K.A. WINFIELD AND J.R. NIMMO 698
3.3.2.8 Determination of Soil Water Characteristic by Freezing Method
E.J.A. SPAANS AND J.M. BAKER 704
3.3.2.9 Miscellaneous Methods
J.R. NIMMO AND K.A. WINFIELD 710
3.3.2.10 Computational Corrections
J.H. DANE AND J.W. HOPMANS 714
3.3.2.11 Guidelines for Method Selection
J.R. NIMMO 717
3.3.2.12 References 717
3.3.3 Field
NUNZIO ROMANO AND ALESSANDRO SANTINI 721
3.3.3.1 Introduction 721
3.3.3.2 Field Water Capacity 723
3.3.3.3 Permanent Wilting Point 729
3.3.3.4 Available Water 731
3.3.3.5 Specific Yield 734
3.3.3.6 References 736
3.3.4 Parametric Models
KEN'ICHIROU KOSUGI, JAN W. HOPMANS, AND JACOB H. DANE . . . 739
3.3.4.1 Introduction 739
3.3.4.2 General Characteristics of Water Retention Curves and Important Parameters 740
3.3.4.3 Brooks and Corey Type Power Function 741
3.3.4.4 van Genuchten Type Power Function 742
3.3.4.5 Exponential Function 745

3.3.4.6 Lognormal Distribution Function 745
3.3.4.7 Water Capacity Functions 747
3.3.4.8 Unsaturated Hydraulic Conductivity Functions 747
3.3.4.9 Multimodal Retention Functions 750
3.3.4.10 Soil Water Hysteresis 751
3.3.4.11 Model Fitting 753
3.3.4.12 Comments 754
3.3.4.13 References 755
3.3.5 Property-Transfer Models
RANDEL HAVERKAMP, PAOLO REGGIANI, AND JOHN R. NIMMO ... 759
3.3.5.1 Physically Based Water Retention Prediction Models
RANDEL HAVERKAMP AND PAOLO REGGIANI 762
3.3.5.2 Property Transfer from Particle and Aggregate Size to Water Retention
JOHN R. NIMMO 777
3.3.5.3 References 781
3.3.6 Air–Water Interfacial Area
P.S.C. RAO, HEONKI KIM, AND MICHAEL D. ANNABLE 783
3.3.6.1 Introduction 783
3.3.6.2 Principles 784
3.3.6.3 Aqueous-Static Method 786
3.3.6.4 Aqueous-Dynamic Method 789
3.3.6.5 Gaseous-Dynamic Method 792
3.3.6.6 Comments 794
3.3.6.7 References 795
3.4 Saturated and Field-Saturated Water Flow Parameters
W.D. REYNOLDS, D.E. ELRICK, E.G. YOUNGS, A. AMOOZEGAR, H.W.G. BOOLTINK, AND J. BOUMA 797
3.4.1 Introduction 797
3.4.1.1 Principles and Parameter Definitions
W.D. REYNOLDS AND D.E. ELRICK 797
3.4.1.2 References 801
3.4.2 Laboratory Methods
W.D. REYNOLDS, D.E. ELRICK, E.G. YOUNGS, H.W.G. BOOLTINK, AND J. BOUMA 802
3.4.2.1 Introduction 802
3.4.2.2 Constant Head Soil Core (Tank) Method
W.D. REYNOLDS AND D.E. ELRICK 804
3.4.2.3 Falling Head Soil Core (Tank) Method
W.D. REYNOLDS AND D.E. ELRICK 809
3.4.2.4 Steady Flow Soil Column Method
H.W.G. BOOLTINK AND J. BOUMA 812
3.4.2.5 Other Laboratory Methods
W.D. REYNOLDS AND D.E. ELRICK 815
3.4.2.6 References 816
3.4.3 Field Methods (Vadose and Saturated Zone Techniques)
W.D. REYNOLDS, D.E. ELRICK, E.G. YOUNGS, AND A. AMOOZEGAR 817
3.4.3.1 Introduction 817
3.4.3.2 Ring or Cylinder Infiltrometers (Vadose Zone)
W.D. REYNOLDS, D.E. ELRICK, AND E.G. YOUNGS 818

