DOCUMENT RESUME

ED 295 043 CE 050 265

AUTHOR Pavelis, George A., Ed.
TITLE Farm Drainage in the United States. History, Status, and Prospects. Miscellaneous Publication Number 1455.
INSTITUTION Economic Research Service (DOA), Washington, D.C.
PUB DATE Dec 87
NOTE 186p.; Photographs may not reproduce clearly.
AVAILABLE FROM Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402.
PUB TYPE Collected Works - General (020) -- Books (010)

EDRS PRICE MF01/PC08 Plus Postage.
DESCRIPTORS Agricultural Engineering; Agricultural Production; *Agriculture; Agronomy; Depleted Resources; Ecology; Estuaries; *Farm Management; *Land Use; Natural Resources; *Soil Conservation; *Soil Science; *Water
IDENTIFIERS *Drainage

ABSTRACT

This publication covers the historical, technological, economic, and environmental aspects of agricultural drainage. It draws from the combined knowledge of academic and U.S. Department of Agriculture professionals in public policy, drainage theory, planning, engineering, environmental science, and economics. The main purpose is to review the evolution of modern farm drainage and to identify farm drainage objectives for agricultural extension specialists and agents, environmental specialists, drainage consultants, installation contractors, and educators. Chapters include "A Framework for Future Farm Drainage Policy" (Smith, Massey); "A History of Drainage and Drainage Methods" (Beauchamp); "Advances in Drainage Technology: 1955-85" (Fouss, Reeve); "Purposes and Benefits of Drainage" (Fausey et al.); "Preserving Environmental Values" (Thomas); "Principles of Drainage" (Skaggs); "Drainage System Elements" (Ochs et al.); "Planning Farm and Project Drainage" (Hodges, Christensen); "Drainage for Irrigation" (Hoffman, van Schilfgaarde); "Drainage Institutions" (Sandretto); "Economic Survey of Farm Drainage" (Pavelis); "Drainage Potential and Information Needs" (Daugherty, Lewis); and "Drainage Challenges and Opportunities" (Swader, Pavelis). (KC)

Sales Information

Additional copies of this publication can be purchased from the Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402. Ask for the publication by name, and write to the above address for price information, or call the GPO order desk at (202) 783-3238. You can also charge your purchase to your VISA, MasterCard, Choice, or GPO deposit account. Bulk discounts available. Foreign address customers please add 25 percent extra for postage.

Microfiche copies ($6.50 each) can be purchased from the National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161. Ask for the publication by name. Enclose check or money order, payable to NTIS; add $3 handling charge for each order. Call NTIS at (703) 487-4650 and charge your purchase to your VISA, MasterCard, American Express, or NTIS deposit account. NTIS will RUSH your order within 24 hours for an extra $10; call (800) 336-4700.

The Department of Agriculture has no copies for free mailing.

FYI-CE

Farm Drainage in the United States: History, Status, and Prospects. Edited by George A. Pavelis. Economic Research Service, U.S. Department of Agriculture. Miscellaneous Publication No. 1455.

Abstract

This publication covers the historical, technological, economic, and environmental aspects of agricultural drainage. It draws from the combined knowledge of academic and U.S. Department of Agriculture professionals in public policy, drainage theory, planning, engineering, environmental science, and economics. The main purpose is to review the evolution of modern farm drainage and to identify farm drainage objectives for agricultural extension specialists and agents, environmental specialists, drainage consultants, installation contractors, and educators. Farm production, water management, and other benefits and costs associated with the drainage of wet soils on farms are described within the context of existing USDA programs and other Federal policies for protecting wetlands.

Keywords: Soil and water management, irrigation, drainage development, drainage benefits, environmental improvement, drainage districts, drainage models, drainage planning.

Cooperators

- *Agricultural Research Service*
- *Cooperative State Research Service*
- *Economic Research Service*
- *Extension Service*
- *Soil Conservation Service*
- *Cornell University*
- *North Carolina State University*
- *Ohio State University*
- *Utah State University*
- *University of Wisconsin-Madison*

This bulletin was processed in the Information Division, Economics Management Staff, USDA, by Jim Carlin, editorial assistance, and Susan Yanero, graphics.

Washington, DC 20005-4788 December 1987

Foreword

The U.S. Department of Agriculture (USDA) is pleased to release this cooperative publication on farm drainage, primarily as a general information document. Several factors prompted its preparation: (1) wide recognition of the public policy connections between the economic and environmental aspects of drainage, accentuated most recently by stringent wetland protection provisions in the Food Security Act of 1985; (2) a drainage technology still undergoing important changes; and (3) the uncertain status of information collection activities on drainage, particularly at the Federal level.

The most recent rapid developmental era for drainage reclamation drew to a close about 1965. Drainage is the most extensive soil and water management activity in agriculture. Approximately 110 million acres of the land within farms are artificially drained in the United States. About 9 million acres, or 25 percent, of the irrigated cropland in the Western States are artificially drained.

Drainage can also have adverse effects in some situations by reducing or degrading wetlands vital to wildlife and serving hydrologic functions such as flood flow regulation. Drainage activities can also affect the quality of water bodies receiving drainage water.

Drainage investigations in USDA began with the Reclamation Act of 1902. This act is best known as creating the Bureau of Reclamation in the Department of the Interior. A drainage unit to service irrigation project planning was simultaneously authorized for USDA. In 1962, Public Law 87-732, the Drainage Referral Act, was enacted which prohibited USDA from assisting landowners in draining potholes and marshes in Minnesota and the Dakotas if wildlife would be materially harmed.

Currently, USDA technical and financial assistance is no longer provided as a matter of policy except in unique circumstances as part of a conservation system related to irrigation water control, or as an essential element of an environmental system of practices. Thus, for USDA, this publication represents an end to the era of strong USDA support and assistance for drainage development activities.

Under USDA's Water Bank Program, begun in 1970 under the authority of Public Law 91-559, wetlands along major migratory waterfowl flyways can be protected from agricultural use or drainage development by 10-year rental agreements with eligible owners or operators. As of 1987, about 8,000 agreements covering 870,000 acres of wetlands or adjacent land had been negotiated with farmers. Two-thirds of these agreements are still in force. In USDA's Agricultural Conservation Program (ACP), financial assistance for farm drainage is prohibited by appropriation language unless it is an essential element of an erosion control, water quality, or environmental system of practices. By the late 1970's, less than 4 percent of all costs of installing or maintaining farm drainage systems came from ACP cost sharing or Farmers Home Administration loans. Cost sharing for limited drainage assistance as described above is now less than 1/20th of 1 percent of all ACP cost shares.

Since 1973, USDA's Soil Conservation Service has not provided technical assistance for the drainage of specified wetlands. as defined by the Fish and Wildlife Service of the Department of the Interior. Since 1975. the policy has been broadened to include nearly all freshwater and saline-water areas.

Drainage activities of USDA are subject also to the provisions of Executive Order 11990, issued in May 1977. Executive Order 11990 is intended to "avoid to the extent possible the long and short term adverse impacts associated with the destruction or modification of wetlands and to avoid direct or indirect support of new construction in wetlands whenever there is a practicable alternative." The Food Security Act, signed by President Reagan in December 1985, denies farm program benefits to producers who grow annual crops on wetlands drained after December 1985.

It is within such laws and policies that USDA will assist in improving drainage on existing cropland through better design, construction, and maintenance. For example, adequate drainage is sometimes necessary for successful no-till conservation farming. Also, intensive irrigation, as practiced on a large scale in the Western States, requires continued attention to drainage to prevent rising water tables and damaging accumulations of soluble salts in soils, and in controlling chemicals or other harmful agents in drainage waters.

This publication is the product of efforts by several USDA agencies and cooperating universities to consolidate up-to-date knowledge on farm drainage. It draws from the combined knowledge of specialists in public policy, drainage science, planning, engineering, and economics (see appendix C). It is not highly technical or policy oriented, but reviews the history, purposes, social and economic implications, and modern methods of farm drainage.

USDA greatly appreciates the assistance of the following academic cooperators:

- Cornell University, College of Agriculture and Life Sciences, Department of Agricultural Economics.
- North Carolina State University, College of Agriculture, Department of Agricultural and Biological Engineering.
- Ohio State University, Department of Agricultural Engineering.
- Utah State University, College of Agriculture and Agricultural Experiment Station, Department of Agricultural and Irrigation Engineering.
- University of Wisconsin-Madison, College of Agricultural and Life Sciences, School of Natural Resources.

Orville G. Bentley Assistant Secretary Science and Education	**George S. Dunlop** Assistant Secretary Natural Resources and Environment	**Ewen M. Wilson** Assistant Secretary for Economics

Summary

Drainage, the practice of removing excess water from agricultural land, has its origin at least 2,500 years ago when Herodotus wrote about drainage works near the city of Memphis in Egypt. Today, drainage is practiced widely, being criticized severely by some and praised by others.

Without drainage, it is hard to imagine the U.S. Midwest as we know it in the 20th century, the epitome of agricultural production. Much of Ohio, Indiana, Illinois, and Iowa originally was swamp, or at least too wet to farm. Aquatic plants, swarms of mosquitoes, and outbreaks of malaria and other diseases were common. Without drainage, irrigation development in the Western United States would have failed through waterlogging and salination, as is happening in some areas. Drainage was part of the "developmental ethos," the drive to develop the land and make it productive.

Because of drainage, better than half the original wetlands in this country are no more. In addition to impairing various hydrologic functions of wetlands, drainage has drastically reduced the habitat for water-based wildlife, and flyways for migrating birds have been severely affected. In some States, as much as 95 percent of the wetlands have been converted. These conversions have affected the opportunities for hunters and recreationists to enjoy their sport. Possibly more important, they have affected the natural balance of nature and may well have endangered, or at least severely restricted, a number of species of birds and other wildlife.

Recently, evidence shows that not only the loss of wetland habitat is involved, but that drainage effluent can have severe adverse effects on water and land quality. High concentrations of toxic elements in California's Kesterson Reservoir have been attributed to agricultural drainage upslope. Thus the "environmental ethic" is at odds with the "developmental ethic." While the benefits of drainage can be counted in terms of enhanced development and increased economic activity, the cost to the environment may also be high.

This bulletin provides an overview of agricultural drainage. Included are a historical perspective of drainage, a review of its practical purposes, an assessment of technological progress, some economic evaluations, a discussion of institutional mechanisms, and a consideration of environmental values. Finally, an attempt is made to place these various components into a challenging perspective in relation to present and future needs.

Highlights

Controversy has frequently been associated with drainage. In the Middle Ages, the fens in England were drained to stabilize and increase agricultural production. These actions were not appreciated by the fishermen and fowlers who saw their livelihood threatened. Interest in drainage ebbed from the early years until the 19th century, when there was renewed activity in Europe and the United States. Early interest in the United States was not confined to development and enhanced agricultural production, but also stressed human health aspects, as illustrated by the draining of Central Park in New York City in 1858. In recent years, these health benefits were taken for granted, or overlooked, in part because we now operate at the margin: the great swamps and extensive breeding grounds for mosquitoes have been eliminated.

An important initial Federal milestone was the passage of the Swampland Acts of 1849 and 1850. These acts transferred federally held swamplands to the States on condition that proceeds from their sale be invested in works needed to reclaim them. The Reclamation Act of 1902 illustrates another milestone in Government policy in that it signaled the intention of the Federal Government to become directly involved in land reclamation and associated drainage enterprises.

The Flood Control Act of 1944 and the Federal Watershed Protection and Flood Prevention Act of 1954 broadened Government involvement in drainage activities. They were preceded by the work of the Civilian Conservation Corps during the Depression and the technical or financial assistance programs of USDA's Soil Conservation Service (SCS) and Agricultural Stabilization and Conservation Service (ASCS). While ASCS financial assistance is no longer provided and technical assistance from SCS is restricted, these programs have played an important role in improved soil and water management on farms.

The pendulum has swung away from development in the last 20 years as a balance was sought between development, reclamation, and drainage on the one hand, and preservation of environmental values on the other. This balance is illustrated by the National Environmental Policy Act of 1969, the Clean Water Act as amended in 1977, and Executive Order 11990 issued by President Carter in 1977. The order instructs Federal agencies to avoid where possible the long- and short-term adverse effects of destroying or modifying wetlands.

Further, new farm legislation, the Food Security Act of 1985 signed by President Reagan in December 1985, denies price support and other farm program benefits to producers who grow crops on converted wetlands. Also, the elimination of investment tax credits and restrictions on expending farm conservation investments under the Tax Reform Act of 1986 are further disincentives to bringing new lands into production through drainage.

Thus, current USDA programs are intended, within the limitations noted above, to help landowners improve drainage on existing agricultural fields where excessive wetness, waterlogging, or salinity hamper efficient production. It is USDA policy to preserve remaining wetlands and protect wildlife values wherever possible. Corrective measures are also required where agricultural practices, including drainage, threaten offsite environmental values.

Technology has evolved along with drainage policy. After centuries of hand-installed drainage systems, the introduction of the trenching machine and the steam engine revolutionized the practice in the late 19th century. Another leap forward occurred in the 1960's with the introduction of corrugated plastic tubing installed with laser-beam controlled high-speed trenchers or drain plows. In the late 1970's, there came into practice the application of drainage theory in the form of computerized design methods and models. Thus, we have witnessed in the past 20 years a dramatic modernization of drainage practices, with the potential for cost reduction, better design, and advanced installation practices. The most recent technological change is the application of water management systems that incorporate drainage, drainage restrictions, and subirrigation in one sophisticated operation to optimize soil water conditions for crop growth. At the same time, sufficient experimental data are available to make at least approximate assessments of the effect of drainage on crop yield, so that economic optimization procedures can be applied to develop "best" drainage system designs.

In making the decision whether and how to drain land, one must be aware of the benefits and drawbacks associated with the practice. The purpose of drainage varies with the climate and the type of farming. In humid areas, its dominant purpose is to remove excess soil water. This allows equipment movement into fields for timely farm operations, warms soils early in the season, provides adequate aeration for root activity and crop growth, reduces diseases in livestock and crops, and reduces surface runoff. These benefits in turn reduce erosion and surface waste pollution, especially by phosphates. The benefits include reduced risk in farming and higher yields of better quality crops, thus tending to increase income as well as reduce its variability.

In arid regions where land is irrigated, the dominant purpose of drainage is to remove salts from the root zone. Salts always accumulate in irrigated fields unless drainage is present, ultimately causing severe salination and environmental degradation. "Ultimately" may be in a matter of a few years, or many decades.

Juxtaposed to the benefits are potential disbenefits. Nitrogen, from fertilizer or natural sources, may be leached out of the soil and contribute to eutrophication (a reduction in oxygen) in downstream water bodies. Some mobile pesticides may also be leached out. The leaching of salts from irrigated lands to keep the lands productive may cause increased salt loads downstream. Primarily, the removal of wetlands by drainage changes the landscape, alters hydrologic processes, and reduces habitat for waterfowl and other wildlife.

Not recognized as a significant potential problem until recently was the leaching by drainage waters of trace elements in toxic concentrations from natural geologic formations. Unexpected high levels of selenium (and possibly other elements, such as boron and molybdenum) were found in the early 1980's in soils, waters, plants, and wildlife in the Kesterson Reservoir, an area used for disposal of agricultural drainage water. Similar natural resource problems related to irrigation drainage may be occurring elsewhere. The Department of the Interior is currently investigating 19 such situations in the Western States.

The planning and design of drainage systems require a thorough understanding of the various components of such systems and their interaction. The primary components are the outlet, the collection system (including both surface and subsurface drains), and certain land treatment systems such as bedding or smoothing. The planning may involve one landowner or many and often concerns agricultural interests as well as environmental groups. Good planning takes into account various environmental values as well as those of agriculture, provides for flood protection if large projects are involved, and considers the economic impacts as well as the financial and political realities of implementing the plan.

Because of the need for cooperation among landowners to provide appropriate outlets to dispose of drainage waters, a variety of drainage organizations has been created under State laws. The most common of these is the corporate drainage district. This is an organization with taxing powers that constructs and maintains drainage outlets for the area it serves. In recent years, a number of States have enacted legislation permitting multiple-purpose districts, often called conservancy districts. Their objectives may include drainage but can go well beyond that to consider numerous other water and resource management objectives. Whereas in the past, the activity of drainage districts often has been dominant in the drainage field, of late more drainage is completed privately than through district organizations.

At what rate have drainage organizations and individual farmers improved land by drainage and invested in drainage improvement? How does this investment compare to the total capital investment in agriculture and what have been the returns? Reliable information on these questions is hard to obtain. Combining whatever data could be gleaned from the Census of Drainage and the Census of Agriculture from 1920 forward, with statistics from USDA and other specialists, reveals the following picture.

As of 1985, an estimated 110 million acres of agricultural land in the United States benefited from artificial drainage. At least 70 percent of the drained land is in crops, 12 percent in pasture, 16 percent in woodland, and 2 percent in miscellaneous uses. Although recent trends have been toward more farm drainage systems, 60 percent of the area drained still depends on public outlets installed by counties or drainage and conservancy districts.

The average U.S. real cost of providing group drainage outlets was $225/acre in 1985, and has been essentially constant since 1915. The cost of providing surface drainage has risen since 1965 (to $140/acre), while the cost of subsurface drainage has dropped substantially (to $415/acre). These trends reflect the impact of the new plastic materials for subsurface drains and more efficient trenching methods.

The capital value of all U.S. farm drainage work now in place is estimated to be over $40 billion, based on replacement costs as of 1985. This includes $15 billion (36 percent) for public drains and $25 billion (64 percent) for onfarm systems. Allowing for depreciation, the net capital value of all U.S. farm drainage work as of 1985 was estimated to be near $25 billion—$15 billion (60 percent) for public drains and $10 billion (40 percent) for onfarm systems.

Compared with the market value of all farm real estate in the United States ($690 billion in 1985), drainage improvements represent between 4 and 6 percent of the total (up to 7 percent if buildings are excluded). Percentages for highly drained States range considerably more—up to 30 percent in Michigan; 25 percent in Indiana and Ohio; 20 percent in Louisiana; 15 percent in Arkansas, Delaware, and Mississippi; and 10 percent in Florida, Iowa, Minnesota, and the two Carolinas. Details are in table 11-7.

The aggregate nature of available data makes it impossible to estimate the actual increase in value for all land that has been drained. However, by separating economic statistics for counties with a relatively high incidence from those with a low incidence of drainage, one can show a substantial difference in value of crops and livestock sold, and of land values, in favor of a high incidence of drainage. An analysis of 1982 Census of Agriculture data indicates that real estate values per acre for 256 predominantly agricultural counties throughout the Eastern States with a high incidence of drainage averaged 27 percent more than values in 1,422 other agricultural counties. This translates to an expected average capital benefit of about $270 per drained acre in 1982. By 1985 the average benefit was down to $200 per acre, the result of generally declining agricultural land values. In 1986, the average expected benefit figure fell further, to about $175 per acre.

It would be useful to have continuing overall estimates of the increased value of production associated with drainage, or of the returns on the investment, because the feasibility of drainage changes with costs, commodity prices, and other factors. While a general farm-level benefit/cost (B/C) ratio for drainage in the East fell from 1.30 to 0.75 between 1982-86, the B/C ratios appeared to still exceed 1.0 in seven Eastern States: Arkansas, Missouri, Kentucky, Virginia, Missisippi, South Carolina, and Florida.

The technologies exist to make fairly precise B/C evaluations for specific field situations, as illustrated in figure 6-10. Such "anecdotal" calculations verify that the return on investment can be very high. It also is clear that the response is highly site specific. For example, the irrigated Imperial Valley in California would be out of production for all practical purposes were it not for intensive drainage. In other irrigated areas, natural drainage rates are high enough to require no artificial drainage at all.

To the extent statistics are available, it is clear that investment in drainage has been substantial. It is equally clear that investment will continue. First of all, there will be an increasing need for repair, maintenance, and replacement of existing systems. Second, there will be pressures for additional drainage, either to control salinity in irrigated soils or to enhance production on presently cultivated land.

Perceptions about the status and trends of agricultural drainage are a function of the extent and quality of available data. Existing information tends to give an incomplete picture. It is based on "unstable" data in the sense that the data collected at different times are based on different definitions and techniques and thus tend to be unreliable, especially for comparisons over time. Interest in drainage as such may be decreasing, but interest in wetlands, or their remnants, is increasing. A good data base is crucial to informed decisionmaking or policy development.

Future Trends and Prospects

What of the future? USDA's National Resources Inventory (NRI) of 1982 indicates that nearly 28 million acres of existing nonirrigated crops and pastures have drainage problems, of which 15-20 percent are also considered wetlands. An added 12 million acres of rural land have at least a medium potential for drainage and conversion to crop production. Nearly 30 percent of the potentially drained and converted acres are now wetlands. About 25 percent of the wetlands vulnerable to conversion are prime waterfowl habitat. Thus, the pressure for drainage to expand agriculture tends to be for lands generally not considered of prime value to waterfowl, although other environmental benefits may also be sacrificed. There are definite restrictions, and no national need to expand the cultivated land base through drainage.

Unless economic conditions change drastically, it is expected that drainage activity will be concentrated at the "intensive margin" rather than the "extensive margin." Landowners will strive to improve production efficiency by raising production per acre and product quality. This will place greater demands on intensive drainage on currently cultivated lands. In the same vein, there is likely to be more emphasis on repair and maintenance of existing systems, and on replacement of deteriorating systems, activities not usually in conflict with the environment, wildlife, or other interests.

There is a growing realization that drainage is simply a component of a total water management system. Total water management may be seen as a combination drainage and subirrigation system with semiautomatic feedback controls. On a broader scale, it may be seen as also including management of ground-water quality and offsite effects. One may expect technological advances to make far more effective control of soil water status possible and profitable. One also may anticipate greater conceptual recognition in integrating various interests in the development and execution of water management plans.

A specific example of the need for a total water management approach is provided by the drainage of irrigated land. The 1982 NRI indicated that improved drainage or other water conservation and management measures would benefit at least a third of our irrigated cropland. More and more, it will be imperative to integrate the planning and operation of irrigation and drainage systems so as to provide maximum benefit to the land and minimum disbenefit downstream. To achieve this, the salt load in the drainage water must be managed explicitly. The occurrence of toxic substances other than the traditionally recognized salts may introduce important new management challenges.

Drainage technology plays an important role in these situations, but it does not operate in isolation. Returning to the Kesterson Reservoir case, a solution to the kinds of complex environmental issues encountered there may involve, besides drainage, irrigation technology, desalting, waterfowl, and other wildlife toxicology investigations, wildlife management, institutional changes, and legal or contractual arrangements.

On a broader base, the need is clear for better and more explicit standards for decisionmaking. Using an assumed value of waterfowl hunting, an economic comparison can be made of the relative value of wetlands for agricultural production or for recreation. In the abstract, the same can be done for other, intrinsic or explicit, values of wetlands. In practice, neither the methodology nor the data base exist for such an analysis. Whether a totally rational economic analysis ever can or should be the basis for deciding the advisability of further drainage may be debated. However, there can be no argument that better decisions can be expected if the information base is improved.

The improved data base requires information on the value of drainage for agricultural production; the value of wildlife habitat for recreation and other ecologic purposes; the value of wetlands for hydrologic management of ground and surface water; and the value of wetlands for maintaining flyways. Specific decisions on individual parcels of land require specific information. Assessing the effectiveness of existing policies and institutions, or determining the need for changes in them, one needs aggregate data. Historic data bases have suffered from lack of continuity, from changes in definitions over time, and from inconsistencies of data from different sources.

Better information is needed. The decennial census of drainage was eliminated by Congress late in 1986. This will require new approaches and coordinated data collection programs. The slack may be taken up by periodic entories conducted in USDA. The importance of drainage in terms of ital investment as well as its effect on production warrant good data, ecially because interactions with wildlife and environmental interests e becoming more important with time. There is more interest in environmental issues than in past decades. Moreover, the stress on the environment from expanding development and growing populations makes the interaction more acute technically.

Drainage will continue to play an important part in water and land management. Drainage technology will continue to change as it has in the last 30 years. Emphasis will shift to management of total systems, with increasing importance of offsite effects and of interaction between agricultural production interests and nonagricultural concerns. The need for national assessment of alternative strategies, using sound economic methodology, will become greater as the pressure on natural resources continues to increase.

Drainage in the past could be characterized as driven by the developmental ethos. It then encountered, and clashed with, the environmental ethic. In the future, one can expect a coming to terms of the two viewpoints. Solutions will be sought that enhance both agricultural production and a variety of environmental values, including wildlife protection.

Jan van Schilfgaarde
Director, Mountain States Area
Agricultural Research Service, USDA

Contents

Page

Chapter 1. A Framework for Future Farm Drainage Policy: The Environmental and Economic Setting by Stephen C. Smith and Dean T. Massey 1

The Policy Context for Future Drainage 2
The Extensive Margin 5
The Intensive Margin 8
References 11

Chapter 2. A History of Drainage and Drainage Methods by Keith H. Beauchamp 13

The Early Background 13
Drainage in the United States 15
Materials and Methods for Subsurface Drainage 19
Surface Drainage Measures and Techniques 24
Excavating Ditches and Channels 25
Pumping for Drainage 27
References 28

Chapter 3. Advances in Drainage Technology: 1955-85 by James L. Fouss and Ronald C. Reeve 30

Technological Challenges 30
Advances in Materials and Materials Handling 31
Corrugated Plastic Tubing 33
Synthetic Drain Envelope Materials 36
Drainage Equipment 38
Laser Automatic Grade Control 43
Drainage and Water Management Systems 45
References 45

Chapter 4. Purposes and Benefits of Drainage by N. R. Fausey, E. J. Doering, and M. L. Palmer 48

Purposes of Drainage 48
Primary Benefits of Drainage 49
Associated Benefits of Drainage 51

Chapter 5. Preserving Environmental Values by Carl H. Thomas 52

Identification and Measurement 52
Ecological Concerns 59
Comprehensive Evaluations 61
References 61

Chapter 6. Principles of Drainage by R. Wayne Skaggs 62

Drainage Requirements 63
Drainage Theory and Practice 65
Surface Drainage 70

Contents

Page

Simulation of Drainage Systems 71
Subirrigation 72
Offsite Effects 74
References 76

Chapter 7. Drainage System Elements
by Walter J. Ochs, Richard D. Wenberg, and
Gordon W. Stroup 79

Outlets 79
Collection Systems 80
Land Treatment Practices 83
Land Protection Practices 89
Drainage System Combinations 89
References 90

Chapter 8. Planning Farm and Project Drainage
by Thomas C. G. Hodges and Douglas A. Christensen 91

General Design and Economic Considerations 91
Planning Farm Drainage 92
Planning Project Drainage 93
Drainage in Irrigation Project Planning 95
References 95

Chapter 9. Drainage for Irrigation: Managing Soil Salinity
and Drain-Water Quality
by Glenn J. Hoffman and Jan van Schilfgaarde 96

Elements in Salinity Control 96
Leaching 96
Additional Drainage 97
Drain Depth 98
Drain-Water Disposal 98
Minimizing Adverse Effects 99
References 100

Chapter 10. Drainage Institutions
by Carmen Sandretto 101

Elements of Drainage Law 101
Public Drainage Organizations 103
Multipurpose Districts 107
References 108

Chapter 11. Economic Survey of Farm Drainage
by George A. Pavelis 110

Areas and Uses of Drained Land 110
Investment and Drainage Cost 117
Growth of Drainage Capital 119
Status of Drainage in 1985 120
Drainage in the Humid East 126

Contents

Page

Drainage and Irrigation 131
References 135

Chapter 12. Drainage Potential and Information Needs
by Arthur B. Daugherty and Douglas G. Lewis 137

Remaining Drainage Potential 137
Drainage Information 139
References 142

Chapter 13. Drainage Challenges and Opportunities
by Fred Swader and George A. Pavelis 144

Preservation of Wetlands 144
The Function of Wetlands 145
Rates of Wetland Conversion 146
Supply of Wetland Products 147
Do Wetlands Need More Protection? 147
National and Regional Wetland Conversions 148
Balancing Competing Natural Resource Values 152
Improving Drainage Information 154
Maintenance and Repair Challenges 155
Salinity and Water Quality Control 156
Drainage is Water Management 156
Challenges for Research and Education 157
References 158

Appendix A: Executive Order No. 11990:
Protection of Wetlands 160

Appendix B: Selected State Drainage Authorities 162

Appendix C: Acknowledgments and Contributors................ 167

Appendix D: English and Metric Conversion Equivalents 170

Chapter 1

A Framework for Future Farm Drainage Policy: The Environmental and Economic Setting

Stephen C. Smith
School of Natural Resources
College of Agriculture and Life Sciences
University of Wisconsin-Madison

Dean T. Massey
Economic Research Service, USDA
University of Wisconsin-Madison[1]

Farm drainage had been a part of U.S. land policy debates since colonial times and will remain an active policy issue into the foreseeable future. The socioeconomic context for making these policy decisions has not been static over the centuries, despite a similarity in the issues underlying arguments over major land use changes. Conflicts have arisen over a broad array of policy questions, such as clearing and draining the Mississippi Delta, draining prairie potholes, managing return flows irrigated land, controlling water levels on coastal lands, and draining wet soils.

Figure 1-1 shows the distribution of remaining wetlands in the United States. Conflicts have also focused on definitional differences between wetlands and wet soils for use in State or local legislation. These statements can help achieve broader agreement: Wetlands are lands where saturation with water is the dominant factor determining the nature of soil development and the types of plant and animal communities living in the soil and on its surface. Technically, wetlands are lands transitional between terrestrial and aquatic systems, where the table is usually at or near the surface or the land is covered by shallow water. Wetlands must have one or more of the following three attributes: (1) at least periodically, the land supports predominantly hydrophytes; (2) the substrate is predominantly undrained hydric soil; and (3) the substrate is nonsoil and is saturated with water or covered by shallow water at some time during the growing season of each year (Cowardin and others, 1979).

"Wet soils" are those in which excess water is the dominant limitation on their use for crops in an area. They are not synonymous with hydric soils or wetlands (Diedrick, 1980). USDA's National Resource Inventory for 1982 indicated that there were 78 million acres of remaining non-Federal "wetlands," but 96 million acres of undrained "wet soils" not in crops. Heimlich (1986) reports that about 40 percent of the wet soils cropped in 1982 were also classed as wetlands under the Cowardin system now used by the Fish and Wildlife Service.

In this chapter we will first outline some important general considerations influencing current and future drainage policy. We will then examine conflicts at the "extensive margin," or where major land use change is occurring, such as converting wetlands to agricultural or urban uses. Institutional innovations are taking place because of the shift in the forces impinging upon the decisions to extend agriculture and urban land uses onto wetlands. The demands for land use products and the political context in which these demands are expressed are in transition. The last section deals with the "intensive margin," the situation of obtaining more pro-

---

[1] The authors appreciate the assistance and contributions of Marc D. Robertson, Jane Kohlwey, Carla Eakins, and Susan L. Collins, University of Wisconsin-Madison.

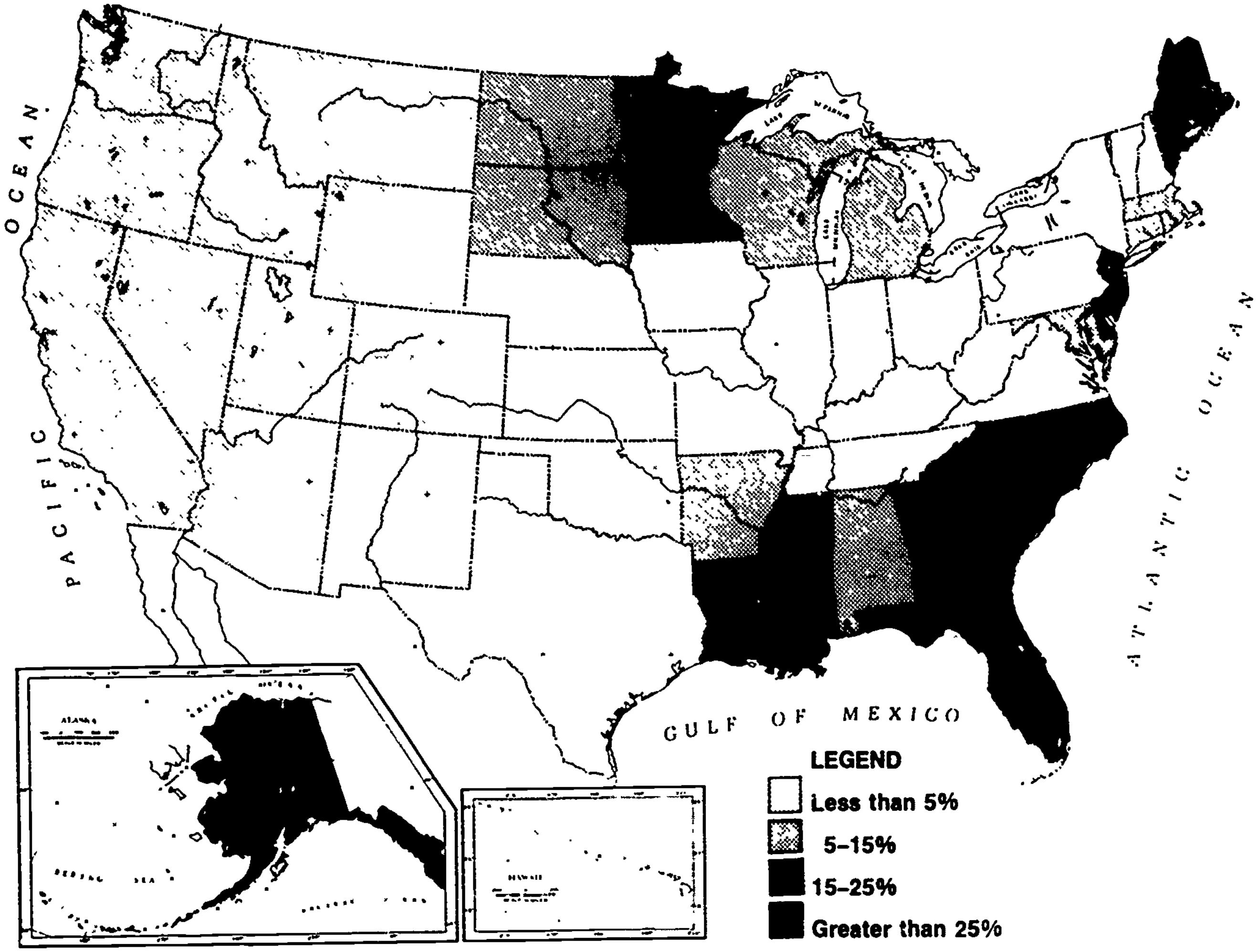


Figure 1-1—U.S. wetlands lie mostly east of the Rocky Mountains.

duction from existing agricultural land. An example is achieving higher yields from wet soils. Technological research, farm economics, and agricultural environmental considerations will continue to play dominant roles in programs at this margin.

The Policy Context for Future Drainage

Drainage policy has been a part of the Nation's developmental ethos, of the historic westward movement, and of U.S. land policy for two centuries. The frontier was to be conquered. Governmental policy enhanced land development by converting the public domain into privately owned land and developed institutional mechanisms for individuals to deal with problems that extended beyond the farm fence. The Jeffersonian concept of landownership was a driving ideal even though it provided cover for land speculation, aggrandizement, and, at times, fraud. Yet land did become widely owned, and the concept of the individual's landed stake in the future has continued to be a force driving individuals and policy.

Standing water often lay in the way of such land development. Large portions of the forested frontier, the land east of the "famous 100th meridian," had to be both cleared and drained to sustain agriculture. For example, horses walked belly-deep in water over large sections of northeastern Indiana (Wooten, 1955).* Drainage and clearing were part of an early, unsuccessful attempt to convert northern Wisconsin into a dairy land (Christensen, 1958). The "Alluvial Empire" of the lower Mississippi Valley required diking and draining to manage water so the land could be cleared and tilled (Harrison, 1961). Surveyors' notes from Iowa and Minnesota report that they had to hold instruments high over their heads as they waded in water (Murray, 1953).

The Swamp Land Acts of 1849, 1850, and 1860 converted 64.9 million acres of public domain land in both Eastern and Western States from Federal to State ownership so it could be sold in order to drain selected portions (U.S. Dept. of Interior, Fish and

---

*References are listed at the end of this chapter.

Wildlife Service, 1972). In the arid West, drainage presented different problems because of the variable character of the soil, and irrigation. Yet drainage was often still necessary for a sustained agriculture.

Drainage continues to inspire public debate almost 100 years after Frederick Jackson Turner, the University of Wisconsin historian, observed that the Census of 1890 no longer marked a line distinguishing a frontier (Turner, 1938). Turner outlined the ways in which the frontier shaped the character of its inhabitants and their culture. These traits of independence and the value of land can still be seen in the drive to drain and "conquer" the swamp. Of course, the underlying potential for substantial capital gains and a better life for the developer should not be neglected. The strength of this drive can be seen today in the continued loss of wetlands. Yet, "... thoughtful students will remember that across the Delta lie the skeletons of many abandoned attempts toward its reclamation" (Harrison, 1961). The same is true of all regions of the Nation.

The push to drain is very old. Early settlers brought with them experience in drainage and an awareness of the differing and conflicting values involved. The draining of England's fens is an example. In the Middle Ages, fishers and fowlers did not appreciate the reduction of the natural channels and habitat, although farmers were pleased that the productivity of marketable crops increased per acre (Summers, 1976). Drained land produced different products. People valued these products and activities differently, resulting in conflicts. Such conflicts over wetland use persist in England today and are the subject of intense political struggles and headlines in the daily press (*Observer*, June 24; July 1; October 5, 1984).

Many of these same values are at stake today, but with a difference. The developmental ethos today faces a strong challenge from proponents of the "environmental ethic" (Leopold, 1949). This counterbalancing is the essence of the current public policy debate over draining wetlands. The 1960's and 1970's were decades of expanded and deepened environmental understanding. The issues raised by the environmentalists were not new, because people had been expressing concerns about draining wetlands for decades.

The 1960's and 1970's were, nevertheless, threshold years of change. For the first time, a broad base of public support was mobilized for significant political, legislative, and judicial action favoring an environmental perspective. Federal and State laws were enacted, new administrative rules were promulgated, and court decisions were rendered dealing with vanishing wetlands.

The environmental ethic encompassed more than the older conservation ethic by considering whole ecological systems.[2] Greater attention will be given to the ecological-environmental effects of draining both wetlands and wet soils. The steps in deciding to drain will need clear delineation, and the market and nonmarket effects from draining or not draining will have to be analyzed. At times these considerations may limit drainage; at other times, drainage may be essential for achieving the desired public and private products.

The 1960's and 1970's were also years of expanding world agricultural markets and of production adjustments to meet market demands of timeliness. Agriculture's response to these market developments put pressure on both the extensive and intensive margins. The extensive margin was changed by draining wetlands and converting them to agricultural uses, as in the Mississippi Delta. Intensive margins were likewise pushed by tiling wet soils, which increased production per acre. The area of intensive land use increased while the area of extensive land use decreased. The boundary of transference between these margins is at the heart of the debate between using land for food and fiber or for "environmental" products and services. Market forces will continue to affect the demand for agricultural products and, consequently, the demand for optimally drained land. The dynamics of these markets put a premium on avoiding risks from excessive moisture and thus tend to encourage drainage.

Technological change in agriculture will be another strong force affecting drainage. The history of technical change is well known, and the productivity of U.S. agriculture is a wonder in today's world. American consumers have benefited by resultant low-cost food and fiber. Farm numbers, especially midsized farms, and farm production have declined. The number of smaller and larger farms continues to increase. These changes have produced greater income equity between commercial farm and nonfarm employment.

All of the ramifications of past technological triumphs in agriculture are not the primary concern here, but the forces that shaped these trends must be considered because they bear on drainage policy. The future will be shaped by a blend of these shifting forces and will include new technologies. Within

---

[2] The conservation ethic received broad-based support at the turn of the century with the establishment of the Forest Service and the National Park Service. Notable conservation leaders of the time were Theodore Roosevelt, John Muir, and Gifford Pinchot.

this context, there lies a potential for revolutionary change in agricultural production.

Estimating future production, however, is increasingly difficult because of the changing structure of agriculture and its supporting industries. Not only will new production techniques have to be mastered, but their articulation into the system will follow new and significantly different institutional and organizational channels (Ruttan and others, 1979). In fact, agriculture could avoid the problems that have plagued sectors of U.S. manufacturing, like the automobile and steel industries, if the issues of articulation are appropriately addressed.

Why will the future be different? Smaller and decreasing numbers of farms and farmers will have had and continue to have important political implications in terms of legislative representation at all levels of government. Coalitions between agricultural interests and other groups will be increasingly important in accomplishing related legislative objectives. Marshalling legislative support for considering agricultural as well as other views of wetland laws will require skilled political talent to attract urban votes and to gain the understanding of those who promote environmental interests. These changes become significant since the demands for the environmental products of wetlands are largely expressed through governmental organizations.

The market for technical innovations will change, altering the path of technology adoption. The number of buying firms will continue to decline but they will be bimodally distributed in size, lumped at the lower and higher ends of the scale. The characteristics of the remaining firms will determine whether this distribution and organization will affect the use of pesticides, seed corn, semen, and induced animal "twinning." Projections for increased productivity have been based on the traditionally correct assumption of a large number of competitive farms. That market is changing, and this may affect both the production and application of new technology. Will the same forces for rapid adoption work with a smaller number of highly commercial farms as in the past? Will the incentive structure for innovation remain the same? How will contract sales as a form of production and marketing affect innovation and per-unit production?

The structure of the everchanging farm supply industry will significantly determine when and under what conditions new technology is released. The "biotech" industry has gone through the first flutter of adjustment. As maturity comes, as foreign competition becomes more intense, and as large corporate structures and their decision processes exert influence, estimating future onfarm productivity becomes very difficult because of the multiple forces affecting new technology.

The thrust for future productivity increases will come from research (English and others, 1984). There is a ferment and excitement in laboratories across the Nation about potentials for major technical change. In some areas, commercialization is moving rapidly and broadly covering sectors of food and fiber production. The technical capability of increasing food and fiber productivity appears to be at the threshold of a dramatic upward surge.

Observers suggest that photosynthesis enhancement, crop bioregulators, and twinning techniques are ready for early adoption by farm operators (Lu and others, 1979). A survey of plant scientists by Merz and Neumeyer indicates that new technologies can increase the yield of corn up to 40 percent (Rosenblum, 1983).

Gains in livestock production can come from such innovations as shortening the time between generations, determining sex, increasing efficiency in the use of feed, improving health, and transplanting embryos. For example, "Milk production may be increased by between 10 to 33 percent without proportionately increasing feed intake" (Rosenblum, 1983).

The Economic Research Service (ERS) labels the future as fueled by "science power" in contrast to the mechanical power, horse power, or hand power of past decades (Lu and Quance, 1979). Conferences and studies during the past few years point in this direction. ERS economists have recently summarized productivity growth estimates for purposes of making long-range projections to the year 2000 and beyond (Maetzold and others, 1983). These authors suggest using an annual growth rate of 1.5 to 2 percent for estimating future agricultural productivity. Rates of productivity increase have not tapered off or flattened, as was projected in the late 1970's.

Productivity increases are highly correlated with public and private investment in research (Johnson and Wittner, 1984). By continuing to invest in productivity increases, the Nation will be offered a broader array of policy options for resource management, including drainage, than would happen without a priority on research to increase productivity. Thus, the argument for both private and public investment in research is justified by more than greater farm income and low-cost food and fiber. The ability to consider alternative resource management options is generated by the ability to supply food and fiber from a smaller land base. Thus, innovative policy options are increasingly viable. Within the intensive margin, policy options preserve prime agricultural land and, at the extensive margin, they restrict using land for agriculture with severe limitations, such as wetlands, highly erosive land, and land with a depleted ground-water supply.

If the increased per-unit productivity potential is realized, the Nation may be able to produce enough food and fiber to satisfy the U.S. market and help supply the world on a smaller land base. Pressure on the extensive margin, such as draining wetlands, could be reduced. Drainage policymakers would have to consider this change in pressure and develop program options which encourage agricultural production only on areas of highest productivity. In such a situation, wetlands most valuable as wetlands would not have to be drained. Production increases would come at the intensive margin by improving the use of the existing land base, including the use of drainage. In the competition for land for agricultural use, a policy premium assisted by legislation might be placed on prime agricultural land.

