DRAINAGE FOR AGRICULTURE
AGRONOMY

A Series of Monographs

The American Society of Agronomy and Academic Press published the first six books in this series. The General Editor of Monographs 1 to 6 was A. G. Norman. They are available through Academic Press, Inc., 111 Fifth Avenue, New York, NY 10003.

1. C. EDMUND MARSHALL: The Colloid Chemical of the Silicate Minerals. 1949
2. BYRON T. SHAW, Editor: Soil Physical Conditions and Plant Growth. 1952
3. K. D. JACOB, Editor: Fertilizer Technology and Resources in the United States. 1953
5. GEORGE F. SPRAGUE, Editor: Corn and Corn Improvement. 1955
6. J. LEVITT: The Hardiness of Plants. 1956

The Monographs published since 1957 are available from the American Society of Agronomy, 677 S. Segoe Road, Madison, WI 53711.

7. JAMES N. LUTHIN, Editor: Drainage of Agricultural Lands. 1957
8. FRANKLIN A. COFFMAN, Editor: Oats and Oat Improvement. 1961
9. A. KLUTE, Editor: Methods of Soil Analysis. 1986
   A. L. PAGE, R. H. MILLER, and D. R. KEENEY, Editor: Methods of Soil Analysis. 1982
   (Out of print; replaced by no. 22)
15. CLARENCE H. HANSON, Editor: Alfalfa Science and Technology. 1972
17. JAN VAN SCHILFGAARDE, Editor: Drainage for Agriculture. 1974
19. JACK F. CARTER, Editor: Sunflower Science and Technology. 1978
20. ROBERT C. BUCKNER and L. P. BUSH, Editors: Tall Fescue. 1979
22. F. J. STEVENSON, Editor: Nitrogen in Agricultural Soils. 1982
25. N. L. TAYLOR, Editor: Clover Science and Technology. 1985
27. M. A. TABATABAI, Editor: Sulfur in Agriculture. 1986
33. H. G. MARSHALL and M. E. SORRELLS, Editors: Oat Science and Technology, 1992
34. L. E. MOSER, D. R. BUXTON, and M. D. CASLER, Editors: Cool-Season Forage Grasses, 1995
DRAINAGE FOR AGRICULTURE

Edited by

JAN VAN SCHILFGAARDE

Director, U. S. Salinity Laboratory, Agricultural Research Service, U. S. Department of Agriculture, Riverside, California

Managing Editor: RICHARD C. DINAUER

Assistant Editor: MARGARET E. DAVIS

Editor-in-Chief ASA Publications: MATTHIAS STELLY

Number 17 in the series
AGRONOMY

American Society of Agronomy, Inc., Publisher
Madison, Wisconsin USA
1974
The pen and ink sketches on the section title pages are by Ruth C. Poulsen, staff artist with the American Society of Agronomy, Madison, Wis. The composition for the text pages was done by Mrs. Linda Nelson on a IBM Selectric Composer using the Baskerville and Univers type fonts.

Copyright © 1974 by the American Society of Agronomy, Inc.  
ALL RIGHTS RESERVED  
No part of this book may be reproduced or utilized in any form or by any means, electronic or mechanical, including xerography, photocopying, microfilm, and recording, or by any information storage and retrieval system, without permission in writing from the publisher.


The American Society of Agronomy, Inc.  
677 South Segoe Road, Madison, Wisconsin, USA  53711

Library of Congress Catalog Card Number: 74-76651

Printed in the United States of America
# CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GENERAL FOREWORD</td>
<td>xi</td>
</tr>
<tr>
<td></td>
<td>FOREWORD</td>
<td>xiii</td>
</tr>
<tr>
<td></td>
<td>PREFACE</td>
<td>xv</td>
</tr>
<tr>
<td></td>
<td>CONTRIBUTORS</td>
<td>xvii</td>
</tr>
<tr>
<td></td>
<td>CONVERSION FACTORS FOR ENGLISH AND METRIC UNITS</td>
<td>xxiii</td>
</tr>
<tr>
<td></td>
<td>CONTENTS—DRAINAGE OF AGRICULTURAL LANDS</td>
<td>xxv</td>
</tr>
<tr>
<td></td>
<td>SECTION I—INTRODUCTION</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 Introduction</td>
<td></td>
</tr>
<tr>
<td></td>
<td>JAN VAN SCHILFGAARDE</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>SECTION II—DRAINAGE AND CROP PRODUCTION</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 Crop Growth and Wet Soils</td>
<td></td>
</tr>
<tr>
<td></td>
<td>JANS WESSELING</td>
<td></td>
</tr>
<tr>
<td></td>
<td>I. Introduction</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>II. Aeration and Plant Growth</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>A. Gas Exchange Systems</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>B. Measuring Soil Aeration</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>C. Plant Response and Aeration</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>III. Plant Growth and Soil Temperature</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>A. Heat Transfer in Soils</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>B. Thermal Properties of Soils</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>C. Plant Response to Soil Temperatures</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>D. Drainage and Soil Temperature</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>IV. Drainage and Nitrogen Supply of the Soil</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>V. Ground-Water Depth and Crop Yield</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>3 Crop Growth and Salinity</td>
<td></td>
</tr>
<tr>
<td></td>
<td>LEON BERNSTEIN</td>
<td></td>
</tr>
<tr>
<td></td>
<td>I. Introduction</td>
<td>39</td>
</tr>
<tr>
<td></td>
<td>A. Irrigation Water Quality and Soil Salinity</td>
<td>39</td>
</tr>
<tr>
<td></td>
<td>B. Salinity Hazards Not Controlled by Drainage</td>
<td>41</td>
</tr>
<tr>
<td></td>
<td>C. Parameters Significant for Plant Growth in Salt-Affected Soil</td>
<td>42</td>
</tr>
<tr>
<td></td>
<td>D. Climatic Factors and Salt Tolerance</td>
<td>44</td>
</tr>
<tr>
<td></td>
<td>II. Effects of Salinity on Plant Growth and Yields</td>
<td>44</td>
</tr>
<tr>
<td></td>
<td>A. Osmotic Effects</td>
<td>44</td>
</tr>
<tr>
<td></td>
<td>B. Specific Ion Effects</td>
<td>46</td>
</tr>
<tr>
<td></td>
<td>C. Effects of Exchangeable Sodium</td>
<td>47</td>
</tr>
<tr>
<td></td>
<td>III. Salt Tolerance Lists and Data</td>
<td>47</td>
</tr>
<tr>
<td></td>
<td>A. Tolerance of Plants to Salinity</td>
<td>47</td>
</tr>
<tr>
<td></td>
<td>B. Tolerance of Crops to Exchangeable Sodium</td>
<td>51</td>
</tr>
<tr>
<td></td>
<td>C. Tolerance of Crops to Boron</td>
<td>51</td>
</tr>
<tr>
<td></td>
<td>IV. Concluding Discussion</td>
<td>51</td>
</tr>
<tr>
<td></td>
<td>A. Salt Tolerance Data and Maximum Permissible Salinities in Root Zones</td>
<td>51</td>
</tr>
<tr>
<td></td>
<td>B. Controlling Soil Salinity by Adjusting Amenable Factors</td>
<td>53</td>
</tr>
</tbody>
</table>
## 4 Drainage and Timeliness of Farming Operations