3.4.3.2.a Single-Ring and Double- or Concentric-Ring Infiltrometers
W.D. REYNOLDS, D.E. ELRICK, AND E.G. YOUNGS 821
3.4.3.2.b Pressure Infiltrometer
W.D. REYNOLDS AND D.E. ELRICK 826
3.4.3.2.c Twin- or Dual-Ring and Multiple-Ring Infiltrometers
W.D. REYNOLDS, D.E. ELRICK, AND E.G. YOUNGS 836
3.4.3.2.d References 842
3.4.3.3 Constant Head Well Permeameter (Vadose Zone)
W.D. REYNOLDS AND D.E. ELRICK 844
3.4.3.4 Auger-Hole Method (Saturated Zone)
AZIZ AMOOZEGAR 859
3.4.3.5 Piezometer Method (Saturated Zone)
AZIZ AMOOZEGAR 870
3.4.3.6 Other Saturated Zone Methods 877
3.5 Unsaturated Water Transmission Parameters Obtained from Infiltration
BRENT CLOTHIER AND DAVID SCOTTER 879
3.5.1 Basic Theory 879
3.5.2 One-Dimensional Infiltration Equations and Their Use 881
3.5.3 Horizontal Absorption—The Bruce and Klute Experiment . . . 884
3.5.4 Three-Dimensional Infiltration Using Disk Permeameters. . . . 888
3.5.4.1 Early-Time Observations
J.-P. VANDERVAERE 889
3.5.4.2 Steady-State Observations
BRENT CLOTHIER AND DAVID SCOTTER 894
3.5.5 Conclusions. 896
3.5.6 References. 896
3.6 Simultaneous Determination of Water Transmission and Retention Properties. 899
3.6.1 Direct Methods 899
3.6.1.1 Laboratory 899
3.6.1.1.a Long Column
ARTHUR T. COREY 899
3.6.1.1.b Steady-State Centrifuge
JOHN R. NIMMO, KIM S. PERKINS, AND ANGUS M. LEWIS 903
3.6.1.1.c Wind and Hot-Air Methods
LALIT M. ARYA 916
3.6.1.1.d Suction Crust Infiltrometer
H.W.G. BOOLTINK AND J. BOUMA 926
3.6.1.1.e Bypass Flow
H.W.G. BOOLTINK AND J. BOUMA 930
3.6.1.1.f References 933
3.6.1.2 Field 937
3.6.1.2.a Instantaneous Profile
GEORGES VACHAUD AND J.H. DANE 937

4.2.2 Sampling 1077
4.2.2.1 Air-Filled Pores Above the Water Table 1078
4.2.2.2 Soil Water Sampling 1081
4.2.3 Gas Analysis 1083
4.2.3.1 Principles of Gas Chromatography 1084
4.2.3.2 Laboratory Analysis by Gas Chromatography 1089
4.2.3.3 Field-Based Gas Chromatography Systems 1091
4.2.3.4 Alternative Gas Analysis Systems 1092
4.2.4 In Situ Analyses at the Gas–Liquid Interface 1096
4.2.4.1 Platinum Microelectrode Methods 1097
4.2.4.2 Membrane-Covered Electrode Methods 1103
4.2.4.3 Miscellaneous Gas-Sensing Probes 1106
4.2.5 References 1106
4.3 Gas Diffusivity
DENNIS E. ROLSTON AND PER MOLDRUP 1113
4.3.1 Introduction 1113
4.3.2 Laboratory Methods 1114
4.3.2.1 The Currie Method 1114
4.3.2.2 The Two-Chamber Method 1122
4.3.3 Field Method 1126
4.3.3.1 The MacIntyre and Philip Method 1126
4.3.4 Predicting Gas Diffusivity 1131
4.3.4.1 Undisturbed Soil 1131
4.3.4.2 Sieved, Repacked Soil 1134
4.3.4.3 Values of D_0 1136
4.3.5 References 1137
4.4 Air Permeability
BRUCE C. BALL AND PER SCHJØNNING 1141
4.4.1 Introduction 1141
4.4.2 Laboratory Methods 1142
4.4.3 Field Methods 1143
4.4.3.1 Acoustic Method 1145
4.4.3.2 Buried Probe and Well Techniques 1146
4.4.4 Recommended Laboratory Method 1146
4.4.4.1 Apparatus and Materials 1146
4.4.4.2 Procedures 1147
4.4.4.3 Comments 1149
4.4.5 Recommended Field Method 1149
4.4.5.1 Apparatus and Materials 1150
4.4.5.2 Procedures 1150
4.4.5.3 Comments 1151
4.4.6 Choice of Method, Including Scaling and Variability Aspects . 1152
4.4.7 Predicting Air Permeability 1153
4.4.8 Conclusions and Summary 1156
4.4.9 References 1157
4.5 Soil–Atmosphere Gas Exchange
GORDON L. HUTCHINSON AND GERALD P. LIVINGSTON 1159
4.5.1 Introduction 1159