The Extensive Margin

Nationally, the extensive margin of agricultural land use is dynamic, with land continuously going into and out of agricultural uses. If the total agricultural land base is conceptualized, the extensive margin is at the edge of transference between farming and extensive land uses such as forest land, rangeland, and wetlands. As a part of the process of change, wetlands continue to be converted to agricultural and other uses. "New" land also continues to be brought into cultivation by irrigation, with drainage often being an integral component.

Because drainage has been an essential part of the Nation's agricultural development for the past two centuries, the area of wetlands has continued to diminish. Clear quantitative estimates of the loss of "original" wetlands are not available due to "lack of sound baseline data. . . ." (Weller, 1981). However, estimates by the U.S. Congress' Office of Technology Assessment (OTA) indicate that ". . . as much as 50 percent of the original wetlands may have been converted" (OTA, 1984). In some regions, only "remnant" wetlands remain with between 90 and 95 percent of the original area lost in Illinois, Iowa, and lowland forests in Missouri (Weller, 1981).

In other regions, according to the OTA, the percentage of remaining wetlands is substantial, still with a national estimate of ". . . 50 percent of the original wetland . . . being . . . converted." This percentage is based on an original area of 185 million acres. Between the mid-1950's and 1970's, the "actual loss of freshwater vegetated wetlands totaled 14.6 million acres. Agricultural land use was responsible for 80 percent of these losses" (OTA, 1984). Estimates from the National Wetlands Inventory are similar. They indicate that 54 percent of the original wetlands have been drained, of which 87 percent have been converted to agriculture (Tiner, 1984). The extensive agricultural margin has continued to expand into wetlands in all regions of the Nation.

Estimates from a National Research Council (NRC) report on "Impacts of Emerging Agricultural Trends on Fish and Wildlife Habitat" indicate that "86 percent of the original Mississippi bottom land will be destroyed by 1995 . . . and . . . all of the remaining (prairie potholes) area will be lost by 2055 . . ." (NRC, 1982). Weller contends ". . . most wetlands would disappear between 2000 and 2200 if the present rate of drainage continues" (Weller, 1981). Such declines are sufficient to render the small size of remaining wetlands increasingly visible. A broadly based public with a heightened environmental ethic is capable of focusing attention on the environmental and ecological consequences of these losses. Such a concentrated focus plays a significant role in the process of social and public valuation as well as in benefit-cost calculation of whether or not to drain. Many of the contending interests and values are not new and were evidenced 500 years ago in the British fens. The fowlers of that day valued the water fowl breeding grounds, much as the duck hunters of today value the prairie potholes and the backwaters of the Mississippi Delta.

Agriculture's expansion across the Nation with the assistance of drainage was accomplished through the use of a set of institutions built both upon concepts of private property and the valuation of these rights through markets for land, corn, wheat, soybeans, cotton, timber, and the like. Governmental agricultural policy generally supported these markets and the resulting distribution of income. Land and water policies (even levee construction) were used to subsidize this system of property rights and markets.

The products of wetlands, such as water fowl, water quality, water flow regulation, or fisheries are not owned as private property. Evaluating them in their natural state involves a nonmarket decision made without market criteria. During periods of "abundance" in the 1880's, wildlife products were sold after capture on local markets, but extinction and dramatic population reductions raised issues of public concern. Federal and State governments have maintained their proprietary interests and developed systems of regulations for managing these resources, but they have not generally relied upon the market as a mechanism for evaluating or distributing rights.

The public policy actions supporting drainage have been numerous at all levels of government, with Federal policy dating back to the Swamp Land Acts of 1849, 1850, and 1860. The Agricultural Conservation Program (ACP), the Soil Conservation Service (SCS), and federally supported educational and research programs also furthered the extension of drainage. In addition, general agricultural price support programs and other policies have encouraged the expansion of agriculture onto newly drained land (Goldstein, 1971).

State laws enabled drainage districts at the local level to deal with legal and financial problems of drainage extending beyond the farm fence. Federal and local efforts in levee construction, dating back to the early 1700's, contributed to both urban and agricultural development, including irrigation and related drainage. Governmental structures have been used by local interests to support the historic development policy which included drainage and the loss of wetlands. For the most part, these policies have been fashioned around and supportive of private property and markets.

Products from drained land are largely valued through markets while products from undrained land are valued outside of the market. They are "nonmarket" goods and services. Nonmarket valuations depend on other institutional forms, such as referenda, legislative bodies, and governmental administrative agencies. For these institutions to be effective, a base of public consensus must be created and reflected through the organizational processes.

The environmental movement of the 1960's and 1970's spawned increasing interest in the importance of wetlands and support for restricting drainage. Environmental and supply-management considerations prompted the elimination of ACP cost-share payments to farmers who drained land to bring new farmland into production. SCS Regulation 108 recognized the value of wetlands and eliminated technical assistance for bringing new wetlands into production. Environmentalists also used the National Environmental Policy Act (NEPA) to oppose drainage projects, and they supported the Federal Water Bank Program in 1970, which provided Federal funds to rent wetlands from landowners for a 10-year period to prevent their drainage.[3, 4*]

The lack of clear, understandable, and additive national wetland data was recognized with the establishment of a national inventory and with inventories in many States. Such inventories grew from an understanding that wetlands were disappearing increment by increment without a clear appreciation of the effect of losing one more increment. It was not possible to focus public decisionmaking without knowing the size and importance of the remaining aggregate of all wetlands and how an incremental loss would affect that whole. Public decisions at the local, State, and national levels needed to be based upon a definition of the resource and upon reasonably accurate estimates of its quality and quantity. Such a perspective is no different than that of the agricultural or urban land developers. They also look at the resources under their control, and generally evaluate their actions on the basis of a market outcome for the proposed product. Because markets do not exist for the public goods and services of wetlands, a public interest over private property had to be established. This processs is going on in the courts, Congress, State legislatures, and administrative agencies. Michigan. Minnesota, and Wisconsin have adopted legislation requiring statewide programs for mapping and inventorying wetland resources.[5, 6, 7]

Much of the political argument over these programs focused upon disagreements over the definition of wetlands. Circular 39 (U.S. Dept. Interior, 1972) and other Fish and Wildlife Service classification schemes (Cowardin, 1979) have significantly ameliorated many disputes. State legislators and political interests, however, have had their own economic concerns to protect, thus necessitating negotiation as well as self-education. Farm drainage interests have often questioned and, at times, on principle, opposed inventories as well as wetland management legislation. The redefinition of property rights has been at issue.

The States have related their mapping programs to State decisionmaking. For example, Minnesota has a provision for its own water bank and wetland tax credits.[8, 9] Michigan has a program giving the State an option to purchase wetlands.[10] Wisconsin establishes links with shoreland protection legislation.[11]

---

*These and subsequent footnotes refer to legal citations listed after the chapter's text.

Wetland inventories are increasingly viewed as essential for proper wetland management and for making decisions on whether to allow the drainage of additional wetlands.

State laws relating to wetlands have increased dramatically in the past 50 years. States adopted 79 laws relating to wetlands from 1795 to 1934. In the 20 years from 1935 to 1954 the number was 110. Then 70 were adopted during 1955-64. But during the 14-year period from 1965 to 1978, State legislatures adopted 355 wetland-related laws (USDA, RCA, 1980).

Navigable waterways have historically been a Federal responsibility. This was recognized further in the Rivers and Harbors Act of 1899, which gave the Army Corps of Engineers authority over the discharge of refuse, dredge, and fill material.[12] The authority evolved in part into section 404 of the Clean Water Act of 1977, which extends the authority beyond navigation to one of preventing pollutant discharges and of promoting the purposes of the Act.[13] Environmental groups have used this section to restrict drainage and to insure clean water. Permits issued under section 404 are for individual actions, and backlogs can exist if a high percentage of permits are contested. The Corps wanted to speed up decisionmaking by changing the permit procedure. Interim rules were issued in 1982, and the procedure became part of the reauthorization debate for the Clean Water Act.

Environmental groups feared that wetlands would be more rapidly depleted under the interim rules and that a basis for litigation would be denied.[14] An agreement was reached February 10, 1984, and approved by the U.S. District Court for the District of Columbia, on an order that overturned some of the interim rules. The court's order gives protection to wetlands, such as an estimated 700,000 acres of prairie potholes, and directs the Corps to apply. nationwide, the decision in *Avoyelles Sportsmen League v. Alexander*. It held that discharges caused by land clearing are subject to section 404 permits.[15] Before then, the Corps had applied the Alexander decision only within Louisiana.

The coastal zone also has received national and State attention because of the effect of drainage. Recognizing the National Marine Fisheries Service as a consultant for section 404 determinations as well as other Federal and State interests, highlights the importance of fishery interests in the wetlands of the thin perimeter around the contiguous 48 States.

Wildlife and other supporting groups see section 404 authority as important legislation and would like to have it continue to be a part of the wetland decision process. In essence, a complex of legislative authorities come into play with the control of navigable waters, such as the authority in the Clean Water Act to prevent pollutant discharges, the authority of the Fish and Wildlife Service over migratory waterfowl, the authority of USDA to provide cost-sharing and technical assistance for conservation practices, and USDA's general farm support programs with incentives for moving onto less productive agricultural land (Goldstein, 1971).

The above complex is pluralistic, and built upon older authorities. But the pieces are beginning to take shape for a reformulation of propertied relationships. New public interests are emerging. Perhaps it is time to stand back from the fray of economic and jurisdictional controversy and begin to evaluate the adequacy of Federal, State, and local wetland policies.

Several areas of concern related to drainage might be noted, such as fishery values or flood water retention, but migratory waterfowl and its habitat illustrate the need for policy re-evaluation and a reformulation of propertied relationships. Habitat for migratory waterfowl, of course, is international in character, but we shall only note the prairie pothole situation, the river backwaters and floodplains, and bayous and waterways along the Mississippi and the coast. Farm drainage has interacted with the ecology of these flyways for many years. The potholes are often grouped within the intensive margin in our terminology. Draining potholes, however, means changing land use and pushing cultivated agriculture onto noncultivated land, even though the geographic area is within the farm firm.

We have had a Federal policy (and many States have had their own policies) of purchasing selected wetlands to preserve migratory waterfowl habitat, but can enough land be purchased in the right places to do an adequate job? To make these decisions, not only are wetland inventories needed, but also better ecological information on the various species to be protected. The direction of much public action is to attach clear public value to the ecological system and to consider this whole as the economic product. Migratory birds are covered by Federal legislation: can the value attached to these birds be extended to their habitat? The full definition of this product needs exploration in economic, legal, scientific, and aesthetic terms (Stone, 1976). An array of public processes such as purchase, taxation, cost-sharing, and police power could be brought to a focus, including attaching public property rights to the ecological system. (Note the Wyoming Federal Court ruling to eliminate fencing on private land to protect antelope habitat under the Unlawful Enclosures of Public Lands Act. U.S.A. vs. Wyoming *Wildlife Federation*. Case No. C84-013 6-B, U.S. Dist. Court, Wyoming.)

The movement for wetland protection at the State level has gone beyond the inventory, taxation, and public purchase stages to the use of police power. As of 1986, 13 States had adopted comprehensive legislation addressing the issue of freshwater and coastal wetland preservation. For example, see [16, 17, 18, 19, 20]. These statutes depend on good wetland mapping programs and other information, and establish police power authority by findings that describe wetland values and consequences of unregulated development. These findings provide the policy underlying the statute, alert property owners and the general public to the need for regulation, and aid the appropriate agency in interpreting the act and administering permits. At least five other States are at various stages of discussing and passing comprehensive legislation: California, Idaho, Illinois, Indiana, and Nebraska.

Regulated activities vary from State to State and are the subject of heated debate. They include specific conduct, such as drainage and filling, as well as any activity that impairs the natural value of wetlands. Exemptions to drainage are bargained, as in Massachusetts, where the statute specifies that the regulation shall not apply to any mosquito control work, to maintenance of drainage and flooding systems of cranberry bogs, or to work performed for normal maintenance or improvement of land in agricultural use.[21] Some issues under this statute have been litigated, with its constitutionality supported. For our purposes, it is enough to note the movement toward comprehensive wetland legislation to deal with the specific land at the extensive margin through the use of policing.

The developmental ethos with its strong private property value is still an active national force. It has fueled the drainage movement and given it a base of legitimacy. The economic gain from converting vast areas of wetlands was reflected in increased income, capital gains, and settlement of the continent. But the markets that produce such benefits do not reflect all the societal values in drainage or wetlands. The environmental movement gave new policy weight to the conservation and the environmental ethic as largely nonmarket values. The synthesis of this confrontation, arising from a maturing Nation, is really just beginning.

The earlier expansion of the extensive margin was seldom easy or cost-free, but there was a supporting consensus that it was right. That consensus no longer exists, and future drainage will have to be justified in an increasingly detailed fashion. Imagination and innovation will be needed in policy, and new legal doctrines will be developed. The justification will assume an added dimension as new technology contributes to per-unit production increases. Are the acres drained to extend the margin for agricultural production necessary to meet agricultural production goals, and are they in the public interest?

The pushing back of the extensive margin by drainage is only partly market-driven. The market for farm and forest products and the market for land remain major forces, but nonmarket valuation will be increasingly important. The valuations will be made by Federal, State, and local agencies, and also by courts, legislatures, and a variety of other means. The pluralistic character of this process is frequently of great value since incremental adjustments at times forestall all-out commitments with possible major pitfalls. Pluralism also requires insight and imagination to insure the decisions will not be choked by the burden of "too many wheels to turn." The challenge is to define more clearly the product to be created with this interaction between drainage and wetlands.

The Intensive Margin

The intensive margin refers to additional drainage on existing farms. Generally, the issue is not the conversion of nonagricultural land to agriculture but increasing the intensity of agriculture through drainage and achieving greater production and net return.

Increasing the intensity of use is not a new objective of drainage. The tile drain introduced in New York State in 1835 by John Johnston was an effort in this direction. Johnston claimed that "he never made any money farming until he drained his land" (USDA, Yearbook of Agriculture, 1938). Land grant college experiment stations and USDA have for many years directed research toward a better understanding of soil-plant-moisture relationships. The science of dealing with wet soils and drainage has moved forward on a worldwide basis, supported by a long history of work in the Netherlands and in less developed countries. With an excellent network of scientific communication, these efforts are part and parcel of current and future high-technology agriculture. Hanson and Larson observed that through drainage, irrigation, and improved tillage, significant physical improvements in soil have been made. "But relative to the changes that will be made, we have literally scratched the surface. Substantial acres. . .produce low yields because of too much or too little water" (Hanson and Larson, 1983). Drainage research and practice will be a major issue in an age of "high-tech." An increasingly important element of crop production will be providing the plant with optimum water for an economic return as well as a high-quality environment.

The intensive margin has been and continues to be influenced by the major forces noted in the policy introduction to our discussion. The developmental ethos contained a drive for expansion onto new land. But increased productivity per unit was also an ingrained social value master workmanship (Brewster, 1953). These values were expressed in such common phrases as "making two blades of grass grow where only one did before," and "making the desert bloom through irrigation rather than dryland farming."

Accepted modes of behavior are beginning to shift with the environmental movement playing no small part. Some new programs are in place, so when farmers calculate a net return from an investment in drainage, they must relate to the water bank, property tax credits, income tax considerations, and interest rates, besides yield changes on various soils under alternative conditions of wetness and dryness. The work habits of yesterday are quite different than those of today. The "rubble" of conservation tillage is beginning to "look good," and wetlands for habitat have a broader base of acceptance among agricultural landowners.

Drainage has an environmental effect that is only now being recognized in some regions of the Nation, though not new to the irrigated West. This is no longer just a Western issue. In fact, the American Society of Civil Engineers held a 1982 Conference on "Environmentally Sound Water and Soil Management" in Florida (Kruse, 1982). Soil salinity control, flows, ground-water protection from contamination, managed recharge percolation, and reduced flood flows are environmental benefits of drainage. Thus, drainage at the intensive margin also has values not clearly reflected in the market.

Drainage is an important water management tool for achieving acceptable levels of quality as well as quantity in both the East and West. The quality of the return flow, with or without irrigation, will be increasingly important and will become a part of environmental chemical management. Questions will be asked about the chemical composition of the water that comes out of farm drains and flows into district systems. For example, water purity problems plagued the Kesterson Wildlife Refuge, Calif., when excess selenium appeared in return flows. The necessity of an environmentally sound management of agricultural chemicals is clear: some aspects are understood, but the research agenda is long and difficult. Drainage in water-quality management will be a significant issue for the next two decades.

Today's science will be pushing tomorrow's technology. Commercial plant breeders are moving with the market and developing varieties designed for conservation tillage and greater salinity tolerance as well as higher yields on prime land. Many questions, however, await better answers. To what extent can plants be adapted to conditions which will reduce the need for drainage? And, can pest resistance be integrated to reduce the need for chemicals and thus the need to drain for improved water quality?

Managing water will be an important component of more intensive plant management, and in many situations drainage will help achieve technical precision. Because of the variability of conditions throughout the Nation, the role of drainage will differ by locality, necessitating area-by-area evaluations. Questions concerning both new investment and reinvestment will be raised. Millions of acres are already drained, and many farm operations will have to evaluate their existing drainage systems. They must determine if the existing system performs optimally, or if reinvestment would yield a sufficiently high economic return to warrant change and redesign.

These determinations can be complex. Current technologies of drainage must be assessed as well as those of related disciplines associated with integrated crop management. Also, new materials, advanced equipment, and computer assistance have added a precision unknown in earlier days. These advances, coupled with progress in soil science and in determining soil-water-plant relationships, as well as improved operating techniques, result in a decision process that is a process of sophisticated integration.

The decisionmaking sciences have continued to advance along with the biological and physical sciences. Studies have revealed the diversity of needs on a State-by-State basis. These studies integrate the appropriate information into an economic frame of reference with indicators of profitability, or lack of it, under specified conditions. Such research is useful for local situations, but because of limited assumptions and purposes, it does not provide details for making broader generalizations. For example, interest rates, discount rates, rental alternatives, tax assumptions, and the effects of excess moisture on crops are dealt with in a variety of ways. An outline of the decision path and an explanation of alternatives would be useful for individual farmers and public entities. Such an outline would not only aid farm operators and public officials, but also soil scientists, drainage engineers, and plant specialists as they approach their respective tasks.

Computer software is beginning to address this problem through programs which relate drainage system design, crop yield, water management, and economic return. The number of economic and engineering modeling packages such as DRAINMOD will increase. As these programs are improved, accepted, and used, the ability to compare analyses from various regions will increase. Thus, the areas where drainage at the intensive margin is profitable can be more clearly defined. A review of selected research suggests that drainage can be a profitable investment at the district and individual farm level on some of the most poorly drained land. In other situations, the net benefit is zero or a loss. At some locations, drainage is going forward with the objective of achieving a break-even level of intensification, with the long-term goal being a capital gain associated with a change in land use. (The studies examined included Barrows and others, 1982; Dudek and Horner, 1981; Fritz and others, 1980; Horner and Dudek, 1980; Horner and others, 1983; Kanwar and others, 1983; Leitch and Scott, 1977; Leitch and Kerestërs, 1981; Nolte and Dudek, 1984; Schwab and others, 1975; Schwab and others, 1981; and Skaggs and Nassehzadeh-Tabrizi, 1983.)

The focus on the intensive margin, however, does not mean that individual farm operators can always accomplish successful water management by themselves. Collective action for water management has a long history and will remain important for carrying water management beyond the farm. For example, drainage districts were organized to convey drainage water from many farms to a "natural" waterway. Some form of collective action was necessary to finance projects, to deal with questions of trespass, and to overcome blocking action by uncooperative individuals. For example, in 1839, the Michigan legislature provided that, upon petition, the lands of persons "who would not voluntarily permit the construction of a ditch" could be opened to drain swamps, bogs, meadows, or other lowlands (Lauer, 1959). Many States developed comparable legislation for formalizing collective action into district-enabling acts. History and the associated law cannot be delineated in detail here other than to note a complex legal and political backgound. Districts represent local economic interests attempting to extend and enhance individual property values. Today the role of the older, single-purpose drainage district is often incorporated into county governments or commissions.

If exploiting the intensive margin continues to be economical, the increased sophistication and size of farm businesses may require a rethinking of many farm drainage systems because of the increased load such systems will have to handle and the need to control soil moisture and chemicals more precisely. Old small districts may have to reorganize to deal with today's larger problems. Such reorganizations tend to create organizations capable of providing more comprehensive water management. This trend will be important for providing adequate service to the farmer as well as for meeting an increasingly broad spectrum of Federal and State water requirements. Farm drainage at the intensive margin will be included within the web of comprehensive water planning and management, requiring the integration of water quality, quantity, and rights.

The full potential of drainage at the intensive margin has not been realized. Productivity gains from better water control and longer term resource enhancement are often possible. Also, environmental enhancement at the intensive margin through water quality control will be significant. Achievement of these values will depend upon scientific advances and market value of agricultural products.

Footnotes

[3] 42 U.S. Code, Sec. 4321 et seq. (1982).
[4] 16 U.S. Code, Secs. 1301 to 1311 (1982).
[5] Michigan Compiled Laws Annotated, Secs. 321.10(1)(j), (g) (Supp. 1983-1984).
[6] Minnesota Statutes Annotated, Sec. 105.391 (Subd. 1) (West Cum. Supp. 1984).
[7] Wisconsin Statutes, Sec. 23.32(2)(a) (1981-1982).
[8] Minnesota Statutes Annotated, Sec. 105.392 (West 1977 & Cum. Supp. 1984).
[9] Minnesota Statues Annotated, Secs. 272.02 (Subd. 1) (15), 273.115 (West Cum. Supp. 1984).
[10] Michigan Compiled Laws Annotated, Sec. 321.206(2) (Cum. Supp. 1983-1984).
[11] Wisconsin Statutes, Sec. 59.971 (1981-82).
[12] 33 U.S. Code, Sec. 401-412 (1982).
[13] 33 U.S. Code, Sec. 1344 (1982).
[14] Nebraska v. Rural Electrification Admin., 12 Environmental Reporter-Cases 1156 (D. Neb. 1978).
[15] 511 Fed. Supp. 278 (Western District Louisiana 1981).
[16] Connecticut General Statutes, Sec. 22a-36 to 45 (1983).
[17] Massachusetts Annotated Law, Chap. 131, Secs. 40, 40A (Michie/Lawyers Co-op, 1981).
[18] New Hampshire Revised Statutes Annotated, Secs. 483-A:1 to :6 (1983 and Cum. Supp. 1983).
[19] New York Environmental Conservation Law, Sec. 24-0101 to 15-0601 (McKinney Cum. Supp. 1983-1984).
[20] Rhode Island General Laws, Sec. 2.1-18 to -25 (1976 & Cum Supp. 1983).
[21] Massachusetts Annotated Laws, Chap. 131, Sec. 40 (Michie/Lawyers Co-op, 1981).

References

Barrows, R., David Henneberry, and Sarah Schwartz. 1982. "Individual Economic Incentives, The Tax System and Wetland Protection Policy: A Study of Returns to Wetland Drainage in Southeastern Wisconsin." ASAE Paper No. 82-2034. Am. Soc. Agr. Engr., St. Joseph, Mich.

Bishop, R. A. 1981. *Iowa's Wetlands*. Proceedings, Iowa Academy of Science, Vol. 88, pp. 11-16.

Brewster, John M. 1958. "Technological Advance and the Future of the Family Farm," *Journal of Farm Economics*, Vol. 40, pp. 1,596-1,612.

Carstensen, Vernon. 1958. *Farms or Forests*. College of Agriculture, Univ. of Wisconsin, Madison, July, p. 6.

Cowardin, Lewis M., Virginia Carter, Francis Golet, and Edward LaRoe. 1979. *Classification of Wetlands and Deepwater Habitats of the United States*. U.S. Dept. Int., Fish and Wildlife Serv., p. 103.

Diedrick, R. T. 1980. *The Agriculture Value of Wet Soils in the Upper Midwest*. Staff paper, U.S. Dept. Agr., Soil Cons. Serv., St. Paul, Minn.

Dudek, Daniel, and Gerald L. Horner. 1981. "Return Flow Control Policy and Income Distribution Among Irrigators," *American Journal of Agricultural Economics*, Vol. 63, No. 3, pp. 439-446.

English, Burton C., James A. Maetzold, Brian R. Holding, and Earl O. Heady. 1984. *Future Agricultural Technology and Resource Conservation*. Proceedings of the RCA Symposium: Future Agricultural Technology and Resource Conservation. Ames, Iowa: Iowa State Univ. Press.

Frayer, W. E., T. J. Monahan, D. C. Bowden, and F. A. Gaybill. 1983. *Status and Trends of Wetlands and Deepwater Habitats in the Conterminous United States, 1950's to 1970's*. U.S. Dept. Int., Fish and Wildlife Serv., p. 32.

Fredrickson, L. H. 1981. Paper prepared for the House Subcommittee on Fisheries and Wildlife.

Fritz, J. C., Gerald Horner, and J. H. Snyder. 1980. *The Economic Feasibility of Installing Subsurface Tile Drainage in the Panoche Water District, San Joaquin Valley, California*. Information Series 80-3, Giannini Foundation of Agricultural Economics, Univ. of California.

Goldstein, Jon. 1971. *Competition for Wetland in the Midwest: An Economic Analysis*. Resources for the Future, Inc. Baltimore: The Johns Hopkins Press.

Hanson, L., and W. E. Larson. 1983. "Frontiers in Soil Science: The Next Twenty Years," *Minnesota Science*, Vol. 38, No. 3, pp. 2, 3, 14.

Harrison, Robert W. 1981. *Alluvial Empire: A Study of State and Local Efforts Toward Land Development in the Alluvial Valley of the Lower Mississippi River*. Little Rock, Arkansas: Pioneer Press.

Heathcote, J. M. 1876. *Reminiscences of Fen and Mere*. London: Longmans, Green & Co.

Heimlich, Ralph E. 1986. Personal compilation of land use capability subclass "w" land by types of wetland; data from the 1982 National Resources Inventory.

Horner, G., and D. J. Dudek. 1980. "An Analytical System for the Evaluation of Land Use and Water Quality Policy Impacts upon Irrigated Agriculture," *Operations Research in Agriculture and Water Resources*. Amsterdam: North Holland Publishing Co., pp. 537-568.

Horner, G. L., C. V. Moore, and R. E. Howitt. 1983. "Increasing Farm Water Supply by Conservation," *California Agriculture*, Vol. 37, Nos. 11 and 12, pp. 6-7.

Johnson, G. L., and S. H. Wittner. 1984. *Agricultural Technology Until 2030*. Special Report No. 12, Mich. Agr. Expt. Sta., East Lansing.

Kanwar, R. S., H. P. Johnson, D. Schult, T. E. Fenton, and R. D. Hickman. 1983. "Drainage Needs and Returns in North Central Iowa," Transactions of the ASAE, Vol. 26, No. 2, pp. 457-464.

Korte, P., and L. H. Fredrickson. 1977. "Loss of Missouri's Lowland Hardwood Ecosystem," *Transactions of North American Wildlife and Natural Resources Conference*, Vol. 42, pp. 31-41.

Kruse, E. Gordon, Chuck R. Burdick, and Yousef A. Yousel (co-editors). 1982. *Environmentally Sound Water and Soil Management*. New York: Am. Soc. Civ. Engr.

Lauer, T. E. 1959. "District Control of Water Resources," *University of Detroit Law Journal*, Vol. 37, No. 1, pp. 28-35.

Leitch, Jay A., and Daniel Kerestes. 1981. *Agricultural Land Drainage: Costs and Returns in Minnesota*. Staff Paper P 81-15, Dept. Agr. and Appl. Econ., Univ. of Minnesota, St. Paul.

Leitch, Jay A., and D. P. Scott. 1977. "Economic Impact of Flooding on Agricultural Production in Northeast Central North Dakota." Agr. Econ. Rpt. No. 120, Dept. Agr. Econ., No. Dak. Agr. Exp. Sta., Fargo.

Leopold, Aldo. 1949. *A Sand County Almanac.* Oxford Univ. Press.

Lu, Yeo-Chi, and Leroy Quance. 1979. *Agricultural Productivity: Expanding the Limits.* AIB-431. U.S. Dept. Agr., Econ. Res. Serv.

Lu, Yeo-Chi, Philip Cline, and Leroy Quance. 1979. *Prospects for Productivity Growth in U.S. Agriculture.* AER-435. U.S. Dept. Agr., Econ. Res. Serv.

Maetzold, Jim, Thyrele Robertson, Klaus Alt, Neill Schaller, and Tom Dempster. 1983. "Issue Paper for Basic Assumptions Work Group: Agricultural Production Technology Estimates for the RCA and RPA Process." U.S. Dept. Agr., Econ. Res. Serv.

McLean, J. J. P., and G. O. Schwab. 1983. "Flood Peak Flows and Subsurface Drainage." ASAE Paper No. 82-2053, Am. Soc. Agr. Engr., St. Joseph, Mich.

Murray, William G. 1953. *Appraisal of Potawatomi Tracts in Iowa and Kansas, 1846.* Prepared for the U.S. Dept. Justice. Ames, Iowa.

National Research Council. 1982. *Impacts of Emerging Agricultural Trends on Fish and Wildlife Habitat.* Wash., DC: National Academy Press.

Nolte, B. H., and R. D. Devick. 1984. "Economic Factors of Drainage Related to Corn Production," *National Corn Handbook.* Coop. Ext. Serv., Ohio State Univ., Columbus.

Pavelis, George A. 1978. *Natural Resource Capital Stocks: Measurement and Significance for U.S. Agriculture Since 1900.* Abstract No. 199, Proceedings of the American Association for the Advancement of Science. AAAS Pub. 78-2.

Redelfs, Ann Ellen. 1983. "Wetland Values and Losses in the United States." M.S. thesis, Oklahoma State Univ., Stillwater.

Rosenblum, John W. (editor). 1983. *Agriculture in the Twenty-first Century.* New York: John Wiley and Sons.

Ruttan, Vernon W., Robert E. Evenson, and Paul E. Waggoner. 1979. "Economic Benefits from Research: An Example from Agriculture," Science, Vol. 205, pp. 1,101-1,107.

Schrader, T. A. 1955. "Waterfowl and the Potholes of the North Central States," *Water: Yearbook of Agriculture, 1955.* U.S. Dept. Agr., pp. 596-604.

Schwab, G. O., N. R. Fausey, and C. R.Weaver. 1975. *Tile and Surface Drainage of Clay Soils.* Ohio Agr. Res. and Dev. Ctr., Wooster.

Schwab, G. O., B. H. Nolte, and M. L. Palmer. 1981 and 1982. *Drainage—What is it Worth on Corn Land,* and *Drainage—What is it Worth for Soybeans Land?* Soil and Water Series Nos. 23 and 24, Agr. Engr., Ohio State Univ., Columbus.

Skaggs, R. W., and A. Nassehzadeh-Tabrizi. 1983. *Optimum Drainage for Corn Production.* Tech. Bul. No. 273, North Carolina Agr. Res. Serv., State Univ.. Raleigh.

Stone, Christopher. 1976. *Toward Legal Rights for Natural Systems.* Proceedings from the 41st North American Wildlife Conference, Wash., DC, pp. 31-38.

Summers, Dorothy. 1976. *The Great Level, A History of Drainage and Land Reclamation in the Fens.* North Pomfret, Vermont: David and Charles.

Tiner, Ralph W. 1938. *Wetlands of the United States: Current Status and Recent Trends.* U.S. Dept. Int., Fish and Wildlife Serv.

Turner, Henry Jackson. 1938. "The Significance of the Frontier in American History." Presented at Am. Hist. Assoc., July 12, 1938. In *The Early Writings of Frederick Jackson Turner.* Freeport, N.Y.: Books for Libraries Press.

U.S. Congress, Office of Technology Assessment. 1984. *Wetlands: Their Use and Regulation.*

U.S. Congress, U.S. Department of Agriculture. 1980. "Soil, Water and Related Resources of the United States: Analysis of Resource Trends." Part II, 1980 RCA Appraisal.

U.S. Department of Agriculture. 1938. *Soils and Men: Yearbook of Agriculture, 1938.*

U.S. Department of the Interior, Fish and Wildlife Service. 1972. *Wetlands of the United States.* Circ. No. 39.

van Schilfgaarde, Jan. (editor). 1974. *Drainage for Agriculture.* Monograph No. 17, Am. Soc. Agronomy, Madison, Wisc.

Weller, Milton W. 1981. "Estimating Wildlife and Wetland Losses Due to Drainage and Other Perturbations," Jour. Paper No. 1794. Minn. Agr. Exp. Sta., St. Paul.

Wooten, Hugh H., and Lewis A. Jones. 1955. "The History of Our Drainage Enterprises," *Water: Yearbook of Agriculture, 1955.* U.S. Dept. Agr., pp. 478-491.

Chapter 2

A History of Drainage and Drainage Methods

Keith H. Beauchamp
Consulting Drainage Engineer
Soil Conservation Service Engineer (ret.)
Jacksonville, Illinois

From earliest days, mankind has devised ways of managing water by various means involving its supply, removal, or regulation. Archeological studies indicate that land drainage began thousands of years before the Christian era. In one account van Schilfgaarde (1971) reported that water management for agricultural purposes could be traced to Mesopotamia some 9,000 years ago. Herodotus, a Greek historian of the fifth century B.C., wrote that on a voyage to Egypt, the priests there told him of drainage work around the ancient city of Memphis, accomplished by Min, the first king of Egypt.

This chapter documents how farm drainage has evolved from the contributions of various civilizations and individuals, first in the Old World and then in the United States. These original developments are the context of the subsequent discussion of present-day technologies by Fouss and Reeve.

The Early Background

About 400 B.C., the Egyptians and Greeks drained land using a system of surface ditches to drain individual areas. The oldest known engineering drawing, illustrated on Egyptian papyrus around 250 B.C., is a Greek plan of a rectangular ditching system. It is preserved at the University of Lille in France (Sutton, 1958).

Historic evidence indicates that serious drainage problems developed in irrigated areas. A major reason for the decline and disappearance of some ancient civilizations based on irrigation was their failure to heed the drainage hazard (Donnan, 1976).

Marcus Porcius Cato, 234 to 149 B.C., apparently wrote the first specific directions for draining land. A Roman statesman and orator and also the first important Latin prose writer, Cato, late in life turned to agriculture and farmed on a large scale. His only complete surviving work is a treatise on agriculture written about 160 B.C. Manley Miles (1892) quotes Cato:

> In the winter it is necessary that the water be led off from the fields. On a declivity it is necessary to have many drains. When the first of the autumn is rainy there is a great danger from water; when it begins to rain the whole of the servants ought to go out with sarcles, and other iron tools, open the drains, turn the water into its channels, and take care of the corn fields, that flow from them. Wherever the water stands amongst the growing corn, or in other parts of the corn fields, or in the ditches or where there is anything that obstructs its passage, that should be removed, the ditches opened, and the water let away . . . If the place is wet, it is necessary that the drains be made shelving, three feet broad at the top, four feet deep, and one foot and a quarter wide at the bottom. Lay them in the bottom with stones. If there are no stones to be got, lay them with green willow rods, placed contraryways; if rods cannot be got, tie twigs together.

The Romans first used open drains to remove ponded surface water; closed drains soon followed for removing surplus water from the soil itself. Placing a layer of gutter or house tile face up in the bottom of the drain to prevent washing was recommended for covered drains. The trenches were then half filled with stones or gravel or bundles of brush fitted together. The rest of the trench was filled in with the excavated material. These Romans were apparently the sole authorities on land drainage, and their methods were used with little improvement for more than 1,000 years. Donnan (1976) reported that the Roman Empire's easternmost province of Panonia had drainage ditches constructed in the third century A.D. which are still functional. The Romans drained the Po, Arno, and Tiber Valleys and exported their knowledge of drainage to colonies in North Africa and Asia Minor. Later writers generally followed Cato's recommendation with some improvements and variations (Weaver, 1964).

The European Heritage

Weaver (1964) reported on a 1770 discovery in England of an underground drain in Sussex County filled with alder branches, probably built about 1400 A.D. The reclamation of the English fens is discussed by Pickels (1925), Donnan (1976), and in an unpublished paper by Elmer Gain, a former drainage engineer in SCS. Gain lists Wheeler (1868) and Darby (1940) in his references. The English fens cover an area of about 680,000 acres on the east coast of England. This area originally consisted of fresh and tidewater peat marshes, frequently flooded by storm tides from the North Sea and the overflow from several converging rivers. The land is now protected from the sea by dikes and levees. Interior drainage is through numerous ditches leading to the dikes, where water is raised and discharged by pumps.

The Romans were the first to install drainage in Britain with considerable success. However, their works generally deteriorated after their occupation ended.

About 1250 A.D., work began in England to prevent flooding. About 1500, the first large design for drainage was started. An Act of Parliament in 1600 provided for the reclamation of hundreds of thousands of acres of marshes. However, the drained peat land subsided over time and natural flow was no longer possible by 1700.

Windmills were used to pump the water from small dikes to a main drain and from the drain to the rivers, probably starting about 1640. Eventually flows from the rivers were pumped against the tide into the sea. About 1820, the steam engine began replacing the windmill. Drainage improvements continued during the 19th and 20th centuries. The fens are now a prosperous agricultural region.

The practice of building dikes to protect and reclaim lands along the lower reaches of the rivers and sea coasts abounds in most of northern Europe. Probably the most important and successful drainage works of this nature are in The Netherlands (Donnan, 1976).

Approximately two-fifths of The Netherlands lies below sea level. Without protection by dikes and dunes, these areas would be inundated by tides twice daily. In the first century A.D., the inhabitants of these marsh areas built extensive mounds to live on. Attempts to secure greater protection by building dikes were made in the eighth and ninth centuries. By 1300, various regions of the nation's coastal belt were enclosed by dikes as protection against either the sea or rivers. Up until 1450, bursting dikes devastated many villages or caused whole areas to disappear. Better dike placement and construction have since provided more successful reclamation projects.

A problem from protective embankments that arose almost immediately in Holland was the need for also removing excess precipitation. Since the 13th century, a complicated organization of landholders gradually developed to deal with this problem. Small tracts of land reclaimed by dikes, known as polders, were directly or indirectly used as storage basins for collecting this water, which was then pumped to the sea or rivers by windmill power.

In 1839, the Government of Holland began draining Haarlem Lake (Pickels, 1925). The original plans for this project, calling for windmills, had been developed by Leeghwater some 200 years before. The lake was about 15 miles long, 8 miles wide, 13 feet deep, and covered about 44,000 acres, with the lake bottom below sea level. It was emptied by large pumps after being enclosed by a dike. The work was completed in 1848. The bottom of the former lake is now cultivated and provides homes for several thousand people. Large pumps are used to remove the interior drainage water from open ditches.

Pickels also notes that several similar large projects were carried out in France, including the La Gironde project, with about 1.5 million acres, and the Forez project, with about 140,000 acres.

Early Methods and Materials

Subsurface drainage conduits made of sticks, brush, and stones were generally used in Europe until at least the 17th century. However, Weaver (1964) suggested that clay tiles similar to those used today may have been used at the time of Christ. French farmers are generally credited with being the first to use clay tile for farm drainage purposes. They used a modified form of medieval clay roofing tile. This type of tile drainage was used at least into the 14th or 15th centuries.

Weaver indicated that in the garden of the Monastery of Maubeuge, in France, a system of pipe drains was discovered laid at a depth of 4 feet throughout the whole garden. This work had probably been completed before 1620. About 10 inches long and 4 inches in diameter, these pipes are the first known cylindrical tile drains. These types of early clay drain tile became forgotten for generations.

In Britain, the use of tile drainage has been traced at least to the 15th century, but it seems that interest in drainage waned after the decline of the Romans; its potential was "rediscovered" in the 18th century (van Schilfgaarde, 1971).

A horseshoe-shaped tile was the first form of clay tile drainage used in England. The tiles formed a simple arch or tunnel when placed open side down, end to end, along the bottom of a trench and covered with soil. Later, these horseshoe tiles were placed on a flat piece of burned clay or pallet the length and width of the tile. The pallet protected the bottom of the trench and made a closed conduit for the water to flow through. These tiles were handmade and consequently very costly. Weaver (1964) reported on the use of horseshoe tile laid in 1760 on the Grandbury estate in Suffolk, England.

Cylindrical drainage pipes were first manufactured in England in 1810 by John Reade, a gardener at Horsemenden. His handmade tiles were a great improvement over the old brush and stone drains and proved more popular than horseshoe drains. A machine for making clay tile was invented in 1840; it became the forerunner of a clay pipe extruder patented in 1843. This new machine greatly reduced the cost of drain tile and led to its increased use. Portland cement was first used to make drain tile in 1830 (Donnan, 1976).

Mole drainage was also used centuries ago in Europe. This was accomplished by a machine known as a mole ditcher. It consisted of a bullet-nosed steel cylinder attached to some type of wheel frame or plow. The ditcher was pulled by oxen through the soil to form a tunnel to carry away drainage water (King and Lynes, 1946).

Drainage in the United States

American farmers have drained their lands since the early days of settlement. Land drainage has been an important factor in developing our Nation and increasing farm wealth. Even urban development has depended upon drainage. In New York City, for example, Central Park was drained in 1858, primarily for public health purposes.

Colonial Period

Events and developments in Europe from the close of the 15th through the 17th centuries set the groundwork for American drainage practices. Early settlers in America brought European drainage methods with them, such as small open ditches to drain wet spots in fields and cleaning out small streams. At first only small, scattered areas were drained by the individual owners. Extensive drainage outlets beyond individual property boundaries were at first seldom necessary along the eastern seaboard. There was one notable exception: in 1754, the Colony of South Carolina passed an act for draining the Cacaw Swamp.

In 1763, the Dismal Swamp area of Virginia and North Carolina was surveyed by George Washington and others with a view to land reclamation and inland water transportation. In 1778, while Washington was President, the Dismal Swamp Canal Company was chartered by Virginia and North Carolina.

The first known colonywide drainage law was enacted in New Jersey on September 26, 1772, and re-enacted in the new State constitution on July 2, 1776. A drainage outlet for the City of New Orleans was constructed around 1794 (Gain and Patronsky, 1973). Early drainage works also were constructed in Delaware, Maryland, New Jersey, Massachusetts, South Carolina, and Georgia, under the authority of colonial and State laws.

American farmers increasingly found that large outlets beyond individual farm boundaries were necessary to provide proper farm drainage. The construction of such outlets has been facilitated greatly by the establishment of drainage districts, county drains, or other drainage enterprises organized under State laws. These outlets have been effective in draining large areas in the coastal plains, the upland prairies of the midwestern farm States, lake plains, and along many streams and river bottoms.

The first onfarm drainage involved only small open ditches. However, although ditches might make it possible to cultivate the land, they did not lower ground-water tables fast enough after rains to permit the land to produce a maximum yield of crops. The shallow ditches were seldom deep enough to intercept hillside seepage. But if more ditches were used they occupied too much land. The solution was to have small covered drains emptying into open ditches, thus permitting the land over the drains to be cultivated.

Early settlers in New York and New England used subsurface drainage in addition to open ditches. Material used for buried drains prior to the use of tile included poles, logs, brush, lumber of all sorts including sawmill slabs, stones laid in various patterns, bricks, and straws. The latter was sometimes twisted into rope by a special machine. Logs were either bored or split with the inside scraped out. Concrete made of hydraulic cement, lime (which hardens under water), and coarse sand was also used to shape a conduit. The only limit to the type of material or method of use was the imagination of the user. Weaver's book (1964) has many sketches on how these drains were constructed.

Drainage Moves West

By the 1850's, population pressure and a need for more and better farmland than was available on the eastern seaboard precipitated full-scale settlement of the Ohio and Mississipppi River Valleys. In its natural state, much of the fertile land in northwestern Ohio, northern Indiana, north-central Illinois, north-central Iowa, and southeastern Missouri was either swamp or frequently too wet to farm.