**R. C. REEVE and N. R. FAUSEY**

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. Introduction</td>
<td>55</td>
</tr>
<tr>
<td>II. Days Suitable for Field Work</td>
<td>58</td>
</tr>
<tr>
<td>III. Trafficability</td>
<td>61</td>
</tr>
<tr>
<td>IV. Effect of Drainage on Timeliness of Farming Operations</td>
<td>64</td>
</tr>
<tr>
<td>V. Probability and Drainage Design</td>
<td>65</td>
</tr>
<tr>
<td>VI. Other Benefits of Drainage Associated with Timeliness</td>
<td>66</td>
</tr>
</tbody>
</table>

### 5 Developing Drainage Design Criteria

**HERMAN BOUWER**

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. Introduction</td>
<td>67</td>
</tr>
<tr>
<td>II. Steady-State Condition</td>
<td>67</td>
</tr>
<tr>
<td>III. Falling Water Table</td>
<td>69</td>
</tr>
<tr>
<td>IV. Fluctuating Water Table</td>
<td>70</td>
</tr>
<tr>
<td>V. Salinity Control</td>
<td>71</td>
</tr>
<tr>
<td>VI. Trafficability Control</td>
<td>76</td>
</tr>
<tr>
<td>VII. Reduction of All Drainage Requirements to Steady-State Criterion</td>
<td>76</td>
</tr>
<tr>
<td>VIII. Adjusting Drainage Criterion to Natural Drainage Intensity</td>
<td>78</td>
</tr>
<tr>
<td>IX. Research Needs</td>
<td>79</td>
</tr>
</tbody>
</table>

### LITERATURE CITED FOR SECTION II

81

## SECTION III—CURRENT DRAINAGE PRACTICES

### 6 Current Drainage Methods in the USA

**W. W. DONNAN and G. O. SCHWAB**

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. Introduction</td>
<td>93</td>
</tr>
<tr>
<td>II. Drainage System Selection</td>
<td>93</td>
</tr>
<tr>
<td>III. Topographic Factors</td>
<td>94</td>
</tr>
<tr>
<td>IV. Soil Factors</td>
<td>95</td>
</tr>
<tr>
<td>V. Water Factors</td>
<td>96</td>
</tr>
<tr>
<td>A. Precipitation</td>
<td>97</td>
</tr>
<tr>
<td>B. Irrigation</td>
<td>97</td>
</tr>
<tr>
<td>C. Seepage</td>
<td>98</td>
</tr>
<tr>
<td>VI. Open Ditches</td>
<td>99</td>
</tr>
<tr>
<td>A. Side Slopes</td>
<td>99</td>
</tr>
<tr>
<td>B. Cross Section</td>
<td>99</td>
</tr>
<tr>
<td>C. Location</td>
<td>100</td>
</tr>
<tr>
<td>D. Spacing</td>
<td>100</td>
</tr>
<tr>
<td>E. Construction</td>
<td>100</td>
</tr>
<tr>
<td>F. Maintenance</td>
<td>100</td>
</tr>
<tr>
<td>VII. Surface Field Drains</td>
<td>101</td>
</tr>
<tr>
<td>A. Land Grading and Smoothing</td>
<td>102</td>
</tr>
<tr>
<td>B. Random Field Drains</td>
<td>103</td>
</tr>
<tr>
<td>C. Parallel Field Drains</td>
<td>103</td>
</tr>
<tr>
<td>D. Construction and Maintenance</td>
<td>104</td>
</tr>
<tr>
<td>VIII. Subsurface Drains</td>
<td>104</td>
</tr>
<tr>
<td>A. Tube Drainage Systems</td>
<td>105</td>
</tr>
<tr>
<td>B. Random and Parallel Systems</td>
<td>106</td>
</tr>
<tr>
<td>IX. Interceptor Systems</td>
<td>109</td>
</tr>
<tr>
<td>A. Depth</td>
<td>109</td>
</tr>
<tr>
<td>B. Drawdown Upslope</td>
<td>110</td>
</tr>
<tr>
<td>C. Drawdown Downslope</td>
<td>110</td>
</tr>
<tr>
<td>D. Amount of Flow Intercepted</td>
<td>110</td>
</tr>
<tr>
<td>E. Choice of Drain Type</td>
<td>111</td>
</tr>
<tr>
<td>X. Filters</td>
<td>111</td>
</tr>
</tbody>
</table>
7 Current Drainage Practices in Flat Areas of Humid Regions in Europe