4.5.2 Computation from Fick's Law 1160
4.5.2.1 Principles 1160
4.5.2.2 Apparatus, Materials, and Procedure 1162
4.5.2.3 Comments and Cautions 1162
4.5.3 Chamber Systems 1163
4.5.3.1 Principles 1163
4.5.3.2 Apparatus and Materials 1165
4.5.3.3 Procedure 1170
4.5.3.4 Comments and Cautions 1175
4.5.4 Sampling Design, Data Analyses, and Data Summaries 1176
4.5.5 Concluding Remarks 1179
4.5.6 References 1180

Chapter 5 Soil Heat

5.1 Temperature
KEVIN J. McINNES 1183
5.1.1 Thermocouple Thermometry 1183
5.1.2 Integrated Circuit Thermometers 1190
5.1.3 Resistance Thermometers 1192
5.1.3.1 Platinum Resistance Thermometers 1192
5.1.3.2 Resistance Temperature Detectors 1192
5.1.3.3 Thermistors 1193
5.1.4 Nonelectric Thermometers 1195
5.1.5 Infrared Radiation Thermometers 1195
5.1.6 Installation and Operation 1197
5.1.7 References 1199
5.2 Heat Capacity and Specific Heat
G.J. KLUITENBERG 1201
5.2.1 General Introduction 1201
5.2.2 General Principles 1201
5.2.2.1 Basic Definitions 1201
5.2.2.2 Relationship Between Volumetric Heat Capacity and Specific Heat 1202
5.2.3 Methods 1203
5.2.3.1 De Vries Approximation 1203
5.2.3.2 Dual-Probe Heat-Pulse Method 1204
5.2.4 References 1208
5.3 Thermal Conductivity
KEITH L. BRISTOW 1209
5.3.1 Introduction 1209
5.3.2 Predictive Methods 1210
5.3.2.1 Predicting Soil Thermal Conductivity, Including Temperature Effects 1211
5.3.2.2 Predicting Soil Thermal Conductivity from Readily Available Soils Data 1215