What these tracts were once like is described in the report on Long's expedition to the source of the St. Peter's River in 1823. Sutton (1957) quoted from a part of this report as follows:

> Near to this house we passed the state line which divides Ohio from Indiana. . . The distance from this to Fort Wayne is 24 miles, without a settlement; the country is so wet that we scarcely saw an acre of land upon which a settlement could be made. We traveled for a couple of miles with our horses wading through water, sometimes to the girth. Having found a small patch of esculent-grass (which from its color is known here by the name of bluegrass), we attempted to stop and pasture our horses, but this we found impossible on account of the immense swarms of mosquitos and horse flies. From Chicago to the place where we forded the Des Plaines, the country presents a low, flat and swampy prairie, very thickly covered with high grass, aquatic plants, and among others the wild rice.

Pickels (1925) noted that Government Land Office records show that one-fourth of Illinois and still larger portions of other States were swampland. Twenty-one counties in northwestern Ohio and northeastern Indiana included much low land originally too wet to cultivate. At the time of settlement, much of the land in north-central Iowa was in shallow sloughs too wet for normal cultivation. Large areas in western Minnesota, northeastern Arkansas, the gulf plains of Texas, and the delta areas of Mississippi and Louisiana were originally swamp and overflow areas. Drainage permitted cultivation of these areas (Wooten and Jones, 1955).

Hay and Stall (1976) reported on the development of surface drainage in east-central Illinois covering a basin of 1,250 square miles in parts of Ford, Champaign, and Vermilion Counties. To quote from their report on early conditions of areas in the north-central States:

> "In its natural state, east-central Illinois was a wide flat of gently rolling swampy expanse covered with tall bluestem and cord grass. Forested areas of various sizes were found along the three river channels, North Fork, Middle Fork, and Salt Fork in the Vermilion watershed. Some trees also grew along the tributary creeks. All early settlements were located in these wooded areas along the streams. The prairies were of little interest to early settlers, but presented formidable barriers to be crossed. A Vermilion County history . . . describes the 'raw prairies with miles and miles of swamps with a heavy wild grass, and there was no drainage at all. Streams had worn no channels for the water courses.' The swampy land was considered worthless for farming, but was grazed by cattle in dry seasons. It was only after outlet channels were opened that the swampy areas could be tiled and cultivated.
>
> "Life in the early settlements of this region was hard, especially near the swamps. Problems of human health were frequently reported in the records. There were epidemics of malaria with 'severe sickness and fatalities without exception.' One senior citizen in Cham-

paign County told of illness due to malaria in her family every summer and fall as late as 1900. Accounts also tell of cholera, milk sickness, ague, and fever. Plagues of mosquitoes and flies were also reported. It is easy to understand the account of the young man who refused to trade his horse and saddle for a full section of swampy land in that period. At 1976 prices a 640-acre tract would sell for more than a million dollars.

"Transportation at the time of the early settlements was extremely difficult. The early trails followed the glacial moraine ridges whenever possible. The lowlands were impassable in wet seasons, and bridges across the streams were few and far between. Reports tell of travel by boat across lower areas and skating for miles in winter. An 1867 map of Vermilion County, which was well settled at that time, shows no 'through roads.' They generally extended a few miles from a town past several farmsteads, only to come to a dead end at some farm...

"Thus problems of health and transportation as well as agriculture crippled by poorly drained fields existed in this region through the early years of settlement. Satisfactory solutions were not achieved until 'hundreds of miles of ditches and thousands of miles of tile drains' were installed on the land. This area now ranks as the most productive land in Illinois and in the entire Cornbelt."

The Swamp Land Act

Beginning about 1830, increased public pressure was brought on Congress to release for private development large areas of swamp and wetlands still owned by the Government. After 20 years of deliberation, Congress passed the Swamp Land Acts of 1849 and 1850. These were the first important pieces of Federal legislation relating to land drainage. The Acts granted nearly 64 million acres to Louisiana in 1849, and to 14 other States in 1850 and 1860. These vast areas of swampy and overflow lands went to the States on condition that funds from their sale be used to build the drains and levees necessary to reclaim them. No important reservations were attached to this transfer, and the States were free to dispose of the land as they saw fit (Wooten and Jones, 1955; Harrison, 1961).

The States did not immediately develop the lands as anticipated. State legislatures, facing the same dilemma as Congress, passed the holdings on to the counties for sale to private owners and corporations. After 20 years of experimenting, landowners learned of the great costs in reclamation work. Little or no progress occurred in land sales until State laws permitted organization of drainage and levee districts, or allowed county governments to establish projects with the consent of the majority of beneficiaries.

Figure 2-1—The Little River Drainage District's flooding ditches seen north from the Cotton Plant Road, Dunklin County, Missouri.

An early example of such a project was the Little River Drainage District in southeastern Missouri. This district, 90 miles long and from 4 to 30 miles wide, contained about 500,000 acres of rich alluvial land. The district provided outlets into the Mississippi River for an additional 614,000 acres and a diversion system for discharging runoff from another 750,000 acres of Ozark highlands.

First petitioned in 1905, the Little River District was incorporated in 1907 after lengthy court litigation. Construction lasted from 1914 to 1929. A headwater diversion system with 50 miles of channel and 40 miles of levees was built by dragline. The interior drainage outlet channels, 887 miles in length, were originally built with floating dredges and were later maintained by draglines. Almost 88 million cubic yards of earth were moved in constructing the channels and levees. The required $11-million construction cost was raised by the sale of bonds, which were redeemed by taxes assessed on 436,000 acres. The Corps of Engineers provided protection from the Mississippi River floods with levees and floodways along the river (fig. 2-1) through which district drainage was discharged (Gain and Patronsky, 1973).

In the lower Mississippi Valley States, administering swampland funds was a major political, economic, and social issue for more than 30 years. State and Federal legislators alike underrated the complexity and cost of flood control and drainage in the area. Receipts from the sale of swamplands were a pittance compared with the cost of flood control and drainage. The experience in flood control and drainage engineering gained in trying to meet the provisions of the grants formed the basis for large drainage projects subsequently undertaken by local districts, the States, and the Federal Government. Many of the legal and administrative concepts and procedures developed under the Swamp Land Acts became imbedded in later flood control and drainage projects (Wooten and Jones, 1955).

Reclamation and Other Federal Programs

With the Reclamation Act of 1902 began the gradual reversal of the Swamp Land Act precedent of only State and local involvement in land reclamation. The Reclamation Act, in setting up the Bureau of Reclamation, resulted in the establishment of a drainage specialist position and staff in USDA. This specialist's first duty was to investigate drainage methods to correct alkali damage caused by irrigation water seepage. Within 2 years, these duties were enlarged to include other drainage problems. Thus, what was USDA's Bureau of Agricultural Engineering (BAE) became involved in agricultural drainage.

During the 1920's and 1930's, the Depression and unforeseen difficulties in developing lands forced many drainage enterprises to default on their debts and generally neglect maintenance work. The capacity of many systems was insufficient to provide good drainage. Many farms within project areas were sold for taxes or mortgage foreclosure.

In 1935, Congress authorized the Reconstruction Finance Corporation to refinance drainage and irrigation districts in distress. This assistance enabled districts in 26 States to continue operations during the Depression. Drainage enterprises also received assistance through Civilian Conservation Corps (CCC) camps and other Federal relief agencies.

In 1935, the BAE became responsible for 46 CCC camps involved in the rehabilitation and reconstruction of drainage improvements organized under State drainage laws. In December 1938, responsibility for the CCC camps as well as other drainage activities in USDA was then assigned to the SCS.

Figure 2-2—Drainage rehabilitation work occurred during the Depression thanks in part to the Civilian Conservation Corps.

Drainage work carried on by the CCC (fig. 2-2) and other public works programs played an important part in conditioning drained land for the needed great expansion in agricultural production during and following World War II (Sutton, 1957). In 1941, drainage and irrigation work had been approved by USDA as conservation practices to be included in farm conservation plans.

The Flood Control Act of 1944 authorized the Corps of Engineers to construct major drainage outlets and flood control channels. This work encouraged the organization or reactivation of many drainage districts, particularly in the Mississippi River Valley, in order to improve local drainage ditches and reap the benefits of better outlet drainage. In 1954, the Federal Watershed Protection and Flood Prevention Act (P.L. 83-566) authorized USDA to plan and construct various watershed works of improvement, including drainage outlet channels, in cooperation with State and local governments. Working through local soil conservation districts, SCS provided technical assistance on farm drainage measures and practices in farm conservation plans. These measures have included field ditches, subsurface drains, structures to admit water into ditches to prevent erosion, protection of tile outlets, and development of surface field drainage.

Drainage of Western Irrigated Lands

In personal communication (1984), William W. Donnan, consulting drainage engineer, Pasadena, California, offered this account of some of the history of drainage in the arid West:

> "Drainage problems were an almost inevitable consequence of irrigation development in the arid west. One can trace the ancient irrigation canals out of the Salt River in Arizona, near present day Phoenix. These canals were built by the Hohokam Indians in about 900 A.D. Their lands eventually became waterlogged and the only vestige of their occupation in the area is the Casa Grande Monument. It is interesting to note that by 1911, with the completion of Roosevelt Dam, the Salt River Valley was again developed for irrigation. Drainage soon became a problem once more! In 1918, a study by James Marr showed that pumping would lower the water table. By 1922 over 100,000 acre feet of ground water was being pumped and the drainage problem was eliminated.
>
> "Other western irrigation projects quickly evidenced a need for drainage remedial measures. The Newlands Project in Nevada, the first project ever developed by the Bureau of Reclamation, became so waterlogged that much of the land was unfit for cropping. M.R. Lewis and Sidney Harding made an investigation which prescribed open drains to combat the problem. Samuel Fortier and V.C. Cone made investigations of the drainage problems in the San Joaquin Valley of California in 1905 and 1906. As a result, from 1907 to 1922, the Modesto Irrigation District spent $356,000 to construct an open, gravity system for 45,000 acres. Later they resorted to pumping for drainage, installing 77 wells. The pumped water was used to irrigate additional acres of land. W. L. Powers made investigations of methods for draining the marsh lands of Western Oregon in 1916-18. At the same time Dean Bloodgood demonstrated that pumping for drainage in the Mesilla Valley of New Mexico was successful.
>
> "Perhaps the grand-daddy of all drainage problems in the early days of the irrigated west was the Imperial Valley of California. Irrigation was first brought into the valley in 1901 from the Colorado River. A U.S. Department of Agriculture Soil Survey of 1902 called attention to the potential drainage hazard. In 1908 C.E. Tait recommended the need for drainage remedial measures on some of the waterlogged areas. By 1919 some 200,000 acres were in some degree affected by high water tables and salt accumulation. In 1921, the Imperial Irrigation District started construction on an open drain system costing $2,500,000. This system was only partially successful but it did provide an excellent outlet system for the subsequent tile drainage systems on the individual farms. In 1929 the District purchased a tile laying machine and installed the first 5 miles of tile drains. Subsequently drainage contractors came into the Valley to perform this service. For many years over 200 miles of drains were installed each season. Today over 80 percent of the cropland is tile or tube drained.
>
> "Almost all of the Bureau of Reclamation Irrigation Projects have had to provide for drainage remedial measures. Projects such as the Columbia Basin in Washington, the Grand Valley (Nebraska), Big Horn Basin (Montana and Wyoming), Oahe (South Dakota), Weber Basin (Utah), Garrison (North Dakota), Big Thompson (Colorado), have all had drainage problems as a consequence of irrigation enterprise."

Materials and Methods for Subsurface Drainage

The first use of clay tile for underground farm drainage in the United States is attributed to John Johnston, a native of Scotland who lived in the Finger Lakes region of New York State, near Geneva. Weaver (1964) records that Johnston imported patterns for horseshoe-type drain tile from Scotland in December 1835. Tiles were made from these patterns at the B.F. Whartenby pottery at Waterloo, New York, in 1835. The first tiles were made entirely by hand out of plastic clay rolled into sheets about a half-inch thick. These sheets were cut into rectangles of the desired size and bent over a pole in the shape of a horseshoe; they were allowed to air-dry and then baked in a kiln.

Clay Tile Fabrication

A crude molding machine installed in the Whartenby factory in 1838 made the process of making tile much cheaper and faster. Then, sometime after 1851, John Dixon developed a much-improved machine for making horseshoe tile. Dixon also introduced numerous other improvements in tilemaking. In 1866, he invented the Down Draft Inside Flue tile kiln.

Another new method of tilemaking appeared in the 1870's that did not use a conventional mold. It employed a rectangular slab of clay, which was pressed around the lower part of the workman's leg to form a horseshoe tile. The piece was then air-dried and baked in a kiln. Quite naturally it came to be called a shinbone tile.

Around 1875, pipe-tiles were made by forming the clay mortar around a pole. A pole of the desired diameter for the inside of the pipe was covered by about a half-inch layer of clay mortar and then smoothed to a circular outside shape. The pole was withdrawn and the resulting pipes then cut to the desired lengths, cured, and baked.

The first tilemaking machine, the "Scraggs" was brought to America in 1848 from England. This machine operated on the extrusion process. Many locally manufactured tilemaking machines followed the Scraggs machine. Most of these early manufacturers were located in New York State. These new machines increased the efficiency of production of clay tile and reduced its cost, an important factor in spreading the use of tile drainage. The manufactured clay tile might be a horseshoe tile; a circular tile called a pipe tile or pipe drain; or a sole tile. The latter was circular with an attached plate or sole. Tile lengths varied from 12 to 15 inches. Weaver (1964) listed advertised tile prices in the period 1849-62 for 1,000 pieces as follows: 3-inch horesehoe tile at $10.00 to $12.50 and 4-inch horseshoe at $12.15 to $15.00; 3-inch pipe tile at $14.00 to $15.00 and 4-inch pipe tile at $16.00 to $40; 3-inch sole tile at $16.20 and 4-inch sole tile at $20.25. The price of plates for horseshoe tile was about $6.00 to $8.00 per 1,000. These prices were at the factory; when shipping charges were added, the average total cost was around $25.00 for 1,000 pieces. Trenching costs generally varied from 12 to 14 cents per rod (16.5 feet).

From these beginnings, the manufacture and installation of tile spread westward. By 1882, the number of tile factories had increased rapidly, with 486 in Indiana, 320 in Illinois, 230 in Ohio, 63 in Michigan, 18 in Iowa, and 13 in Wisconsin. By 1867, the center of tile manufacture had moved from the east to the Midwest (Weaver, 1964). By 1867, Ohio produced over 2,000 miles of drain tile per year, mostly from 500 steam-powered tile plants (Alpers and Short, 1966).

Figure 2-3—A Newton County, Indiana, farmer carefully positions spade to take out the top cut in a drainage ditch.

Concrete Tile

Weaver (1964) also wrote of some early uses of concrete for subsurface drainage. In 1862, David Ogden developed a machine for making drain pipes from cement and sand. This machine could make pipe with an inside diameter of 2-1/4 inches to 24 inches. Another idea used was to place concrete in the trench around a glass liner. The liner was 1-3/4 inches in diameter and 22 inches long. By 1881, concrete tile was maunfactured in place by means of a simple machine operated in a properly graded ditch. Cement mortar was fed into the machine through a hopper. It came out of the machine as a continuous pipe, smooth inside and out. The pipe was cut into any desired length in such a way that the bottom was left continuous, yet sufficient crevices were left for the entrance of water.

Until 1900, concrete drain tile was used primarily where good clay was not available. A concrete tile plant could be built for a fairly small investment. At first the industry was largely confined to scattered plants operated by individuals. Some operators lacked previous experience in drainage or in the manufacture of concrete products, and the result was poor quality tile. This was generally due to skimping on the amount of cement, to using of dirty or improperly graded sand and gravel, or to inadequate curing facilities. However, many large manufacturers of concrete sewer pipe made good-quality drainage pipe.

In the 1950's, when ACP permitted cost-sharing payments for underground tile drainage, the tile had to meet American Society for Testing Materials (ASTM) specifications. This rule and related educational activities were important in assuring the manufacture of good-quality clay and concrete tile. For example, Miller and Manson of the University of Minnesota recommended that where soil acids and sulphates were a problem, the concrete tile should be made with a cement having high sulphate resistance. Figures 2-3, 2-4, and 2-5 show some tile-laying operations typical of 1940.

Fiber and Plastic Tubing

In the 1940's, bituminized fiber pipe was used in some locations, especially in the Eastern States. Early-generation plastic tubes were also introduced for subsurface drains. But because these had to be thick-walled to provide proper bearing strength, their cost was not competitive with clay or concrete tile.

Figure 2-4—Workers lay 6-inch tile in New York State.

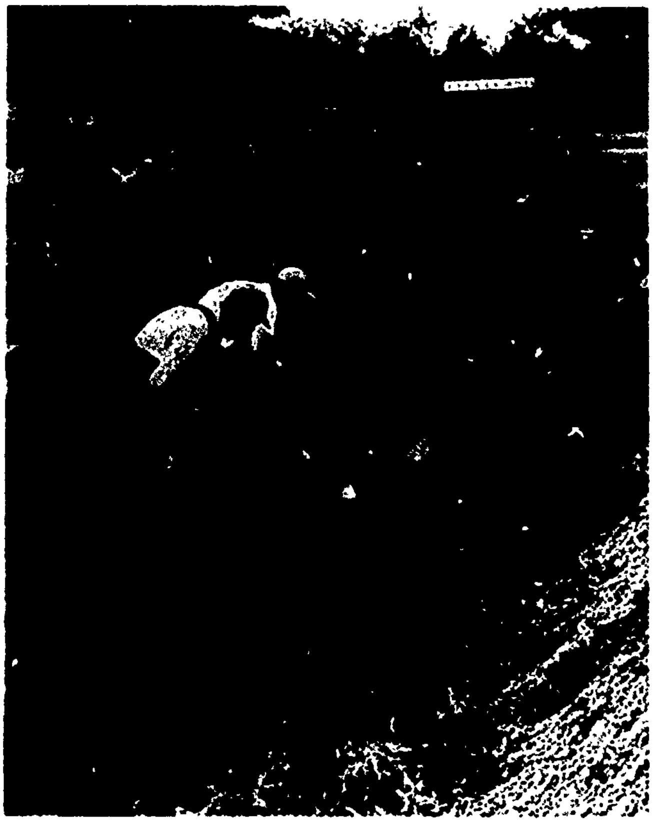


Figure 2-5—With mechanical help, workers lay tile. Hay is blinded over the title joints to reduce siltation in sandy soil to improve drainage.

By the early 1960's, corrugated plastic tubing was manufactured from polyvinyl and polyethylene resins. The corrugations provided sufficient bearing strength to allow a thin-wall configuration, and also at a competitive cost. When buried, this tubing was not subject to deterioration from ultraviolet rays, acids, or alkali solutions. It could be extruded in a continuous tube and packaged into a lengthy coil. Very light and flexible, it drastically reduced handling and shipping costs, and tile alignment problems were avoided.

As the demand for corrugated plastic tubing increased, many large tile manufacturing plants closed. Some converted to making tubing or brick. The high cost of operating and rebuilding the smaller plants caused most of them to close or convert to making small-size corrugated plastic tubing. As most subsurface drainage systems presently being installed involve the use of corrugated tubing, its evolution and uses are discussed at more length by Fouss and Reeve in the next chapter.

Drain Envelope Materials

Soil particles entering and clogging subsurface drains have been a problem since the beginnings of tile drainage. In an early drainage textbook by French (1859), a recommended method of preventing drain sedimentation used double-walled or sheathed drains with collars; a second method surrounded the drain with clean, fine gravel. Over the years, envelope materials used for surrounding subsurface drainage conduits have included many kinds of permeable porous materials that are readily available in large quantities and are relatively economical.

According to Willardson (1974), the primary purposes for the drain envelope are: (1) to prevent the movement of soil particles into the drain which may settle and clog the conduit; (2) to provide material in the immediate vicinity of the drain-wall openings that is more permeable than the surrounding area; (3) to provide suitable bedding for the drainage conduit; and (4) to stabilize the soil material on which the drainpipe is laid. Willardson also gives a detailed historical accounting of the various envelope materials used and significant research findings.

The most common and widely used envelope materials for subsurface drainage are naturally graded coarse sands and fine gravels. Such materials are readily available in many areas and are as permanent as the soil particles themselves. Detailed procedures for designing gravel envelope filters for drains are spelled out in various standards and specifications, for example, Soil Conservation Service, *Drainage of Agricultural Land*, USDA, SCS National Engineering Handbook, Section No. 16, 1971; American Society of Agricultural Engineers, Engineering Standard No. EP302.2 on *Design and Construction of Subsurface Drains in Humid Areas* (1983); and *Land Drainage Techniques and Standards*, U.S. Bureau of Reclamation, Reclamation Instruction Series 520 (1966).

Most of these standards provide criteria and procedures to design a sand and/or gravel drain envelope with the proper particle size distribution to improve permeability around the tile and to prevent sedimentation for various soil types and installation conditions. For example, Section 16 in the SCS Handbook above recommends that all of the envelope material should pass through a 1-1/2-inch sieve, 90 percent of the material should pass through a 3/4-inch sieve, and not more than 10 percent should pass a No. 60 sieve. If the envelope also serves as a filter to stabilize soil material and prevent sedimentation, further specifications are given. These involve obtaining a sample of soil from the depth that the draintile is to be installed and conducting a mechanical analysis to determine the distribution of soil particle sizes. Then the gradation of the designed filter is made to match closely the base soil particle size distribution. Much research has been conducted on this by the U.S. Bureau of Reclamation and the U.S. Army Corps of Engineers.

Some areas do not have natural sand and gravel for use as envelope material. This has led to a search for manufactured materials that could be used as substitutes. Fiberglass received the most attention in research trials and field testing in the early 1950's (Overholt, 1959). However, the fiberglass sheet had poor tear-strength properties and had to be handled carefully during installation. In some soils, the fiberglass material functioned more like a filter than an envelope, which resulted in the fabric clogging up with soil particles and prevented the drain from functioning. Willardson noted that many authors used the word filter in referring to drain envelopes. Willardson indicates "that a filter, by definition, would be self-defeating, because soil matter will be deposited on or in the filter, thereby reducing the permeability." He said that porous material placed around a subsurface drain should therefore be referred to as a drain envelope (Willardson, 1974, p. 179).

Trenching for Subsurface Drains

Subsurface drains were first dug with shovels, followed by a combination of plowing and hand digging (figs. 2-2 and 2-3). A breaking plow was used to plow a width needed for the trench depth, two furrows deep. The loose soil was shoveled out after each plowing. Next, a subsoil plow was used to plow to a depth of 24 to 36 inches, and the loose soil was again shoveled out. This spading usually brought the trench to the required depth. With this method, two persons with a team of horses could trench 20 to 30 rods per day in good digging ground.

Probably the first revolving-wheel type trencher was the Pratt Ditch Digger introduced around 1855. This horse-drawn machine consisted of a set of blades mounted on a wheel, which elevated the soil loosened by a plow share and then discharged it to both sides of the trench. Depending on ground conditions, this trencher could excavate 2 to 4 inches in each pass of the trencher.

Following the Pratt machine, several other horse-powered machines were developed, but they all required a number of passes over the trench to excavate it to the required depth. Among these early machines were the Hickok and the Rennie elevator ditchers, patented in 1869. Another was the Johnson Tile Ditcher made in Ottawa, Illinois. It was drawn by eight horses, four abreast r revolving wheel

Figure 2-5—Old No. 88 proudly stands in retirement at Garwood Industries, Findlay, Ohio, as a reminder of when the steam-powered Buckeye Ditcher cut trenches throughout the Midwest and other States.

containing small spades first loosened the soil, then elevated and threw it to one side of the ditch at each pass of the trencher. It was claimed that this trencher could cut from 100 to 150 rods of a 3-foot trench per day. By 1880, several types of these ditching machines were in use.

Single-pass machines powered by horses came next. One example was the Blickensderfer Tile Ditching Machine, manufactured in Decatur, Illinois. This machine consisted of a large revolving wheel with attached excavators or buckets mounted on a four-wheel frame. Curved steel teeth attached to, and projecting beyond, the buckets loosened the soil, which was then lifted and worked out by a simple manipulation of the revolving wheel. The power was provided by a single horse used upon a sweep around the machine, which revolved the buckets and at the same time moved the machine ahead. This ditcher could cut a trench 4 feet deep in one pass over the ground.

Another similar one-pass ditcher was the Heath's Ditching Machine that operated on a wooden track, powered by one horse on a sweep. There were also Paul's Ditching Machine and the Fowler Drainage Plow.

The steam-powered Plumb Ditching Machine came in 1883, followed by the the Buckeye steam-powered wheel-type trencher built in Ohio in 1892. It was capable of cutting from 80 to 100 rods of a 4-1/2-foot deep trench per day. Its cost was around $1,100. In 1908, steam power was replaced with a 14-horsepower, one-cylinder horizontal gasoline engine with planetary reversing clutches. The Buckeye Trencher (fig. 2-6) was doubtless the forerunner of the Cleveland (fig. 2-7) and today's high-speed trenchers and laser-controlled drain plows.

Mole Drainage

Mole drainage was another method of opening the soil for subsurface drainage. This method was restricted to a relatively few locations where mineral or organic soil conditions were most favorable for it, such as in Florida on fibrous peat soils (Stephens, 1955). Various types of mole ditchers have been used but the early mole ditcher usually consisted of a steel cylinder (mole) with a pointed end or nose. The mole was fastened to the lower end of a long sturdy cutting blade, much like the standing colter of a plow. The upper end of the cutting blade was anchored to a plow-beam struc-

Figure 2-7—Capable of cutting a ditch 19 inches wide and 5-1/2 feet deep, this Cleveland trencher works a 1940's farm in Macclesfield, North Carolina. Note the sight bar which helps the driver control the grade.

ture attached to an axle with wheels. The mole formed a tunnel in the soil and packed the subsoil into a fairly tight liner on mineral soils. Soil water that filtered in would often cause the wall to crumble and fill up the tunnel, requiring going over the field again with the ditcher in order to provide continued drainage.

According to Weaver (1964), the first mole plow in the United States was introduced in 1867 in Steuben County, New York. However, in 1859, B. Briggs of Sharon, Ohio, used a machine much like a mole plow to lay tile without digging a ditch. Tile was strung on a rope and pulled into the mole tunnel as the machine moved forward. This was probably the beginning of today's mole-type machines that can pull in corrugated plastic tubing on grade.

Surface Drainage Measures and Techniques

Surface drainage of fields, while commonplace, has actually been one of the most neglected phases of agricultural drainage. Shallow ditches have been used since colonial days to remove surface water from farm fields. However, the continuing problem has been to get all the runoff water into the ditches. Even on subsurface drained fields, it has been found that adequate surface drainage is also necessary. On flat, tight soils, where subsurface drainage is not practical or economical, complete surface systems are needed.

Bedding and Field Ditches

Methods of surface drainage have changed along with other farming practices. Early settlers in the United States used "bedding" extensively in the flat eastern coastal and lake areas. Bedding, using very little planning or design, involves working the field in narrow beds in such a manner that surface drainage would first be to the dead furrows, then to a collection ditch into the main outlet ditch.

With the migration of farmers from the Eastern to the Midwest States, surface drainage was generally accomplished by bedding or random ditch systems. Little thought was given to individual field surface drainage. The early methods were geared to horsedrawn plows, cultivators, and harvesters. Depressions slow to dry were skirted early in the season, then plowed and planted later. Farms were small at the time so there was generally plenty of time to cultivate and plant piecemeal. As farms became larger and more mechanized, these old practices hampered operations. Large, fast equipment required a good, smooth roadbed without wet depressions or potholes.

In Louisiana, surface drainage of sugarcane land has been practiced since the 1860's. Improvements in the practice have continued. The system generally involves lateral ditches, known as split ditches, constructed with the slope of the land and usually parallel. When the capacity of these ditches is reached, they are intercepted by a cross ditch. Crop rows are laid off parallel to the split ditches. Water from the rows is carried by small plow-made cross ditches or quarter drains to the split ditches. Research on this method, known as the sugarcane system, has produced many important results (Stewart and Saveson, 1955).

In the early 1940's, ideas began to develop for planning complete surface drainage systems for farms. The principle involved was to avoid letting water stand by providing farm ditches to collect water from the rows on fields and to keep it moving to an outlet. In this way, it was possible to prevent the land from becoming wet and soggy and to allow the sun and wind to dry the soil as soon as possible after a rain. After evaluating various research and field applications of surface drainage, four basic surface drainage systems with design criteria were recommended in 1950. These principal systems were bedding, random ditch, cross-slope ditch, and parallel ditch (Beauchamp, 1952).

Land Forming and Smoothing

By the mid-1940's, it became apparent a system of ditches like those described above could not easily drain land with numerous small pockets, where water is likely to pond because it cannot get to the surface drains. The answer was to allow each crop row to carry its runoff to its outlet without erosion, ponding, or overtopping. This led to the idea of land forming, whereby the entire land surfaces are modified by grading and smoothing.

Row drainage and land forming were studied and criteria suggested by the research work of A.J. Wojta of the University of Wisconsin; L.L. Saveson of USDA's Agricultural Research Service (ARS); L.F. Hermsmeier and C.L. Larson in the Red River Valley of Minnesota; and W. Harris of the University of Arkansas. In 1947, the SCS conducted field trials and demonstrations of land forming in many conservation districts of the North-Central States. After 1950, there was a slow but definite acceptance of this practice in the Midwest, East, and South. In 1952, the practice was included for the first time in the ACP National Bulletin as "Shaping or Land Grading to Provide Permanent Slopes Needed for Surface Drainage."

Water Table Control

Draining peat and muck soils and high water tables on sandy soils has always been a major problem. Drainage studies on organic soils were initiated in the early 1900's. Another problem was overdrainage, followed by subsequent settling of the organic soils when a low water table existed over an extended period of time (Stephens, 1955). The practice of controlled drainage began about 1930. This generally consisted of installing check dams with stop logs which were raised or lowered to control the water level in open ditches. The attempt here was to take off only that amount of water that was detrimental, keeping the water table as high as possible for the good of the crop. The success of this method varied with the amount and distribution of rainfall and the seepage of water into the controlled area. Studies of early controlled drainage were reported by Clayton and Jones (1941) in the northern Everglades of Florida and by Harker (1941) on sand and muck lands in Indiana. Figure 2-8 shows a water control gate used in South Carolina.

Figure 2-8—A water-control gate operates at capacity after heavy rains near Neggetts, North Carolina.

Complete water table control then came into use. This is a combination of controlled drainage and sub-irrigation, where the water table is raised by pumping water into the system. This practice can be used only where there is a sufficient supply of irrigation water. In controlled drainage, water is pumped into subsurface drains or into open ditches with water-level control gates in the drain. These ditches serve both as drainage outlets and irrigation water inlets to a parallel subsurface system. Pumping can remove excess drainage water and also supply irrigation water, thereby maintaining water tables at correct levels for optimum crop growth.

By the late 1940's, water table control was used in Michigan, Indiana, and Ohio. The spread of this practice was aided greatly by farm electrification programs, because automatic controls could then be used for pumping on individual farms.

An early example of group action for water table control was a project in north-central Ohio known as "Marsh Run." Started in the late 1950's, this project involved a number of landowners growing truck crops in organic soil. Irrigation water was provided by pumping high stages of flow from Marsh Run Creek into an above-ground reservoir. Early development and use of this practice in Florida is noted by Stephens (1955).

Excavating Ditches and Channels

Improved methods for constructing large outlet ditches were important factors in the spread and efficiency of drainage. Ditches and channels, even

Figure 2-9—A Schield Bantam backhoe cuts new ditches in extremely wet soils on Edisto Island, South Carolina, in 1958. The wide tracks and shoes allow the machine to straddle the ditch while cleaning it.

the large ones, were first excavated by handtools, such as the ditching spade, round point shovel, scoop, and the wheelbarrow. Then horse- or ox-drawn plows came into use. With such methods, only ditches up to 5 feet deep with a bottom width seldom exceeding 4 feet could be constructed economically. Often ditches did not provide the drainage desired.

A more economical means for constructing large open ditches was sought. It was only after the invention of power machinery, especially the dipper dredge, that land reclamation could be conducted on a large scale. Gain and Patronsky (1973) noted that in 1883 the first mechanical excavator was used by the Mason and Tazewell Special Drainage District in western Illinois. A 14-1/2-mile main channel was constructed with a steam-driven floating dipper dredge. This dredge was similar in principle to a manpowered dredge used on the Seine River in Paris some 200 years before. The steam-powered shovel was mounted on a wide barge hull supported by vertical spuds to prevent tipping. This equipment was said to have revolutionized drainage construction methods.

A bank spud was developed later for this type of dredge to reduce the required hull width. Orange-peel and clam-shell buckets replaced the shovel when dredges operated in soft material because of the longer boom that could be used for a wider reach. By 1900, steam-driven floating and land dredges had become the most economical ditch construction equipment.

Figure 2-10—This group drainage ditch, formed through dragline construction, replaces an inadequate and obstructed 24-inch tile outlet. The new ditch serves 900 acres on seven farms near Griffin, Ohio.

A drag-type scraper was first introduced in 1903 in the construction of the Hennepin Canal near Chicago. In 1906, it was followed by the dragline excavator, using a drag-type scraper. The dragline soon became the universal ditch excavator because it could be made in many sizes for small or large ditch excavation and also permitted the use of wide berms (figs. 2-9 and 2-10). Later the dragline was shifted from steam power and was mounted on caterpillar tracks (Wooten and Jones, 1955).

The crawler tractor has played an important part in drainage work. The crawler was introduced in many locations by the Civilian Conservation Corps in about 1935. It quickly came into common use for drainage. The crawler was generally used for leveling ditch spoil banks and in constructing V- and W-shaped and wide-bottom flat ditches for open drainage systems. Bulldozers, large carryalls, and other similar tractor equipment have been used for levee construction and for land grading (Sutton, 1957).

On a farm scale, figure 2-11 shows the construction of a shallow flat-bottom ditch with flat backslopes,

Figure 2-11—The author drives tractor-drawn scraper to shape a flat-bottomed farm drain in Wisconsin.

using a small carryall scraper drawn by a farm tractor.

Pumping for Drainage

A most important and far-reaching advance in drainage technique was the development and use of efficient equipment for drainage pumping and water control. Pumping was essential where it was not possible to have a complete gravity flow outlet. Pump projects have reclaimed much swamp and overflow land which otherwise would be of little value for farming. In coastal areas, pumping may be used in conjunction with tide gates (fig. 2-12).

The drainage wheel, operated by animal power, was first used on the plantations along the gulf coast, especially on sugar plantations. About 1850, pumps began to be used. As the projects became larger, low-lift centrifugal pumps gradually replaced other types. The wood screw pump was developed in 1915. Other types of pumps were the propeller or axial flow, mixed-flow pumps, centrifugal pumps, and the deep-well turbine pump used in irrigation (Wooten and Jones, 1955).

River bottoms, lake and coastal plains, peat land, and irrigated lands are the main types of land drained by pumps. In the early 1900's, the Corps of Engineers began constructing levees along many navigable rivers on a district basis. This made it possible to drain millions of acres of bottomland along the Mississippi, Missouri, Red, Arkansas, Illinois, and other major rivers. Levees were built to protect the land or district facilities from river overflow. Diversion channels and creeks with tie-back levees diverted hill water from the bottomland. Open ditches and tile collected the interior water and conducted it to the lower end of the district. Pumping plants then lifted the water over the levees into the rivers (Sutton, 1957).

Pumping was used widely in the Mississippi Delta and the coastal areas of Louisiana and Texas where levees and pumping lifts were lower than in the upper Mississippi Valley. Because of this, most of the pumps were axial-flow; some centrifugal pumps were also used. The pumps were powered by internal combustion engines or electrical motors. Pump drainage increased greatly after 1940. According to the Census of Agriculture, 172,000 acres were served by pumps in Louisiana in 1950.

In Florida, most of the land served by pumps is in the Lake Okeechobee-Everglades area. Premature attempts at drainage began about 1880. Intensive drainage operations began in 1906, and by 1928,

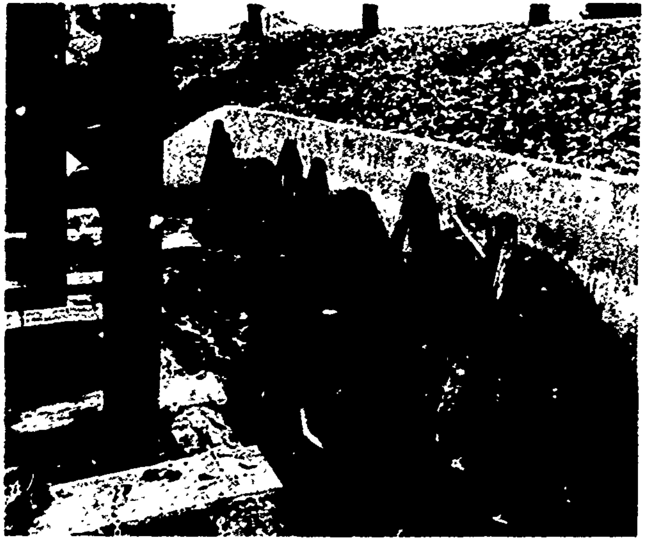


Figure 2-12—The tide is out in Seaside, Oregon, so the tide gates open to drain water off the land.

reversible pumps were necessary to pump water from the fields in wet seasons and then from the canals into the fields during dry seasons. Most of the pumps were of the axial flow or propeller type. In 1950, pumps served 293,000 acres in Florida (Stephens, 1955).

Most of the river drainage and levee districts in the upper Mississippi Valley also operated pumping plants and found them to be essential to drainage work. Most of the pumping districts, particularly along the Illinois River, were established after 1905. The pumps of the early districts were generally too small and were supplemented or entirely replaced by new ones. By 1950, the area served by pumps in Illinois was 315,000 acres, in Missouri 67,000 acres, and in Iowa 82,000 acres (Sutton, 1955).

Before 1914, all pumping districts in the upper Mississippi Valley used steam engines as a source of power. Between 1914 and 1918, all new pumping plants were equipped with electric motors, and some of the old steam plants changed to electric power. The first diesel engine was installed in 1928. Diesel power was then used in most new installations and in many old plants (Pickels, 1929).

Interest in small, individually owned pumping plants increased after the early 1940's. They were used primarily where there was no gravity outlet for subsurface drains within the farm boundary. The outlet ditches in many locations were not deep enough to provide adequate drainage. This type of pumping could often replace long tile mains or long deep outlet ditches. In many cases, pumping allowed landowners to proceed on their own without waiting for district or group action. Individual farm pumping was also used in a water table control system. An example is the low land near the Great Lakes. High lake levels often kept outlets from functioning and caused crop losses. Because pumping lifts were usually low, propeller-type pumps were generally adequate. Progress in the development of onfarm pumping was due mostly to the wide availability of electricity on farms by the mid-1950's, along with improved efficiency of tractors and internal combustion engines for power.

References

Alpers, R. J., and T. N. Short. 1966. *Clay Draintile and Its Use.* Proceedings of the ASAE National Drainage Symposium. Am. Soc. Agr. Engr., St. Joseph, Mich.

Beauchamp, Keith H. 1952. "Systems of Surface Drainage of Tight Soils," *Agricultural* Engineering. Vol. 33, No. 4 (April).

Clayton, B. C., and L. A. Jones. 1941. "Controlled Drainage in the Northern Everglades of Florida," *Agricultural Engineering.* Vol. 22 (August).

Darby, H. C. 1940. The *Draining of the Fens.* Cambridge, England: Cambridge University Press.

Donnan, William W. 1976. *An Overview of Drainage Worldwide.* Proceedings of the Third National ASAE Drainage Symposium. Am. Soc. Agr. Engr., St. Joseph, Mich.

Gain, Elmer W., and Richard J. Patronsky. 1973. *Historical Sketches on Channel Modification.* ASAE Paper No. 73-2537. Am. Soc. Agr. Engr., St. Joseph, Mich.

Harker, David H. 1941. "Controlled Drainage," *Agricultural Engineering.* Vol. 22, No. 4 (April).

Harrison, Robert W. 1961. *Alluvial* Empire: *A Study of State and Local Efforts Toward Land Development in the Alluvial Valley of the Lower Mississippi River.* Little Rock, Ark.: Pioneer Press.

Hay, Ralph C., and John B. Stall. 1976. *History of Channel Improvements in an Illinois Watershed.* ASAE Paper No. 76-2506. Am. Soc. Agr. Engr., St. Joseph, Mich.

King, James A., and W. S. Lynes. 1946. *Tile Drainage.* (4th edition). Mason City, Iowa: Mason City Brick and Tile Company.

Miles, Manley. 1892. *Land Drainage.* New York: Orange Judd Company.

Overholt, Virgil. 1959. "Fiberglass Filter for Tile Drains," *Agricultural* Engineering. Vol. 40, pp. 604-607.

Pickels, George W. 1925. *Drainage and Flood-Control Engineering.* New York: McGraw-Hill Book Company.

Pickels, G. W., and F. B. Leonard. 1929. Engineering *and Legal Aspects of Land Drainage in Illinois.* Bulletin No. 12. Illinois Geological Survey.

Soil Conservation Society of America. 1956. Our *Water Resource.* Des Moines, Iowa.

44

Stephens, John C. 1955. "Drainage of Peat and Muck Lands," *Yearbook of Agriculture, 1955.* U.S. Dept. Agr., pp. 539-557.

Stewart, K. V., Jr., and L. L. Saveson. 1955. "Systems for Draining the Surface," *Yearbook of Agriculture,* 1955. U.S. Dept. Agr., pp. 499-507.

Sutton, John G. 1955. "The Use of Pumps for Drainage," *Yearbook of Agriculture,* 1955. U.S. Dept. Agr., pp. 528-538.

Sutton, John G. 1957. "Drainage Developments During the Past 50 Years," *Agricultural Engineering.* Vol. 8, No. 6 (June).

Sutton, John G. 1958. "Appraising Our Drainage Job," *Land Improvement.* Vol. 5, No. 4 (April).

van Schilfgaarde, Jan. 1971. *Drainage Yesterday, Today, and Tomorrow.* Proceedings of the ASAE National Drainage Symposium. Am. Soc. Agr. Engr., St. Joseph, Mich.

van Veen, J. 1948. *Dredge Drain Reclamation: The Art of a Nation.* The Hague: Mortmas Nishoft.

Weaver, Marion M. 1964. *History of Tile Drainage.* Waterloo, New York: M. M. Weaver.

Wheeler, W. H. 1868. *A History of the Fens of South Lincolnshire.* (Publisher unknown).

Willardson, Lyman S. 1974. "Envelope Materials," *Drainage for Agriculture* (ed. J. van Schilfgaarde). Monograph No. 17. Am. Soc. Agronomy, Madison, Wisc.

Wooten, Hugh H., and Lewis A. Jones. 1955. "The History of Our Drainage Enterprises," *Yearbook of Agriculture,* 1955. U.S. Dept. Agr., pp. 478-491.

Chapter 3

Advances in Drainage Technology: 1955-85

James L. Fouss
Agricultural Research Service, USDA
Baton Rouge, Louisiana

Ronald C. Reeve
Drainage Consultant
Columbus, Ohio

Advances in agricultural drainage technology within the past 30 years are described in terms of changes and improvements in drainage conduit materials and/or installation methods. Drainage technology changed and modernized more during 1965-75 than in the previous 100 years. Slow. inefficient installation of heavy rigid conduit materials (clay and concrete) gave way to light-weight flexible corrugated plastic drain tubing installed with laser-beam-controlled high-speed trenchers and plow-type equipment (Fouss, 1974; Reeve, 1978; Teach, 1972).

We accordingly review major technological developments in materials and equipment, plus other technology developed to design drainage and water management systems through computerized simulation and design procedures (Skaggs, 1980).

Technological Challenges

The development of a rapid and low-cost technique for subsurface drainage has challenged engineers and inventors for centuries. Many ideas have emerged, but very few have found widespread use or application. With the advent of the power trenching machine in about 1875, the goal of mechanized drain installation seemed to have been reached—and it lasted about 100 years. However, the extremely large amount of drainage work that was needed around the world required even less labor, more speed, and lower costs. Efforts to modify the mole drainage concept and installation methods were particularly important. The goal was to use the inherent high speed of installation of mole drainage and its elimination of relatively slow ditching and backfilling operations associated with conventional drainage methods. Because the mole drain collapsed after a short time in many soils, much of the research concerned stabilizing the mole channel with structural support, using a tube or liner.