S. RAADSMA

I. Introduction
II. Open Ditches
   A. Application of Ditches
   B. Hydraulic Design of Open Ditches
III. Surface Field Drains
IV. Mole Drains
   A. Principle and Application
   B. Construction and Lifetime
   C. Design
   D. Outfalls
V. Tube Drains
   A. Principles, Materials and Systems
   B. Depth and Spacing
   C. Hydraulic Design of Tube Drainage
   D. Installation and Maintenance
VI. Design of Parallel Subsurface Drainage Systems
   A. Methods
   B. The Drain Spacing Formulas of Hooghoudt and Ernst
   C. Design Criteria
VII. Main Drainage Systems and Drainage Outlets
   A. Main Drainage Systems
   B. Outlets

LITERATURE CITED SECTION FOR SECTION III

SECTION IV—MATERIALS AND METHODS

8 Drain Tube Materials and Installation

J. L. FOUSS

I. Introduction
II. History of Drainage Materials and Methods Research
   A. Inventions and Research Before 1940
   B. Plastic Drain Tubing
   C. Plastic-Lined Mole Drains
   D. Miscellaneous Drainage Conduit Materials
   E. Corrugated Plastic Drainage Tubing
III. Flexible Drainage Conduits
   A. Flexible Conduit Failure Theories
   B. Soil Loads on Flexible Conduits
   C. Flexible Conduit Design
IV. Specifications and Standards
   A. Sand-Box Test
   B. Possible Future Test Methods
   C. Installation Conditions
V. Installation Equipment
   A. Modified Trencher
   B. High-Speed Trenchers
   C. Drainage Plows
   D. Automatic Grade Control
VI. Drainage Materials Handling
   A. Palletized Tile .......................... 173
   B. Coilable Plastic Tubing ................. 174
   C. Rigid and Semirigid Plastic Drain Pipe 175
   D. Drain Envelope Materials ............... 176

9 Envelope Materials
   I. Introduction ............................. 179
   II. Materials for Envelopes ............... 180
      A. Organic Materials ..................... 180
      B. Inorganic Materials ................... 181
      C. Man-made Materials .................... 182
   III. Principles of Design ................... 183
      A. Strokes’ Law Design .................... 183
      B. Exit Gradients in Soil Near Drains .... 185
      C. Drain Envelope Design ................ 185
   IV. Drain Envelope Installation .......... 192
      A. Placement of Envelopes ............... 193
      B. Envelope Combinations With Other Materials 195
      C. Envelope Thickness .................... 195

LITERATURE CITED FOR SECTION IV ......... 197

SECTION V–SATURATED FLOW THEORY AND ITS APPLICATION

10 Steady Flow to Drains and Wells
    DON KIRKHAM, SADIK TOKSÖZ, and R. R. VAN DER PLOEG
    I. Introduction ............................. 203
    II. Tile and Ditch Drainage of Flat Land .... 204
        A. Drain Spacing Equations by Potential Theory .... 204
        B. Drain Spacing Equations by Dupuit-Forchheimer (D–F) 207
        C. Youngs’ Inequality for Drain Spacing Calculations 212
    III. Tile Drainage of Layered Soil .......... 215
    IV. Drainage of Ponded Water as for Leaching .... 229
    V. Drainage of Sloping Land ................ 234
    VI. Interceptor Drains ..................... 236
    VII. Steady Drainage by Vertical Wells .... 243

11 Nonsteady Flow to Drains
    JAN VAN SCHILFGAARDE
    I. Introduction ............................. 245
    II. Flow Equations ......................... 245
    III. Falling Water Table and D–F Theory .. 250
        A. Linearized D–F Solutions for Parallel Drains .... 251
        B. Nonlinearized D–F Solution for \( d=0 \) ........ 253
        C. Nonlinearized D–F Solutions for \( d\neq 0 \) .... 254
    IV. Falling Water Table and Potential Theory .... 256
    V. Intermittent Recharge ................... 262
    VI. Applications of Nonsteady Flow Theories .... 265
12 Flow Through Heterogeneous Media

LARRY G. KING

I. Introduction .................................................. 271
II. Definition of Heterogeneity ................................. 273
III. Theory for Obtaining Conductivity Distribution ....... 278
IV. Physical and Computational Considerations in Applying Theory ........................................................................ 284
   A. Dimensions Considered ........................................ 285
   B. Measurement of Potential ...................................... 285
   C. Measurement of Boundary Conductivity ................. 286
   D. Solving New Problems ........................................ 286
   E. Use of Time History of Potential .......................... 287
   F. Requirements of Models ....................................... 289
V. Methods for Obtaining Conductivity Distributions ....... 293
   A. Functional Representation of Potential .................... 293
   B. Grid Values of Potential ...................................... 295
VI. Theory for Horizontal Flow with Storage Coefficient and Accretion Term ........................................... 300
VII. Significance to Drainage Engineers ......................... 300