5.3.3 Steady-State Methods 1216
5.3.3.1 Guarded Hot Plate Method 1216
5.3.4 Transient-State Methods 1217
5.3.4.1 Theory 1217
5.3.4.2 Probe Design and Construction 1218
5.3.4.3 Single Heat Probe Method 1220
5.3.4.4 Dual-Probe Heat-Pulse Method 1221
5.3.5 Comments Concerning Thermal Conductivity 1223
5.3.6 References 1224
5.4 Soil Thermal Diffusivity
ROBERT HORTON 1227
5.4.1 Laboratory Method for Determining Soil Thermal Diffusivity 1228
5.4.1.1 Principles 1228
5.4.1.2 Measurements 1228
5.4.1.3 Analysis of Soil Column Temperature Observations . 1229
5.4.2 Field Method for Determining Soil Thermal Diffusivity 1229
5.4.3 References 1231
5.5 Heat Flux Density
THOMAS J. SAUER 1233
5.5.1 Calorimetric 1235
5.5.1.1 Principles 1235
5.5.1.2 Equipment 1236
5.5.1.3 Procedures 1236
5.5.1.4 Commentary on Advantages and Limitations 1237
5.5.2 Gradient 1238
5.5.2.1 Principles 1238
5.5.2.2 Equipment 1238
5.5.2.3 Procedures 1239
5.5.2.4 Commentary on Advantages and Limitations 1239
5.5.3 Combination 1240
5.5.3.1 Principles 1240
5.5.3.2 Equipment 1240
5.5.3.3 Procedures 1240
5.5.3.4 Commentary on Advantages and Limitations 1241
5.5.4 Soil Heat Flux Plate 1242
5.5.4.1 Principles 1242
5.5.4.2 Equipment 1243
5.5.4.3 Procedures 1244
5.5.4.4 Commentary on Advantages and Limitations 1247
5.5.5 References 1247
5.6 Coupled Heat and Water Transfer
IBRAHIM N. NASSAR AND ROBERT HORTON 1249
5.6.1 Introduction 1249
5.6.2 Soil Thermal Water Diffusivity 1250
5.6.3 References 1251

Chapter 6 Miscible Solute Transport

6.1 Solute Content and Concentration 1253
6.1.1 Introduction
JAN M.H. HENDRICKX, JON M. WRAITH, DENNIS L. CORWIN, AND R. GARY KACHANOSKI 1253
6.1.2 Measurement of Solute Content Using Soil Extraction
JAN M.H. HENDRICKX AND LOUIS W. DEKKER 1255
6.1.2.1 General Principles 1255
6.1.2.2 Equipment 1256
6.1.2.3 Procedure 1256
6.1.2.4 Comments 1260
6.1.3 Measurement of Solute Concentration Using Soil Water Extraction 1261
6.1.3.1 Suction Cups
DENNIS L. CORWIN 1261
6.1.3.2 Passive Capillary Samplers
JOHN S. SELKER 1266
6.1.3.3 Porous Matrix Sensors
DENNIS L. CORWIN 1269
6.1.4 Indirect Measurement of Solute Concentration
JAN M.H. HENDRICKX, B. DAS, DENNIS L. CORWIN, JON M. WRAITH, AND R. GARY KACHANOSKI 1274
6.1.4.1 Relationship between Soil Water Solute Concentration and Apparent Soil Electrical Conductivity
JAN M.H. HENDRICKX, B. DAS, DENNIS L. CORWIN, JON M. WRAITH AND R. GARY KACHANOSKI 1275
6.1.4.2 Electrical Resistivity: Wenner Array
DENNIS L. CORWIN AND JAN M.H. HENDRICKX 1282
6.1.4.3 Electrical Resistivity: Four-Electrode Probe
DENNIS L. CORWIN 1287
6.1.4.4 Time Domain Reflectometry
JON M. WRAITH 1289
6.1.4.5 Nonintrusive Electromagnetic Induction
JAN M.H. HENDRICKX AND R. GARY KACHANOSKI 1297
6.1.5 Emerging Methods
JAN M.H. HENDRICKX 1306
6.1.5.1 Fiber Optic Sensors
JAN M.H. HENDRICKX 1307
6.1.5.2 Capillary Absorbers
CARL KELLER AND JAN M.H. HENDRICKX 1308
6.1.6 References 1311
6.2 Solute Diffusion
MARKUS FLURY AND THOMAS F. GIMMI 1323
6.2.1 Introduction 1323
6.2.2 Theory of Diffusion 1324
6.2.2.1 Fick's Laws of Diffusion 1324
6.2.2.2 Estimation of Diffusion Coefficients in Liquids 1324
6.2.2.3 Temperature Dependence of Diffusion Coefficients . 1327
6.2.2.4 Type of Diffusion Coefficients 1328