A second technological challenge involved developing a means to design optimal agricultural drainage systems on a probability basis that would properly account for the spatial variations in the drained soil and the time variations in weather, as described and recommended by van Schilfgaarde (1965). Optimized drainage system design had long evaded drainage engineers. With high-speed computers, substantial progress has been made in meeting this challenge, thus providing another significant advance in drainage technology.

Progress was also made possible in the drainage industry because of technological developments in other industries and areas, such as plastic materials, synthetic fabrics, construction equipment, electronic (laser) equipment, and computer industries. A number of the advances in these other fields seemingly came along just in time to meet the needs of a developing new thrust in the drainage field. Some of the innovations came about directly in the drainage industry, but many were adopted and/or adapted from developments originally intended for other purposes. Examples are heavy earth-moving machinery developed for construction, lasers developed for alignment tasks in civil construction, and synthetic fabrics developed by

Figure 3-1—Eaton County, Michigan, workers haul palletized tile on a "chariot" connected directly to the tile machine.

the petrochemical industry for restraining landfill areas and roadways in civil engineering applications.

Corrugated-wall plastic tubing, originally developed in the United States in the mid-1960's for underground electrical and telephone line conduit applications was modified and perforated to serve as a subsurface drainage tube. Significant advances have been made in the manufacture and perforation of plastic tubing, especially as larger pipe sizes were introduced. The high strength-to-weight ratio of the corrugated wall tubing, its continuous and coilable length, corrosion resistance, nonbiodegradable characteristics, and structural performance under soil loading, made it an ideal and superior product for the new subsurface drainage conduit.

Advances in Materials and Materials Handling

Numerous innovations and improvements in drainage equipment and conventional draintile materials handling were made during the 1960's. largely because of the rapid development of plastic draintube products and the expected competition. Palletized handling was developed to replace piece-by-piece handling of clay and concrete draintile during manufacture, shipment, and installation. By the mid-1960's, much of the clay, shale, and concrete draintiles installed (particularly in the midwestern United States) were handled on pallet, each containing about 325 feet of tile. This packaging method permitted manufacturers to use forklift trucks to store and load the tile for shipment, thus reducing cost and speeding operations.

Another improvement was the use of self-unloading trucks at the job site, thus reducing labor cost. During installation, a chariot or wagon designed to haul one or more pallets was pulled alongside the moving trenching machine. The tile sections were manually removed from the pallet and placed into a tile-laying chute (fig. 3-1). The need for a person in the trench could be eliminated in some cases. Mechanized tile handling reduced the work crew, but the maximum speed of installation was still limited to the rate at which tile could be inserted into the tile chute—about 25 feet per minuie with one person and 50 feet per minute with two people. The heavy weight of the loaded tile chariot also limited its use to when the soil surface was fairly dry and traction conditions good. Widespread use of the palletized tile handling decreased as plastic drain tubes were introduced and adopted in the early 1970's.

Smooth-Wall Plastic Tubing

Polyethylene plastic tubing, a British development, was first manufactured in the United States in about 1941. According to Schwab (1955), the Corps of Engineers investigated the use of "perforated plastic tubing" installed with cable-laying machines for airport drainage as early as 1946. Schwab's research from 1947 to 1954 is the earliest known use of plastic draintubes for agriculture in the United States.[1] He conducted field experiments in Iowa where smooth-wall polyethylene plastic tubes of various diameters and wall thicknesses were pulled into a mole-drain channel in clay soil with a mole plow. Schwab indicated that it was necessary to handle the smooth-wall plastic drain in 20-foot straight lengths because the tubing would kink when coiled.

From these early studies, Schwab developed guidelines on minimum tube-wall thickness for various drain diameters to insure drain conduit deflection of less than 20 percent of the original diameter. When inspected in 1966, 17 years after installation, these drains remained in good condition (Fouss, 1968). The results from these pioneering experiments provided many of the technical background data for the initial ASTM minimum requirements for plastic drain strength-deflection standards.

In the United States, smooth-wall plastic tubing was not used widely for agricultural subsurface drainage, primarily because of its higher unit cost and the greater material weight per unit length requirement as compared with other materials and configurations. In the mid-1960's, limited use was made of 4-inch diameter, smooth-wall, polyethylene plastic drain tubing in the Lower Rio Grande Valley of Texas. The tubing was installed as deep as 6 feet with a special narrow-wheel trencher (Myers and others, 1967; Rektorik and Myers, 1967).

In The Netherlands, De Jager (1960) conducted experiments with polyethylene tubes pulled into mole drains, but finally selected a narrow trenching machine to install 6-meter (19.7 feet) lengths of rigid vinyl plastic drain pipe. According to van Someren (1964), by the late 1960's, trenched-in polyvinylchloride (PVC) plastic drain pipes were used on up to 80 percent of the installations in The Netherlands.

Plastic-Lined Mole Drains

Considerable international research was conducted from the late 1940's to the mid-1960's on the use of plastic liner as a structural reinforcement for the mole-drain channel. The results of this research were important in providing the foundation for subsequent investigative and developmental work leading to significant input to current drainage technology (Edminster, 1965). Janert (1952) developed a machine that formed and installed a semirigid vinyl plastic drain from rolls of sheet film. The plastic strip was heated to provide sufficient flexibility for forming it into a tubular drain. The plow-type, drain-laying machine was constructed with an inclined planelike digging blade which opened a trench about twice the diameter of the drain. Production models of this machine were sold in East Germany in the late 1950's, but its use was not widespread.

In the United States, Busch (1958) modified a mole plow for feeding a PVC plastic strip into a mole-drain channel and forming it into an arch-shaped mole liner. This research precipitated a series of refinements, modifications, and new developments by both American and British investigators. A tubular mole liner, formed from a PVC sheet, was developed in 1960 by a team at the Caterpillar Tractor Company. Further studies led to the development and testing of the stronger zippered-type tubular PVC plastic mole liner (Fouss and Donnan (1962) in the United States and Ede (1963) and Boa (1963) in the United Kingdom).

Most of these early experimental plastic drains were 2-1/2 to 3 inches in diameter. Materials handling for the plastic mole liner was exceptionally efficient. For example, a 60-pound roll of 0.015-inch thick PVC sheet, 10 inches wide by 10 inches in diameter would form 600 feet of installed 3-inch diameter drain (lined mole channel). This was a truly remarkable materials handling advantage over conventional practice. Ede (1965) and Fouss (1965) reported that thin-walled plastic liners, although offering significant materials handling advantages, were not strong enough to withstand deformation under long-term soil loading. Thus, the plastic-lined mole drain concept was not pursued further, primarily because of the appearance of the superior corrugated-wall plastic tubing which could be easily placed in a trench or a subsurface channel formed with plow-type equipment.

This early research on plastic-lined mole drains demonstrated the need for a systems approach in

---

[1] The authors acknowledge this pioneering research of Professor Schwab and his generous help in reviewing this chapter.

48

developing new drainage methods. The drainage materials, materials handling, and installation equipment required integrated system development to minimize cost and also to ensure compatibility and operational efficiency for high-speed installation of subsurface drainage systems.

Corrugated Plastic Tubing

By the mid-1960's, almost all the research and development on drainage materials and methods of materials handling had begun to focus on corrugated-wall plastic tubing, primarily because of the advantages of low material requirement versus high-strength ratio and flexibility for ease of handling. Continuous extrusion and molding machinery for manufacturing the new plastic tubing had been perfected earlier in Germany. Underground drainage with the new conduit (about 2 inches in diameter) caught on rapidly in Germany and soon spread to other regions of Europe. The first U.S. uses of corrugated plastic tubing were for underground electrical and telephone conduits.

Applications in Agriculture

Research in the United States on developing polyethylene corrugated plastic tubing, of 3- and 4-inch diameters, for agricultural subsurface drainage began in 1965 (Fouss, 1965, 1968). The corrugated-wall tube structure developed for polyethylene plastic (fig. 3-2) provided high strength to resist radial type loads such as from over-burden soil, but with a considerably reduced requirement for wall thickness as compared with smooth-wall tubing. Both tubing unit weight and unit cost are reduced significantly by corrugation.

The cost of corrugated tubing is almost directly proportional to tubing weight. The longitudinal flexibility of the corrugated-wall tubing (a desirable quality) made it coilable for ease of handling, but the coilability characteristic also made it stretchable (like an accordion). Thus, a compromise in design of corrugation shape was necessary, and special materials handling procedures were needed. (The reader is referred to Fouss (1973, 1974) and Fouss and Altermatt (1985) for detailed discussions on optimal design procedures for corrugated plastic drainage tubing for resistance to both deflection and stretch.)

By 1967, corrugated plastic drainage tubing was being manufactured commercially in the United States for the agricultural market, and the new industry grew rapidly (Fouss, 1974; Reeve and others, 1981). By the mid-1970's, corrugated plastic drainage tubing had wide acceptance for agricultural drainage, highway berm drainage, septic tank leach field, and construction site applications. By 1983, 95 percent of all agricultural subsurface drains installed annually in the United States, and more than 80 percent in Canada, were corrugated plastic tubing (Schwab and Fouss, 1985).

Tubing Standards

Specifications and performance standards were developed during the early 1970's for these new drainage products under the auspices of ASTM.

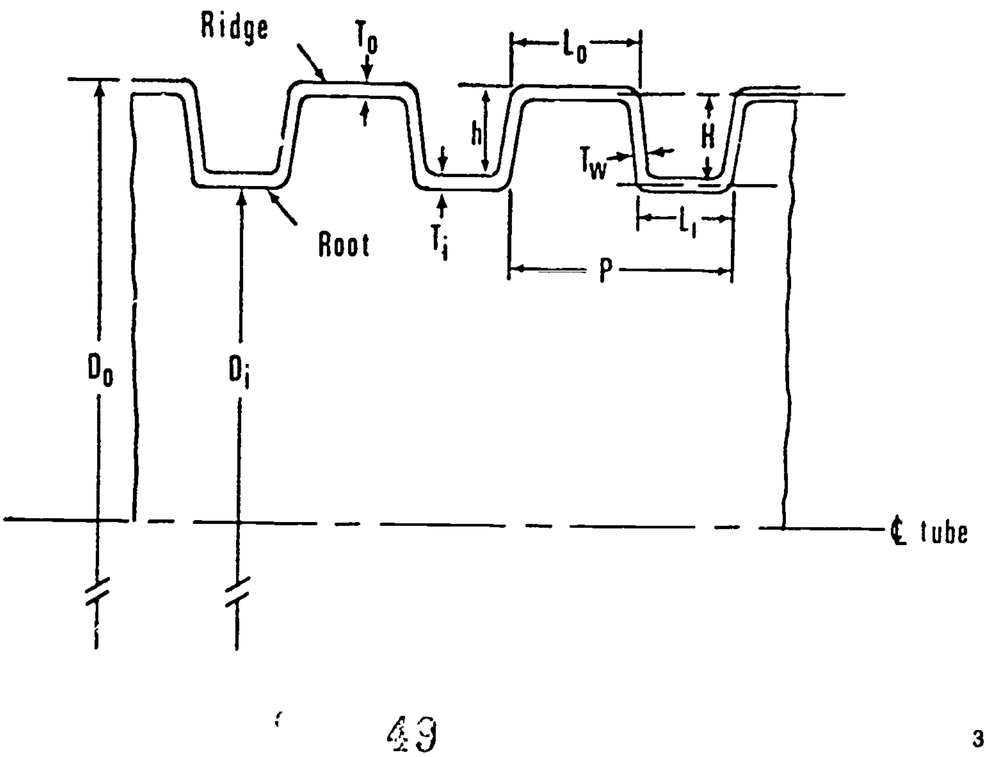


Figure 3-2—Tube-wall corrugation for polyethylene plastic drainage tubing.

which involves voluntary and cooperative efforts among industry, government, and public groups. This resulted in an ASTM Standard Designation F405 entitled 'Standardization Specification for Corrugated Polyethylene Tubing" (ASTM, 1974). A major step in the development of this standard was the recognition by the cooperating groups that corrugated plastic tubing is a flexible-type conduit with properties substantially different from the classical rigid draintile such as clay, shale, or concrete.

Under field conditions, a flexible conduit gains most of its vertical soil load-carrying capacity from the support provided by the soil compressed at the sides of the conduit (Watkins, 1967). The density of this sidefill material is the key element in load-carrying capability of the pipe-soil composite structure. The sidefill material provides lateral support to the conduit to give it more rigidity and acts in combination with the conduit to form a vertical load-carrying arch (Watkins and others, 1983).

During the early marketing stages of this new product in the United States, a sand-box test was devised as a quality standard (Herndon, 1969). The inadequacy of this test as a product standard was soon realized because of the interaction of the pipe with the sand envelope material. As recommended from research (Sorbie and others, 1972), a parallel plate method for measuring the deflection resistance of the corrugated plastic tube was developed as an integral part of the ASTM F405 standard (fig. 3-3). This standard was developed to provide minimum values for physical and chemical properties as related to product performance, including handling and installation. Minimum deflection resistance is specified for 5- and 10-percent deflection of tubing diameter. The standard also includes a requirement on elongation (stretch) resistance, which limited elongation to 5 percent when a specified tensile load is applied. Finally, in a 1978 revision of the standard, a falling "Tup" impact test, conducted at a cold temperature, was specified to detect brittle or poor-quality plastic resin.

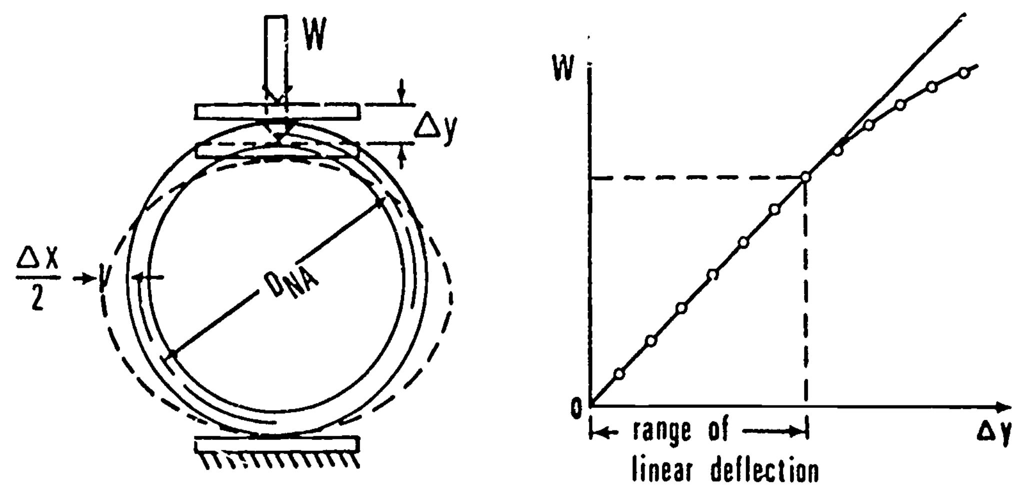
Fabrication and Marketing

Water entry openings are made in the corrugated draintube wall during the manufacturing operation by punching or drilling holes, sawing short narrow slots, or other means of perforation. Typically, the openings are formed in the corrugation roots (valleys) rather than on the crowns (outside diameter), and are positioned in three or more rows along the length of the tubing. The cross-sectional area of openings for water entry to the drain varies among manufacturers, but ranges from 1 to more than 7 square inches per linear foot of drain. ASTM Standard F405 requires a minimum of 1 square inch per linear foot of pipe. Because the drainwall openings are controlled in the manufacturing operation, the quality of installation improved significantly with corrugated tubing compared with ceramic tile. The crack spacing between ceramic draintile sections had to be controlled during installation, thus giving rise to great variability in drain quality among contractors.

The use of corrugated tubing greatly reduced labor and energy requirements in drainage materials handling. Initially, the typical 4-inch diameter tubing used for laterals was supplied in 250-foot coiled lengths and weighed about 80 pounds. This compared with a weight of about 2,000 pounds for clay or concrete tile of the same size and length.

As the demand of, and use for, corrugated plastic drainage tubing grew in the United States, contractors desired larger and larger coils to make the

Figure 3-3—Schematic of parallel-plate, load deflection method of testing flexible plastic drainage tubing.



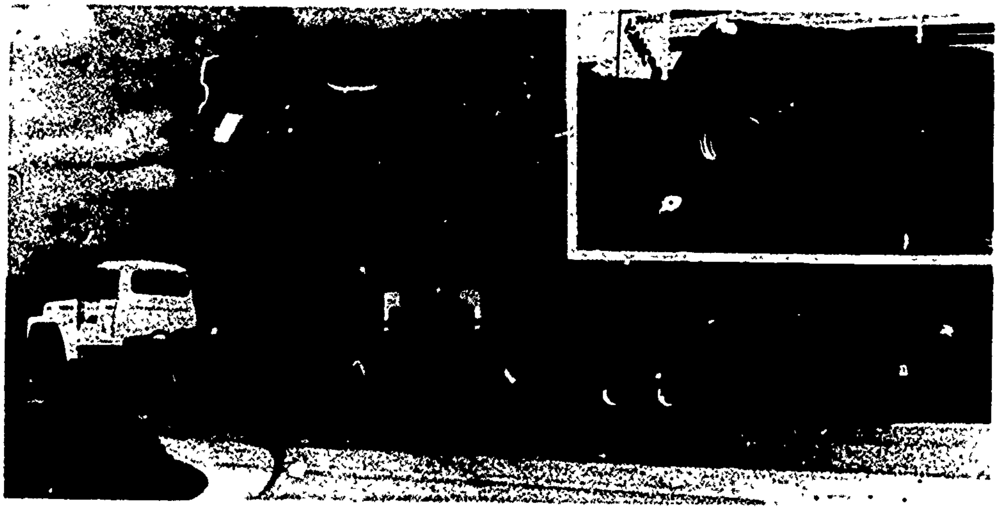


Figure 3-4—It takes heavy-duty hauling to move this 5,000-foot jumbo-coil of 4-inch diameter corrugated plastic drainage tubing. Insert shows a 3,000-foot maxi-coil.

materials handling operation even more efficient. In 1984, typical coil sizes available for 4-inch tubing were 3,000-foot "maxi-coils" and 5,000-foot "jumbo-coils" (fig. 3-4). The 250-foot coil is still commonly used for many small agricultural jobs, for industrial installations, and around housing projects. Several types of self-loading trailers and wagons became available to string tubing in the field (fig. 3-5). As illustrated in figure 3-6, special reels were developed for mounting directly onboard the drainage equipment to uncoil the tubing as it was installed (Fouss, 1982; and Fouss and Altermat, 1982).

Most of the early corrugated plastic drainage tubing was black, but by the mid-1970's, tubing was produced in lighter colors such as white, yellow, gray, and red. Ultraviolet stabilizers and antioxidants were incorporated in the plastic resin to increase its resistance to weathering when tubing was stored outside and exposed to sunlight. The lighter color tubing was developed partially for marketing purposes, but improved performance during handling and installation was also realized because strength and stretch resistance were maintained, even when exposed to the hot sun. The darker tubing was more prone to absorbing the sunlight which elevated the tube-wall temperature, thus reducing the tubing's stretch resistance during handling and installation.

Use of the maxi-coils and special reels for stringing tubing reduced tubing stretch problems during installation, even for black tubing on hot, sunny days. The 2-percent carbon-black used as the ultraviolet light inhibitor in black tubing is superior in performance and lower in cost than the lighter pigments, permitting outdoor storage of the product. The power tubing feeder designed to eliminate the natural stretch-producing drag at the top of the tub-

Figure 3-5—(left) A farmer tows a trailer that uncoils 3,000-foot maxi-coils. A wagon stands ready to install 250-foot coils of 4-inch diameter plastic drainage tubing.

Figure 3-6—Four-inch diameter plastic tubing is wound on its self-loading, machine-mounted reel.

ing chute was one of the most significant developments in minimizing the adverse effects of stretch.

Diameters of corrugated plastic pipe increased from the original 4 inches in the mid-1960's to 24 inches by 1982. Sizes up through 10 inches are commonly coiled for shipment and handling. Drain sizes larger than 12 inches are typically manufactured and shipped in 20-foot lengths. There is a noteworthy market for 3-inch corrugated tubing, which is typically shipped in 350-foot standard coils, or 5,000-foot coils. Interest in 3-inch diameter tubing was greatest during the 1973 world oil shortage, but by 1984 the 4-inch tubing was considered the minimum tube size for lateral drains in many areas of the United States and Canada. A 5-inch diameter is specified as the minimum-size lateral drain in Iowa; in Minnesota, a 6-inch drain is the preferred minimum.

Corrugated plastic tubing larger than 12 inches in diameter is generally more expensive than the same-size clay or concrete tile, but the market demand and use for the lighter and easier to handle corrugated plastic is increasing significantly. These large-size corrugated conduits (12-24 inch) are also used extensively for culvert applications (Watkins and others, 1983), which was an area formerly thought to be reserved for concrete and steel pipe. The noncorrosive nature of the product and the advances in the structural performance of plastics for this use are milestones in the drainage industry.

Synthetic Drain Envelope Materials

The technology of sand and gravel envelopes, including the particle size relationship between envelope and base material had been developed during 1930-60, and applied not only to minimize sedimentation, but also to drain stabilization and alignment. Also, the machinery and the mechanics of applying gravel envelopes of uniform thickness around the subsurface drains were developed and used extensively in the Western United States (Luthin and Reeve, 1957; Willardson, 1974).

There are distinct advantages in the performance of sand and gravel envelopes over thin membranes. Where envelopes are installed in very unstable base materials, drain stabilization, as mentioned before, is a major advantage. The much greater thickness of the granular envelope also provides free three-dimensional flow in the immediate vicinity of the drain, thus minimizing entry head loss. Dutch scientists and engineers have used thick fabric and fiber materials, but decreased flow resistance has often come at the expense of effectiveness in restraining sediments.

Most of the synthetic materials that have been used for drain envelopes have been of the "thin-membrane" type. The primary reasons for the development of thin-membrane envelopes are: (1) the lack of readily available and suitable sand and gravel envelope materials in many of the drainage areas of the country, (2) the advent of strong durable, nonbiodegradable fiber materials, (3) the much reduced cost and reduction in labor-installed synthetics, and (4) the increased control of quality from preapplication of the envelope to the pipe before installing in the field.

Although gravel envelopes have distinct advantages, the cost is generally prohibitive in areas where natural gravels are not readily available. For this reason and for the fact that thin-membrane fabrics are easily handled and installed, especially in conjunction with plastic corrugated pipe, synthetic envelopes have become widely used throughout the major drainage areas of the Midwest and East.

With the rapid and widespread use of corrugated plastic drainage tubing in the United States and Canada, the development of synthetic fabrics as envelopes to protect these drains against sedimentation advanced rapidly. Because subsurface drain envelopes are used primarily to protect the drain from the inflow of sediment and still maintain free open flow of gravity water into the drain, the development of envelopes has been mostly centered around the performance of thin membranes with fine sand and coarse silt-size particles (0.005-0.125 mm). Understanding of the basics and development of improved practices in the use of drain-synthetic envelopes have both advanced significantly in the past two decades.

The terminology of drain envelopes is still in a state of flux. But the term "envelope" seems to be preferred to the term "filter" because filter commonly refers to a filtering action, where the associated build-up of a "filter-cake" on the membrane would defeat the purpose of a drain envelope (Willardson, 1974; Reeve, 1978b, 1979, 1982).

Fabrics that were developed by several major world chemical and oil companies for other engineering applications were readily available from the 1960's through the 1980's and thus gave a boost to the use of these materials for subsurface drain envelopes. From among the many materials that have been tested, polyester, nylon, and polypropylene were commercially available in North America and have been used most widely for this application. While woven, knitted, and spun-bonded productions of the above materials have been used, the most commonly used products from among these are knitted polyester (sock), spun-bonded nylon (Cerex™, Drainguard™), and spun-bonded polypropylene (Typar™, Remay™).

By the late 1970's, as much as 8 percent of the corrugated plastic drainage tubing installed had a synthetic fabric envelope. These synthetic envelopes are light in weight and compact for ease of handling during transportation and installation. They are also relatively low cost compared with sand or gravel envelopes. The synthetic fabrics may be placed directly onto the tubing during manufacturing, or the envelope is placed on the tubing during installation.

Standards and specifications for the synthetic fabric envelope or filter materials were still not developed by late 1984, even though such products had been in use for about 15 years. Developing such standards is complicated by the many variables involved in installation and hydraulic variables encountered in the field. Research has been conducted to determine why fabric materials plug up in some soil types, particularly in clays and silty clay loams, but results have not been definitive. In other cases where the fabric mesh size is too large and the sediments are extremely fine, such as in very fine sand and/or silt loams, envelopes fail by allowing excess sediment to pass through the fabric and into the drain tubing.

In 1977, Broughton and others conducted extensive field and laboratory tests on a large number of the major commercial synthetic products, primarily in sandy-type soils. They reported significant reduction in drain outflow during the first 1 to 3 months after installation of most products and attributed the probable cause to the "fine soil particles within the sand forming a filter cake in the soil outside the filter material." A similar reduction in outflow rate was reported for a coarse sand envelope, but the sustained peak flow rates after 2 years were much higher for the sand envelope than for the synthetic fabrics.

The performance of a thin-membrane envelope depends primarily on the conditions of the soil at the time of installation, the imposed hydraulics on the system, and the installation practice itself. Failures are more likely where the conditions are extremely wet, where the soils are unstable and subject to "quick" conditions, and where the initial hydraulic head imposed on the drain is much higher at installation than will likely ever occur again once the drain is functioning and the water table has been drawn down. Drains installed with envelopes, even in very fine sandy or silty soils, have performed satisfactorily when installed where the water table had been low, the surface soil had been dry for better machine operation, and no excess hydraulic heads had been imposed on the system during installation. After the drain is installed and functioning, the soil in the vicinity of the drain stabilizes and the hydraulic head at the drain then becomes a function of head conditions as modified by the head loss or resistance to flow in the soil.

Experience and research have shown that favorable installation conditions and extreme care on the part of the contractor are both very important to the quality and proper functioning of drains with thin-membrane envelopes.

Willardson (1974, 1979) has advanced the concept of excessive hydraulic gradients in the synthetic envelope material as a contributing cause for plugging or sedimentation failure. Broadhead, Schwab, and Reeve (1983) have reported on a laboratory evaluation procedure that tested the soil particle-size distribution to determine the suitable opening sizes for the synthetic drain envelope. They also tested noncohesive sandy soils and showed that drain sedimentation can be prevented by selecting an envelope material with an effective opening or mesh size that is less than about 2.4 times the diameter of the 60-percent (D-60) size of the sand particles.

An ASTM Task Force Committee used a laboratory testing program with problem soils to evaluate the suitability of various synthetic envelope materials for the purpose of developing a workable specification and standard. The Committee's work on commercial synthetic envelope materials in the late 1970's did not lead to conclusive results or a tentative standard, and thus the Committee was disbanded.

Drainage Equipment

Along with the rapid adoption of corrugated plastic drainage tubing worldwide, many significant improvements and innovations were made in drainage equipment and materials handling methods. Of particular significance was the development of new and improved methods for automatically controlling depth and grade on modern high-speed installation machines. By the mid-1970's, a totally new outlook was given to installation and its cost, and many innovative revisions were made in field operational procedures.

Trenching Machines

There are two basic types of trenching machines used to install subsurface drainage: the wheel-type and the ladder- or chain-type. The wheel-type machine remained essentially unchanged in basic design for almost a full century (1850 to 1950) except for improvements in engines, power train, steering, and quality and hardness of steel used in the parts subject to wear. Drainage contractors made many of the design improvements to the digging wheel mechanism, power plant, and traction systems. From about 1945 to 1960, almost all trenching machines sold were first modified by contractor-owners before they were put in service. Whereas track-type trenching machines were the standard for many decades, rubber-tired, wheel-type trenchers were introduced in the early 1950's and became popular among contractors. The rubber-tired machine could often travel over public roadways to the next job site, something not possible with the earlier track-laying machines.

By the [illegible] 1960's, higher speed trenching machines were [illegible]mand because of the greater ease of handling the corrugated plastic drainage tubing. The development of high-speed trenchers (those capable of installing at least 50 feet of drain per minute) became practical with the concurrent development of laser-beam automatic grade control.

The new generation of trenchers utilized supercharged engines and hydrostatic transmission drives. A modern high-speed wheel-type trencher and a high-speed ladder-chain-type machine are shown in figures 3-7 and 3-8. Figure 3-9 is a backfilling machine. There are several manufacturers of these types of trenching machines (figs. 3-7 to 3-12). Modern trenchers include five typical features: machine-mounted reels for coils of tubing, tube feeding and guiding devices, grooving devices for trench bottoms, blinding and backfilling attach-

Figure 3-7—A high-speed trencher on low-pressure rubber tires lays tubing.

Figure 3-8—Workers place drainage tubing by using a high-speed, ladder-chain trenching machine.

Figure 3-10—This trenching machine performs two jobs on a farm in Genessee County, Michigan. It installs drainage tubing and then backfills the soil.

Figure 3-12—This wheel-type trencher has an attached "shoe" which allows installation of deep drains, mainly for salinity control in California's Imperial Valley.

Figure 3-9—A backfilling machine augers the soil back into the ditch. A tile trencher had been used on this farm in Edgecombe County, South Carolina.

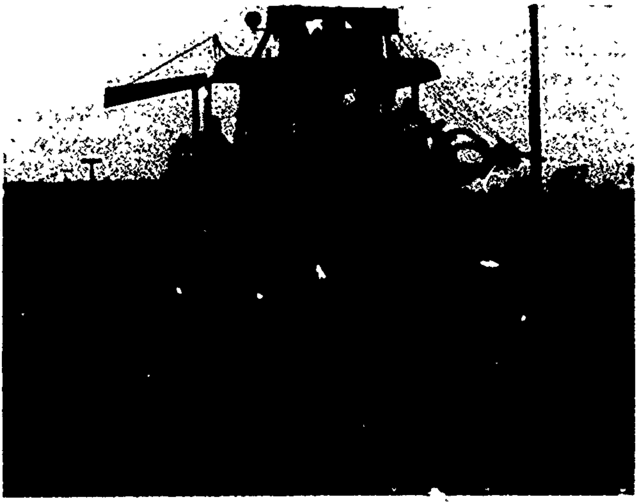


Figure 3-11—Wheel-type trenchers can lay tubing surrounded by an underground gravel envelope by using this machine.

Figure 3-13—A California farm prepares for the installation of 8- to 16-inch diameter drainage tile.

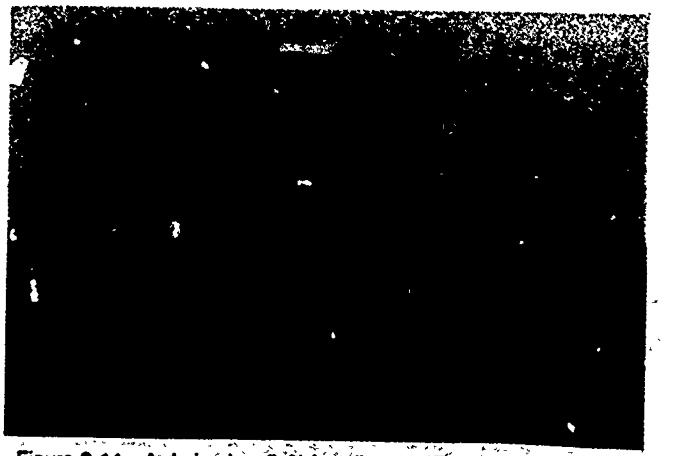


Figure 3-14—A drain plow (left) installs corrugated plastic tubing in a gravel envelope. Coarse sand envelope material is recharged into a hopper at right.

ments, and automatic laser-beam grade control systems. Special attachments have also been developed to feed gravel envelope materials along with the corrugated plastic tubing (figs. 3-11 to 3-13).

Estimates in the early 1980's indicate there were more than 2,500 trenching machines installing subsurface drainage in the United States. Several hundred more machines were reported to be operating in Canada.

Drainage Plows

The concept of "plowing-in" subsurface drainage conduits dates back to at least the mid-1850's (French, 1859, p. 246; and Weaver, 1964, fig. 102). It became practical only in the mid-1960's with the development and introduction of corrugated-wall plastic tubing. Fouss (1965) reported on early U.S. field trials of 2-inch diameter corrugated plastic drains installed with a tube feeder attached to a modified mole plow. The drainage tubing was fed into the ground through the slit opening created by passing the plow blade through the soil, eliminating the slow, costly trenching operation.

The high installation speed possible with the plow (typically 80 to 150 ft/min ground speed) required an automatic means to control depth and grade. Thus, the laser grade control system was developed primarily to meet the needs of the drainage plow (Fouss and Fausey, 1967; and Fouss, 1968). Drainage plows were not used commercially in North America until 1969, but their adoption and use since then has increased steadily (Reeve, 1978). By 1982, about 350 drainage plows were operating in the United States and about 150 in Canada. The total number of plows is small compared with the number of trenching machines, but, because of their higher ground speed, plows were estimated to be used for 40-50 percent of the agricultural subsurface drainage systems installed annually.

Several plow-type drainage machines have been developed commercially, primarily in Europe and Canada. They fall into six classes as to the method or mechanism of depth control: (1) depth-gauge

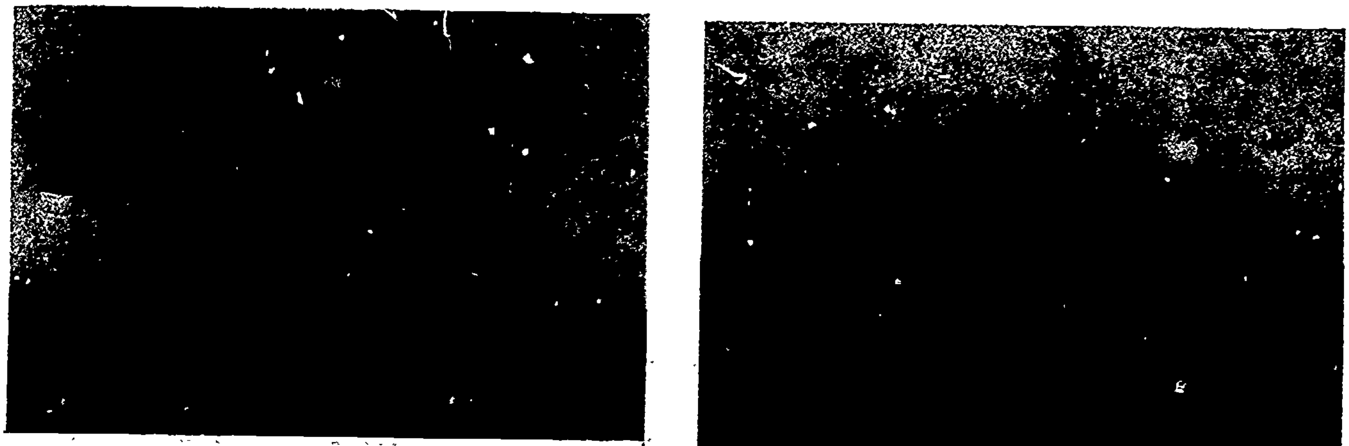
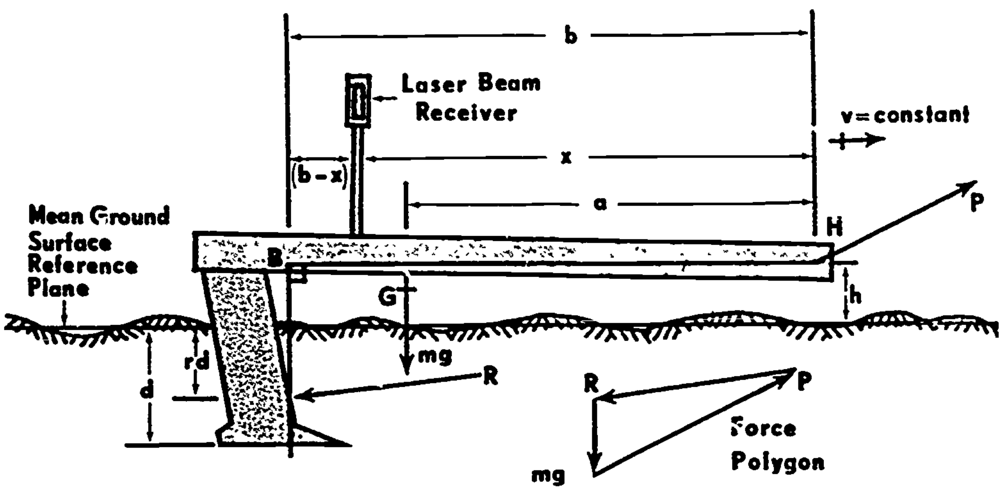


Figure 3-15—This USDA research model of a long, floating-beam drainage plow was equipped with the latest laser-beam grade control system.

Figure 3-16—The principles of laser-beam technology.



wheels with fixed blade, (2) rigid floating beam with fixed blade, (3) floating rigid beam with hinged blade, (4) roller-link beam and floating blade, (5) dual-link floating beam, and (6) hinged cantilever-beam.

The depth-gauge wheel-type plow uses a constant plowing depth operation and is best suited where the land slope is uniform and/or pregraded to a designed complex slope (fig. 3-14). For the irregular ground surfaces commonly encountered on much of the Nation's farmland, a floating-beam-type plow is better suited. Most draintube plows are based on the principle of a long floating beam to improve the depth and grade control during drain installation (fig. 3-15).

The floating beam can be a rigid physical beam (fig. 3-16), where the hitch pin (H) is located several feet foward of the plow blade (B). (Also, see fig. 3-15.) The counteracting rotational force provides the moments of force about the hitch pivot; that is, the plow weight (mg) and soil resistance or draft (R), balance each other, and the plow operates in a floating action mode. Change in the vertical position of the hitch relative to the ground surface controls the grade. Such changes are not immediately reflected in the plowing depth as the tractor pulls the plow forward. This delayed response allows time to correct the hitch height during forward travel to compensate for ground surface irregularities, as determined in fundamental studies by Fouss and others (1972). This function is performed by the laser grade control system. The plow beam can also be virtual (imaginary), but still operating with the floating-beam principle. Plows in classes (4) and (5) above have virtual beams formed by the linkage system attached to the blade. (Also, see Reeve, 1978.)

One of the first plows commercially available (about 1969) in North America was the Badger Minor (fig. 3-17), a production version of a design originally developed by Ede (1961) in England. The blade and tractor are connected by a pair of rollers which run in a curved track or roller-track beam mounted on the rear of the tractor. The center-of-curvature of the roller track acts as a virtual hitch point for the floating blade. The virtual hitch was located at the approximate center of the crawler tracks, isolating the blade from most of the pitching movements of the tractor.

Two units of similar design, the Zor Plow and the Krac Plow, developed in Canada in the early 1970's, used two nonparallel floating links instead of the roller track to make the connection with the blade. Figure 3-18 shows the Krac Plow mounted on a rubber-tired, 4-wheel-drive (4WD) tractor. The 4WD tractor, with a special low-speed transmission, became popular with contractors during the mid-1970's for operating draintube plows. These

Figure 3-17—A Badger-Minor drainage plow lays roller-link corrugated plastic drainage tubing.

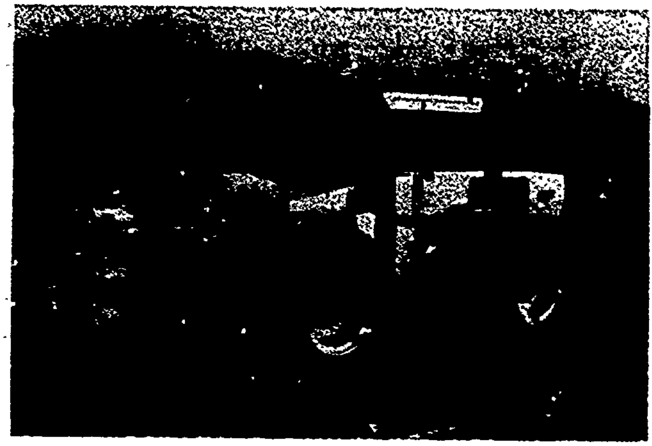


Figure 3-18—A rubber-tired, 4-wheel-drive tractor is mounted with a dual-link Krac-Plow.

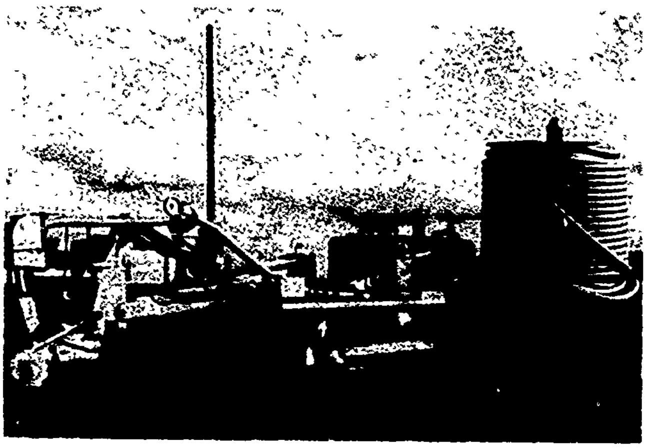


Figure 3-19—This tractor carries, at left, a Hoes Plow with a floating rigid-beam and hinged blade.

machines, like rubber-tired trenchers, can be driven to the next job site. Other nonparallel floating-link-type plows like the Link and RWF are manufactured in Canada. The Wedge Plow is made in the United States.

The German-manufactured Hoes Plow (fig. 3-19) and the Hollanddrain Plow from The Netherlands have a floating rigid beam with hinged blade. The physical hitch points on these plows are mounted in a central location between the tracks, improving traction by the downward component of the plow draft. The close-coupled blade and hydrostatic track drives make these plows easy to maneuver. The plowing depth and grade are controlled during forward motion by hydraulically changing the angle between the rigid floating beam and the plow blade. The [illegible]th Plow, manufactured in The Netherlands, is an example of the parallel-link beam; it can also be operated as a hinged cantilever-beam plow. Specifications and performance characteristics of most drainage machines available in the world, including trenchers, plows, and backhoes, are published in the *Drainage Contractor's Blackbook*, prepared by Agri-Book Magazine of Exeter, Ontario, Canada.

Today's plows can generally install corrugated plastic drains up to 6 inches in diameter and up to 10 inches diameter for some plows. Drains 8 inches and larger, if used for collector main lines, are often installed with trenching equipment. Thus, many contractors who use plows also have a trencher to install the larger size main lines.

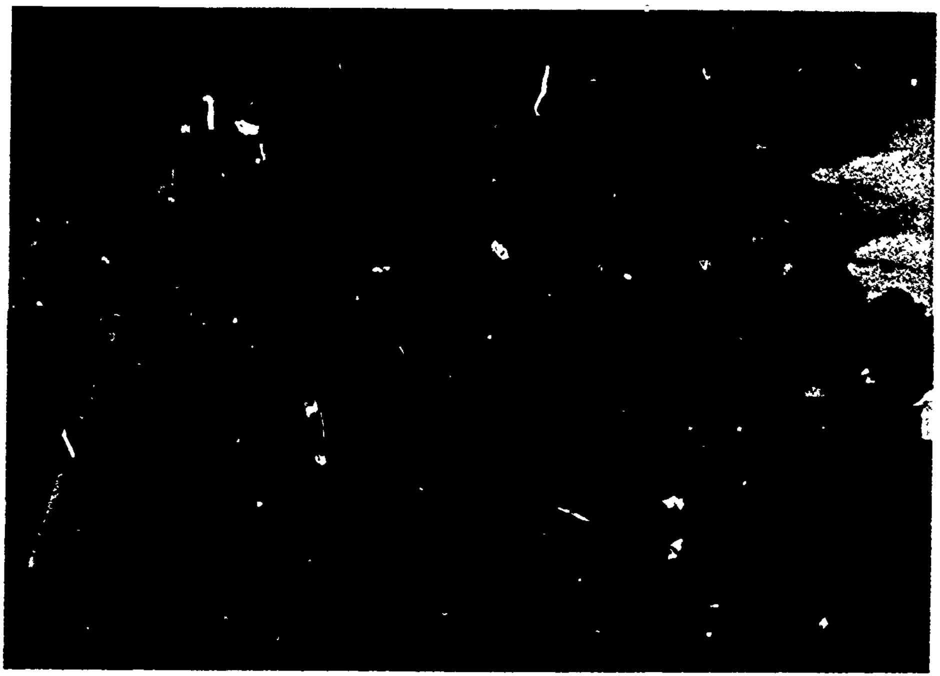
Soil type, soil moisture content, and buried rocks affect the operation and field performance of most drainage plows. Operational problems with plows usually differ from those encountered with trenchers under similar conditions. For example, a few buried rocks that can completely immobilize a trencher pose little, if any, problem for most plows. Rocks up to 12 inches in diameter are often merely lifted or pushed out of the way as the plow blade passes through the soil.