LITERATURE CITED FOR SECTION V ............................................. 303

SECTION VI—UNSATURATED FLOW THEORY AND ITS APPLICATION

13 Movement of Water in the Unsaturated Zone Near a Water Table

P. A. C. RAATS and W. R. GARDNER

I. Introduction ..................................................... 311
II. The Physical-Mathematical Model ......................... 313
   A. Balance of Mass ............................................. 313
   B. Specific Yield ................................................ 317
   C. Expressions for the Flux and the Velocity ............. 319
   D. Matric Flux Potential and Critical Pressure Head .... 321
   E. Empirical k(h) Relationships ............................... 323
III. Steady Vertical Flows .......................................... 328
   A. Pressure Head and Water Content Profiles ............. 328
   B. Upward Flows (q* > 0) ...................................... 332
   C. Downward Flows (q* < 0) ................................... 336
IV. Uptake of Water by Plants ................................... 338
V. Time-Invariant Profiles ........................................ 342
   A. Isochoric Flows .............................................. 344
   B. General Profile Preserving Flows Above a Moving Water Table ......................................................... 345
   C. Specific Yield ................................................ 350
VI. Column Drainage ................................................. 350
VII. Steady, Horizontal Flow Above a Water Table .......... 355

14 Some Applications of Unsaturated Flow Theory

K. K. WATSON

I. Introduction ..................................................... 359
II. Numerical Procedures ........................................ 361
   A. One-Dimensional System .................................... 361
   B. Two-Dimensional System .................................... 364
   C. Hydrologic Characteristics .................................. 365
III. Two-Dimensional Drainage of a Ponded Profile ....... 371
IV. Water Table Hydrographs Using Unsaturated Flow Analysis
   A. Initially Saturated Profile
   B. Infiltration and Redistribution
   C. Comparison with Drainable Porosity Results
   D. Comparison with Two-Dimensional Solutions
V. One-Dimensional Studies
   A. Intermittent Infiltration
   B. Heterogeneous Media
VI. Field Investigations

LITERATURE CITED FOR SECTION VI

SECTION VII—SALTS AND WATER MOVEMENT

15 Soil Salts and Their Effects on Water Movement
   B. L. McNeal
   I. Introduction
   II. Precipitation and Dissolution of Soil Salts
      A. Precipitation of Alkaline-Earth Carbonates
      B. Precipitation of Gypsum and Evaporite Minerals
      C. Formation of Indurated Layers During Salt Precipitation and Dissolution
   III. Effects of Salt Concentration and Composition on Soil Water Movement
      A. General Effects of Salinity and Sodium on Soil Structure
      B. Effects of Salinity and Sodium on Soil Permeability
   VI. Conclusion

16 Drainage for Salinity Control
   J. D. Rhoades
   I. Introduction
   II. Leaching Requirement
      A. Salinity Control
      B. Chloride and Boron Control
      C. Sodicity Control
      D. Miscellaneous Factors Affecting the Drainage Requirement
   III. Attainable Leaching Fractions
   IV. Leaching and Drainage Needs in Reclamation of Salt-Affected Soils
      A. Saline Soils
      B. High Boron Soils
      C. Sodic Soils
   V. Depth to Water Table Drainage Requirement
   VI. Salt Balance as a Criterion of Leaching and Drainage Adequacy in Irrigation Projects
   VII. Salinity Problems not Controllable by Leaching and Drainage
   VIII. Summary and Conclusions

LITERATURE CITED FOR SECTION VII
SECTION VIII—QUALITY OF DRAINAGE WATERS

17 Salinity of Drainage Waters

I. Introduction ...................................................... 471
II. Factors Determining the Quality of Agricultural Drainage Waters ...... 472
III. Generalized Quality Characteristics of Agricultural Drainage Waters ...... 477
IV. Effect of Agricultural Drainage Waters on the Quality of Surface and Ground Waters ...... 477
V. Reducing Quality Degradation of Surface and Ground Waters by Drainage Water from Irrigated Lands ...... 486

18 Nutrients and Other Chemicals in Agricultural Drainage Waters

A. J. MAC KENZIE and F. G. VIETS, JR.

I. Introduction ...................................................... 489
II. Nitrogen in Agricultural Drainage Waters ................................ 490
III. Phosphorus in Agricultural Drainage Waters ................................ 497
IV. Trace Elements in Agricultural Drainage Waters ................................ 500
V. Pesticides in Agricultural Drainage Waters ................................ 500
VI. Conclusions ...................................................... 506

LITERATURE CITED FOR SECTION VIII ............................................. 509

SECTION IX—MODELS AND ANALOGUES FOR THE STUDY OF GROUND-WATER FLOW

19 Introduction

JAMES N. LUTHIN 515

20 Drainage Analogues

JAMES N. LUTHIN

I. Electric Analogues .............................................. 517
A. Uses of Electric Analogues .................................. 517
B. Theory and Construction of Electric Analogues ................. 518
II. The Resistance Network .................................... 520
A. Uses of the Resistance Network ........................... 520
B. Theory and Construction of Resistance Networks ............. 521
III. The Resistance-Capacitance Network ......................... 531
A. Uses of the Resistance-Capacitance Network ................. 531
B. Theory and Construction of the Resistance-Capacitance Network ........................................... 532
IV. The Membrane Analogue ..................................... 534
A. Uses of the Membrane Analogue ................................ 534
B. Theory and Construction of the Membrane Analogue ............ 534
V. Sand Tanks for Studying Flow Conditions .................... 535
21 Hydraulic Models