6.2.2.5 Diffusion of Nonreactive Solutes in Porous Media .. 1328
6.2.2.6 Estimation of Diffusion Coefficients for Nonreactive Solutes in Porous Media 1330
6.2.2.7 Diffusion and Convection 1332
6.2.2.8 Diffusion and Reactions 1332
6.2.3 Methods 1333
6.2.3.1 Steady-State Methods 1333
6.2.3.2 Transient Methods 1334
6.2.3.3 Other Methods 1347
6.2.4 Conclusions 1348
6.2.5 References 1348
6.3 Solute Transport: Theoretical Background
TODD H. SKAGGS AND FEIKE J. LEIJ 1353
6.3.1 Elementary Concepts 1353
6.3.1.1 Solute Transport Experiments 1353
6.3.1.2 Breakthrough Curves 1354
6.3.1.3 Moments 1356
6.3.1.4 Mass Balance 1358
6.3.1.5 Flux and Resident Concentrations 1359
6.3.2 Convection–Dispersion Model 1360
6.3.2.1 Dimensionless Parameters 1361
6.3.2.2 Flux Concentrations 1361
6.3.2.3 Boundary Conditions 1362
6.3.2.4 Analytical Solutions 1364
6.3.2.5 Moments 1365
6.3.3 Nonequilibrium Models 1368
6.3.3.1 Two-Region Model 1369
6.3.3.2 Two-Site Model 1370
6.3.3.3 General Nonequilibrium Formulation 1371
6.3.3.4 Analytical Solutions and Moments 1372
6.3.3.5 Additional Nonequilibrium Formulations 1372
6.3.4 Stochastic–Convective Model 1372
6.3.4.1 Transfer Function Modeling 1372
6.3.4.2 Stochastic–Convective Transfer Function Model 1374
6.3.4.3 Convective Lognormal Transfer Function Model ... 1375
6.3.4.4 Field Applications 1375
6.3.4.5 Comments 1377
6.3.5 Transport Equation Generalizations 1377
6.3.6 References 1378
6.4 Solute Transport: Experimental Methods
TODD H. SKAGGS, G.V. WILSON, PETER J. SHOUSE, AND FEIKE J. LEIJ 1381
6.4.1 Laboratory 1381
6.4.1.1 Introduction 1381
6.4.1.2 Sample Collection and Preparation 1381
6.4.1.3 Apparatus 1382
6.4.1.4 Displacing and Resident Solutions 1385
6.4.1.5 Procedures 1386

6.4.1.6 Calculations and Data Presentation. 1389
6.4.1.7 Additional Apparatuses 1389
6.4.1.8 Additional Procedures 1390
6.4.1.9 Comments 1392
6.4.2 Field. 1392
6.4.2.1 Introduction 1392
6.4.2.2 Water and Solute Application 1392
6.4.2.3 Solute Monitoring and Measurement 1393
6.4.3 Tracers. 1396
6.4.4 Equipment Sources 1397
6.4.5 References. 1398
6.5 Solute Transport: Data Analysis and Parameter Estimation
TODD H. SKAGGS, D.B. JAYNES, R. GARY KACHANOSKI, PETER J. SHOUSE, AND A.L. WARD 1403
6.5.1 Least-Squares Fitting
TODD H. SKAGGS AND PETER J. SHOUSE. 1403
6.5.1.1 Principles 1403
6.5.1.2 Software 1405
6.5.1.3 Convection–Dispersion Model 1406
6.5.1.4 Nonequilibrium Models 1412
6.5.1.5 Transient Water Flow and Depth-Dependent Water Content 1414
6.5.2 Method of Moments
TODD H. SKAGGS AND PETER J. SHOUSE. 1416
6.5.2.1 Principles and Procedures 1416
6.5.2.2 Example 1418
6.5.2.3 Recommendations 1418
6.5.3 Determination of θ_{IM} and α Using a Disk Permeameter and Multiple Solutes
D.B. JAYNES 1419
6.5.3.1 Principles 1419
6.5.3.2 Procedure 1420
6.5.3.3 Example 1421
6.5.4 Determination of Travel-Time Probability Density Function from Concentration Data
TODD H. SKAGGS 1422
6.5.5 Determination of Field Solute Mass Flux (Travel Time Probability Density Function) Using Time Domain Reflectometry
R. GARY KACHANOSKI AND A.L. WARD 1423
6.5.5.1 Principles 1425
6.5.5.2 Vertically Installed Probes. 1426
6.5.5.3 Equipment and Methodology 1428
6.5.6 References. 1431
6.6 Solute Transport During Variably Saturated Flow—Inverse Methods
JIŘÍ ŠIMŮNEK, MARTINUS TH. VAN GENUCHTEN, DIEDERIK JACQUES, JAN W. HOPMANS, MITSUHIRO INOUE, AND MARKUS FLURY 1435
6.6.1 Introduction. 1435
6.6.2 Theory of Flow, Transport, and Optimization 1436