The performance of most plows varies considerably with soil moisture content, particularly for cohesive (clay type) soils. Because draft requirements decrease with increasing soil moisture, a moist soil is best for plowing-in drains. However, excessively wet soils may cause a serious loss in traction for the crawler tractor, and especially for the 4WD, rubber-tired tractor. For extremely dry cohesive soils, draft requirements for the plow may become very high and make plow installation of drains impractical. Some attention has been given to oscillating and/or vibrating plow blades to reduce draft requirements in dry soils (Child and others, 1979).

The speed at which subsurface plastic drains can be plowed-in ranges from 80 to 150 ft/min. Under many field conditions, 2,000 ft of draintube can be installed per working hour; the typical range is 1,500 to 3,000 ft/hr for many installation conditions. Plowing-in 20,000 to 30,000 feet of drain tubing per day is common practice. The high production (installation) capabilities of the draintube plow make it well-suited for large-scale projects. The farmer-customer often prefers that drainage installations be done with plow-type equipment, because the contractor can get into and out of the field much more quickly with a minimum of damage to crops and little soil disturbance.

The capital investment cost for most drainage plows is somewhat greater than for the typical modern trenching machine, but the installation charge per unit length for plowed-in drains is typically 15-25 percent less than the charge for trenched-in drains.

Figure 3-20—Tile installation involves a laser beam to control trench grade. A laser transmitter (foreground) sends a beam to a photocell receiver on the trencher. This 1968 Ohio State University photo shows one of the earliest field installations using laser-beam grade control.



Often farmers are willing to pay a unit charge equal to that for trenching because the plow equipment can complete the installation faster and allow quicker access to the field for tillage and planting. Because of the increasing competition that had developed by the early 1980's and the high capital investment in drainage equipment, contractors with plows found it necessary to adopt improved business management techniques to schedule and utilize more effectively their equipment and thus stay competitive.

Several other improvements in the early 1980's further streamlined and improved the efficiency of plow-in drainage. These included improved blade design, hydraulic blinder/backfillers, and onboard maxi-coil reels (Fouss, 1982). The new design of the plow blade involved a soil-lifting shaped blade coupled with a special tube feeder boot to insure more positive soil placement over and around the drainage tubing as it is installed. The new disc blinder/backfiller attachment is designed to complete the blinding and covering of the pipe. By use of onboard maxi-coils of corrugated tubing, the feeding operation is more effectively controlled, thus minimizing stretch and preventing other installation damage.

Laser Automatic Grade Control

The laser-beam automatic grade-control system was developed to meet the specific requirements of the high-speed drainage plows, because grading methods using sight-bars or stretched wires were slow, costly, and/or unsatisfactory (Fouss and Fausey, 1967; Fouss, 1968). Commercial versions of the laser-beam grade-control system were available on the U.S. market in 1967, before operational drainage plows were fully developed for commercial use. Those versions of automatic grading systems were used on conventional tile trenching machines by late 1968 (Studebaker, 1971; and Teach, 1972). An early installation is shown in figure 3-20. By the early 1970's, many farmers expected or demanded that their subsurface drainage systems be installed with laser-controlled equipment. By 1970, almost all of the drainage plows introduced and sold in North America were equipped with laser grade-control systems.

The basic principle of automatic depth and grade control for drainage equipment, using a projected laser-beam datum (grading reference line or plane) and an onboard laser tracking-receiver which automatically controls depth of drain installation, was reported in detail by Fouss (1968) and Teach (1972). The typical laser used for this application is the continuously emitting helium-neon gas laser, which projects a brilliant tail-light red beam of collimated light. Figure 3-16 shows the laser-beam receiver mounted on the plow frame, and the laser-beam datum projected from a remote source. Fouss and others (1972) conducted computer simulation studies and field testing to develop guidelines for the optimum placement of the laser-beam receiver onboard the drainage plow (that is, distance "b-x" in fig. 3-16) to ensure acceptable accuracy of automatic grade control for a wide range of field installation conditions.

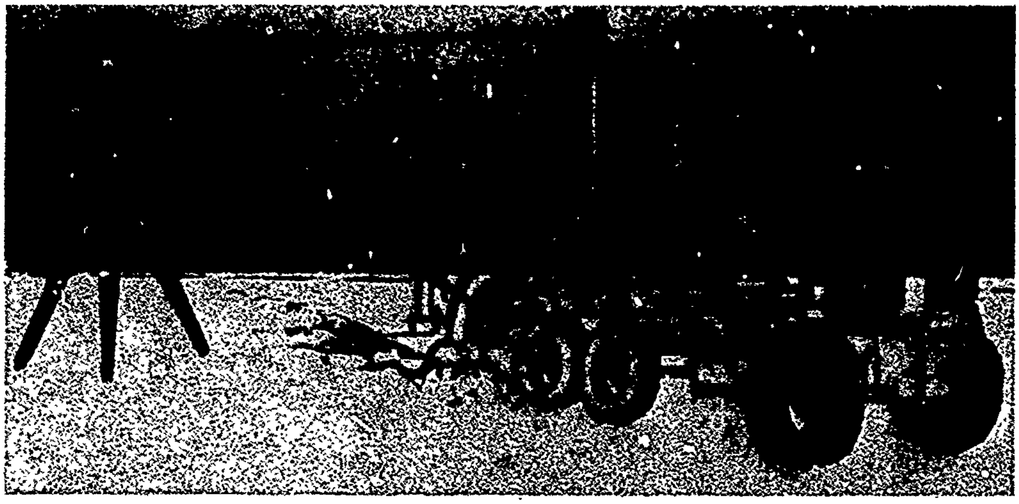


Figure 3-21—Pictured is an automatic grade control system on a trenching machine. A trencher and drainage plow operate in the same field.

By 1971, three different types of laser-beam grading systems, based upon the projected helium-neon gas laser, were in use and available from a number of commercial sources. The first laser type is a single laser light beam or line projected parallel to the desired grade and along the direction of drainage machine travel. The second type is a partial-plane or segment of circle (arc) projected parallel to the desired grade in the direction of machine travel and also parallel to the cross-slope level. The third type is a circular laser plane reference created by rapidly rotating the laser source (5 to 10 revolutions per second), much like a lighthouse beacon, where one axis in the plane is aligned parallel with the desired drain grade and the other axis aligned either horizontally or parallel to the general land slope. The laser-plane reference system, shown schematically in figure 3-21 for a trenching machine and plow operating in the same field, became popular because the elevation or grading datum covered a large field area, up to 100 acres, with each setup of the battery-powered laser transmitter unit. A heavy-duty car battery allowed it to operate for a full work day without a recharge.

Most of the laser tracking-receivers included a vertical array of closely spaced photocells connected to an electronic logic and controller circuit. The machine hydraulics were operated by the controller to provide the corrective feedback motion of the plow or trencher hitch (figs. 3-16 and 3-21), thus automatically keeping the receiver unit centered "ON" the laser-beam or laser-plane datum. For most tile trenching machines, a simple ON-OFF, stepwise hydraulic feedback correction has proven adequate. For the high-speed plows, a pure ON-OFF and/or proportional corrective feedback motion has typically been needed to maintain adequate grade control (Fouss and others, 1972; and Teach, 1972).

As with the general pattern in any technologic development, the first 20 years of use for the laser-beam and laser-plane grade control systems on subsurface drainage installation equipment has been filled with a series of important improvements and innovations. The self-leveling laser-plane transmitter greatly increased the efficiency of the system and was quickly adopted for general use by drainage and construction contractors. Several useful mechanisms and techniques were developed for creating and/or changing the desired drain grade, even during forward machine motion, without resetting the projected laser-beam or laser-plane reference. A popular approach involves vertically moving the onboard laser receiver, relative to its machine mounting, as a selective function of ground travel distance. Thus, any desired grade can be created for a given (preset) or plane slope, even when the reference is projected horizontally. This approach also permits changing the drain grade at any point of travel along the drain line, eliminating the need to reset the laser reference for each drain gradient change.

With the development and successful commercialization of the laser-beam and laser-plane automatic grade control systems in the 1970's and 1980's, the laser-beam-controlled drainage plow for installing corrugated plastic drainage tubing became an effective and practical method of subsurfacing drainage installation. Laser-beam alignment and/or guidance systems have found worldwide applications in other areas, such as surveying, land grading, pipelines, tunnels, buildings, and other engineering and construction work, including military applications.

Drainage and Water Management Systems

Drainage has traditionally been considered separately from irrigation and other water control practices. We now recognize that these practices should be considered together in total water management systems for agriculture.

In the mid-1980's, a significant amount of technical investigative work and commercial market development in the broad area of agricultural water management technology focused on combination (or dual-purpose) drainage and subirrigation systems, particularly in the humid climate regions of the United States. The development of the water management simulation model, DRAINMOD, gave engineers a practical and computerized means for designing agricultural water management systems based on the recorded variation of weather conditions over a long period of time (20 to 30 years). (See Skaggs (1980) and chapter 6 in this bulletin.) New approaches using computer simulations and field testing were investigated to operate and/or manage the dual-purpose drainage-irrigation systems for humid climate conditions (Doty and others, 1984; Smith and others, 1985; and Fouss, 1985b).

The future promises that the farmer or farm manager can be provided with sufficiently sophisticated monitoring and control/management systems to fully achieve onfarm water management, so as to conserve water resources, use natural rainfall effectively, reduce plant stresses from excess or deficient soil water, reduce energy costs, and maximize operating profits.

Computers are increasingly providing the needed control for total water management. Significant advances have been made in the development of sophisticated sensing equipment for monitoring and feedback systems. Computer software is under development that will operate systems and daily management decisions to make total water management an onfarm reality. These developments will also help farmers make better risk and benefit decisions and will help them select management options. These options will almost certainly include current weather forecast information (Fouss, 1985a) down to the geographical coordinates of farms.

References

American Society for Testing and Materials (ASTM). 1974. *Standard Specification for Corrugated Polyethylene Tubing (F405-74).* ASTM Subcommittee F-17.65 on Land Drainage Systems.

Boa, W. 1963. "Development of a Machine for Laying Plastic Drains," *Journal of Agricultural Engineering*. Vol. 8, No. 3, pp. 221-230.

Broadhead, R. G., G. O. Schwab, and R. C. Reeve. 1983. *Synthetic Drain Envelopes and Soil Particle-Size Distribution.* Transactions of the ASAE. Vol. 26, No. 1, pp. 157-160.

Broughton, R. S., and others. 1977. *Tests of Filter Materials for Plastic Drain Tubes.* Proceedings of Third National ASAE Drainage Symposium. ASAE Pub. No. 1-77, pp. 34-39.

Busch, C. D. 1958. "Low Cost Subsurface Drainage," *Agricultural Engineering.* Vol. 39, No. 2, pp. 92-93, ff.

Child, Jr., J.L., J. L. Fouss, and E. K. Nowicki. 1979. *Dynamic Plow Assembly and Methods of Operating Same.* U.S. Pat. No. 4,179,227 (12/18/79). Appl. 825,192 (8/17/77). Assignee: Hancor, Inc., Findlay, Ohio. (18 pages, 14 figures, 42 claims.)

De Jager, A. W. 1960. "Review of Plastic Drainage in The Netherlands," *Netherlands Journal of Agricultural* Science. Vol. 8, No. 4, pp. 261-270.

Doty, C. W., J. E. Parsons, A. N. Tabrizi, and R. W. Skaggs. 1984. *Stream Water Levels Affect Field Water Tables and Corn Yields.* Transactions of the ASAE. Vol. 27, No. 5, pp. 1300-1306.

Ede, A. N. 1961. "Floating-Beam Mole Plough Trials," *Farm Mechanics.* Vol. 13, No. 144, pp. 274-275.

Ede, A. N. 1963. "New Methods of Field Drainage," *Agriculture.* Vol. 70, No. 2, pp. 82-86.

Ede, A. N. 1965. *New Materials and Machines for Drainage.* Proceedings of ASAE Conference on Drainage for Efficient Crop Production. December, Chicago, pp. 58-61.

Edminster, T. W. 1965. The *Challenge of New Technology in Drainage.* Proceedings of ASAE Conference on Drainage for Efficient Crop Production. December, Chicago, pp. 43-45.

Fouss, J. L., and W. W. Donnan. 1962. "Plastic-lined Mole Drains," *Agricultural Engineering.* Vol. 43, No. 9, pp. 512-515.

Fouss, J. L. 1965. *Plastic Drains and Their Installation.* Proceedings of ASAE Conference on Drainage for Efficient Crop Production. December, Chicago, pp. 55-57.

Fouss, J. L., and N. R. Fausey. 1967. "Laser Beam Depth Control for Drainage Machine," *Ohio Report.* Vol. 52, No. 4, pp. 51-53.

Fouss, J. L. 1968. *Corrugated Plastic Drains Plowed-in Automatically.* Transactions of the ASAE. Vol. 11, pp. 804-808.

Fouss, J. L., N. R. Fausey, and R. C. Reeve. 1972. *Draintube Plows: Their Operation and Laser Grade Control.* Proceedings of Second National ASAE Drainage Symposium. St. Joseph, Mich., pp. 39-42.

Fouss, J. L. 1973. *Structural Design Procedure for Corrugated Plastic Drainage Tubing.* TB-1466. U.S. Dept. of Agr., Agr. Res. Serv.

Fouss, J. L. 1974. "Drain Tube Materials and Installation," *Drainage for Agriculture.* (ed. Jan van Schilfgaarde). Monograph No. 17, Am. Soc. Agron. Madison, Wisc., pp. 147-177, 197-200.

Fouss, J. L. 1982. *Modernized Materials Handling and Installation Implements for Plow-type Drainage Equipment.* Proceedings, Second International Drainage Workshop, Washington, DC. December, pp. 41-51.

Fouss, J. L., and W. E. Altermatt. 1982. *Drainage-plow 'Boot' Design to Improve Installation of Corrugated Plastic* Tubing. Proceedings of Fourth National ASAE Drainage Symposium. ASAE Pub. No. 12-82, pp. 102-104.

Fouss, J. L. 1985a. *Daily Weather Forecast Rainfall Probability as an Input to a Water Management Simulation Model.* ARS-30. U.S. Dept of Agr., Agr. Res. Serv. Proceedings of the USDA ARS/SCS Natural Resources Modeling Workshop, October 17-21, 1983. Pingree Park, Col.

Fouss, J. L. 1985b. *Simulated Feedback-Operation of Controlled-Drainage/Subirrigation Systems."* Transactions of the ASAE. Vol. 28, No. 3, pp. 839-847.

Fouss, J. L., and W. E. Altermatt. 1985. *Strength vs. Stretch of Corrugated Plastic Drainage Tubing.* Tech. Bull. 1H, Hancor, Inc., Findlay, Ohio.

French, H. F. 1859. *Farm Drainage.* New York: A. O. Moore and Co.

Janert, H. 1952. "Die Mechanisierung der Drainarbeiten." *Wasserwirtschaft Wassertechnik,* 2, pp. 392-397.

Luthin, J. N., and R. C. Reeve. 1957. "The Design of a Gravel Envelope for Tile Drains." In *Drainage of Agricultural Lands* (ed. James N. Luthin). Monograph No. 7, Am. Soc. Agron. Madison, Wisc., pp. 339-344.

Myers, V. I., R. J. Rektorik, and C. A. Wolfe, Jr. 1967. *Deflection Tests and Trench Conditions for Plastic Drain Pipe."* Transactions of the ASAE. Vol. 10, pp. 454-547.

Reeve, R. C. 1978a. Trench*less Drainage.* Proceedings of the International Drainage Workshop. (ed. Jans Wesseling). May 16-20, 1978, Wageningen, The Netherlands. Paper 3.09, pp. 571-589.

__________. 1978b. "Synthetics at Work," *Drainage Contractor Magazine.* Vol. 5, No. 1, p. 80. Hensall, Ontario, Canada.

__________. 1979, *Synthetic Drain Envelope Materials - Technical Information.* Columbus, Ohio: Advanced Drainage Systems, Inc.

__________. 1981. *Filter and Envelope Materials.* Presented at Subsurface Drainage Workshop. ADS Reprint, Univ. of Ill., February.

__________. 1982. *Synthetic Envelope Materials for Subsurface Drainage.* Proceedings, 2nd International Drainage Workshop, Washington, DC. December 5-11.

Reeve, R. C., R. E. Slicker, and T. J. Lang. 1981. *Corrugated Plastic* Tubing. Proceedings, Am. Soc. Civ. Engr. International Conference on Underground Plastic Pipe. pp. 277-242.

Rektorik, R. J., and V. I. Myers. 1967. *Polyethylene Drainage Pipe Installation Techniques and Field Performance.* Transactions of the ASAE. Vol. 10, pp. 458-459, 461.

Schwab, G. O. 1955. "Plastic Tubing for Subsurface Drainage." *Agricultural Engineering,* Vol. 36, No. 2, pp. 86-89, 92.

Schwab, G. O., and J. L. Fouss. 1985. "Plastic Drain Tubing: Successor to Shale Tile," *Agricultural Engineering.* Vol. 66, No. 7, pp. 23-26.

Skaggs, R. W. 1978. *A Water Management Model for Shallow Water Table Soils.* Technical Report No. 134, Water Resources Institute of the University of North Carolina. N.C. State Univ., Raleigh.

Skaggs, R. W. 1980. *A Water Management Model for Artificially Drained Soils.* Technical Bulletin No. 267, N.C. Agr. Serv., N.C. State Univ., Raleigh.

Smith, M. C., R. W. Skaggs, and J. E. Parsons. 1985. "Subirrigation System Control for Water Use Efficiency." Transactions of the ASAE. Vol. 28, No. 2, pp. 489-496.

Sorbie, F. I., J. L. Fouss, and G. O. Schwab. 1972. *Comparison of Strength Test Methods for Corrugated Plastic Drainage* Tubing. Transactions of the ASAE. Vol., 15, pp. 445-447.

Studebaker, D. C. 1971. "The Laser-plane System," *Agricultural* Engineering. Vol. 53, No. 8, pp. 418-419.

Teach, T. L. 1972. *Automatic Laser Grade Controls.* Society of Automotive Engineers, Earthmoving Industry Conference, Central Illinois Section, Peoria, April 10-12. Paper No. 720386.

van Schilfgaarde, J. 1965. "Transient Design of Drainage Systems," *Journal of the Irrigation and Drainage Division.* ASCE. Vol. 91 (IR3), pp. 9-22.

Van Someren, C. L. 1964. "The Use of Plastic Drainage Pipes in The Netherlands." (Translations from Coltuurtechnik 1,2,3). Government Service for Land and Water Use, Maleibaan 21, Utrecht, The Netherlands.

Watkins, R. K. 1967. *The Development of Structural Concepts for Buried Pipes Externally Loaded.* Bulletin No. 7, Engineering Experiment Station, Utah State Univ., Logan.

Watkins, R. K., R. C. Reeve, and J. B. Goddard. 1983. "Effect of Heavy Loads on Buried Corrugated Polyethylene Pipe." Transportation Research Board, National Academy of Sciences, Washington, DC, pp. 99-108.

Weaver, M. M. 1964. *History of Tile Drainage.* Waterloo, N.Y. Private Publication. (ref. fig. 102),

Willardson, L. S. 1974. "Envelope Materials," *Drainage for Agriculture.* Chap. 9. (ed. Jan van Schilfgaarde). Monograph No. 17, Am. Soc. Agron. Madison, Wisc., pp. 178-200.

Willardson, L. S. 1979. "Hydraulic Gradients in Envelope Materials," ARR-W-8/June. Utah State Univ., Logan.

Chapter 4

Purposes and Benefits of Drainage

N.R. Fausey
Agricultural Research Service, USDA
Ohio State University

E.J. Doering
Agricultural Research Service, USDA
Mandan, North Dakota

M.L. Palmer
Department of Agricultural Engineering
Ohio State University

The importance of drainage to public health and the economic well-being of the Nation is generally not understood, we believe, because of a public perception of drainage as only the process of converting valuable wetlands to other uses. We accordingly review the several purposes and benefits of draining wet soils now in use for cropland, pasture, rangeland, and forestland. However, we do not consider the benefits of, or issues involved in, draining wetlands for conversion to new cropland, development sites, and other uses. According to an Office of Technology Assessment report cited earlier by Smith and Massey (OTA, 1984), agricultural drainage and land clearing have been responsible for most wetland conversions since the mid-1950's, and there is still significant pressure to convert wetlands to other uses.

Although drainage is a mechanism by which this conversion takes place, pressures for and against conversion are exerted by competing economic and other public values. Competition issues are reviewed by Swader. But, our discussion focuses on the more immediate practical purposes and benefits of draining wet soils now in agricultural or forest uses on farms.

Purposes of Drainage

The underlying objectives in draining wet soils on farms are to minimize risk, improve efficiency, and increase net income. Drainage is best viewed as a water management practice, whose practical purposes are different for different climatic regions and land uses. A farmer may drain land for several reasons: to reduce diseases of crops and livestock; to leach salt from irrigated land; or to remove excess soil water, improving trafficability for machinery and the crop rooting environment. Figures 4-1 and 4-2 illustrate the effects of poor drainage on cotton and corn crops.

Another important purpose is to protect the soil from uncontrolled runoff and erosion. Closely related farm or nonfarm purposes of drainage are to stabilize roadways and building foundations, to improve the usefulness of recreation areas, to reduce flooding, and to facilitate land disposal of waste water.

How wet soils are drained depends on soil type, climate, topography, and intended land use. Grading, field ditches, swales, and other improvements may be adequate for managing surface water (fig. 4-3). Subsurface drains must be used to manage excess soil water and to remove excess soluble salts from the soil (fig. 4-3). Both surface and subsurface drainage improvements are often needed to properly manage the excess water. When properly done, drainage has various primary and associated benefits.

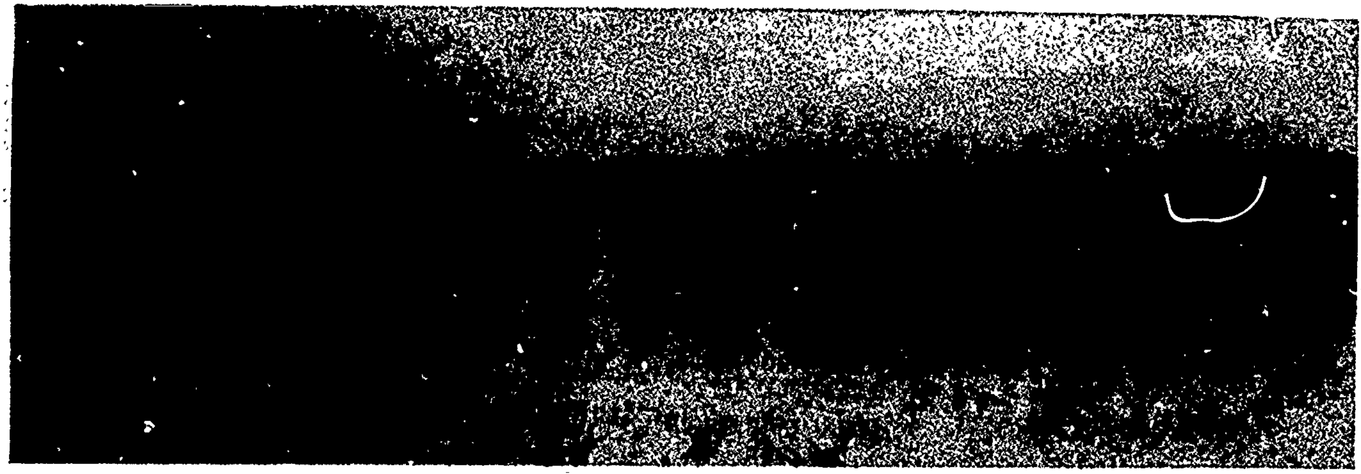


Figure 4-1—Cotton plants sit unharvested in Randolph County, Arkansas, because of standing water. Local landowners later organized a joint rural and urban project to drain the land.

Primary Benefits of Drainage

The primary benefits of drainage go beyond the protection of irrigated land from excess accumulations of undesirable salts and the improvement of plant growth by creating more favorable moisture environments and protecting public health.

Vector Control and Public Health

Drainage eliminates diseases that harm people, crops, and livestock. The benefits for mankind are greater life expectancy and improved quality of life. The benefits for crops and livestock are healthier, more vigorous, and more productive plants and animals, resulting in increased economic value.

In developing areas of the world, health professionals usually lead the effort to initiate drainage improvements. Their concern is to eliminate stagnant water which serves as breeding areas for mosquitos or parasitic organisms that transmit or cause disease and illness. Mosquitoes and flies thrive in poorly drained areas. Effective control methods for malaria and yellow fever rely on drainage to eliminate mosquito-breeding areas.

Organisms causing foot-rot in large animals cannot survive in dry areas. The liver fluke snail flourishes on wet land; the only sure way to prevent the fluke disease is to destroy the snail's habitat by draining wet areas. Drainage reduces or eliminates mildew infections and various root rots of plants because the disease organisms cannot live and multiply in dry conditions.

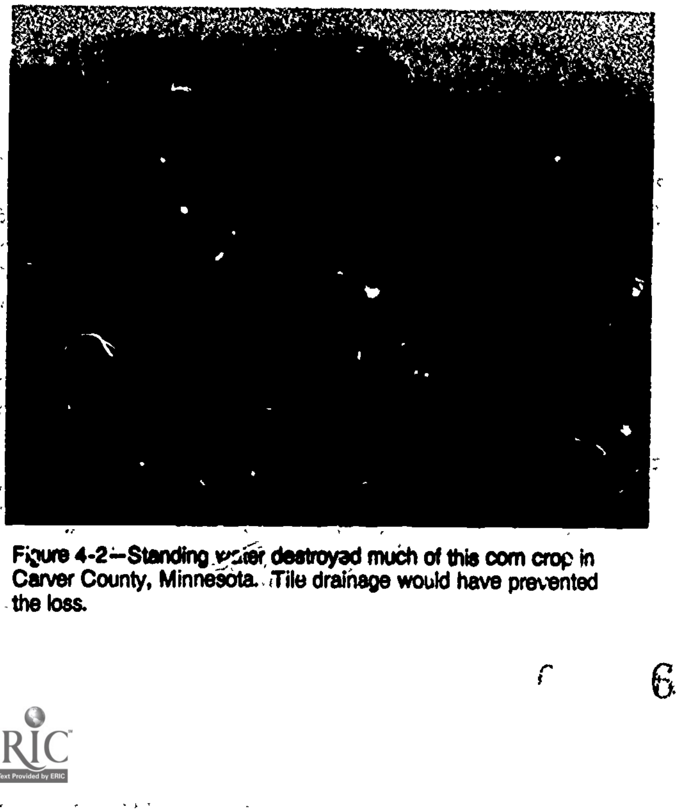


Figure 4-2—Standing water destroyed much of this corn crop in Carver County, Minnesota. Tile drainage would have prevented the loss.

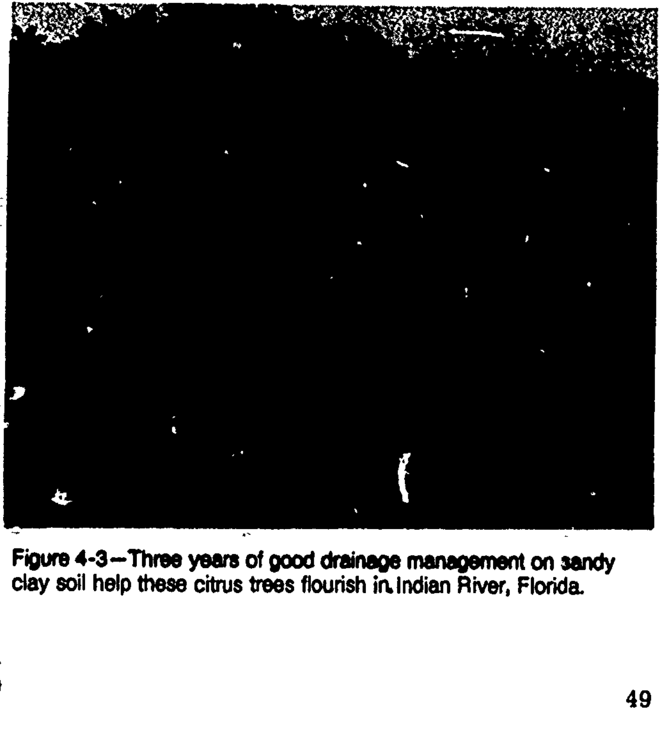


Figure 4-3—Three years of good drainage management on sandy clay soil help these citrus trees flourish in Indian River, Florida.

Figure 4-4—Nearly 4,000 feet of tiling along Hardware River bottomland corrects poor drainage in Chewacla and Wehadkee soils, Albemarle County, Virginia.

Salt Removal

Drainage is the key to successful irrigation agriculture. History clearly documents the demise of advanced civilizations that did not realize the importance of drainage to sustained irrigation in arid regions. The productive potential of irrigated soil can be maintained for an indefinitely long time when drainage is installed and proper leaching techniques control the salt content of the soil.

The dissolved salt content of soils may become quite high as a result of upward capillary flow of water from a saline water table, or perhaps more important, because salt accumulates as water is transpired by plants. The effects on crops can be very severe (fig. 4-5). The rate of capillary salination depends on the depth of the water table, the water-conducting properties of the soil, and the salinity of the ground water.

To counteract the accumulation of salts in the root zone of irrigated soils, irrigation water in excess of the amount needed to satisfy crop needs is applied to leach the salts down and out of the root zone and into the drains (fig. 4-6). The amount of excess irrigation (leaching) water needed depends primarily on the tolerance of the crop to salt, on the quality of the irrigation water, and on the manner in which the irrigation water is applied. Frequent applications that produce a steady downward flow of soil water will require less leaching water than infrequent applications, because the latter allows saline soil water to rise toward the surface between irrigations.

In arid irrigated regions, drains are installed as deeply as possible (often 8 feet or deeper) to minimize the length of drain per unit of area and insure that the midpoint water-table depth between drains is at least 4 feet below the ground surface. This practice minimizes the likelihood that the saline ground water will rise into root zone by capillary flow.

Increased Productivity

Drainage removes excess water from the soil and creates a well-aerated root environment which warms up quickly in the spring and enhances the availability of plant nutrients so plant growth can begin early, continue vigorously, and achieve high productivity. Early growth is important for establishing an extensive root system which can supply nutrients and water to the plant from a large volume of soil. This can minimize the damaging effect of drought during later growth stages.

Without drainage, crop growth may lag in the spring because wet soils warm slowly. Wet soil requires five times more energy to raise its temperature than does dry soil, and the cooling effect of the greater evaporation from wet soils delays a temperature rise. Seeds will not germinate and roots will not grow below a critical soil temperature (usually about 50°F), so rapid, early warming of both surface and subsurface soils is important. Plant roots do not function normally in saturated soil even when adequate nutrients are present. Roots cannot absorb water and nutrients under conditions of oxygen stress or poor aeration.

Plant nutrient availability depends greatly on soil microorganisms that break down organic matter to release nutrients or that fix nitrogen from the

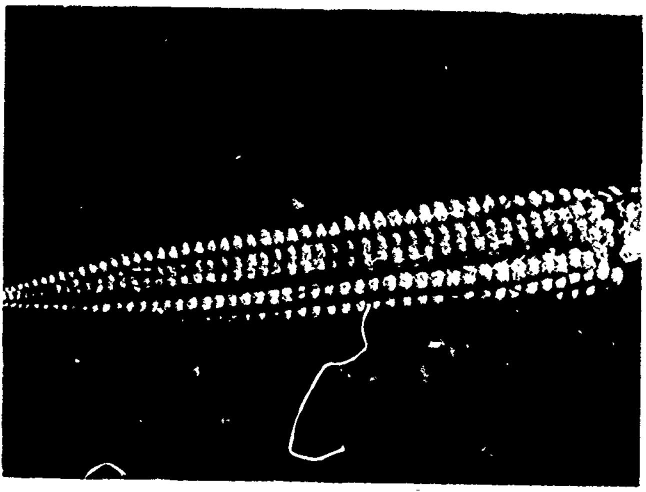


Figure 4-5—This stunted ear of corn is dramatic evidence of salinization— too much salt in the soil, at a farm in Grand Junction, Colorado.

Figure 4-6—Bare soils bespeak the damages of soil salinity. Proper water management and drainage could have saved this cotton crop in the Imperial Valley, California.

atmosphere. These organisms also require a well-aerated, warm environment to function normally. Without drainage, the microorganisms cannot supply nutrients for uptake by plants.

Drainage also stabilizes productivity by reducing the variation in crop yields from year to year. In some years, drainage may not be needed for good yields on normally wet soils, but in other years, very low yields or no yields may result from poor drainage. Drainage can prevent these low yields, increasing the reliability of crop production and minimizing risk.

Associated Benefits of Drainage

The main associated benefits of drainage include improved trafficability for vehicles, implements, improved timeliness of farm operations, and reduced soil erosion.

Trafficability and Timeliness

By removing excess water from the soil, drainage provides a surface soil layer dry enough to handle farm machinery, increasing the number of days available for fieldwork and reducing or eliminating production losses from the delays in planting or harvesting.

Delays in field operations can result in losses ranging from reduced yields to complete crop failure. Performing tillage, weed control, or harvesting operations when the soil is too wet may be impossible because the equipment cannot operate for lack of support or traction. Soil compaction or soil structure degradation are less obvious but more serious problems. Not only must the agronomic timeliness requirements of the crop and soil conditions be met, but the physical integrity of the soil must be preserved. Otherwise, a long-term loss in production potential may result from too much traffic or soil manipulation at a time when puddling or compaction occurs.

Drainage is important in all of trafficability for farming operations. Subsurface drainage removes excess water from the upper layers of the soil profile more rapidly than the natural processes of evaporation and transpiration. Surface drainage can prevent wet spots which often hold up operations on low areas or cause inconvenience and loss of both time and productive area when they must be worked around. Rapid removal of surface water and rapid lowering of the soil-water content aid materially in providing soil moisture conditions suitable for trafficability.

Reduced Erosion

Drainage reduces erosion by controlling the discharge of excess water from the land. Surface drains and terraces are designed to remove water without erosion. Subsurface drains remove water from within the soil, providing storage that reduces the amount of runoff from subsequent rainfall. Reduced erosion also means improved water quality for streams.

Drainage is very important to soil conservation efforts. Conservation tillage systems do not perform we[illegible] poorly drained soils; thus, drainage can be a critical element for conservation tillage systems designed to control erosion. Drainage of grassed waterways by subsurface drains is often essential to dry the channel bottom so that protective vegetation can be maintained, thereby preventing rills and eventually gullies.

Chapter 5

Preserving Environmental Values

Carl H. Thomas
Soil Conservation Service, USDA
Washington, DC

Assessments of drainage needs are incomplete without considering environmental ramifications. Farmland drainage may have both beneficial and adverse effects on the environment. These must be recognized along with any farm production benefits and costs. Environmental components include such items as natural beauty; archeological, historical, biological, and geological resources; ecological systems; and air and water quality. Although many effects of farmland drainage on the environment are not economic in nature, they may provide important evidence for judging the value of proposed plans. Farm drainage programs can benefit the environment or have a neutral effect if multiobjective or multipurpose projects include the management, preservation, or restoration of one or more environmental components.

Identification and Measurement

Modern agriculture has grown more intensive and dependent upon an industrialized technology to meet demands for food, fiber, and forest products. Water management through drainage is an important aspect of this technology. Conflicts often arise between drainage interests and ecological or environmental interests.

The technical responsibility in this situation requires that ecological knowledge be blended with hydrologic knowledge and that both be responsive to the objectives of private landowners and national taxpayers, who subsidize drainage on privately owned lands to the extent that there is Federal participation or assistance. Realistic options can be developed for the conservation, use, and management of all natural resources, including wetlands. The key to decisionmaking on wetlands use is to maximize the well-being of people. In most instances, this happens by explicitly recognizing the functions that wetlands perform and counting the loss as these functions are sacrificed or impaired.

Functional Values of Wetlands

Wetlands are lands transitional between terrestrial and aquatic systems. The water table is usually at or near the surface, or the land is covered by shallow water. Wetlands must periodically support hydrophytes, and the substrate must be predominantly undrained hydric soils. Examples of estuarine as well as forested and emergent freshwater wetlands are in figures 5-1 to 5-4.

Ten specific functional values of wetlands are generally acknowledged: habitat for fisheries, habitat for wildlife, water recharge and discharge, flood storage and desynchronization, shoreline anchoring and dissipation of erosive forces, sediment and contaminant trapping, nutrient retention and removal, food chain support, active recreation, passive recreation, and heritage value. More complete definitions of these functions follow, along with their economic and other values. The descriptions are largely adapted from Adamus and Stockwell (1983).

Habitat for Fisheries. Fisheries are the fin fish and shellfish resources within the interior or coastal areas of the United States. The habitat includes biological, physical, and chemical factors that affect the food, cover, metabolism, attachment, predator avoidance, and other life requirements of the adult or larval forms. The direct economic significance of providing habitat for fisheries is that fisheries are clearly vital to regional and national economies as well as to the social well-being of people in providing environmental amenities.

Habitat for Wildlife. Habitat pertains to those features which affect the food, water, cover, and reproductive needs for birds, mammals, reptiles, and amphibians in the place where they live. The direct economic significance of wetland habitat for wildlife includes consumptive and nonconsumptive

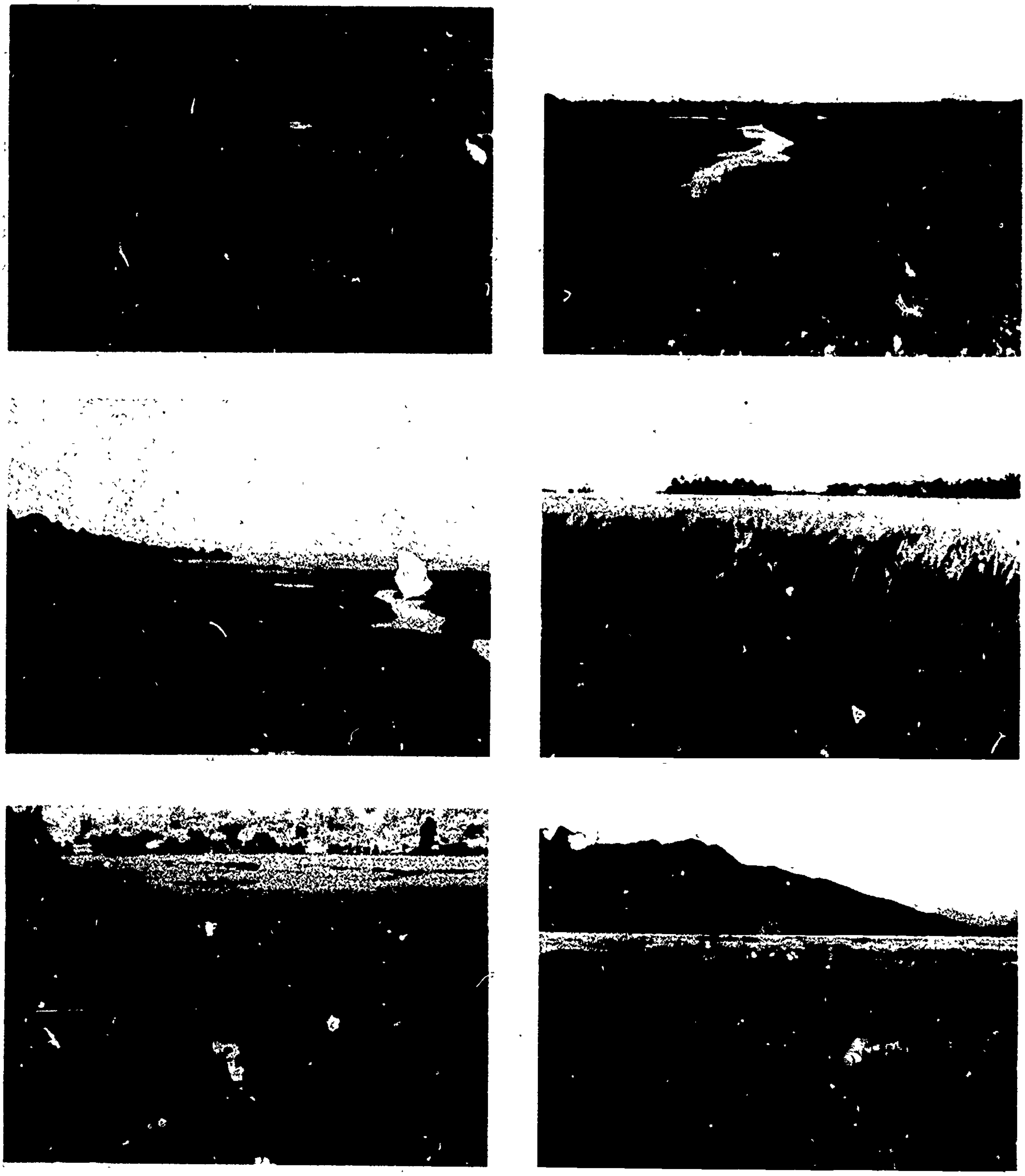


Figure 5-1—These marshes are examples of estuarine emergent wetlands, where a river's current meets the tide. Pictured (clockwise, upper left to right) are: mixed plant community of an irregularly flooded marsh, reed-salt hay cordgrass, regularly flooded cordgrass, black needlerush, Lyngbye's sedge marsh, Alaskan irregularly flooded marsh.

Figure 5-2—Example of forested wetlands (clockwise, upper left to right): red maple swamp, Atlantic white cedar swamp, bald cypress swamp, bottomland hardwood swamp, riparian forested wetlands (those located on the banks of a natural water body), Alaskan forested wetlands mixed with scrub-shrub wetlands.

user days spent in birding, hunting, and other wildlife-oriented recreational activities. Besides providing year-round habitat for resident birds, wetlands are especially important as breeding grounds, overwintering areas, and feeding grounds for waterfowl and numerous other migratory birds (fig. 5-5). Both coastal and inland wetlands serve these valuable functions.

Besides waterfowl, wetlands also support other species of birds, such as egrets, herons, gulls, shore birds, some species of sparrows, and terns. Potholes and other inland emergent wetlands provide important winter cover and nesting habitat for ringneck pheasants.

Wetlands also provide valuable habitat for muskrats in coastal and inland marshes throughout the country. Other furbearers who depend on wetlands include beaver, nutria, otter, mink, raccoon, skunk, and weasels.

Other dependent mammals include marsh and swamp rabbits, numerous species of mice, black bears, brown bears, caribou, moose, and several reptiles and amphibians, such as turtles, alligators, frogs, and some species of snakes (fig. 5-6).

Figure 5-3—Scrub-shrub wetlands emerge in this southern bog or "pocosin."