I. Introduction ................................................................. 537
II. Physical Features ............................................................. 540
   A. Hele-Shaw Viscous Fluid Model ...................................... 540
   B. Glass-Beads Glycerol Model .......................................... 541
   C. Soil Model .................................................................... 542
   D. A Comparison .................................................................. 543
III. Theoretical Development ....................................................... 544
   A. Dimensional Analysis and Similitude .................................. 544
   B. Steady-State ..................................................................... 544
   C. Unsteady-State ............................................................... 546
   D. Differential Equations ..................................................... 547
   E. The Derivation of Grover and Kirkham (1964) ..................... 550
   F. Similar Media .................................................................. 551
IV. Discussion ........................................................................ 554

22 Digital Computers and Drainage Problem Analysis:
Part 1—General Considerations

GEORGE S. TAYLOR

I. Introduction ................................................................. 557
II. The Approach .................................................................. 558
III. Computer Capabilities ..................................................... 559
VI. Iteration by Computers ................................................... 561
V. Computer Transfer Statements ........................................... 563

22 Digital Computers and Drainage Problem Analysis:
Part II—Finite Difference Methods

GEORGE S. TAYLOR

I. Finite Difference Equations ................................................ 567
II. Solution of Finite Difference Equations ............................ 568
III. The Relaxation Technique ................................................ 570
IV. The Tridiagonal Matrix Method ........................................ 573
V. Alternating Direction Implicit (ADI) Method ..................... 577
VI. Illustrative Analysis by Computers .................................... 581
VII. Example of Flow Analysis Solution ................................ 583
   A. The Problem .................................................................. 583
   B. The Numerical Analysis Technique .................................. 584
   C. The Computer Flow Chart .............................................. 584

22 Digital Computers and Drainage Problem Analysis:
Part III—Finite Element Method

G. L. GUYNON

I. Introduction ................................................................. 587
II. A Variational Principle ..................................................... 589
III. Finite Element Representation of Region .......................... 592
IV. Minimization of Variational Principle ............................... 594
V. Handling of the Time-Domain Problem ............................... 596
VI. Convergence .................................................................. 597
VII. Programming Techniques ............................................... 598
VIII. Example Problem ........................................................ 600
IX. Advanced Problems ....................................................... 602

LITERATURE CITED FOR SECTION IX ................................. 603
SECTION X—DETERMINING SOIL PROPERTIES

23 Determining Soil Properties

HERMAN BOUWER and R. D. JACKSON

I. Introduction .......................................................... 611
II. Hydraulic Conductivity ............................................. 611
   A. Measurement of K Below the Water Table .................. 612
   B. Measurement of K in the Absence of a Water Table ....... 627
   C. Measurement of K in Anisotropic Soil ..................... 639
   D. Selection of Method ........................................... 639
   E. Accuracy and Number of Measurements ...................... 640
   F. Interpretation of Field Measurements ...................... 644
III. Unsaturated Conductivity ......................................... 646
   A. Two-Plate Method ............................................. 646
   B. Long-Column Method ........................................... 647
   C. Advance of the Wetting Front Method ...................... 648
   D. Pressure Plate Outflow Method ................................ 649
   E. Instantaneous Profile Method .................................. 650
   F. Entrapped Air Method .......................................... 650
   G. Calculation of conductivity from Water Characteristic ... 651
   H. Computer Techniques ........................................... 655
   I. Field Techniques ............................................... 656
IV. Pressure Head, Water Table, and Capillary Fringe ............ 658
V. Water Content ..................................................... 660
   A. Gravimetric Method ............................................ 661
   B. Neutron Moderation ............................................ 661
   C. Gamma-Ray Attenuation ....................................... 662
VI. Drainable Pore Space .............................................. 663
VII. Aeration .......................................................... 664
   A. Oxygen Diffusion Rate ......................................... 665
   B. Oxygen Concentration ......................................... 665
   C. Aeration Above a Water Table .................................. 666

LITERATURE CITED FOR SECTION X .................................. 666

SECTION XI—WATER MANAGEMENT SYSTEMS

24 Water Management Systems

NATHAN BURAS

I. Model Building for Systems Analysis ............................. 675
II. Irrigation and Drainage Interaction .............................. 678
   A. General Remarks ............................................... 678
   B. A Salt Routing Model .......................................... 680
III. Criteria for Evaluating Water Management System ............ 688
   A. Physical Criteria ............................................. 689
   B. Economic Criteria ............................................. 690
   C. Social Criteria ................................................. 691
   D. Environmental Criteria ....................................... 692
IV. Summary .................................................................. 693

LITERATURE CITED FOR SECTION XI ................................. 694

SUBJECT INDEX .......................................................... 695
The steadily increasing worldwide demand for food supplies makes this volume on drainage especially timely. Intensive farming of existing crop land and the farming of new land now limited in use due to poor drainage are urgently needed to achieve the great food requirements of the future. New developments in the field of drainage can do much to further these objectives. *Drainage for Agriculture*, Agronomy No. 17, presents these developments and their applications.

This new volume, Agronomy No. 17, is also noteworthy in that it is a complement to and not a replacement for Agronomy No. 7, *Drainage of Agricultural Lands*, edited by J. N. Luthin, and published by the American Society of Agronomy in 1957. The first drainage book underwent three printings and 4,200 copies were distributed worldwide. Incidentally, it was the first in the Agronomy series to be published by the society; the first six numbers were published by Academic Press, Inc., of New York. Only volumes no. 7 through 17 are available from the American Society of Agronomy, Inc., at 677 South Segoe Road, Madison, Wisconsin 53711.

As is the case with all of the volumes in this series, the society is indebted to many individuals who contributed much in the way of knowledge, time and patience in the production of this book. A number of authors are nonmembers of the American Society of Agronomy and several are from countries outside the USA. A list of the contributors appears on pages xxi-xxii.