6.6.3 Examples 1439
6.6.3.1 Steady-State Laboratory Flow Experiment with Nonlinear Transport 1439
6.6.3.2 Laboratory Transport Subject to Flow Interruption . . 1440
6.6.3.3 Transient Laboratory Experiment with Equilibrium Solute Transport 1442
6.6.3.4 Field Experiment with Nonequilibrium Solute Transport 1444
6.6.4 Conclusions 1448
6.6.5 References 1448
6.7 Processes Governing Transport of Organic Solutes
SHARON K. PAPIERNIK, J. GAN, AND S.R. YATES 1451
6.7.1 Phase Transfer and Distribution Coefficients 1451
6.7.1.1 Air–Water Distribution 1451
6.7.1.2 Soil–Water Distribution 1454
6.7.1.3 Soil–Air Distribution 1461
6.7.1.4 Implications of Soil–Water–Air Distribution on Solute Transport 1464
6.7.2 Transformation 1465
6.7.2.1 Chemical Transformation 1465
6.7.2.2 Biological Degradation 1471
6.7.2.3 Photodegradation 1474
6.7.2.4 Implications of Transformation on Solute Transport . 1476
6.7.3 References 1476
6.8 Microbial Transport
YAN JIN, MARYLYNN V. YATES, AND SCOTT R. YATES 1481
6.8.1 Introduction 1481
6.8.1.1 Parasites 1482
6.8.1.2 Bacteria 1483
6.8.1.3 Viruses 1484
6.8.2 Laboratory Methods 1485
6.8.2.1 Batch Equilibration Method 1485
6.8.2.2 Flowthrough Columns 1492
6.8.3 Field Studies 1499
6.8.4 Indicators of Human Enteroviruses 1500
6.8.5 Microbial Transport Modeling 1500
6.8.6 References 1505
6.9 Geochemical Transport
JIŘÍ ŠIMŮNEK AND ALBERT J. VALOCCHI 1511
6.9.1 Introduction 1511
6.9.2 Geochemical Reaction Equations 1513
6.9.2.1 Complexation 1515
6.9.2.2 Cation Exchange Reactions 1515
6.9.2.3 Adsorption Reactions 1517
6.9.2.4 Precipitation–Dissolution 1519
6.9.2.5 Reactions with Organic Matter and Effects of Bacteria 1519

6.9.2.6 Activity Coefficients and Thermodynamic Equilibrium Constants 1521
6.9.3 Mass-Balance Transport Equations 1522
6.9.4 Numerical Implementation 1524
6.9.5 Effects of Solution Composition on Hydraulic Properties and Reclamation Models 1525
6.9.6 Applications 1526
6.9.7 Use of Geochemical Transport Models 1529
6.9.8 References 1531