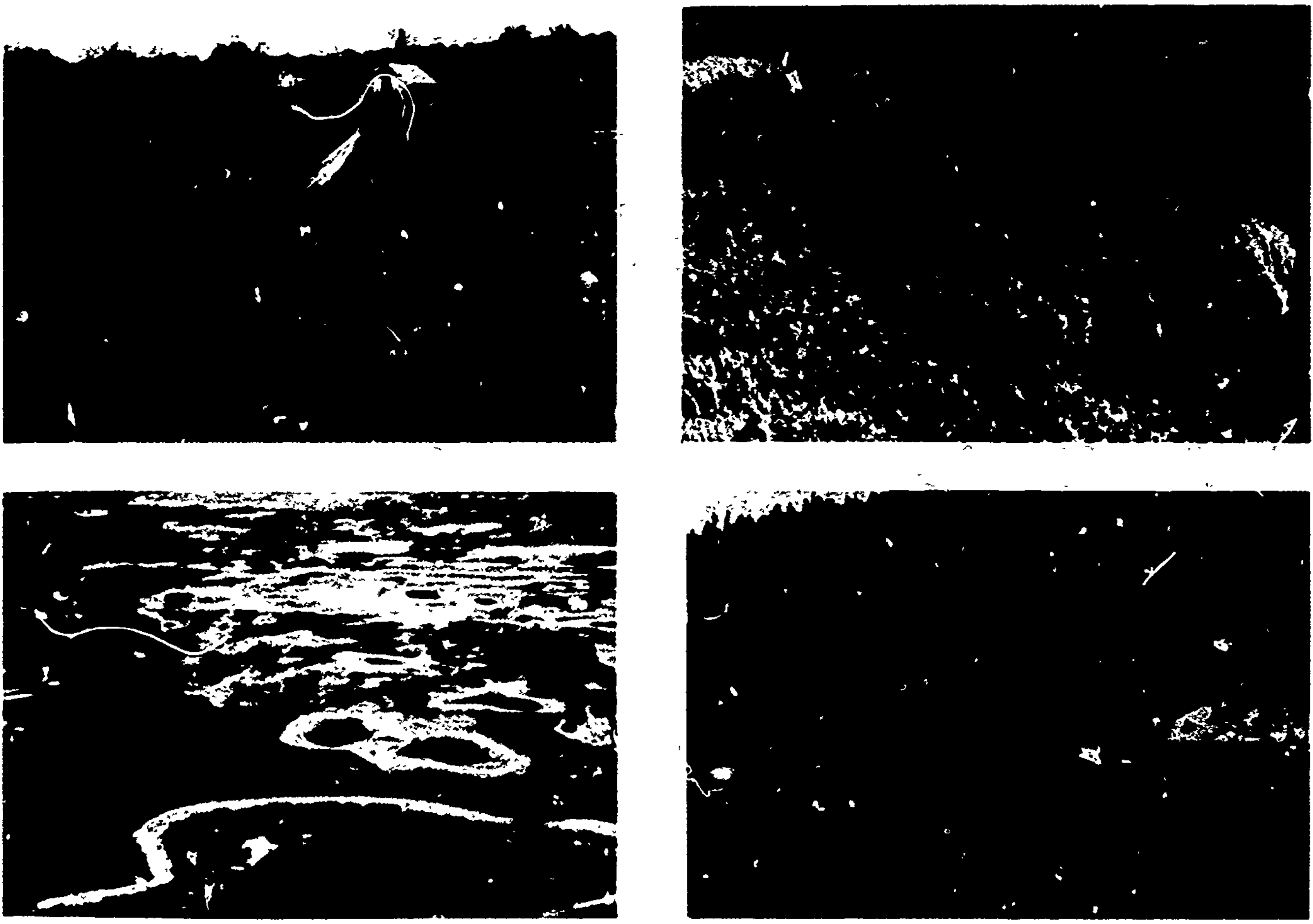


Figure 5-4—Emergent wetlands (clockwise, upper left to right): northeastern sedge meadow, cattail marsh, prairie pothole wetlands, western sedge meadow.

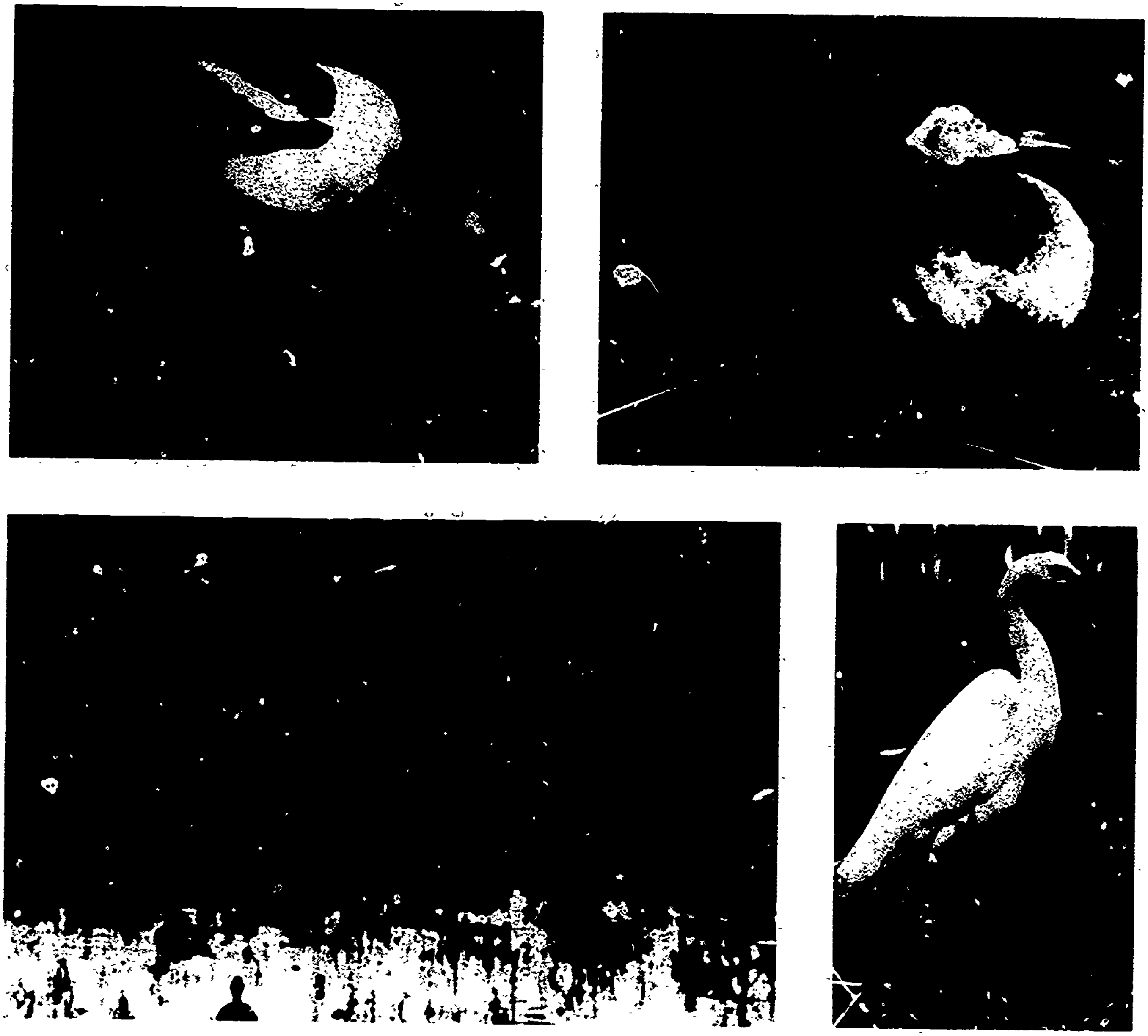


Figure 5-5—Migratory birds find a home in wetlands (clockwise, upper left to right): an American avocet turns her eggs, a red-necked grebe settles onto her nest, a vigilant snowy egret guards the nest, and pintails flock to their feeding grounds.

Ground-Water Recharge and Discharge. Ground-water recharge is the movement of surface water or precipitation into the ground-water flow system. Ground-water discharge is the movement of ground water into surface water. Shallow recharge and minor ground-water discharges are sometimes termed seepage or leakage. When ground-water discharges into streams during dry periods, usually in conjunction with discharge to standing surface water, the process is termed low flow augmentation. Shallow and lateral recharge are local phenomena. They normally are of direct value to fewer water users than deep recharge, because the latter is more pertinent to regional ground-water systems.

Recharge is important for replenishing aquifers used for water supply, especially in those situations where aquifers are threatened by drought, overuse, or pollution from toxic waste or saltwater contained in adjoining aquifers. Discharge may also be critical for maintaining soil moisture in agricultural regions. Another advantage is that when floodwaters enter the ground-water system via wetland basins capable of recharge, flood peaks can desynchronize significantly, thus reducing their potential for causing damage.

Discharge is important not only for maintaining low flows essential to fisheries but also for maintaining vegetation and providing drinking water for wildlife.

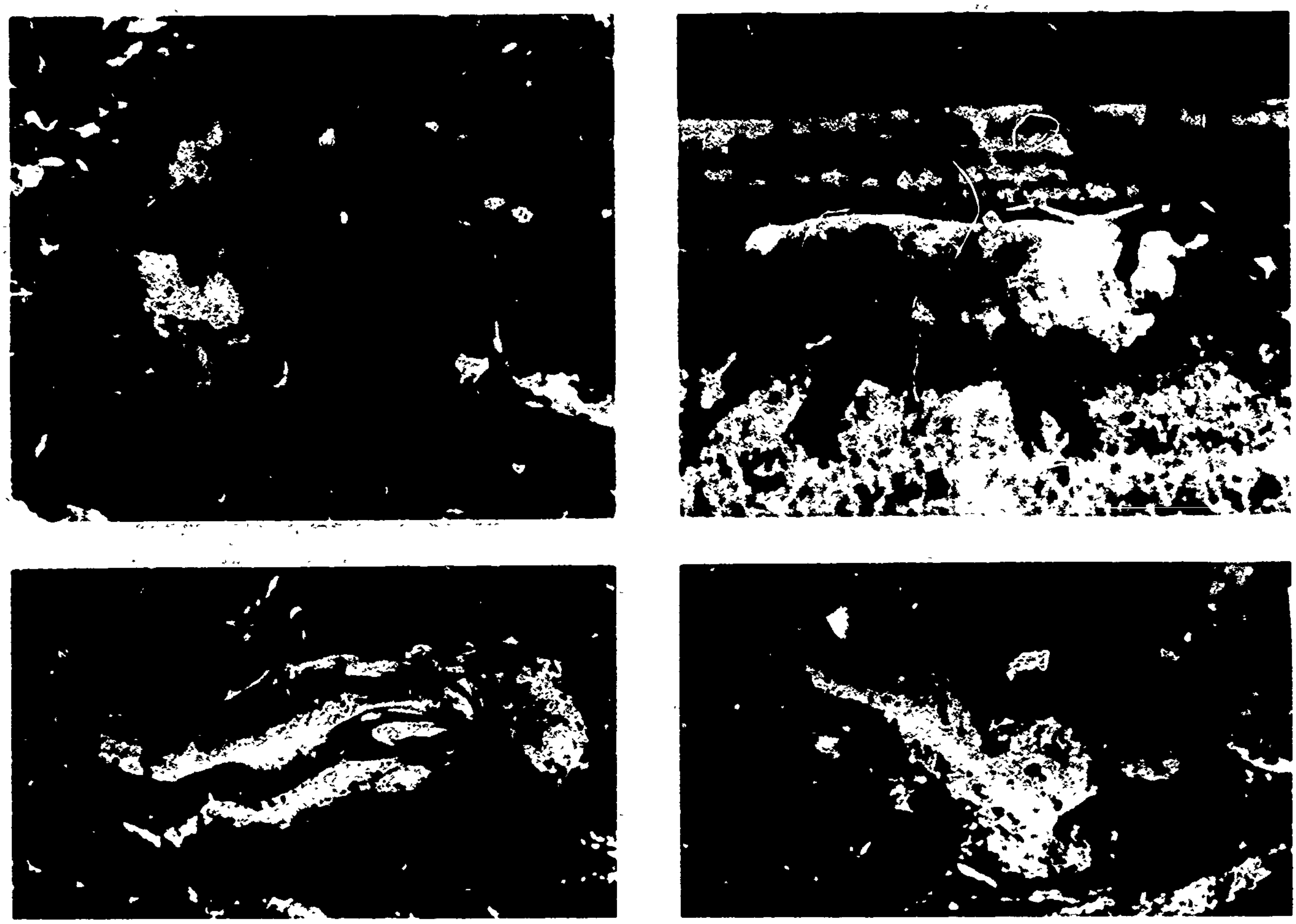


Figure 5-6—Wetlands abound with wildlife, like the beaver, moose, alligator, and spring peeper.

Seepage discharge through gravel is essential to spawning fish. Discharging springs often keep important northern wetlands free of ice for long periods during the winter, increasing their use by waterfowl. Discharge of fresh ground water into estuaries is vital to many commercially harvested species, and discharges into prairie potholes maintain the permanence of vital waterfowl breeding grounds. A large number of rare plant species grow in wetlands which receive ground-water discharge.

Flood Storage and Desynchronization. Flood storage is the process by which peak flows enter a wetland basin and are delayed in their downslope journey. Flood desynchronization is a process by which the simultaneous storage of peak flows in numerous basins within a watershed and their subsequent gradual release in a nonsimultaneous, staggered manner results in the containment of flows within the downstream channel and more persistent flow peaks downstream. Storage may be measured in fractions of an inch or in feet; reductions in flooded areas are measured in square feet or square miles. Flood storage greatly enhances the immediate sediment-trapping capability of wetlands. Such storage also reduces the need for shoreline anchoring in downstream areas.

Shoreline Anchoring and Dissipation of Erosive Forces. Shoreline anchoring is the stabilization of soil at the water's edge or in shallow water by fibrous plant root complexes. It may involve long-term accretion of sediment and/or peat, along with shoreline progradation. Dissipation of erosive forces is the decline in energy associated with waves, currents, ice, water-level fluctuations, or ground-water flow.

The direct economic significance of shoreline anchoring and the dissipation of erosive forces is illustrated by millions of dollars spent annually for jetties, groins, and other structures intended to stop shoreline erosion by waves and current. Such erosion may destroy inhabited structures, eliminate harvestable timber and peat, remove fertile soil, and alter local land uses. Eroded fine sediments may be redeposited in navigable channels, aggravating the need for costly dredging. Eroded fine sediments may be redeposited in portions of a basin where ground-water exchanges occur, eventually slowing the rate of ground-water recharge or discharge. Shoreline anchoring by wetlands may minimize such erosion. Suspended sediment from eroded shorelines may also inhibit the growth and survival of aquatic organisms. Erosion may also directly threaten riparian wildlife habitat. Shoreline erosion is seldom aesthetically appealing, and the erosion of beaches may impair recreation.

Sediment Trapping. Sediment trapping is the process by which inorganic particulate matter of any size is retained and deposited within a wetland or its basin. In practice, distinguishing inorganic from organic sediment may be difficult because organic colloidal substances are readily adsorbed onto inorganic particles. Sediment trapping may be short or long term. Short-term trapping may be defined arbitrarily as the retention of sediments for periods of 30 days to 5 years; long-term trapping involves retention for longer periods. Sediment trapping may involve the retention of runoff-borne sediment before it moves into ground-water aquifers or the deep waters of a basin and the interception and retention of sediment before it is carried downstream or offshore.

The direct economic significance of sediment trapping is that sediment deposited in undesirable locations may require increased expenditures for dredging, channel modification, and water-treatment facilities.

Nutrient Retention and Removal. Nutrient retention is the storing of nutrients, especially nitrogen and phosphates, within the substrates and vegetation of wetlands. Nutrient removal is the purging of nitrogen nutrients by conversion to gas. Nutrient retention may involve trapping both runoff-borne nutrients before they reach deep water and the nutrients borne by flowing surface water before they are carried downstream or to underlying aquifers. Nutrients may be stored either short or long term. Long-term storage is generally more significant to ecosystems. However, short-term storage may also be significant if it helps maintain or improve downstream water quality, especially if such storage occurs during seasons when plants and algae are particularly nutrient-sensitive.

The direct economic effects are that nutrient retention, by controlling eutrophication, may help maintain fisheries of economically important commercial or recreational value. It may also reduce the need for costly construction of waste treatment facilities. Nutrient retention by wetlands can also enhance this functional value by preventing downstream nuisance algae blooms and associated fish kills.

Food Chain Support. Food chain support is the direct or indirect use of nutrients, in any form, by animals inhabiting aquatic environments. The use of the term food chain support pertains primarily to the use by fish and aquatic invertebrates having commercial or sport value. Nutrient export is the net movement of nutrients, particularly carbon, phosphates, and nitrates, out of particular wetlands, but not necessarily out of the basin in which they are located. Movement may be to adjacent deep waters (called inbasin cycling) and/or to downcurrent basins in wetlands. Nutrients may be either in particulate or dissolved form and either organic or inorganic.

The direct economic significance of the food chain support function is that some regional economies depend almost exclusively on fisheries which, in turn, may depend heavily on wetlands for nutrient export and habitat.

Recreational and Heritage Values. Active recreation in wetlands refers to water activities and is a keystone of many local and regional economies. Passive recreation and heritage values include aesthetic enjoyment, nature study, picnicking, education, scientific research, preservation of rare or endangered species, maintenance of the gene pool, protection of archeologically or geologically unique features, maintenance of historic sites, and other mostly intangible uses. Rare botanical features also dot wetlands.

Progress in Evaluation

The importance of the various wetland values described above are being recognized more widely in political, economic, and ecological circles. Considerable research is being devoted to quantifying such values for decisionmaking purposes. Alternative methods for quantifying wetland values are detailed in the following conference proceedings and references:

- Florida Conference. *A National Symposium on Wetland Functions and Values: The State of Our Understanding.* Nov. 1978. (American Water Resources Association, 1979).
- *Evaluation Methods.* In September 1981, the U.S. Water Resources Council issued a report that evaluated various current methodologies for assess-

ing wetland values. (U.S. Water Resources Council, 1981).

- *National Wetland Inventory.* U.S. Fish and Wildlife Service. (Frayer and others, 1983).
- *National Wetlands Workshop.* A National Wetlands Values Assessment Workshop was held in May 1983. (U.S. Dept. Interior, 1984).
- *A Method for Wetland Functional* Assessment. March 1983. Federal Highway Administration. (Adamus and Stockwell, 1983).

Many other technical publications on wetlands have resulted from other symposia, seminars, and workshops. However, generally acceptable methods for quantifying wetland values as marketable goods and services have not yet been developed for many of the wetland functions.

Ecological Concerns

Jahn (1978) wrote that a watershed can be subdivided into three habitat units: freshwater, saltwater, and terrestrial. The interrelationships among these varied aquatic and terrestrial habitats provide stability to ecological systems and processes.

Cairns (1978) noted that any modification of inland water displacing or impairing ecosystem structure or function is a degradation of ecological integrity. Degradation occurs because plant and animal organisms depend on a given set of environmental conditions. When these conditions are disrupted or changed, the dependent species must adjust, move, or die.

Wetland Resources and Losses

Wetlands exist in every State. Their abundance varies with climate, soils, geology, land use, and other regional differences. Estimates of the area of wetlands at the time of original settlement range around 215 million acres for the conterminous 48 United States (Roe and Ayres, 1954). In 1955, an estimated 108 million acres of wetlands existed (Frayer and others, 1983). Today's wetland resources in the conterminous 48 States cover about 99 million areas, or 46 percent of our original wetlands (Tiner, 1984). Tiner estimates Alaska's wetland resources at approximately 200 million acres.

Palustrine wetlands (generally inland), including freshwater marshes and swamps, constituted 94 percent of the wetlands in the 48 States. In 1975, about 93.7 million acres of palustrine wetlands existed, with over half the area forested wetlands and a third emergent wetlands. By contrast, only 5.2 million acres of estuarine wetlands then existed. This amounts to an area approximately the size of Massachusetts, or 0.3 percent of the land surface of the conterminous 48 States (Tiner, 1984).

Small net gains in deepwater habitats—artificial lakes. reservoirs, and coastal waters—occurred between about 1955 and 1975 (Frayer and others, 1983). Total lake area increased by 1.4 million acres; about 94 percent of this gain was in the eastern part of the country These lakes and reservoirs were mostly created from uplands, although some vegetated wetlands were destroyed in the process.

Some additional wetlands have also formed along the edges of new water bodies. During 1955-75, coastal open waters increased by 200,000 acres. Much of this gain was in Louisiana at the expense of coastal wetlands, which were rapidly being flooded permanently. During the same period, 200,000 new acres of unvegetated wetland flats and 2.1 million acres of ponds were created.

Pond area nearly doubled between 1955-75, increasing from 2.3 million acres to 4.4 million acres, primarily because of farm pond construction in the adjacent Central and Mississippi waterflow flyways. Most of the pond acreage was on uplands, although 145,000 acres of forested wetlands and 385,000 acres of emergent wetlands were changed to open water (Tiner, 1984). According to the most recent (1982) National Resources Inventory (NRI) completed by USDA, there were about 78.2 million acres of nonfederally owned wetlands in the United States. Of this total, 65.3 million acres (83 percent) were privately owned while 12.9 million acres (17 percent) were owned by State and local governments.

Tiner (1984) considers agricultural development to be responsible for 87 percent of the recent wetland losses in the United States, while urban and other developments caused 8 percent and 5 percent of the losses, respectively.

Monetary net worth does not describe the total value of wetland protection, maintenance, and/or enhancement. The inability to quantify the full monetary value of wetlands, coupled with the overestimate of monetary benefits, can often result in decisions to drain wetlands at the expense of numerous wetland values.

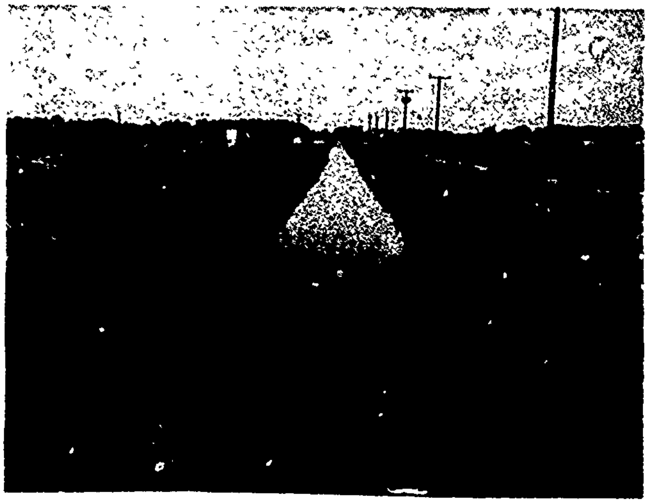


Figure 5-7—An enlarged channel with vegetated side slopes improves drainage in the muck area of the Marsh Run Wastershed, Huron County, Ohio. The waterway also serves as an irrigation water supply channel.

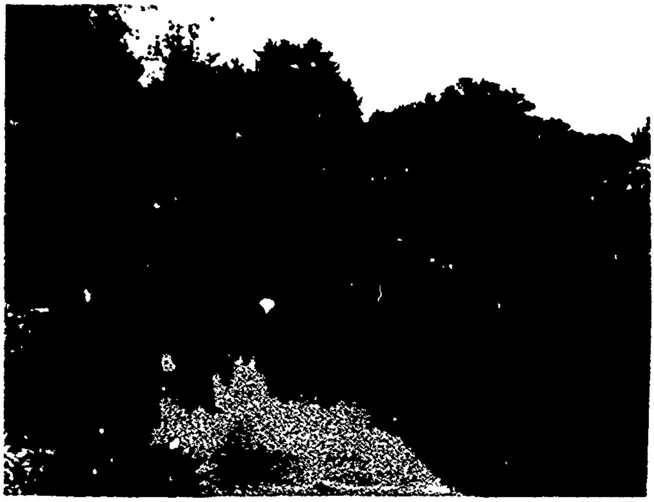


Figure 5-8—This channel in the Boggs Creek Watershed, Martin County, Indiana, was improved by working just one side of the waterway. Vegetation went undisturbed on one bank while the other side was seeded with Kentucky 31 Fescue.

Coordination Mandates

During the past two decades, the terms wetlands and drainage have stimulated varied and sometimes excessive reaction from a variety of agricultural, wildlife, fishing, engineering, economic, water management, and environmental interests. Such interdisciplinary interest and public concern has demanded coordinated action. Various laws, directives, and regulations now mandate the coordinated management of wetlands.

The National Environmental Policy Act of 1969. This act authorizes and directs Federal agencies to give appropriate consideration to environmental amenities and values along with technical considerations. The results of these analyses must be included in proposals for Federal action.

Executive Order on Protection of Wetlands. Executive Order No. 11990 is reproduced in appendix A. Issued in 1977 by President Carter to complement the National Environmental Policy Act of 1969, the order instructs Federal agencies to avoid, to the extent possible, the long- and short-term adverse impacts associated with the destruction and modification of wetlands and to avoid direct and indirect support of new construction in wetlands wherever there is a practical alternative. It directs each Federal agency to provide leadership and take such action to minimize the destruction, loss, or degradation of wetlands, and to preserve and enhance the national and beneficial values of wetlands in carrying out agency responsibilities.

The Clean Water Act, 1977 Amendments. The objective of the 1977 amendments to the Federal Water Pollution Control Act (1972) now known as the Clean Water Act is to restore and maintain the chemical, physical, and biological integrity of the Nation's waters. The amendments established the following six major goals, which have been only partially achieved:

- That the discharge of pollutants into navigable waters be eliminated by 1985;
- That by July 1983 an interim goal of water quality be provided for the protection and propagation of fish, shellfish, and wildlife and recreation in and on waters;
- That the discharge of pollutants in toxic amounts be prohibited;
- That Federal financial assistance be provided to construct waste water treatment plants;
- That areawide waste treatment management planning processes be developed and implemented; and
- That major research and demonstration efforts be made to develop technologies to eliminate the discharge of pollutants into waters.

Channel Modification Guidelines. "Channel Modification Guidelines" is a good example of a cooperative effort to emphasize wetland protection and maintenance. Jointly prepared by the SC and the Fish and Wildlife Service, these guidelines help agency personnel indentify when and where channel modification may be used as a technique for implementing water and related land resource projects under the authorities of the SCS for planning small watershed and resources conservation and development projects (figs. 5-7 and 5-8). The guidelines stipulate that efforts will be made to maintain and restore streams upon which fish and wildlife resources depend (U.S. Depts. Interior and Agriculture, 1979).

Comprehensive Evaluations

Despite current oversupply problems confronting U.S. agriculture, it is unrealistic to assume that on a permanent basis significantly less land will be devoted to agricultural production in the foreseeable future. However, food and fiber production should be balanced with the other products of land, including those produced by wetlands. All possible measures should be incorporated in specific drainage plans and designs to minimize degradation of wetland values. Such evaluations should serve as a positive catalyst to pull together all interests and responsibilities. Mutual cooperation and understanding can lead to the planning and completion of only such added drainage as may be needed in the public interest and within constraints that maintain the important values associated with the remaining wetlands.

This action supports USDA's policy which is to assure that the values of fish and wildlife are recognized and that their habitats, both terrestrial and aquatic (including wetlands), are considered when the Department carries out its missions. USDA supports research and management programs that respond to the economic, ecological, educational, recreational, scientific, and aesthetic values of fish and wildlife. Its goals are to improve, where needed, fish and wildlife habitats, and to ensure the presence of diverse native and other populations of wildlife, fish, and plant species (USDA, 1983).

References

Adamus, Paul R., and C. T. Stockwell. 1983. *A Method for Wetland Functional Assessment.* U.S. Dept. Trans., Fed. Hwy. Adm. Rpt. Nos. FHWA-IP-82-23 and FHWA-IP-83-24.

American Water Resources Association. 1979. *Wetland Functions and Values: The State of Our Understanding.* Proceedings of the National Symposium on Wetlands. Tech. Pub. No. TPS 79-2. Minneapolis.

Cairns, John, Jr. 1978. *Wildlife and America.* Council on Environmental Quality. Govt. Print. Off.

Cowardin, Lewis M., Virginia Carter, Francis C. Golet, and Edward T. LaRoe. 1979. *Classification of Wetlands and Deepwater Habitats of the United States.* U.S. Dept. Interior, Fish and Wildlife Serv. Rpt. No. FWS/OBS-79/31.

Frayer, W. E., T. J. Monahan, D. C. Bowden, and F. A. Graybill. 1983. *Status and Trends of Wetlands and Deepwater Habitats in the Conterminous United States: 1950's to 1970's.* Fort Collins, Colo.: Department of Forests and Wood Sciences, Colorado State Univ.

Jahn, Lawrence R. 1978. "Values of Riparian Habitat to Natural Ecosystems," *Protection and Management of Floodplain Wetlands and Riparian Ecosystems.* Gen. Tech. Rpt. WO-12. U.S. Dept. Agr., Forest Service.

Lonard, Robert L., and others. 1981. *Analysis of Methodologies Used for the Assessment of Wetland Values.* U.S. Water Resources Council, Washington, DC.

Roe, H. B., and Q. C. Ayres. 1954. *Engineering for Agricultural Drainage.* New York: McGraw-Hill Book Company.

Tiner, Ralph W., Jr. 1984. *Wetlands of the United States: Current States and Recent Trends.* U.S. Dept. Interior, Fish and Wildlife Serv.

U.S. Congress, Office of Technology Assessment. 1984. *Wetlands, Their Use and Regulation.* Rpt. No. OTA-0-207. Govt. Print. Off.

U.S. Department of Agriculture. 1983. *U.S. Fish and Wildlife Policy.* Dept. Reg. 9500-4.

U.S. Department of the Interior and U.S. Department of Agriculture. 1979. *Channel Modification Guidelines* (amended).

Chapter 6

Principles of Drainage

R. Wayne Skaggs
Department of Biological and Agricultural Engineering
North Carolina State University, Raleigh

A review of drainage principles appropriately begins with the hydrologic cycle, the main components of which are illustrated in figure 6-1. Precipitation falling to the earth's surface either infiltrates into the soil profile or moves from the area by overland flow which may eventually enter a stream or other surface-water outlet. The infiltrated water may be stored in the unsaturated zone or percolate downward to a saturated zone. Water may be removed from the profile by evapotranspiration (ET) and by natural drainage processes. These processes may include ground-water flow to streams or other surface outlets, vertical seepage to underlying aquifers, or lateral flow (interflow) which may reappear at the surface at some other point in the landscape. In many soils, the natural drainage processes are sufficient for the growth and production of agricultural crops. In other soils, artificial drainage is needed for efficient agricultural production.

Soils may have poor natural drainage for a number of reasons. Lands with surface elevations close to that of the drainage outlet (section D, in fig. 6-1) may have permanently high water tables. Land that is far removed from the drainage outlet, such as sections B and C may have high water during critical periods of the growing season. Other lands may be poorly drained because of seepage from upslope areas (section B) or because they are in depressional areas with no surface water outlet. Water drains slowly from soils with tight subsurface layers, regardless of where these layers are in the landscape; so soils may have poor natural drainage because of restricted permeability or hydraulic conductivity of the profile.

Climate is another important factor affecting the need for artificial drainage. Natural drainage at a rate that may be sufficient for agriculture in a section of Nebraska where annual rainfall is 20 inches per year, for example, may be inadequate in Louisiana where the annual rainfall is 55 inches. Nowhere is this factor more evident than in irrigated semiarid areas. Lands that have been farmed for centuries under dryland cultures often develop high water tables and become water-logged after irrigation is established. By contrast, natural drainage may be adequate in other soils and the several-fold increase in the amount of water applied to the surface because of irrigation will not result in poorly drained conditions. Seepage from unlined irrigation canals or from reservoirs may also result in poorly drained soils in areas where they did not previously exist.

All soils require satisfactory drainage for efficient agricultural production; many need improved or artificial drainage. Soils may be poorly drained because of climate and irrigation practices, position in the landscape in relation to drainage outlets or irrigation canals, or low permeability and/or restricting layers in the soil profile.

In most cases, improved drainage practices can be used to satisfy agricultural requirements. These will be discussed first, followed by the factors controlling the movement and storage of water in the soil profile and methods that can be used to satisfy drainage requirements. Examples are given to describe the design and operation of a drainage system and the concepts of controlled drainage and subirrigation. The concluding section discusses some principles that can be used to consider offsite impacts of drainage and related water management practices.

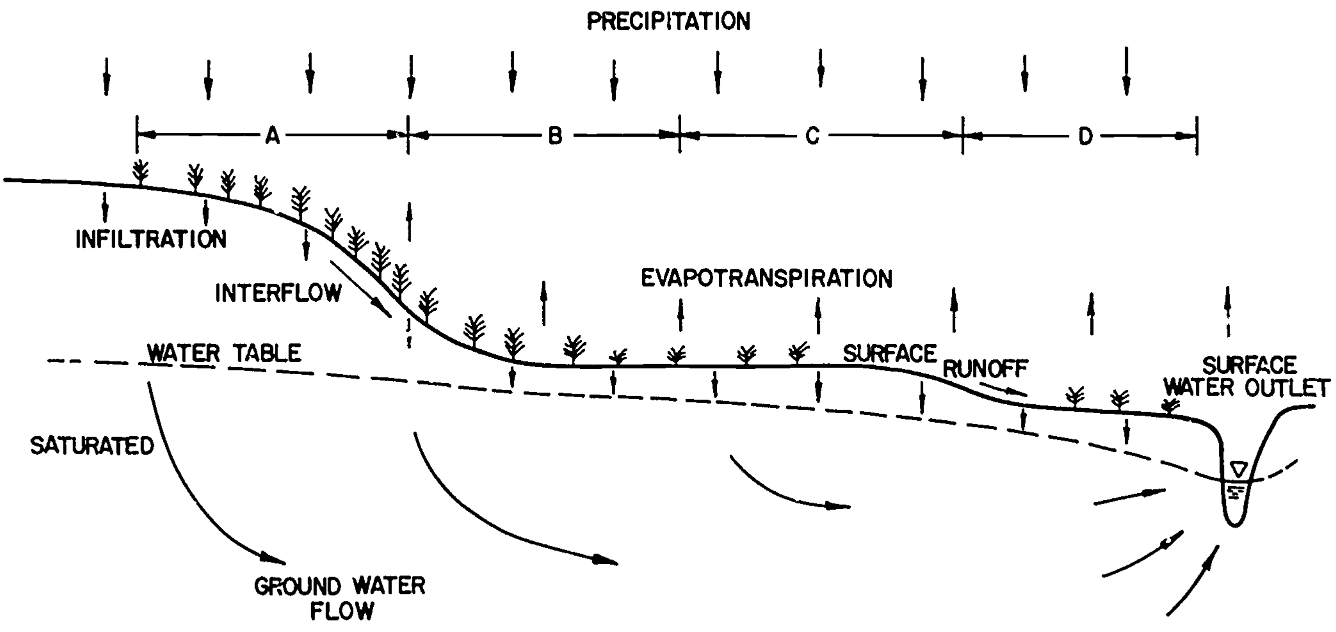


Figure 6-1—Schematic of main components of the hydrologic cycle.

Drainage Requirements

There are basically three reasons for installing agricultural drainage systems: for trafficability so that seedbed preparation, planting, harvesting, and other field operations can be conducted in a timely manner; for protection of the crop from excessive soil water conditions; and for salinity control. In special situations, drainage systems may be installed for other purposes. An example is the use of drainage to increase the amount of wastewater that can be applied and effectively treated on a land application site.

Trafficability

The practical effects of poor drainage on timeliness of farming operations are outlined by Fausey and others in chapter 4 and also by Reeve and Fausey (1974). Soils with inadequate drainage may experience frequent yield losses because essential farming operations cannot be conducted in a timely fashion. The result may range from complete crop failure if planting is delayed too long, to reduced yields if tillage, spraying, harvesting, or other operations are not performed on time. The effects of planting-date delays on corn yield are shown in figure 6-2. Although the mechanisms causing reduced yield because of delayed planting may be different in North Carolina than in Ohio, results are similar. The results are based on data reported by Krenzer and Fike (1977) for North Carolina and Nolte and others (1976) for Ohio. Yields are reduced for late-planted corn because of greater heat stress during the pollination period, shorter day length during yield formation, and increased susceptibility to insects and diseases. Delays in planting may also lead to increased stresses because of deficit soil-water conditions during the critical flowering period, which could cause even greater reductions in yield than those shown in figure 6-2.

Protection from Excessive Soil-Water Conditions

The major effects of excessive soil water on crop production are caused by reduced exchange of air between the atmosphere and the soil root zones. Wet soil conditions may result in a deficiency of oxygen (O_2) required for root respiration, an increase in carbon dioxide (CO_2), and the formation of toxic compounds in the soil and plants. Under field conditions, soil-water-plant systems vary continuously. Evaluating the effect of water content and aeration status on plant growth requires integration of these conditions over time during the entire growing season. One of the parameters that tends to integrate these factors in soils requiring artificial drainage is water table depth (Wesseling, 1974). Although the depth of the water table has no direct influence on crop growth, it is an indicator of the prevailing soil-water status, water supply aeration, and thermal conditions of the soil.

Numerous laboratory and field experiments have been conducted to determine the effect of water table depth on crop yields. Probably the main reason yield has been related to water table depth is that water table depth is easier to measure than

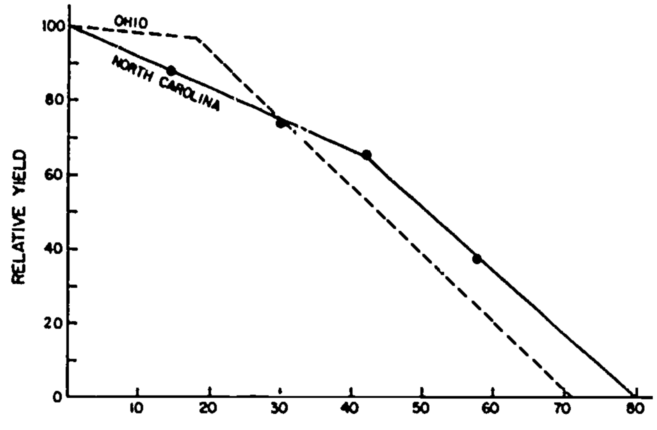


Figure 6-2—Effects of delayed plantings on corn yields in North Carolina and Ohio.

other variables such as the distribution of oxygen in the profile. Most experiments have been directed at relating yields to constant water table depths (Williamson and Kriz, 1970).

An example of the effect of water table depth on yield is given in figure 6-3. The results were obtained from Wesseling (1974) and are based on original research conducted in The Netherlands by W. C. Visser. Both relationships show reduced yields at shallow water table depths because of excessive soil-water conditions, an optimum range, and reduced yields at deeper water table depths because of deficient soil-water conditions. Although it may be possible to define an optimum water table depth, the relative position of curves, such as those given in figure 6-3, and thus the optimum depth, would depend on climate, soil properties, the crop, and also cultural and water management practices. Williamson and Kriz (1970) found that optimum water table depths were greater when irrigation water was applied at the surface.

While cause-and-effect relationships for crop yields are easier to identify for constant water table depths, such steady-state conditions rarely occur in nature. The effects of fluctuating water tables and intermittent flooding on crop yields depend on the frequency and duration of high water tables as well as the crop sensitivity. Approximate methods have developed to quantify the effect of excessive soil-water conditions because of fluctuating water tables for corn (Hardjoamidjojo and others, 1982) and grain sorghum (Ravelo and others, 1982). The method uses the SEW_{30} concept (originally defined by Sieben in Wesseling, 1974) to quantify stress caused by the water table rising into the root zone. The stress-day-index method of Hiler (1969) weights the stress by crop susceptibility factors which depend on the stage of growth. The results are linear relationships between the percentage of optimum yield and the stress-day-index. Stress-day-index values may be computed for a specific set of drainage design parameters, soil properties, weather data, and crop parameters with a simulation model that will be discussed in a subsequent section of this chapter.

Salinity Control

It seems somehow unjust that dry lands of arid and semiarid regions, when irrigated, often require artificial drainage. Luthin (1957) documented drainage problems that have beset irrigators since earliest recorded times. The accumulation of salts in surface soil caused the once fertile Tigris and Euphrates River Valleys of ancient Mesopotamia to return to desert. Relics of abandoned irrigation systems, alkali flats, and saline accumulation throughout the Near East and Sahara Desert show how lack of proper drainage eventually caused economic ruin and probably contributed to the destruction of ancient civilizations. A present-day example is the annual loss of thousands of acres in the San Joaquin Valley of California because of salt accumulation and water logging.

Practically all irrigation water contains some salt. Evaporation and consumptive use of water by plants concentrate the salts in the residual soil water, causing a solution that is usually more saline than the irrigation water. Repeated irrigations continually increase the salinity of the soil water even if the irrigation water is of relatively good quality.

To prevent the buildup of soil-water salinity to a point that it harms plant roots and reduces productivity, irrigation water in excess of the amount needed for evapotranspiration is applied to leach the concentrated soil solution from the root zone. If

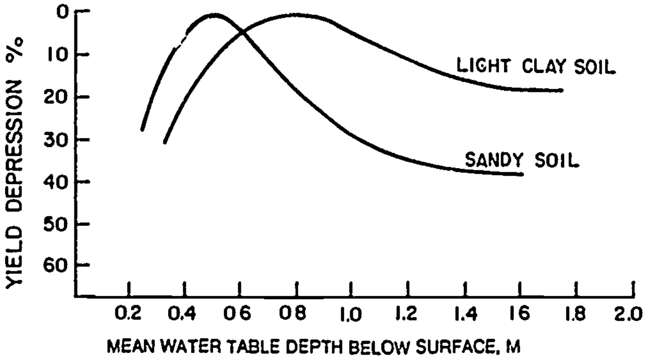
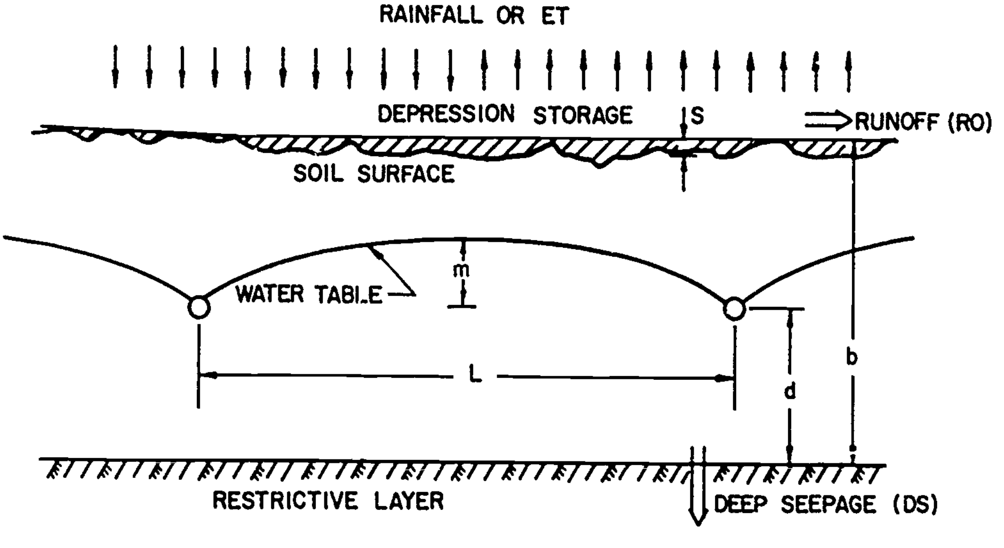


Figure 6-3—Yield depression as a function of mean water table depth during the growing season for two soils.

Figure 6-4—Subsurface drainage intensity depends on the spacing of the drain tubes, while the quality of surface drainage is inversely proportional to the depth of depression storage.



drainage is adequate, the excess irrigation water will carry the concentrated salt solution out of the root zone. If it is not, the water table will rise in response to the excess irrigation water and the salinity will continue to increase in the root zone, so crop yields may then be reduced for two reasons, high salinity and high water tables.

When natural drainage is not sufficient, artificial drainage systems are needed to remove the excess irrigation water from the soil profile. Because the salinity below the water table is usually several times that of the irrigation water, drainage systems are normally designed to hold the water table well below the root depth. The drains should be placed deep enough to prevent salinization because of upward flux from the water table during the fallow period when irrigation water is not applied. Drains are typically placed 2-3 meters (about 7-10 feet) deep in irrigated lands, compared with 0.75-1.5 m (2.5-5 feet) deep in humid areas.[1]

Drainage Theory and Practice

Both surface and subsurface drainage systems are used to meet drainage requirements of poorly drained sites. A schematic of a drainage system is shown in figure 6-4. Subsurface drainage is provided by drain tubes or parallel ditches spaced a distance, L, apart. Most poorly drained soils have a restrictive layer at some depth, shown here as a distance, d, below the drain tubes. When rainfall occurs, water infiltrates at the surface, raising the water content of the soil profile. Depending on the initial soil-water content and the amount of infiltration, some of the water may percolate through the profile, raising the water table and increasing the subsurface drainage rate. If the rainfall rate is greater than the infiltration rate, water begins to collect on the surface. If good surface drainage is provided so that the surface is smooth and on grade, most of the surface water will be available for runoff. However, if surface drainage is poor, a substantial amount of water must be stored in depressions before runoff can begin. After rainfall ceases, infiltration continues until the water stored in surface depressions infiltrates the soil. Thus, poor surface drainage effectively lengthens the infiltration event for some storms, permitting more water to infiltrate and a larger rise in the water table than would occur if depression storage did not exist. Once excess water enters the soil profile, it may be removed by evapotranspiration from the surface and through the plants, by natural drainage processes via deep and lateral seepage, and through artificial systems consisting of drainage tubes, ditches, or wells.