Publication of the Agronomy monograph series represents a significant and continuing effort of the American Society of Agronomy to disseminate information to the public in the interest of human welfare. Since assuming the responsibility for development and publication of titles in the Agronomy series in 1957, there have been over 40,000 copies of numbers 7 through 16 distributed throughout the world. Other recent volumes are no. 16, *Soybeans: Improvement, Production, and Uses*; no. 15, *Alfalfa Science and Technology*; no. 14, *Turfgrass Science*; and no. 13, *Wheat and Wheat Improvement*. Several other topics are either in preparation or under consideration by the society for future monographs.

The society is associated with the Crop Science Society of America and the Soil Science Society of America. The three societies share many objectives and activities in promoting these branches of agriculture and scientific disciplines. The over 8,000 members of the associated societies are
organized into 21 subject matter divisions and are located in over 80 countries around the world.

_Drainage for Agriculture_ should be of great benefit to scientists, engineers, planners, contractors, and other workers who deal with land problems involving drainage of soil. From that standpoint the title could be considered a misnomer. The several chapters on theory offer information useful to a much broader audience than the agriculturists. Other chapters relating to soil properties and drainage principles provide information on numerous and broad types of applications. The American Society of Agronomy as an educational organization offers this book to the public in the hope that through the fundamental and applied material presented, it will help to solve many of the food production, land use, and environmental problems which face the people of the world today.

677 South Segoe Road
Madison, Wisconsin, 53711
March 1974

MATTHIAS STELLY
Editor-in-Chief
ASA Publications
FOREWORD

This monograph is published at a very appropriate time. For the first time in this country, we are concerned that not enough land is available to meet our food, feed, and fiber needs and those of the overseas countries that have depended on the abundance from American agriculture. The era of agricultural surpluses has past and we are now striving to produce those agricultural products which used to be in super abundance.

With the goal of maximum production for American agriculture, comes the need to make every acre give its best level of production. Drainage is a limiting factor on many agricultural lands of this country. During the past two decades, there has been a host of scientific advances in the field of drainage. It is fitting then, that the state of the art be brought up to date. Drainage for Agriculture will make available more widely the newest knowledge, it will stimulate new research, and it will aid American agriculture and, indeed, world agriculture in helping to fulfill mankind's needs.

On behalf of the American Society of Agronomy, I wish to express thanks and appreciation to the members of the monograph committee, the authors, and to the editor, as well as to others who contributed to this book. Their efforts will stand as an important contribution to agriculture and to our profession.

Gainesville, Florida
April 1974

DARELL E. MC CLOUD
President
American Society of Agronomy
Why publish another book on the subject of drainage at this time? This question deserves a thoughtful answer.

Drainage for agriculture has been practiced for over 2000 years. In the second century B.C., the Roman Cato referred to the need for removing water from wet fields, stating that in low-lying areas, it is necessary to have many drains. The second half of the 19th century saw the beginning of the development of drainage theory, as well as the introduction of manufacturing processes for making drain tile and of mechanization for drain installation. The relationship between drainage, irrigation, and salinity was first placed into perspective in this country by E.W. Hilgard around the turn of the century. By the mid-1950's, the drainage industry was well established and a substantial body of knowledge had accumulated on both the practice and the theory. This led to Volume 7 of the present series, published in 1957.

Since that time, the rate of development has been rapid. New materials and new methods have revolutionized the industry while advances in theory, coupled with computer technology, have substantially broadened our understanding. The universal concern with water quality has focused attention on the interrelationships of water management practices and the constituents of drainage water. An expanding world population, together with a thrust towards improving living standards, has sharpened the awareness of the importance of rational water management for food production.

Thus the situation has changed sufficiently to warrant the compilation under one cover of many of the recent advances in drainage that should make possible significant progress in achieving the desired improvement in water management that will help feed the world population while maintaining values of environmental quality.

Within this framework, a small group of leaders in the field was convened in 1967 to delineate the scope of the volume that was to become *Agronomy* no. 17, *Drainage for Agriculture*, to develop an outline, and to identify appropriate contributors. This group consisted of J.W. Biggar, Herman Bouwer, Don Kirkham, and R. C. Reeve. The American Society of Agronomy and, especially, the editor, owe a debt of gratitude to these men for their important contribution to the planning.

The preparation of a book such as this requires the active participation of many individuals. The excellent cooperation of the many authors is gratefully acknowledged, as is the considerable assistance of a number of
individuals who gave unstintingly of their time in reviewing various manuscript drafts.

Special thanks are due Thomas J. Thiel who accepted the task of preparing the index, using a computer program designed for information retrieval. His efforts represented a first for the American Society of Agronomy and, hopefully, the experience gained should lead to significant advances in reducing the time required for such a laborious task.

Riverside, California
March 1974

JAN VAN SCHILFGAARDE
Editor
CONTRIBUTORS

Leon Bernstein  
Plant Physiologist, U. S. Salinity Laboratory, Agricultural Research Service, U. S. Department of Agriculture, Riverside, California

Herman Bouwer  
Director, U. S. Water Conservation Laboratory, Agricultural Research Service, U. S. Department of Agriculture, Phoenix, Arizona

Charles A. Bower  
Formerly, Director, U. S. Salinity Laboratory, Agricultural Research Service, U. S. Department of Agriculture, Riverside, California (retired); now, Soil Scientist, University of Hawaii, Captain Cook, Hawaii

Nathan Buras  
Professor, Technion—Israel Institute of Technology, Haifa, Israel

William W. Donnan  
Consulting Engineer, Pasadena, California

Norman R. Fausey  
Soil Scientist, Agricultural Research Service, U. S. Department of Agriculture, Columbus, Ohio