Chapter 7 Multi-Fluid Flow

7.1 Introduction
R.J. LENHARD, M. OOSTROM, AND J.H. DANE. 1537
7.2 Fluid Contents
M. OOSTROM, J.H. DANE, AND R.J. LENHARD. 1539
7.2.1 Introduction. 1539
7.2.2 Nondestructive Measurements 1540
7.2.2.1 Gamma Radiation 1540
7.2.2.2 X-ray Radiation 1559
7.2.2.3 Other Methods 1561
7.2.3 Destructive Measurements 1563
7.3 Saturation–Pressure Relationships
R.J. LENHARD, J.H. DANE, AND M. OOSTROM. 1565
7.3.1 Introduction. 1565
7.3.2 Air–Nonaqueous Phase Liquid Systems 1567
7.3.3 Two Immiscible Liquids. 1569
7.3.4 Air and Two Immiscible Liquids 1573
7.4 Relative Permeability Measurements
J.H. DANE, R.J. LENHARD, AND M. OOSTROM. 1581
7.4.1 Introduction. 1581
7.4.2 Nonaqueous Phase Liquid–Gas Systems. 1582
7.4.3 Nonaqueous Phase Liquid–Water Systems 1584
7.4.3.1 Theory 1584
7.4.3.2 Equipment and Measurements 1585
7.4.3.3 Summary and Comments 1589
7.5 Prediction of Capillary Pressure–Relative Permeability Relations
R.J. LENHARD, M. OOSTROM, AND J.H. DANE. 1591
7.5.1 Introduction. 1591
7.5.2 Extending Two-Phase Saturation–Pressure Relations to Air–Nonaqueous Phase Liquid–Water Systems: Nonhysteretic 1592
7.5.3 Extending Two-Phase Saturation–Pressure Relations to Air–Nonaqueous Phase Liquid–Water Systems: Hysteretic . . . 1598
7.6 Measuring Interfacial Areas of Immiscible Fluids
K. PRASAD SARIPALLI, P.S.C. RAO, AND MICHAEL D. ANNABLE. 1609
7.6.1 Introduction. 1609

7.6.2 Experimental Techniques for the Measurement of Interfacial Areas . . . 1609
7.6.2.1 Trapped Nonwetting Phase . . . 1610
7.6.2.2 Continuous Nonwetting Phase . . . 1611
7.6.3 Water Saturation–Interfacial Area Relationship . . . 1613
7.6.4 Comments . . . 1614
7.7 References . . . 1615

Chapter 8 Soil Erosion by Water and Tillage
M.J.M. RÖMKENS, SETH M. DABNEY, GERARD GOVERS, AND J.M. BRADFORD

8.1 Introduction . . . 1621
8.2 Soil Erosion by Water . . . 1621
8.2.1 Soil Erosion Measurements . . . 1622
8.2.1.1 Monitoring Erosion during Natural Storm Events . . . 1622
8.2.1.2 Erosion Measurements during Simulated Rain Storms . . . 1624
8.2.1.3 Experimental Area . . . 1625
8.2.2 Soil Erosion Prediction . . . 1626
8.2.2.1 USLE–RUSLE Relationships . . . 1626
8.2.2.2 Water Erosion Protection Project Soil Erosion Prediction Relationship . . . 1639
8.3 Tillage Erosion . . . 1643
8.3.1 Experimental Measurement of Tillage Erosion Using Tracers . . . 1646
8.3.1.1 Principle . . . 1646
8.3.1.2 Equipment, Software, and Supplies . . . 1648
8.3.1.3 Procedural Steps . . . 1649
8.3.2 Measurement of Tillage Erosion by Volumetric Assessment of Soil Translocation . . . 1654
8.3.2.1 Principle . . . 1654
8.3.2.2 Equipment, Software, and Supplies . . . 1654
8.3.2.3 Procedural Steps . . . 1654
8.3.3 Estimation of Tillage Erosion from Cesium-137 Inventories . . . 1655
8.3.3.1 Principle . . . 1655
8.3.3.2 Equipment, Software, and Supplies . . . 1656
8.3.3.3 Procedural Steps . . . 1657
8.4 References . . . 1660

Subject Index . . . 1663