Subsurface Drainage Processes

The principal relationship used to describe water movement in soil was derived experimentally by Henry Darcy in 1856. He found that the flow rate of water through sand beds of different thicknesses was proportional to the hydraulic gradient. Darcy's law is illustrated in figure 6-5 and may be written as:

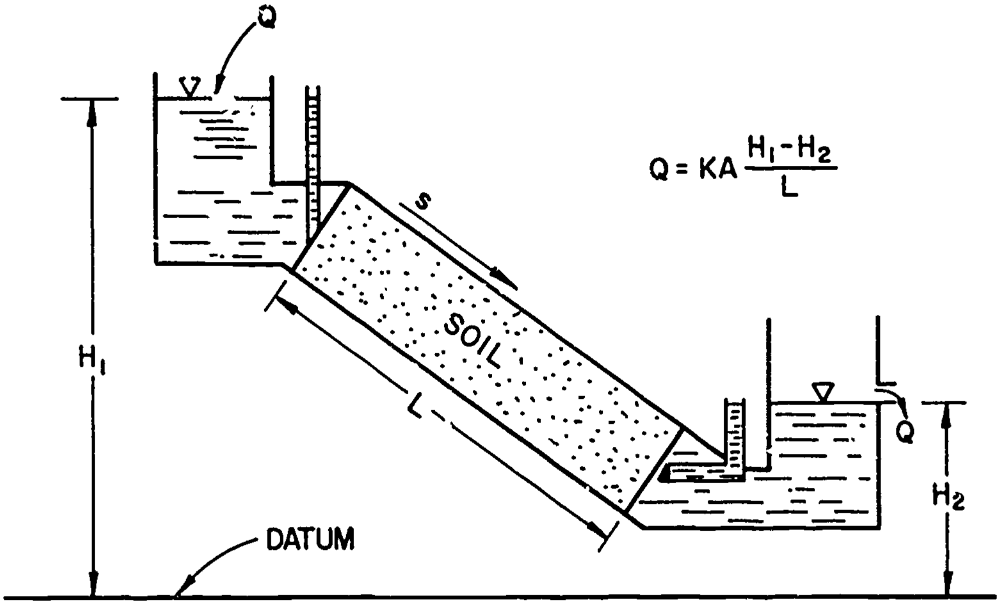
$$Q = KA\,\frac{H_1 - H_2}{L}, \qquad (6.1)$$

where Q is the flow rate through the soil column (cm^3/hr, in^3/hr), A is the cross-sectional area (cm^2,

---

[1] Both metric and U.S. units of measure are frequently given in this chapter to help explain the theory of drainage for all readers. Units, abbreviations, and selected factors for converting to and from U.S. and metric measures are in appendix D.

Figure 6-5—Water table profile shows steady-state drainage under a constant rainfall rate, R.



in^2) L is the column length (cm, in) in the direction of flow, and H_1 and H_2 are the hydraulic heads (cm, in) at the ends of the column. K is the proportionality constant which is termed the hydraulic conductivity. K is also called permeability in some references and has units of cm/hr or in/hr. The flux, or discharge velocity, is equal to the flow rate per unit of cross-sectional area of soil and may be expressed as:

$$q = \frac{Q}{A} = K\frac{H_1-H_2}{L} = -K\frac{\Delta H}{L} \cdot \qquad (6.2)$$

Although the soil-water flux has units of velocity (as cm/hr or in/hr), it is not equal to the velocity in individual pores but is defined as the flow rate per unit area. The flux may be defined at every point a saturated zone in terms of the hydraulic gradient at that point:

$$q_s = -K\frac{dH}{dS}, \qquad (6.3)$$

where s is the direction of flow and the negative sign indicates that flow is in the direction of decreasing hydraulic head. Flux should be regarded as a vector quantity having both magnitude and direction. Then q_s should be interpreted as the flux component in the S direction.

Uniform soils are soils in which K and other properties, such as density and porosity, are constant. Although most natural soils are nonuniform, they frequently consist of relatively uniform layers. Soils in which the hydraulic conductivity is independent of flow direction are called isotropic. Anisotropic soils have K values which are dependent on the flow direction. (Refer to Childs (1969) for a complete discussion of anisotropy.) Buckingham (1970) showed that, by expressing the conductivity as a function of the soil-water content, $K = K(\theta)$, equation 6.3 is also applicable to flow in the unsaturated zone.

When Darcy's law is combined with the principle of conservation of mass, nonlinear partial differential equations describing flow in both the saturated and unsaturated zones may be derived (Richards, 1931). Although numerical methods may be used to solve these complex equations, simpler methods have been employed for design and analysis of most drainage problems. Because the drain spacing is usually large compared with depth to the restrictive layer, flow to the drains is often primarily horizontal and the hydraulic gradient is approximately equal to the slope of the free surface. These approximations are referred to as the Dupuit-Forchheimer (D-F) assumption. When the D-F assumptions are combined with Darcy's law and the principle of conservation of mass, simplified solutions to certain problems can be obtained.

Steady-State Drainage. The relationship between drainflow rate and water table height for steady rainfall can be obtained by using the D-F assumptions. Drainflow rate per unit surface area equals the rainfall rate for steady-state conditions (fig.6-6) and may be expressed as:

$$R = \frac{8Kmd_e + 4Km^2}{L^2}, \qquad (6.4)$$

where m is the midpoint water table elevation above the drain tube and d_e is the effective depth to the impermeable layer, which is less than the real depth to compensate for convergence head losses in the vicinity of the drain (van Schilfgaarde, 1974). The d_e value can be computed by equations presented by Moody (1967), which may be written as follows for $d/L < 0.3$:

$$d_e = K\,A\,\frac{d}{1 + \frac{d}{L}\left(\frac{8}{\pi}\ln\frac{d}{r_e} - 3.4\right)}, \qquad (6.5)$$

where r_e is the effective draintube radius (Skaggs, 1978a). Another equation is used for $d/L > 0.3$.

Equation 6.4 is known as the Hooghoudt equation after the Dutch scientist, Dr. S. B. Hooghoudt. The equation for estimating drain spacings may be written as:

$$L = \left[\frac{8\,K_2\,m d_e + 4K_1 m^2}{R}\right]^{1/2}, \qquad (6.6)$$

where K_1 and K_2 are the hydraulic conductivities of the soil layers above and below the drain, respectively. Although it is clear that water tables, rainfall rates, and drainage fluxes vary with time under natural conditions, equation 6.6 can be used to approximate the required drain spacing if the appropriate m and R values are known. Those parameters are certain to depend on the crop and climate, and therefore location, as well as on other management and cultural practices. A recent simulation study on 12 North Carolina soils (Skaggs and Tabrizi, 1984) showed that an estimate of the optimum drain spacing for corn production could be obtained with equation 6.6 by taking m corresponding to a midpoint water table depth of 0.3 m (12 in) from the surface, and the following design drainage rates:

1. good surface drainage: q = R = 5.4 mm/day (0.21 in./day)
2. poor surface drainage: q = R = 6.2 mm/day (0.24 in./day)

Example—Initial and solution values will be given in U.S. and metric units; calculations and intermediate values are in metric units for simplicity.

A sandy loam soil with an impermeable layer 3 m (9.84 ft) deep has a saturated hydraulic conductivity of 0.75 m/day (29.5 in/day). How far apart should drain tubes be placed such that a steady rainfall rate of 5.4 mm/day (0.2128 in/day) will result in a midpoint water table depth of 0.3 m (about 1 ft)? The drains are to be placed 1m (3.28 ft.) deep and the effective draintube radius is 1 mm (0.0394 in).

Using equation 6.6 with $K_1 = K_2 = 0.75$ m/day, $m = 0.7$ m, $R = 0.005$ m/day, and assuming $d_e = \sqrt{d} = 1.4$ m as a first approximation gives $L = 37$ m. Because d_e depends on L which in turn depends on d_e, iteration must be used to obtain the correct L value. Substituting $L = 37$ m into equation 6.5 gives a better estimate for d_e: $d_e = 1.3$ m. Solving equation 6.6 again with the new d_e value yields $L = 36$ m. Substitution of this L into equation 6.5 results in $d_e = 1.3$, which is the same as the value used to obtain L. Therefore, drains placed 36 m (118 ft) apart and 1 m (3.3 ft) deep will provide a steady drainage rate of 5.4 mm/day (0.21 in/day) with a midpoint water table 0.3 m (1 ft) from the surface. Further examination of the situation would show that the steady state water table profile has an elliptical shape as shown in figure 6-6.

The drain spacing given in this example is approximately the optimum drain spacing for corn production in eastern North Carolina for good surface drainage (that is, q = R = 5.4 mm/day or 0.21 in/day). For poor surface drainage, q = 6.2 mm/day (0.24 in/day), and L = 33 m (108 ft) is obtained from equation 6.6. Although the effect of good surface drainage on the spacing required for optimum pro-

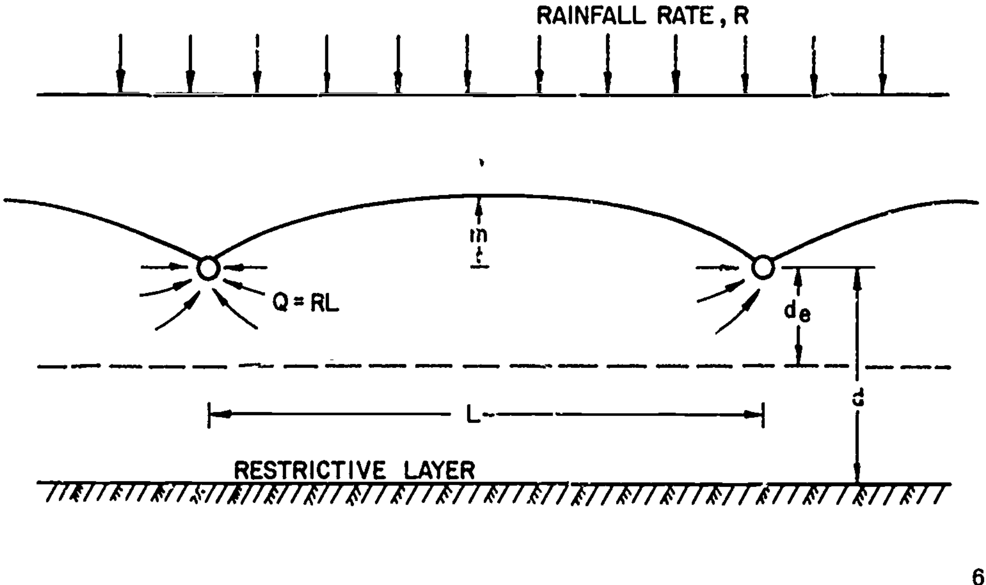


Figure 6-6—Water table profile shows steady-state drainage under a constant rainfall rate, R.

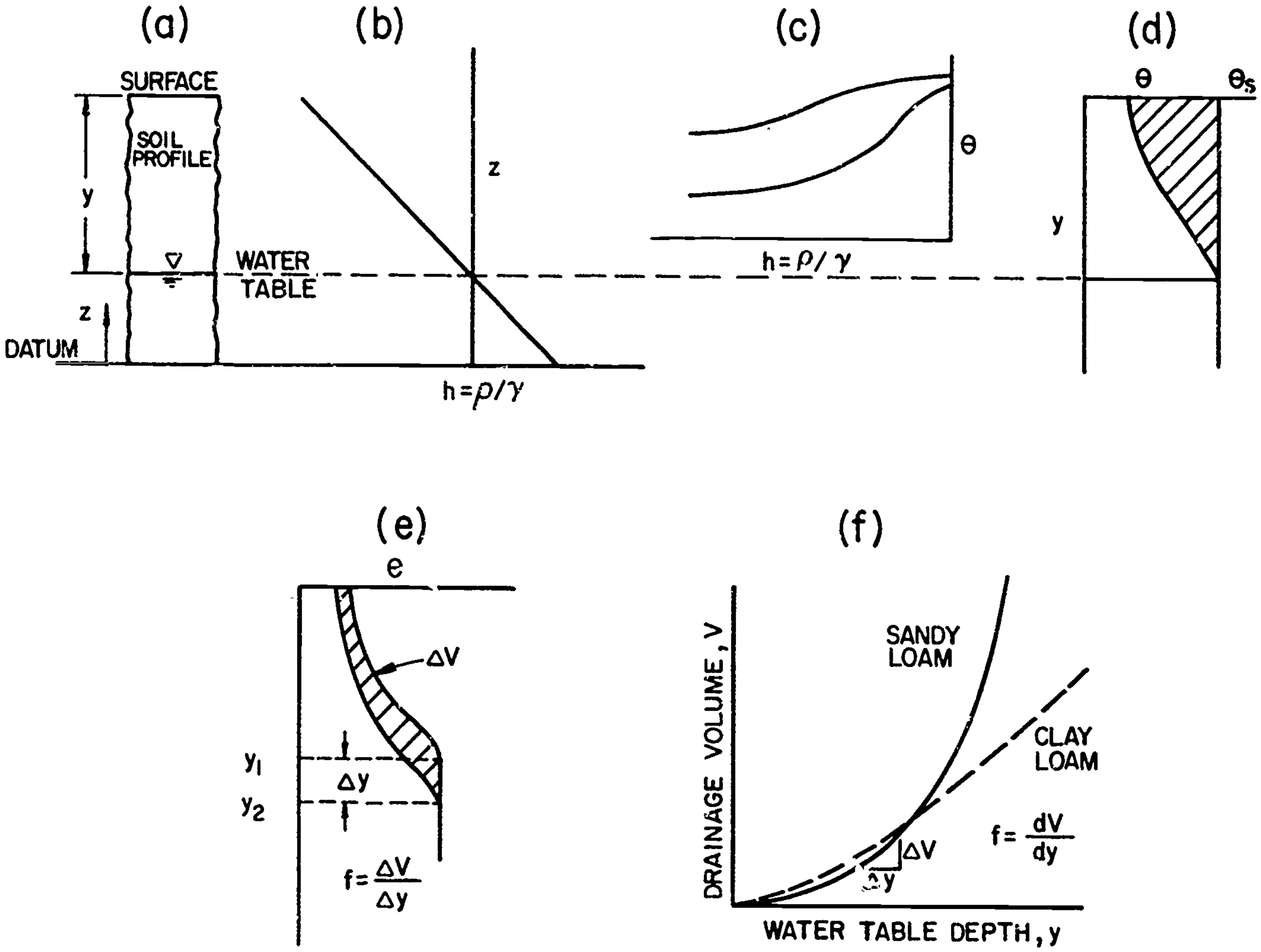


Figure 6-7—A soil column drained to equilibrium. With a water table (a), it has a linear pressure head distribution (b). Given the pressure head at each point, the soil water content, O, can be determined (d) from the soil water characteristic (c). [illegible] characteristics for two soils are shown schematically in (c). The cross-hatched area in (e) represe [illegible] volume of water drained when the water table falls from Y1 to Y2. The drainable porosity, f, is defined as dV/dy and is the slope of the curves shown in (f).

duction is relatively small for this soil, it may have a much more significant effect if subsurface drainage is poor.

Soil-Water Distribution and Drainable Porosity. In most cases, drainage of water from the soil profile lowers the water table, reducing the hydraulic gradient and the drainage rate. The response of the water table to removal or addition of a given volume of water depends on the soil's drainable porosity or specific yield. Solutions to the Richards equations (Skaggs and Tang, 1976) indicate that, except for the region close to the drains, the pressure head distribution above and below the water table during drainage may be assumed nearly hydrostatic (figure 6-7b) for many field-scale drainage systems. This situation happens because, in most fields with artificial drains, the water table drawdown is slow and the unsaturated zone in a sense "keeps up" with the saturated zone. As a result, vertical hydraulic gradients are small. Under these conditions, the soil-water distribution is approximately the same as in a column of soil drained to equilibrium with a static water table. That distribution can be obtained from the soil-water characteristic or soil-water retention curve (fig. 6-7c), which is the relationship between the volumetric soil-water content θ, and the pressure head, $h = p/\gamma$, where p is the soil-water pressure and γ is the specific weight of water. As indicated in figure 6-7c, the soil-water pressure is negative in the unsaturated zone; it is commonly referred to as tension or suction in which it takes a positive sign; that is, h = -25 cm (-9.8 in) would be a suction or tension head of +25 cm (9.8

in). Water is held in the unsaturated soil matrix by adhesive and cohesive forces (Day and others, 1967; Childs, 1969; Kirkham and Powers, 1972). The water content at any given pressure head depends on several factors, including bulk density, texture, structure, and the existence of macropores from roots, worms, or other causes.

Figure 6-7d shows the soil-water distribution for a drained-to-equilibrium profile with the water table at depth d. The crosshatched area indicates the volume of water per unit of surface area, which is actually a depth of water that would have to be removed to lower the water table from the surface to depth y. The amount of water that would have to be drained to lower the water table by a distance Δy is shown by the crosshatched area in figure 6-7e. If we denote this volume (depth in cm or in) as ΔV, the drainable porosity is defined as $f = \Delta V/\Delta z$. If we start with the water table at the surface and determine the drainage volume for progressively increasing water table depths, relationships such as those given in figure 6-7f can be obtained. The drainable porosity would then be defined as the slope of the curve at any given water table depth. These relationships show that the drainable porosity depends on water table depth as well as soil type. Drainable porosity normally increases with water table depth and is higher for sandy soils than for clays. However, these relationships depend on soil layering, macropores in the surface horizons, and other factors.

Water Table Drawdown. Steady-state conditions rarely exist in nature. In most cases, the water table and the soil-water regime above the water table are in a transient state, either increasing due to rainfall or irrigation or decreasing due to drainage and ET. Because high water tables can be tolerated for certain periods of time by most crops, the rate that a drainage system will lower the water table after periods of high rainfall may be more important than its operation under steady-state conditions.

Numerous methods have been developed for predicting water-table drawdown (for example, the Glover methods (Dumm, 1954, 1964); Maasland, 1959; van Schilfgaarde, 1965; and Kirkham, 1964). Many of the methods are based on solutions to the Boussinesq equation which result from using the D-F assumptions in combination with Darcy's law and the continuity equation. Van Schilfgaarde's solution was for an initially elliptical water-table shape and did not require linearizing the Boussinesq equation:

$$t = \frac{f L^2}{9K_d} \ln[m_0(2d + m)/m(2d + m_0)] \qquad (6.7)$$

In this equation, t is the time required for the midpoint water table to fall from its initial elevation above the drain, m_0, to m; f is the drainable porosity, and d_e is defined as in figure 6-6. To account for convergence near the drains, d should be replaced by d_e in the equation. Numerical solutions to the Boussinesq equation have been used to determine the effect of simultaneous drainage and ET on water-table drawdown and the water-table response to a transition from drainage to subirrigation boundary conditions (Skaggs, 1973 and 1975).

Bouwer and van Schilfgaarde (1964) proposed a relatively simple method for predicting water-table drawdown. They noted that the flux per unit of surface area in the steady rainfall case is approximately equal to the instantaneous flux during water-table drawdown, or

$$f \frac{dm}{dt} = -R. \qquad (6.8)$$

Bouwer and van Schilfgaarde used the Hooghoudt equation (equation 6.4) to express R in terms of m and obtained an equation similar to 6.7 for water-table drawdown. They also noted that equation 6.8 could be expressed as:

$$\Delta t = C(\Delta m/\bar{q}f) \qquad (6.9)$$

where Δt is the time required to lower the midpoint water table by Δm and C is the ratio of the average flux per unit surface area, $\bar{q}$ to the flux at the midpoint. In this formulation, tabulated values of $\bar{q}$ versus m, rather than a closed form expression, could be used to compute time increments for successive m values to determine the midpoint water-table position as a function of time. An advantage of this simple formulation, not discussed by the authors, is that variable drainable porosities may be considered, and the effect of ET can be computed by simply setting $\bar{q}$ equal to the sum of the ET and drainage rates. Comparison of results obtained by this method with numerical solutions to the Boussinesq equation have shown good agreement for both drainage alone and for simultaneous drainage and ET (Skaggs, 1979).

Drawdown predictions for the example given in the previous section are plotted in figure 6-8. The water table at time zero was assumed to have an elliptical shape with the midpoint coincident with the surface. The drainable porosity was assumed to be f = 0.05. Solutions are presented for drainage only and for drainage in combination with a steady

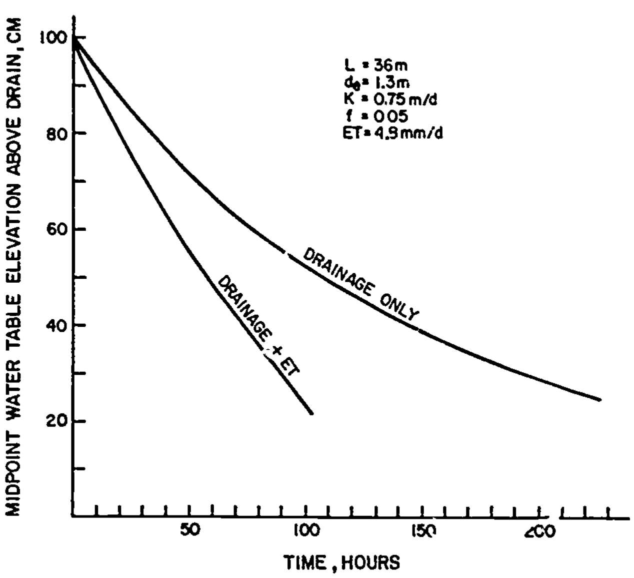


Figure 6-8—Shown is the predicted midpoint water table elevation for the 36-meter (118 feet) spacing. The initial water table shape was elliptical with the midpoint at the surface, 100 cm (25.4 inches) above the drains. Evapotranspiration may have a significant effect on water table drawdown for water tables close to the surface.

ET rate of 4.8 mm/day (0.19 in/day). These results show the significant effect of ET on water-table drawdown. Without ET, 32 hours were required to lower the midpoint water table by 0.2 m for the 36 m drain spacing considered. The same drawdown would occur in only 20 hours with an ET rate of 4.8 mm/day. Because ET may be negligible during critical wet periods, it is usually neglected in the design of drainage systems so as to provide a conservative design. However, the effect of ET may be substantial, and it is an important component of modern drainage simulation models.

Surface Drainage

Surface drainage is the removal of water that collects on the land surface. As noted earlier, water collects on the surface because the rainfall rate is greater than the infiltration capacity. In many flat, poorly drained soils, the most frequent cause of ponded surface conditions is the saturation of the soil profile with the water table rising to the surface. Under these conditions, the infiltration rate is reduced to the subsurface drainage rate, and ponding may exist for a long time if good surface drainage is not provided. For this reason, good surface drainage must be provided for slowly permeable soils and soils with fragipans or tight subsoils.

The next chapter covers the details of drainage design. Here, it is sufficient to note that a surface drainage system usually consists of an outlet channel, lateral ditches, and field ditches. Water is carried to the outlet channel by lateral ditches which receive water from field ditches or sometimes from the field surface. The system may include land smoothing or land grading to eliminate surface depressions and provide a continuous slope for the removal of surface water. The outlet channel and lateral ditches may sometimes serve as outlets for a subsurface drainage system. Conversely, surface inlets leading to buried mains may provide an outlet for local surface drainage.

Land grading or precision land forming is the shaping of land surface with scrapers and land planes to planned surface grades. Excellent surface drainage can be provided by land grading, but its use may be limited on lands where deep cuts that expose subsoils are required. Land smoothing removes small depressions and irregularities in the land surface, normally after land grading.

Field ditches may be either random or parallel. The random ditch pattern is used in fields having depressional areas that are too large to be eliminated by land forming. Field ditches connect the major low spots and remove excess water from them. If possible, the ditches should be shallow enough to permit crossing by machinery. If the topography is such that deeper ditches are required, a subsurface pipe with surface inlets in the low areas may be preferred.

A parallel ditch pattern is frequently used in flat, poorly drained soils in humid regions. The land surface is graded toward the ditches. In many cases, the ditches are placed close enough together, no more than 100 m (325 ft), to provide some subsurface drainage as well as surface drainage. Such ditches are usually over 1 m (3.28 ft) deep and effectively divide the land area into narrow fields often in excess of 800 m (1/2 mile) long. A better system is to place the parallel field ditches further apart with the row direction perpendicular to the ditch. By following this pattern and using buried drain tubes for subsurface drainage, field sizes can be increased with less land devoted to ditches.

The need for surface drainage depends very much on the quality of subsurface drainage. The design or analysis of a water management system should consider both surface and subsurface drainage components.

Simulation of Drainage Systems

The design and operation of each component of a water management system should consider the climate, soil properties, site conditions, and crop requirements. Further, the design of one component should depend on the other components. For example, a field with good surface drainage will require less intensive subsurface drainage than if surface drainage were poor. This requirement has been clearly demonstrated in both field studies of crop response (Schwab and others, 1974) and by theoretical methods. The relative importance of water-management components varies with the weather. In humid regions, a well-designed drainage system may be critical in some years yet provide essentially no benefits in others. Thus, methods for designing and evaluating multicomponent drainage and irrigation systems should provide a capability of identifying sequences of weather conditions that are critical to crop production and of describing the performance of the system during those periods.

An effective method of analyzing multicomponent drainage and irrigation systems is the use of computer-based models to simulate their performance over several years of climatological record. Several models have been developed (Lagace, 1973; Belmans and others, 1983). DRAINMOD, a water-management simulation model developed at North Carolina State University (Skaggs, 1978b, 1980), will be used to demonstrate this approach and to further examine the interactions and effectiveness of surface and subsurface drainage.

Inputs to the model include soil properties, crop parameters, drainage system parameters, and climatological data. The model is based on a water balance in the soil profile which is computed on an hourly basis by using approximate methods to calculate infiltration, drainage, subirrigation, and ET (as limited by both atmospheric and soil-water conditions). The quality of surface drainage depends on the depth of depressional storage, which may vary from about 1 mm (0.0394 in) for land-formed fields that have been smoothed, to greater than 30 mm (1.18 in) for fields with numerous potholes and depressions or that do not have adequate surface outlets (Gayle and Skaggs, 1978). Thus, the effect of improving surface drainage can be simulated by varying the average depth of depressional storage. The intensity of subsurface drainage depends on the drain depth and spacing as well as the hydraulic conductivity of the soil layers and depth to the restricting layer.

Approximate methods based on the stress-day index concept (Hiler, 1969) were incorporated in the model (Skaggs and Tabrizi, 1983) to predict the effect of excessive and deficient soil-water conditions on corn yields. The effect of trafficability and planting date delay are also evaluated by using relationships such as those given in figure 6-2.

The simulation output includes daily infiltration, water-table depth, depth of surface, dry zone, subsurface drainage, runoff, and ET. Monthly and yearly summaries of these values, as well as the number of days suitable for fieldwork are also in the output. The corn yield response as a percentage of the potential yield, which is defined as the average yield that would be obtained if all soil-water stresses were eliminated, is predicted for each year of the simulation.

As an example of the use of simulation models for the analysis of drainage systems, results for an eastern North Carolina soil, Rains sandy loam, will be presented. This soil has a nearly level surface with a hydraulic conductivity of about 1 m/day (39.37 in/day) and a profile depth of 1.4 m (55.12 in). It requires artificial drainage for trafficability and protection from excessive soil water during wet periods. Details of the soil properties and other input data are given elsewhere (Skaggs and Tabrizi, 1983). Simulations were conducted for several drain spacings with both good and poor drainage using weather data from Wilson, North Carolina.

Average predicted relative yields for the 26-year simulation period are plotted as a function of drain spacing in figure 6-9. Relationships for both good (depressional storage, s = 2.5 mm, 0.0985 in) and poor (s = 25 mm, 0.9850 in) surface drainage are presented. A maximum average relative yield (YR of 0.78) was predicted for a spacing of L = 20 m (66 ft) for good surface drainage and for L = 17 m (56 ft) for poor surface drainage. Higher average yields were not obtained because of deficit soil-water conditions which caused drought stresses during several years. Yields increased with better drainage (closer drain spacing) until the maximum was obtained. Further decreases in drain spacing caused the average YR values to drop slightly, showing a tendency for overdrainage if the drains were spaced too closely together.

These results showed clearly that the drain spacing required for a given level of production is dependent on the quality of surface drainage. The beneficial effect of surface drainage increases with drain spacing and is particularly important for poor subsurface drainage. For example, the predicted relative yield on the Rains soil for a 100-meter (328 ft) drain spacing, which is a typical spacing for open ditch drains in eastern North Carolina, is YR = 0.48 for good surface drainage versus YR = 0.37 for poor surface drainage. Assuming an average potential yield (that is, the average yield that would be obtained in the absence of soil-water stress) of 11,000 kg/ha (175 bu/ac), the predicted average yields would be 5,300 kg/ha (84 bu/ac) and 4,000 kg/ha (64 bu/ac), for good and poor surface drainage, respectively.

Economic analyses using present costs and prices determined the drainage treatment that would produce the maximum net profit. Results showed that the maximum profit for this soil would be obtained for a 24 m (78 ft) drain spacing with initial poor subsurface drainage.

Annual relative yields predicted for years 1950-75 are plotted in figure 6-10 for the Rains sandy loam with drain spacings of 24 and 100 m (79 and 328 ft). Average predicted relative yields were 0.76 and 0.47 for these two spacings, respectively. However, differences in the predicted yields between the two spacings varied widely from year to year. In wet years, the closer drain spacing gave much higher yields. For example, in 1961, YR = 100 m. For this year, the closer spacing allowed planting on time (by April 15), and the only decrease in yield was because of a short period when the water table was high early in the growing season. However, planting for the 100 m (328 ft) spacing was delayed until the last of May. High water-table conditions after planting and dry conditions later on during the delayed growing season further reduced yields. The cumulative effect resulted in a relative yield of 0.23 for the 100 m spacing.

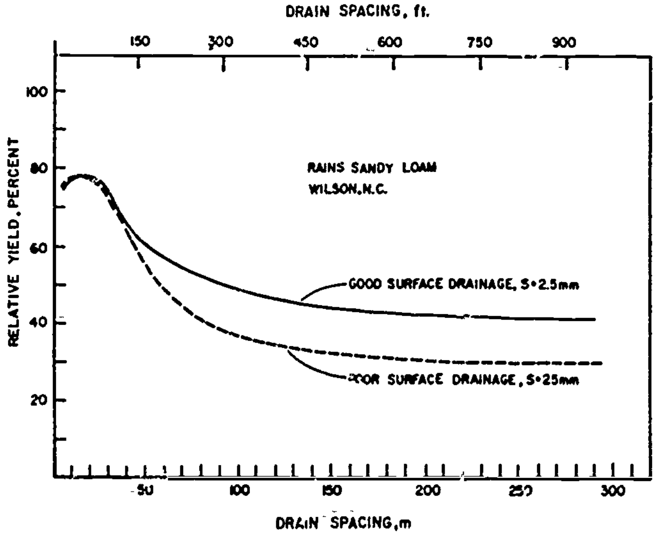


Figure 6-9--The effect of drain spacing on predicted average relative yields for a Rains sandy loam soil in Wilson, North Carolina.

During some years, when yields were limited by deficient soil-water conditions, yields differed very little between the 24 m and 100 m drain spacings. Examples are 1952 and 1964. In some years, such as 1956 and 1970, predicted yields for the 100 m spacing were higher than for the 24 m spacing. This was caused by a sequence of weather events that allowed planting to be completed on time for the closer spacing but delayed planting 20-30 days for the wider spacing. Subsequently, deficit soil-water conditions occurred at a time when the early-planted corn was most susceptible to drought. Corn planted later fared better because rainfall occurred before its period of maximum susceptibility.

Results given in figures 6-9 and 6-10 show that average yields are significantly increased by improved drainage. While the results showed that the benefits of drainage varied widely from year to year, improved drainage increases not only average yields but also the reliability of production. Assuming a corn price of $2.50/bu and present costs for production and drainage materials, the yields shown in figure 6-10 were used to calculate net profit for each of the 26 years for good drainage (L = 24 m, 328 ft). Results showed a net profit in 21 of the 26 years for good drainage compared with only 11 out of 26 years for poor drainage. Good drainage improved the reliability of production and allowed a net profit, based on assumed prices and costs, in over 80 percent of the years. Yields were reduced by drought during the other 5 years, resulting in net losses.

Subirrigation

The same drainage system that removes excess water during wet periods can also be used in some soils for irrigation during periods of deficient soil water. Subirrigation involves raising the water table and maintaining it at a position that will supply water to the growing crop. Subirrigation has been practiced in scattered locations for many years (Clinton, 1948; Renfro, 1955). It has many advantages over other alternatives under certain conditions. However, until recently, the method was not widely used because of the lack of established design criteria and information characterizing the operation of systems in the field. Subirrigation is now being promoted by the drainage industry and public agencies, and its use is increasing rapidly.

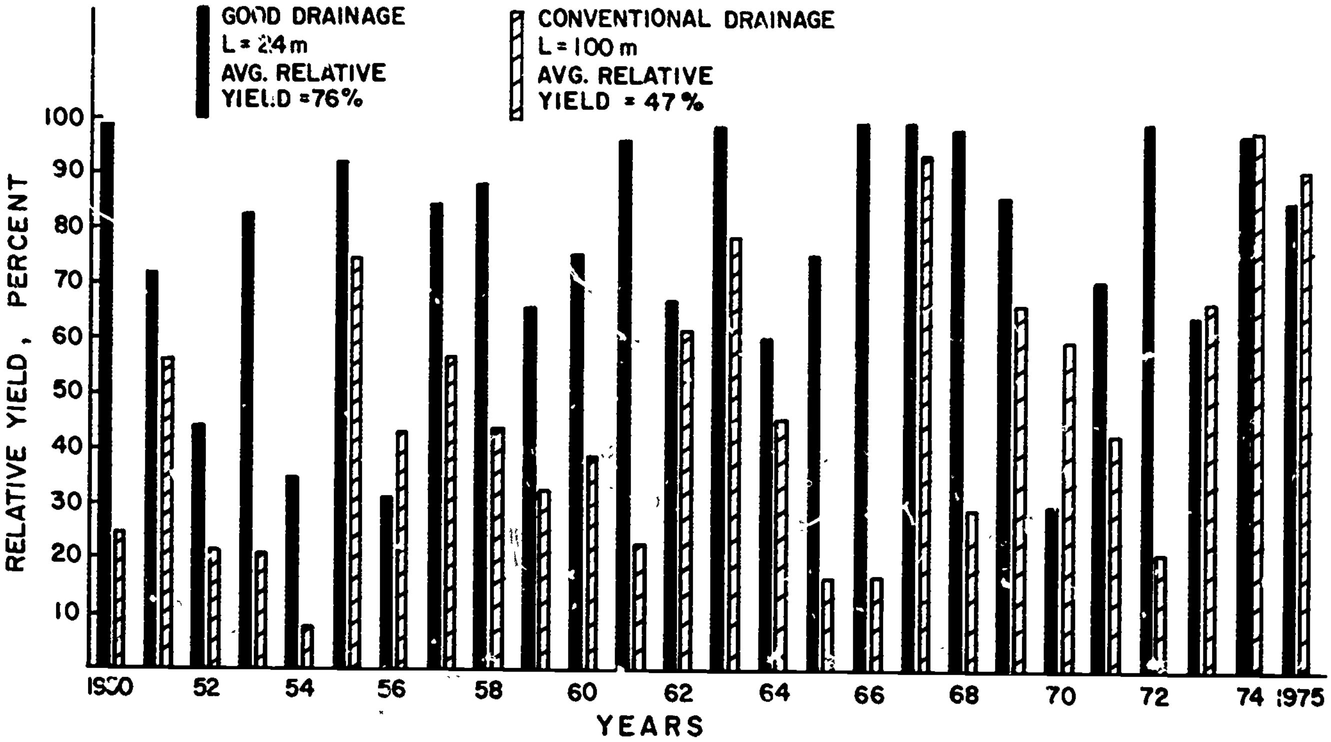


Figure 6-10—Yearly predicted relative corn yields for the optimum drain spacing, 24 meters (79 feet), and the conventional open ditch spacing of 100 meters for a Rains sandy loam soil.

Figure 6-11 sketches both a drainage system and a combination drainage-subirrigation system. Drains lead to a ditch as shown on the right side of the drawing, or to a head control tank. For conventional drainage, the water level in the outlet is maintained at or below the tube. During subirrigation, the water level in the outlet is raised to force water back through the drains and raise the water table as shown in the bottom part of figure 6-11.

For subirrigation systems to be practical, certain natural conditions must exist: an impermeable layer or a permanent water table at a rather shallow depth to prevent excessive seepage losses within about 7 m (23 ft) of the surface; relatively flat land, otherwise the water table might be maintained at an optimum depth on one side of the field while plants suffer from either too much or too little water on the other side; a moderate to high soil hydraulic conductivity so that a reasonable spacing of ditches or drain tubes will provide subirrigation and drainage; and a readily available source of water. These topographical and soil conditions exist for several million acres of land in the humid regions of the United States.

Where suitable conditions exist, combined subirrigation drainage systems offer a number of advantages and can play a significant role in water management strategies. Probably the most outstanding advantage is the cost. Both drainage and subirrigation can be provided in one system, often with a considerable cost reduction compared with separate systems. Other advantages include low labor and maintenance requirements and no delay in cultivation practices because of irrigation. Energy requirements for pumping irrigation water may be considerably lower than for conventional irrigation systems. Messey and others (1983) showed that subirrigation required somewhat more water than conventional irrigation but less than 10 percent of the energy for pumping when a surface-water supply was used. Salt buildup at the soil surface poses no problem in

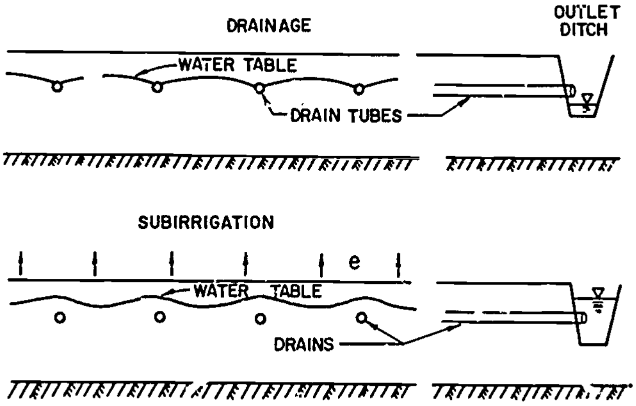


Figure 6-11—Schematic of a system used for both conventional drainage (top) and subirrigation (bottom).

humid regions because of high annual rainfall, whereas subirrigation is not feasible in arid and semiarid areas because of salt buildup. Deterioration of soil structure is a potential problem in humid regions when the water table is maintained at a high position for a long period of time.

Two basic design criteria must be satisfied in the design of subirrigation-drainage systems: first, the system must be capable of moving water to the crop root zone at a rate sufficient to supply plant requirements during peak use periods; second, the drainage component must be designed to remove water from the soil at a rate that will prevent crop damage during wet periods.

It is not always clear which of these criteria is limiting so far as design is concerned. Studies using the DRAINMOD simulation program indicate that the drainage requirement is usually limiting in the Carolinas. That is, drains that are placed close enough together to meet the drainage needs will usually be close enough to supply the irrigation water needs when the outlet water level is raised for subirrigation. On the other hand, simulations for conditions in the Midwest indicate that the irrigation requirement is usually limiting. In this case, drains placed close enough together to satisfy the drainage requirements, even when the system is being used for subirrigation, may not be close enough to supply the irrigation requirements. Methods for predicting the required drain spacing based on steady-state conditions have been presented by Fox and others (1956) and Ernst (1975). Methods have been developed to characterize the rate of water table rise during subirrigation (Skaggs, 1973).

The most critical aspect of design and management of a subirrigation-drainage system is the interaction between the irrigation and drainage functions. Determining in advance what the most critical sequence of weather events might be for a given management strategy is nearly impossible. The most effective way of analyzing the performance of such systems is to use simulation methods such as DRAINMOD and other models discussed in the previous section. SCS and others are using DRAINMOD for designing and analyzing subirrigation systems.

Research continues to develop better methods for managing or controlling these dual-purpose systems. Smith and others (1982) used both field experiments and simulation methods to show that controlling subirrigation applications based on field water levels rather than outlet conditions reduced both water and energy requirements. Fouss (1983a,b) modified the DRAINMOD model to analyze various control strategies for a subirrigation system. He is also investigating the use of weather forecast data as a control variable, a subject studied earlier by Warner (1972). A research need in a slightly different area involves drain-slope and envelope requirements for subirrigation drainage systems. Present research data are not sufficient for determining if envelope requirements are more critical for dual-purpose systems than for conventional drainage needs.

Offsite Effects

The preceding sections have discussed drainage and water-table management in terms of agricultural requirements. Traditionally, the efforts of engineers, technicians, farmers, and contractors have been aimed at one goal: to design and install systems that will satisfy agricultural drainage requirements at the least cost. However, recognition in recent years of agriculture's role in nonpoint source pollution of surface waters places additional constraints on the design and operation of drainage and related water-management systems, particularly where farms are located in environmentally sensitive areas, or where downstream users of water have stringent water quality or quantity requirements. In most cases, several design and operational alternatives can satisfy agricultural drainage needs. Some of those alternatives have different effects on the rate and quality of water leaving the fields than others. The challenge is to identify those alternatives that will satisfy agricultural requirements while minimizing detrimental effects on the receiving waters.

Although research is by no means complete on this subject, considerable work has been done to determine water quality and hydrologic effects of drainage and associated water-management practices. In general, systems that depend primarily on surface drainage tend to have higher runoff rates with more sediment, phosphorus, and pesticides than do systems with good subsurface drainage. However, good subsurface drainage increases the outflow of nitrates with the drainage water. Associated water-management practices, such as controlled drainage and subirrigation, will also have an effect on both the rate and quality of drainage water leaving a field.