James L. Fouss  
Agricultural Engineer, Coastal Plains Soil and Water Conservation Research Center, Agricultural Research Service, U. S. Department of Agriculture, Florence, South Carolina

Wilford R. Gardner  
Professor of Soil Physics, Soils Department, University of Wisconsin, Madison, Wisconsin

J. C. Guitjens  
Associate Professor of Irrigation Engineering, Division of Plant, Soil and Water Science, University of Nevada, Reno, Nevada

Gary L. Guymon  
Associate Professor of Water Resources and Civil Engineering, Institute of Water Resources, University of Alaska, Fairbanks, Alaska

Ray D. Jackson  

Larry G. King  
Formerly, Associate Professor, Agricultural and Irrigation Engineering Department, Utah State University, Logan, Utah; now, Professor of Agricultural Engineering and Agricultural Engineer, Washington State University, Pullman, Washington

Don Kirkham  
Professor of Agronomy and Physics and Curtiss Distinguished Professor of Agriculture, Agronomy Department, Iowa State University, Ames, Iowa

James N. Luthin  
Professor of Water Science and Civil Engineering, Department of Water Science, University of California, Davis, California
Arnold J. MacKenzie  Supervisory Soil Scientist, Imperial Valley Conservation Research Center, Agricultural Research Service, U. S. Department of Agriculture, Brawley, California

Brian L. McNeal  Associate Professor of Soils, Department of Agronomy and Soils, Washington State University, Pullman, Washington

Schelte Raadsma  Formerly, Senior Staff Member, International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands; now Chief Engineer, Land and Water Use Section, International Land Development Consultants, Arnhem, The Netherlands

P. A. C. Raats  Soil Scientist, U. S. Salinity Laboratory, Agricultural Research Service, U. S. Department of Agriculture, Riverside, California

Ronald C. Reeve  Staff Scientist, National Program Staff, Soil, Water and Air Sciences, Agricultural Research Service, U. S. Department of Agriculture, Beltsville, Maryland

James D. Rhoades  Research Soil Scientist, U. S. Salinity Laboratory, Agricultural Research Service, U. S. Department of Agriculture, Riverside, California

Glenn O. Schwab  Professor of Agricultural Engineering, The Ohio State University and Ohio Agricultural Research and Development Center, Columbus, Ohio

George S. Taylor  Professor of Soil Physics, Department of Agronomy, The Ohio State University and the Ohio Agricultural Research and Development Center, Columbus, Ohio

Sadik Toksoz  Consulting Engineer, Istanbul, Turkey

Rienk R. van der Ploeg  Research Soil Scientist, Georg-August University, Goettingen, West Germany

Jan van Schilfgaarde  Director, U. S. Salinity Laboratory, Agricultural Research Service, U. S. Department of Agriculture, Riverside, California


Keith K. Watson  Associate Professor of Civil Engineering, The University of New South Wales, Kensington, N.S.W., Australia

Jans Wesseling  Head, Division of Hydrology, Institute for Land and Water Management Research, Wageningen, The Netherlands

Lyman S. Willardson  Research Agricultural Engineer, Imperial Valley Conservation Research Center, Agricultural Research Service, U. S. Department of Agriculture, Brawley, California
<table>
<thead>
<tr>
<th>To convert column 1 into column 2, multiply by</th>
<th>Column 1</th>
<th>Column 2</th>
<th>To convert column 2 into column 1, multiply by</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Length</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.621 kilometer, km</td>
<td></td>
<td>mile, mi</td>
<td>1.609</td>
</tr>
<tr>
<td>1.094 meter, m</td>
<td></td>
<td>yard, yd</td>
<td>0.914</td>
</tr>
<tr>
<td>0.394 centimeter, cm</td>
<td></td>
<td>inch, in</td>
<td>2.54</td>
</tr>
<tr>
<td><strong>Area</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.386 kilometer², km²</td>
<td></td>
<td>mile², mi²</td>
<td>2.590</td>
</tr>
<tr>
<td>247.1 kilometer², km²</td>
<td></td>
<td>acre, acre</td>
<td>0.00405</td>
</tr>
<tr>
<td>2.471 hectare, ha</td>
<td></td>
<td>acre, acre</td>
<td>0.405</td>
</tr>
<tr>
<td><strong>Volume</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.00973 meter³, m³</td>
<td></td>
<td>acre-inch</td>
<td>102.8</td>
</tr>
<tr>
<td>3.532 hectoliter, hl</td>
<td></td>
<td>cubic foot, ft³</td>
<td>0.2832</td>
</tr>
<tr>
<td>2.838 hectoliter, hl</td>
<td></td>
<td>bushel, bu</td>
<td>0.352</td>
</tr>
<tr>
<td>0.0284 liter</td>
<td></td>
<td>bushel, bu</td>
<td>35.24</td>
</tr>
<tr>
<td>1.057 liter</td>
<td></td>
<td>quart (liquid), qt</td>
<td>0.946</td>
</tr>
<tr>
<td><strong>Mass</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.102 ton (metric)</td>
<td></td>
<td>ton (English)</td>
<td>0.9072</td>
</tr>
<tr>
<td>2.205 quintal, q</td>
<td></td>
<td>hundredweight, cwt (short)</td>
<td>0.454</td>
</tr>
<tr>
<td>2.205 kilogram, kg</td>
<td></td>
<td>pound, lb</td>
<td>0.454</td>
</tr>
<tr>
<td>0.035 gram, g</td>
<td></td>
<td>ounce (avdp), oz</td>
<td>28.35</td>
</tr>
<tr>
<td><strong>Pressure</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14.50 bar</td>
<td></td>
<td>lb/inch², psi</td>
<td>0.06895</td>
</tr>
<tr>
<td>0.9869 bar</td>
<td></td>
<td>atmosphere,* atm</td>
<td>1.013</td>
</tr>
<tr>
<td>0.9678 kg (weight)/cm²</td>
<td></td>
<td>atmosphere,* atm</td>
<td>1.033</td>
</tr>
<tr>
<td>14.22 kg (weight)/cm²</td>
<td></td>
<td>lb/inch², psi</td>
<td>0.07031</td>
</tr>
<tr>
<td>14.70 atmosphere,* atm</td>
<td></td>
<td>lb/inch², psi</td>
<td>0.06805</td>
</tr>
<tr>
<td><strong>Yield or Rate</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.446 ton (metric)/hectare</td>
<td></td>
<td>ton (English)/acre</td>
<td>2.240</td>
</tr>
<tr>
<td>0.892 kg/ha</td>
<td></td>
<td>lb/acre</td>
<td>1.12</td>
</tr>
<tr>
<td>0.892 quintal/hectare</td>
<td></td>
<td>hundredweight/acre</td>
<td>1.12</td>
</tr>
<tr>
<td>1.15 hectoliter, hl/ha</td>
<td></td>
<td>bu/acre</td>
<td>0.87</td>
</tr>
<tr>
<td><strong>Temperature</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\left(\frac{9}{5} ^\circ C\right) + 32)</td>
<td></td>
<td>Fahrenheit</td>
<td>(\frac{5}{9} (\circ F - 32))</td>
</tr>
<tr>
<td>0C</td>
<td></td>
<td>32F</td>
<td></td>
</tr>
<tr>
<td>20C</td>
<td></td>
<td>68F</td>
<td></td>
</tr>
<tr>
<td>100C</td>
<td></td>
<td>212F</td>
<td></td>
</tr>
<tr>
<td><strong>Water Measurement</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8.108 hectare-meters, ha-m</td>
<td></td>
<td>acre-feet</td>
<td>0.1233</td>
</tr>
<tr>
<td>97.29 hectare-meters, ha-m</td>
<td></td>
<td>acre-inches</td>
<td>0.01028</td>
</tr>
<tr>
<td>0.08108 hectare-centimeters, ha-cm</td>
<td></td>
<td>acre-feet</td>
<td>12.33</td>
</tr>
<tr>
<td>0.973 hectare-centimeters, ha-cm</td>
<td></td>
<td>acre-inches</td>
<td>1.028</td>
</tr>
<tr>
<td>0.00973 meters³, m³</td>
<td></td>
<td>acre-inches</td>
<td>102.8</td>
</tr>
<tr>
<td>0.981 hectare-centimeters/hour, ha-cm/hour</td>
<td></td>
<td>feet³/sec</td>
<td>1.0194</td>
</tr>
<tr>
<td>440.3 hectare-centimeters/hour, ha-cm/hour</td>
<td></td>
<td>U.S. gallons/min</td>
<td>0.00227</td>
</tr>
<tr>
<td>0.00981 meters³/hour, m³/hour</td>
<td></td>
<td>feet³/sec</td>
<td>101.94</td>
</tr>
<tr>
<td>4.403 meters³/hour, m³/hour</td>
<td></td>
<td>U.S. gallons/min</td>
<td>0.227</td>
</tr>
</tbody>
</table>

* The size of an "atmosphere" may be specified in either metric or English units.
DRAINAGE OF AGRICULTURAL LANDS

AGRONOMY NO. 7

Edited by JAMES N. LUTHIN

CONTENTS

I. The Physics of Land Drainage

E. C. CHILDS

I. The Nature of Soil Constituents .......................... 1
II. The Internal Soil Architecture .......................... 11
III. The Static Equilibrium of Soil Water .................. 14
IV. The Laws of Soil Water Movement ....................... 38
V. The Physical Nature of Drainage Problems ............... 66

II. The Theory of Land Drainage

I. Approximate Solutions to Drainage Flow Problems ....... 79
JAN VAN SCHILFGAARDE
II. The Water Table in Equilibrium with Rainfall or Irrigation Water ......................................... 113
FRANK ENGELUND
III. The Ponded Water Case .................................. 139
DON KIRKHAM
IV. The Theory of Drainage by Pumping From Wells ......... 181
DEAN F. PETERSON, JR.
V. Soil Anisotropy and Land Drainage ....................... 216
MARINUS MAASLAND

III. Engineering Aspects of Land Drainage

I. Engineering For Land Drainage—General .................. 287
G. O. SCHWAB and PHILIP W. MANSON
II. Drainage of Irrigated Lands ............................ 344
JAMES N. LUTHIN and RONALD C. REEVE
III. Drainage in Humid Areas ................................ 371
T. W. EDMINSTER and G. O. SCHWAB

IV. Drainage Investigation Methods

I. Methods of Measuring Soil Permeability .................. 395
RONALD C. REEVE and JAMES N. LUTHIN
II. Field Investigations ..................................... 446
WILLIAM W. DONNAN

V. Land Drainage in Relation to Soils and Crops

I. Soil Physical Conditions in Relation to Drain Depth ..... 461
J. WESSELING and W. R. VAN WIJK
II. Salinity and Alkali Problems in Relation to High Water Tables in Soils .................................... 505
MILTON FIREMAN
III. Crop Responses at Excessively High Soil Moisture Levels .......................... 514
BESSEL D. VAN'T WOUDE and ROBERT M. HAGAN
REFERENCES .............................................. 579
INDEX ................................................. 613

Agronomy Monograph no. 7 can be ordered from the American Society of Agronomy,
677 South Segoe Road, Madison, Wisconsin USA