Figure 6-12 illustrates the effect of subsurface drainage on peak outflow rates. The runoff hydrographs were measured on adjacent, almost flat 80-acre eastern North Carolina watersheds with

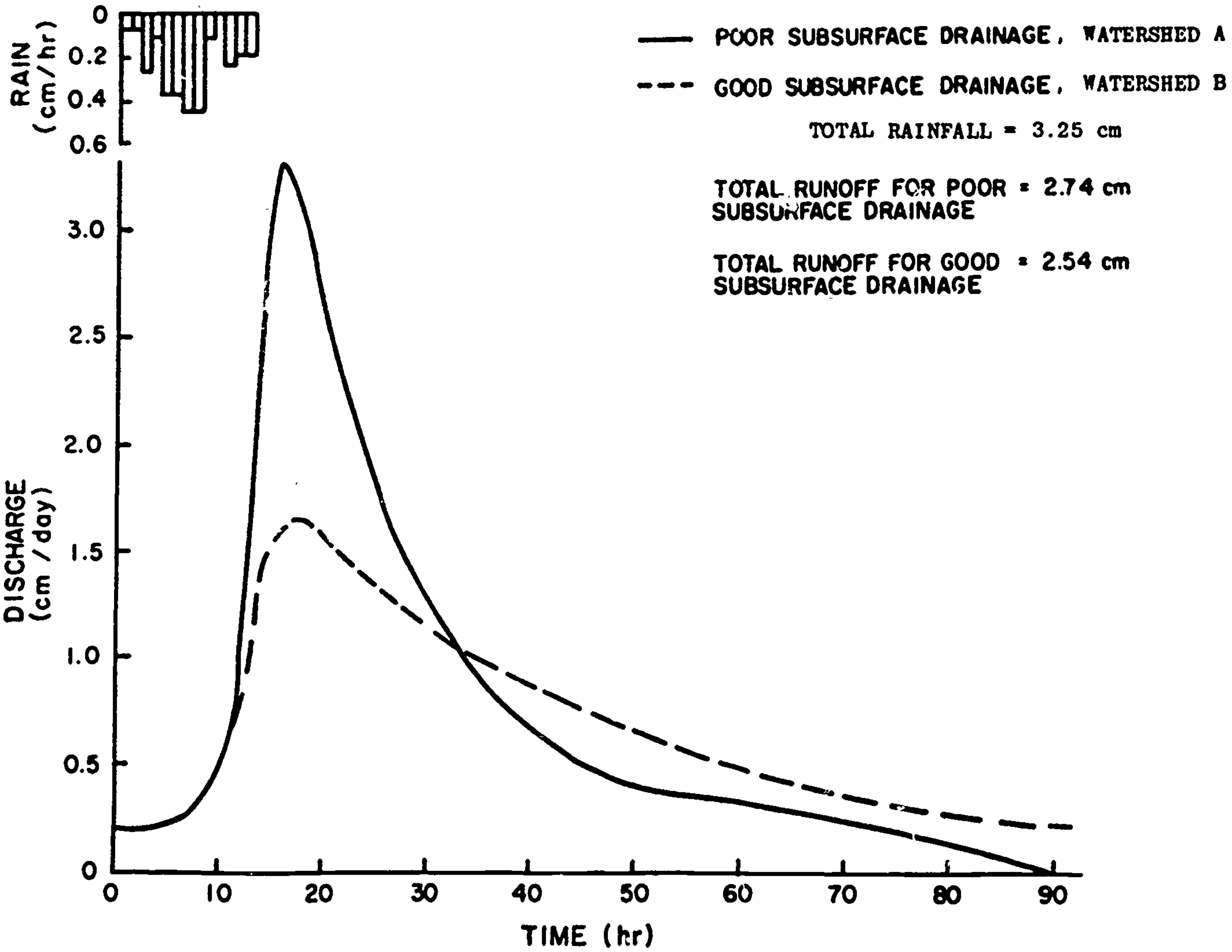


Figure 6-12—These runoff hydrographs chart a 3.25-centimeter (1.27 inches) rainfall in eastern North Carolina on February 28, 1983. The peak runoff rate for watershed A with poor subsurface drainage was more than twice that of the adjacent watershed B which had good subsurface drainage.

identical soils and crops. Watershed A has parallel ditches spaced 100 m (328 ft) apart which provide good surface drainage but relatively poor subsurface drainage. Watershed B has the same surface drainage system but drain tubes at 33 m (108 ft) intervals between the ditches which provide good subsurface drainage. The results show that, while total drainage from the 3.25 mm (1.27 in) storm was about the same for both watersheds, the peak outflow rate from the fields with good subsurface drainage was less than half of that from the fields with poor subsurface drainage. Good subsurface drainage removed excess water from the profile slowly over a longer period of time. It lowered the water table and provided more storage for infiltrating rainfall than systems which depended primarily on surface drainage. Thus, in areas where high surface runoff rates caused flooding and related problems, subsurface drainage tended to reduce the peaks. These effects may be very important in lands close to estuarine nursery areas where high runoff rates may cause unnatural salinity fluctuations and consequently reduced productivity of fish and shellfish.

The effects of subsurface drainage on water-quality parameters for watersheds A and B are tabulated below. Both have good surface drainage.

Watershed	Concentration (milligrams per liter)			
	NO_3-N	TKN	Total P	Ortho P
A (poor subsurface drainage)	1.3	1.9	0.16	0.04
B (good subsurface drainage)	3.8	1.6	.08	.01

The tabulated values are mean concentrations of nitrogen and phosphorus measured continuously over a year. These results showed that good subsurface drainage increased nitrate outflow but reduced the loss of phosphorus (P) to drainage waters. Improvement of surface drainage has the opposite effect. Thus, if P concentrations in receiving waters are critically high, better subsurface drainage would improve the situation. Improved surface drainage or the use of drainage outlet controls to increase surface runoff would also reduce nitrate outflow. Controlled drainage methods have been used (Willardson and others, 1972; Gilliam and others, 1979) to promote denitrification and to reduce the amount of nitrate entering ground and surface waters. Skaggs and Gilliam (1981) used field results and simulation modeling to show the effects of drainage design and operation on nitrate losses from a soil with poor natural drainage. The systems considered satisfied agricultural drainage requirements for corn. Results showed an annual average loss of 39 kg/ha (35 lbs/ac) for a conventional system with poor surface drainage and good subsurface drainage. By improving the surface drainage and controlling the subsurface outlet during the winter months, the annual nitrate loss could be reduced to 14.5 kg/ha (12.9 lbs/ac).

These examples emphasize that various drainage and associated water-management practices have different effects on the rate and quality of runoff water. By careful design and operation of water-management systems, agricultural management requirements may be satisfied while minimizing offsite detrimental effects. To achieve this goal, the principles involved and the factors controlling offsite conditions and requirements as well as farm drainage needs must be understood and considered.

References

Belmans, C., J. G. Wesseling, and R. A. Feddes. 1983. "Simulation Model of the Water Balance in a Cropped Soil: SWATRE," *Journal of Hydrology*. Vol. 63, pp. 271-286.

Bouwer, H., and J. van Schilfgaarde. 1963. *Simplified Method of Predicting the Fall of Water Table in Drained Land*. Transactions of the ASAE. Vol. 6, No. 4, pp. 288-291, 296.

Buckingham, E. 1907. *Studies of the Movement of Soil Moisture*. Bull. No. 38, U.S. Dept. Agr., Bureau of Soils.

Childs, E. C. 1969. *Introduction to the Physical Basis of Soil Water Phenomena*. London: Wiley-Interscience, pp. 125-128

Clinton, F. M. 1967. "Invisible Irrigation on Egin Bench," *Reclamation Era*. Vol. 34, pp. 182-184.

Day, P. R., G. H. Bolt, and D. M. Anderson. 1967. "Nature of Soil Water," *Irrigation of Agricultural Lands* (ed. R. M. Hagan and others). Monograph No. 11. Madison, Wisc.: Am. Soc. Agron., pp. 193-208.

Dumm, L. D. 1954. "New Formula for Determining Depth and Spacing of Subsurface Drains in Irrigated Lands," *Agricultural Engineering*. Vol. 35, pp. 726-730.

Dumm, L. D. 1964. *Transient Flow Concept in Subsurface Drainage: Its Validity and Use*. Transactions of the ASAE. Vol. 7, No. 2, pp. 142-146.

Ernst, L. F. 1975. *Formulae for Groundwater Flow in Areas With Subirrigation by Means of Open Conduits With a Raised Water Level*. Misc. reprint 178. Wageningen, The Netherlands: Institute for Land and Water Management Research.

Fouss, J. L. 1983a. *Simulated Controlled Operation of Subsurface Drainage - Irrigation Systems*. ASAE Paper No. 83-2567. St. Joseph, Mich.: Am. Soc. Agr. Eng.

Fouss, J. L. 1983b. *Daily Weather Forecast Rainfall Probability as an Input to a Water Management Simulation Model*. Proceedings of the Natural Resources Modeling Symposium, U.S. Dept. Agr., Agr. Res. Serv.

Fox, R. L., J. T. Phelan, and W. D. Criddle. 1956. "Design of Subirrigation Systems," *Agricultural Engineering*. Vol. 37, No. 2, pp. 103-107.

Gayle, G. A., and R. W. Skaggs. 1978. *Surface Storage on Bedded Cultivated Lands*. Transactions of the ASAE. Vol. 21, No. 1, pp. 102-104, 109.

Gilliam, J. W., R. W. Skaggs, and S. B. Weed. 1979. "Drainage Control to Diminish Nitrate Loss from Agricultural Fields," *Journal of Environmental Quality*. Vol. 8, pp. 137-142.

Hardjoamidjojo, S., R. W. Skaggs, and G. O. Schwab. 1982. *Predicting Corn Yield Response to Excessive Soil Water Conditions*. Transactions of the ASAE. Vol. 25, No. 4, pp. 922-927, 934.

Hiler, E. A. 1969. *Quantitative Evaluation of Crop-Drainage Requirements.* Transactions of the ASAE. Vol. 12, No. 3, pp. 499-505.

Kirkham, D. 1964. *Physical Artifacts and Formulas for Approximating Water Table Fall in Tile-Drained Land.* Soil Sci. Soc. Amer. Proc., Vol. 28, pp. 585-590.

Kirkham, D., and W. L. Powers. 1972. *Advanced Soil Physics.* New York: Wiley-Interscience.

Krenzer, E. G., Jr., and W. T. Fike. 1977. Corn *Production Guide—Planting and Plant Population.* North Carolina Agr. Ext. Serv., N.C. State Univ., Raleigh.

Lagace, R. 1973. "Modele de Comportenent des Nappe en Sol Agricole," *Genie Rural - Laval,* (Quebec, Canada), Vol. 5, No. 4, pp. 26-35.

Luthin, J. N. 1957. "Drainage of Irrigated Lands," *Drainage of Agricultural Lands* (ed. J. N. Luthin). Monograph No. 11. Madison, Wisc.: Am. Soc. Agron., pp. 344-371.

Massey, F. C., R. W. Skaggs, and R. E. Sneed. 1983. *Energy and Water Requirements for Subirrigation Versus Sprinkler Irrigation.* Transactions of the ASAE. Vol. 26, No. 1, pp. 126-133.

Moody, W. T. 1966. "Nonlinear Differential Equation of Drain Spacing," *Journal of the Irrigation and Drainage Division.* ASCE. Vol. 92(IR2), pp. 1-9.

Nolte, B. H., D. M. Byg, and W. E. Gill. 1976. *Timely Field Operations for Corn and Soybeans in Ohio.* Bull. 605. Coop. Ext. Serv., Ohio State Univ., Columbus.

Ravelo, C. J., D. L. Reddell, E. A. Hiler, and R. W. Skaggs. 1982. *Incorporating Crop Needs into Drainage System Design.* Transactions of the ASAE. Vol. 25, No. 3, pp. 623-629, 637.

Reeve, R. C., and N. Fausey. 1974. "Drainage and Timeliness of Farming Operations," *Drainage for Agriculture.* Monograph No. 17 (ed. J. van Schilfgaarde). Madison, Wisc.: Am. Soc. Agron., pp. 55-66.

Renfro, George, Jr. 1955. "Applying Water Under the Surface of the Ground." *Water: Yearbook of Agriculture,* 1955. U.S. Dept. Agr., pp. 173-178.

Richards, L. A. 1965. "Physical Conditions of Water in Soil," *Methods of Soil Analysis.* Monograph No. 9, Madison, Wisc.: Am. Soc. Agron.

Schwab, G. O., N. R. Fausey, and D. W. Michener. 1974. *Comparison of Drainage Methods in a Heavy Textured Soil.* Transactions of the ASAE. Vol. 17, No. 3, pp. 424, 425, 428.

Skaggs, R. W. 1973. *Water Table Movement During Subirrigation.* Transactions of the ASAE. Vol. 16, No. 5, pp. 988-993.

Skaggs, R. W. 1975. "Drawdown Solutions for Simultaneous Drainage and ET," *Journal of the Irrigation and Drainage Division.* ASCE. Vol. 101(IR4), pp. 279-291.

Skaggs, R. W. 1978b. *A Water Management Model for Shallow Water Table Soils.* Technical Report No. 134. Water Resources Research Institute of the Univ. of North Carolina. N.C. State Univ., Raleigh.

Skaggs, R. W. 1979. *Factors Affecting Hydraulic Conductivity Determinations from Drawdown Measurements.* ASAE Paper No. 79-2075, presented at the summer meeting of the Am. Soc. Agr. Eng., Winnipeg, Manitoba.

Skaggs, R. W. 1980. *A Water Management Model for Artificially Drained Soils.* Technical Bulletin No. 267. North Carolina Agri. Res. Serv., N.C. State Univ., Raleigh.

Skaggs, R. W., and J. W. Gilliam. 1981. *Effect of Drainage System Design and Operation on Nitrate Transport.* Transactions of the ASAE. Vol. 24, No. 4, pp. 929-934.

Skaggs, R. W., and A. Nassehzadeh-Tabrizi. 1983. *Optimum Drainage for Corn Production.* Technical Bulletin No. 274. North Carolina Agri. Res. Serv., N.C. State Univ., Raleigh.

Skaggs, R. W., and A. Nassehzadeh-Tabrizi. 1984. *Determining Design Drainage Rates for Optimum Drainage.* ASAE Paper No. 84-1055, St. Joseph, Mich.: Am. Soc. Agr. Engr.

Skaggs, R. W., and Y. K. Tang. 1976. "Saturated and Unsaturated Flow to Parallel Drains," *Journal of Irrigation and Drainage Division*. ASCE. Vol. 102(IR2), pp. 221-238.

Smith, M. C., R. W. Skaggs, and J. E. Parsons. 1982. *Subirrigation System Control for Water Use Efficiency*. ASAE Paper No. 82-2520. St. Joseph, Mich.: Am. Soc. Agr. Engr.

van Schilfgaarde, J. 1965. "Transient Design of Drainage Systems," *Journal of the Irrigation and Drainage Division*. ASCE. Vol. 91(IR3), pp. 9-22.

van Schilfgaarde, J. 1974. "Nonsteady Flow to Drains," *Drainage for Agriculture*. Monograph No. 17. (ed. J. van Schilfgaarde). Madison, Wisc.: Am. Soc. Agron., pp. 245-270.

Warner, R. C. 1972. *A Management Model for a Controlled Drainage and Subirrigation System*. M.S. thesis, Clemson Univ., Clemson, S.C.

Wesseling, J. 1974. "Crop Growth and Wet Soils." *Drainage for Agriculture*. Monograph No. 17 (ed. J. van Schilfgaarde). Madison, Wisc.: Am. Soc. Agron., pp. 7-37.

Williamson, R. E., and G. J. Kriz. 1970. *Response of Agricultural Crops to Flooding, Depth of Water Table and Soil Composition*. Transactions of the ASAE. Vol. 13, No. 1, pp. 216-220.

Willardson, L. S., and others. 1972. *Nitrate Reduction with Submerged Drains*. Transactions of the ASAE. Vol. 15, No. 1, pp. 84-90.

Chapter 7

Drainage System Elements

Walter J. Ochs
Soil Conservation Service, USDA
Washington, DC

Richard D. Wenberg
Soil Conservation Service, USDA
Forth Worth, Texas

Gordon W. Stroup
Soil Conservation Service, USDA
Portland, Oregon

A successful drainage system consists of a number of elements or land-management practices. The primary elements are the outlet, the collection system, land-treatment measures, and land-protection measures. The design of each element can be related to the level of management desired in an individual water-management system. Operation, maintenance, cropping, and cultural practices affect the selection and design of individual elements.

Drainage investigations determine the extent of problems and the site conditions to be considered in designing elements that will result in an effective system.

Outlets

The adequacy of outlets for a drainage system is an important initial consideration. Outlet capacity can be evaluated by careful analysis of design discharges. The outlet is usually considered adequate if downstream flows in the receiving stream are not increased by the design discharge from the drainage system to the point where damages are expected. Outlets can be divided into two primary types: pumped or gravity. A comparison of relative elevations will generally indicate whether a gravity outlet is available or if pumping will be required. Special outlet structures may also be needed (fig. 7-1).

Gravity Outlets

Gravity outlets for drainage systems are usually constructed channels or excavated ditches, but rivers, streams, or lakes may be used. Large outlet conduits are sometimes used when excavation through deep cuts would remove excessive amounts of land from production or when excavation would cause serious aesthetic, safety, or environmental problems.

Open ditches or channels must be designed so that design flow will not cause erosion. Channel banks or side slopes must also be stable. Depth and width requirements are based on the drainage system discharge rates, bank stability requirements, and the elevation of inflow and outflow waters. Channel outlet maintenance enhances the effective life of most drainage systems. Vegetation, phreatophytes, and sediment deposition must be controlled through sound maintenance programs if an effective channel

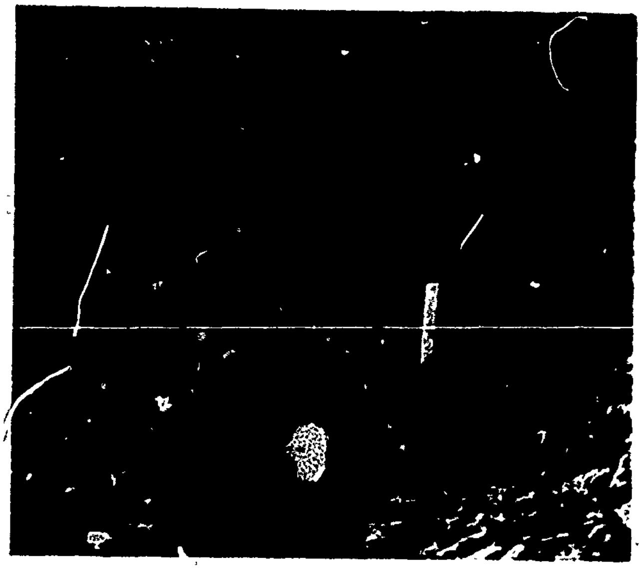
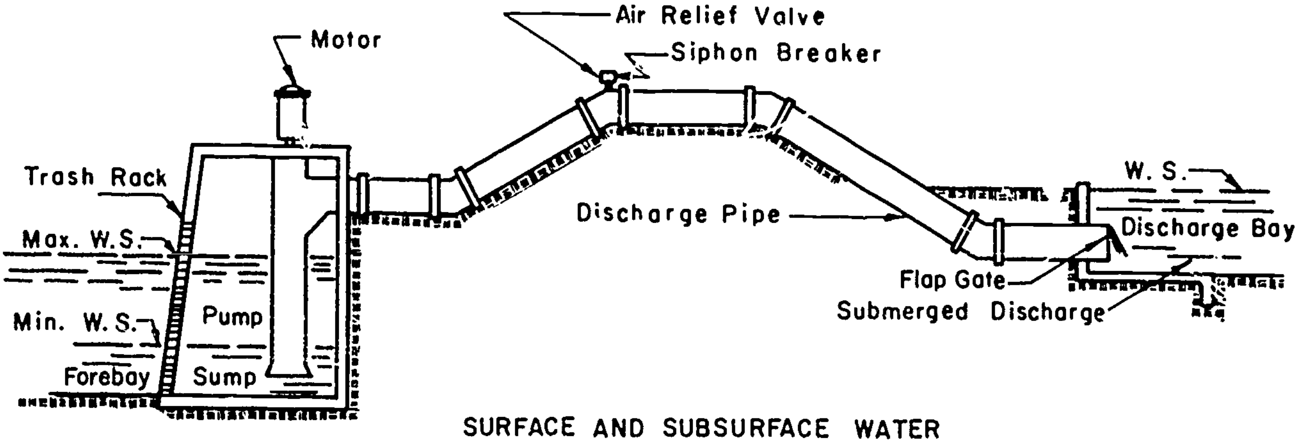
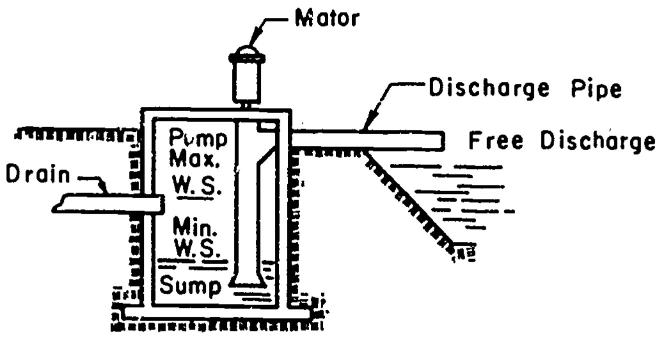


Figure 7-1—Two 24-inch tiles drain 1,200 acres to protect against erosion in Miami, Ohio.



SURFACE AND SUBSURFACE WATER



SUBSURFACE WATER ONLY

Figure 7-2—A schematic of pumping plant layouts.

and drainage system is to continue to function (USDA, SCS, 1971).

Pumped Outlets

Pumps can be used for the discharge of water from drainage systems when a gravity flow outlet cannot be obtained because of insufficient outlet depth, or if outlet capacity is restricted because of backwater from storm or tidal flooding. Pumped outlets are normally more expensive than gravity outlets when the entire life of a drainage system is considered because of the initial equipment cost as well as the maintenance costs and energy requirements. A detailed evaluation is often needed to detemine the most effective and economical method of discharging the drainage water. Pumped outlets may be preferred in some systems to protect wetland areas which are valuable wildlife habitats.

Pumping plants can include one or more pumps, power units, and appurtenances for lifting collected drainage water to a shallower gravity outlet (fig. 7-2). Planning a pumped outlet requires consideration of the entire drainage system so that diversions, storage areas, channels, and gravity outlets are used to the best advantage in determining capacity, size, and operation of the pumps. Some pump outlets operate for relatively short periods when high water levels in the receiving stream would restrict flow capacity enough to cause excessive crop damage.

Collection Systems

A drainage system must include drains to collect water from surface depressions, very flat surfaces, and excessive soil water in the crop root zone. The collection system contains elements such as drainage field ditches, subsurface drainage conduits, pumped well drains, and/or combinations of the three. Subsurface drains and surface drainage field ditches are often constructed on the same land. Both are often needed to provide the cropping environment desired for effective production. Collection systems must be designed to remove excess water from the surface of the soil and the crop root zone in time to prevent damage to crops (USDA, SCS, 1971).

Drainage Field Ditches

Field ditches, normally shallow, graded collection channels with flat side slopes, allow farm equipment to cross. These ditches provide a specific water removal rate for surface waters and are located and constructed so as to collect excess water in the field (fig. 7-3). The three types of collection systems using field ditches are parallel, random, and cross-slope or diversion, depending on the way they are laid out.

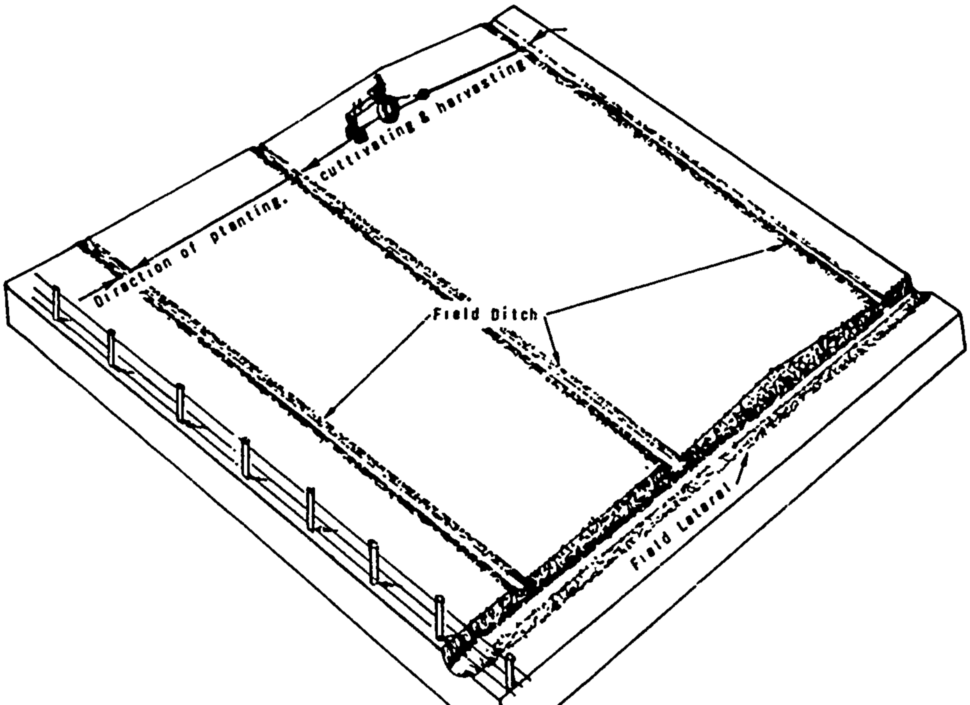
Parallel Systems. Parallel systems usually drain flat, uniform land. The field ditches are established in a parallel but not necessarily equidistant pattern and must have sufficient grade to prevent ponding. Orientation of the field ditches depends upon the direction of land slope and the location of other facilities in the field, such as diversions and outlet channels. The parallel field ditches usually run across a field to discharge into outlet ditches on the borders of the field (fig. 7-4). The minor outlet ditches in a field are called laterals and should be deeper than field ditches to provide free discharge (fig. 7-5).

Figure 7-3—A surface drainage system carries water in Paulding County, Ohio.

Random Systems. Random systems drain irregular but flat or gently sloping land where wet depressional areas occur randomly over the field (fig. 7-6). The field ditches transect as many depressions as possible along a course through the lowest sections of the field (fig. 7-7). Two or more ditches may join into a single field ditch as the water flows toward an available outlet. Deep earth cuts should be minimized when locating the field ditches (USDA, SCS, 1971).

Cross-Slope Systems. Cross-slope systems, sometimes called diversion systems, drain sloping land that may be wet because of slowly permeable soil (fig. 7-8). Such a system prevents water ac-

Figure 7-4—A parallel drainage system.



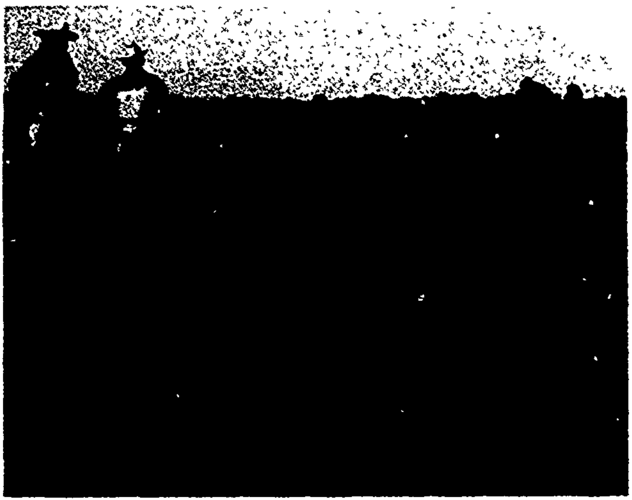


Figure 7-5—Tallulah, Louisiana, growers inspect a lateral outlet ditch in a parallel drainage system. Seeded to Kobe lespedeza, the ditch is mowed 3 to 5 times a year.

cumulating from higher land concentrated in shallow pockets within a field. As water flows downhill, it is intercepted by the cross-slope system, then carried off by a field ditch. Field ditches in these systems may be built to resemble a terrace or diversion (USDA, SCS, 1971).

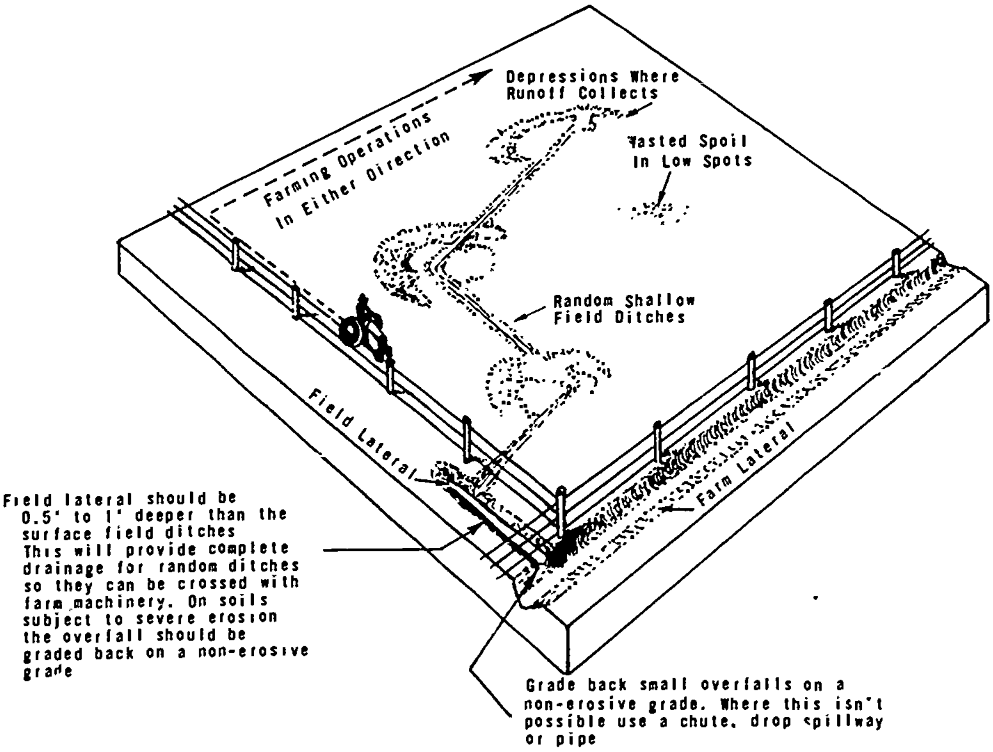
Subsurface Drains

Subsurface drains usually consist of underground pipe systems designed to collect excess soil water from the root zone. These drains are normally installed to lower the water table and promote the downward movement of water and salts in the crop root zone, especially if the land is being irrigated. Open channels can be used to provide subsurface drainage, but they must be deeper than closed drains, which is a disadvantage because of the area removed from production and the division of fields into small areas that are difficult to farm. As illustrated in figure 7-9, subsurface drains are often divided into two classes: relief drains and interception drains (Ochs and others, 1980).

Relief Drainage. Relief systems lower high water tables which are generally flat or of very low gradient. Subsurface drainage conduits are generally perforated pipe or tubing, or open joint tile or pipe. Common materials used for subsurface drainage conduits during the past 50 years have been clay, concrete, and plastic.

Relief drains (fig. 7-10) normally consist of a system of parallel collection drains (open or closed) connected to a main drain located on the low side of a field or along a low waterway in the field. The main drain transports the collected waters to the outlet system. Subsurface collector lines used for relief drainage are approximately 3 feet deep in humid areas and 6-9 feet deep in arid and semiarid areas. Sometimes random subsurface drain lines provide relief drainage in areas where scattered isolated wet soils are the problem. If individual wet areas

Figure 7-6—A random system drains irregular but flat or gently sloping land. Field ditches transect many random depressions along their courses through the lowest sections of the field.



are large, a system of pattern parallel drains may be used, with the random collection lines serving as an outlet.

Interception Drainage. Interception drainage is most common where topography causes water-table surface gradients to slope and where lateral seepage occurs (fig 7-11). Collector lines intercept, reduce, and lower the surface level of ground-water flows. Often an interceptor drain consists of a single drain which intercepts the lateral flow of ground water caused by canal seepage, reservoir seepage, or levee-protected areas. These drains are usually perpendicular to the flow of ground water that is to be intercepted. Multiple lines are used if water quantities are high.

Pumped Well Drains

Pumped well drains can be used effectively as relief drains if an aquifer of deep sand and gravel underlies the area to be drained and if there is good vertical movement of water between the root zone of the crops and the aquifer. Wells are spaced apart to create overlapping cones of depression, thus controlling the excess water in the root zone of crops (USDA, SCS, 1971). A line of pumped well drains can also be used as an interceptor drain.

Land Treatment Practices

While they are not specifically drainage practices, various land treatment measures may be needed in conjunction with drainage practices to ensure the proper, most advantageous functioning of the drainage system (American Society of Agricultural Engineers, 1979).

Clearing and Snagging

Clearing and snagging is the removal of snags, stumps, debris, or other obstructions from a drainage channel to establish suitable outlets for a drainage system, especially after a period of abnormally high flows or as periodic maintenance to remove accumulated growth and debris (figs. 7-12 and 7-13). Failure to remove this material reduces flow capacity of the channel, promotes bank erosion from eddies, causes formation of silt bars, and increases the possibility of blockage by snow and ice.

Bedding

Bedding is a land-treatment measure used on very flat cropland where normal cropping and tilling operations interfere with the flow of surface water from the field (fig. 7-14). Bedding is the grading of a land surface to form a series of low, broad ridges separated by shallow, parallel drainage channels sent in the direction of greatest land slope. These channels connect with field drains in the normal drainage system.

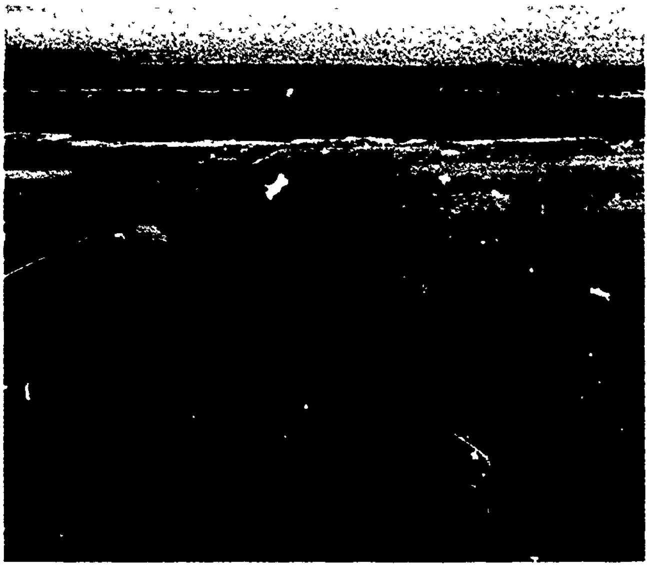


Figure 7-7—A random tile drain system cuts through Kewaunee-Manawa complex soils in Mantiwoc County, Wisconsin. Meantime, a grassed waterway for erosion control is under construction through the middle of the farm.

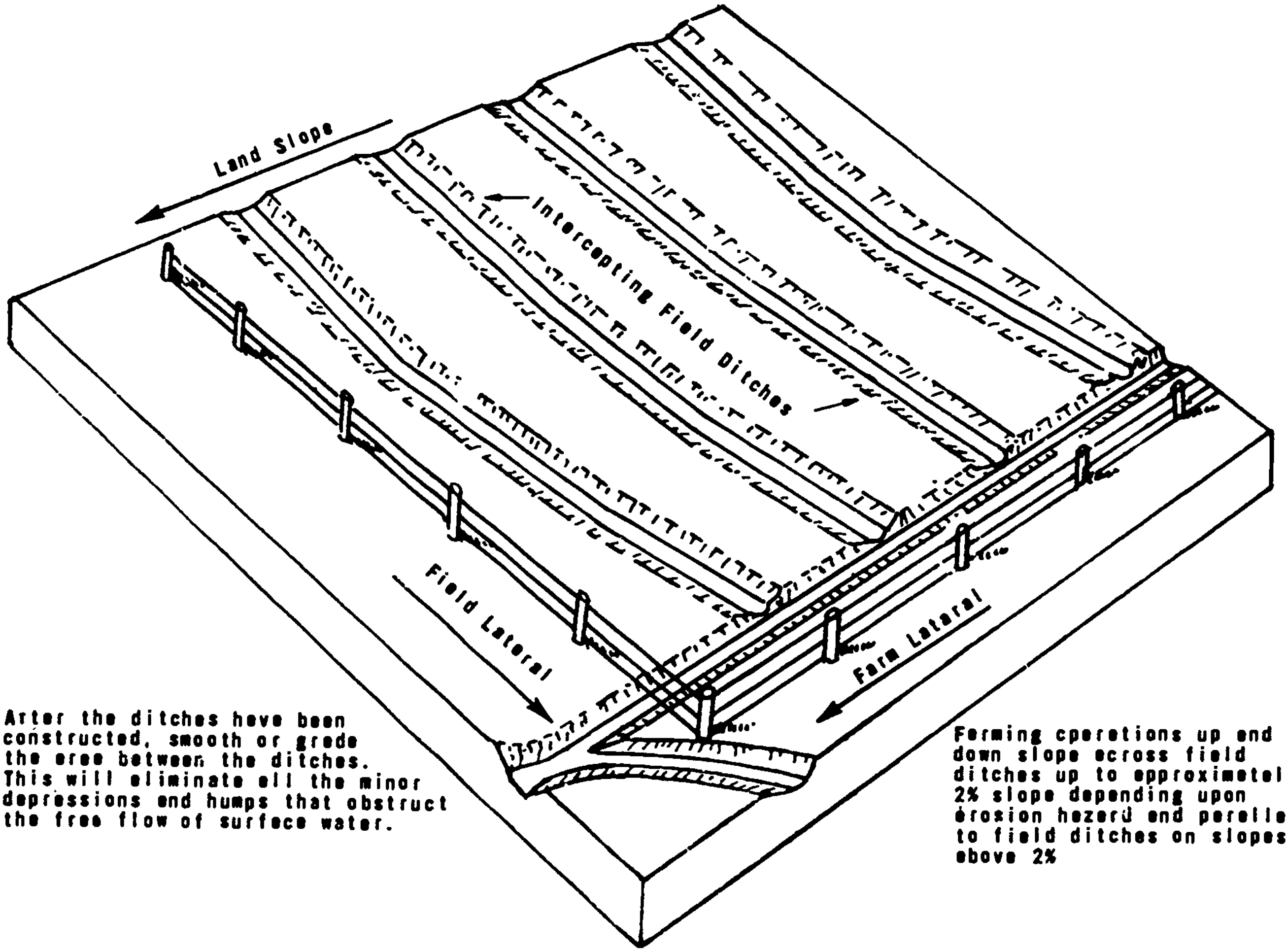
Formation of the alternate ridges and channels creates sufficient land slope so that excess surface water moves relatively quickly to the channels where it flows readily to the field drains.

Land Smoothing

Surface irregularities in the land surface can cause troublesome wet areas which affect much larger portions of a field. Such areas may be eliminated with land smoothing, usually done with special earthmoving equipment, such as land levelers or land planes (fig. 7-15). The soil surface irregularities may be dead-furrows, old field boundaries, fence rows, roadways, or similar features. Usually only specific areas are treated without changing the general topography of the field.

Land Grading

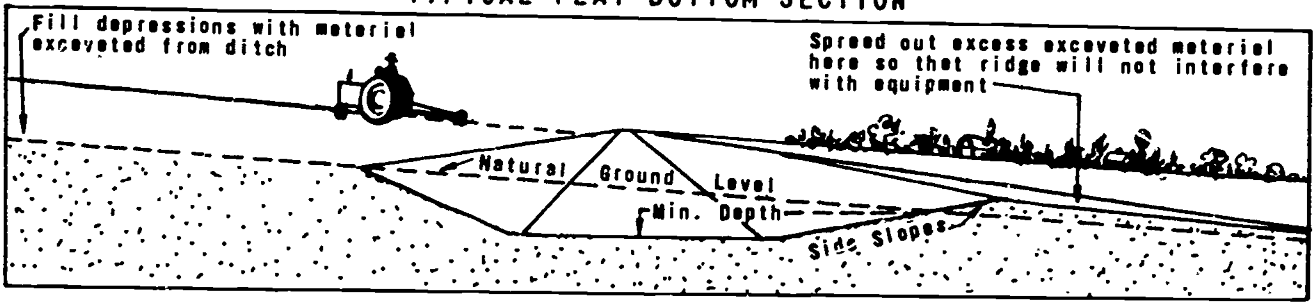
Land grading, the forming of land surfaces to predetermined grades so that each row or surface slopes to a drain, is used where natural slopes are too flat for adequate surface drainage and must be increased, or for changing direction of surface slopes to fit an overall farming arrangement or



After the ditches have been constructed, smooth or grade the area between the ditches. This will eliminate all the minor depressions and humps that obstruct the free flow of surface water.

Farming operations up and down slope across field ditches up to approximately 2% slope depending upon erosion hazard and parallel to field ditches on slopes above 2%

TYPICAL FLAT BOTTOM SECTION



Fill depressions with material excavated from ditch

Spread out excess excavated material here so that ridge will not interfere with equipment

TYPICAL V-CHANNEL SECTION

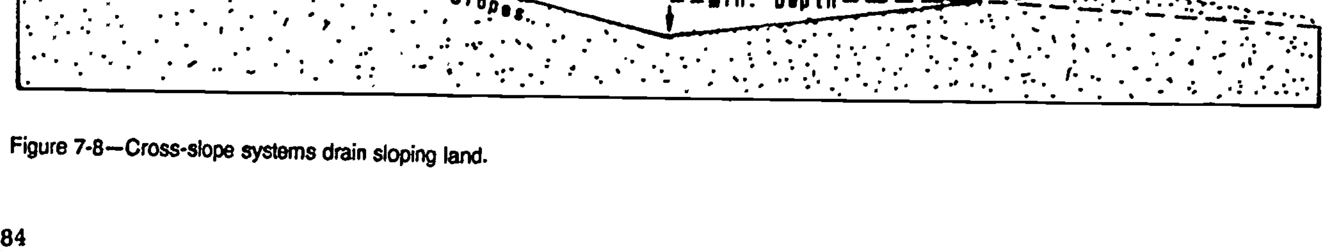


Figure 7-8—Cross-slope systems drain sloping land.

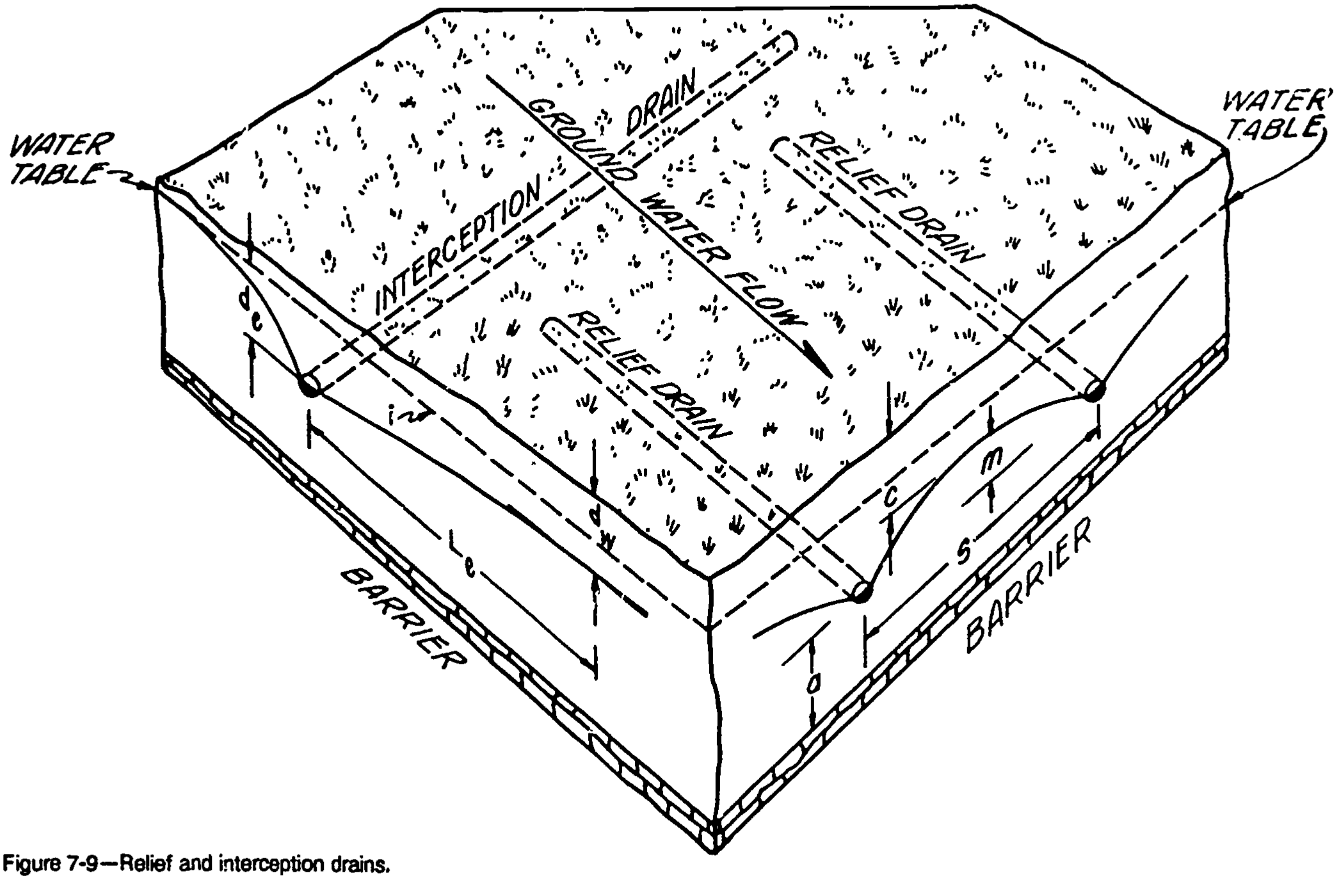


Figure 7-9—Relief and interception drains.

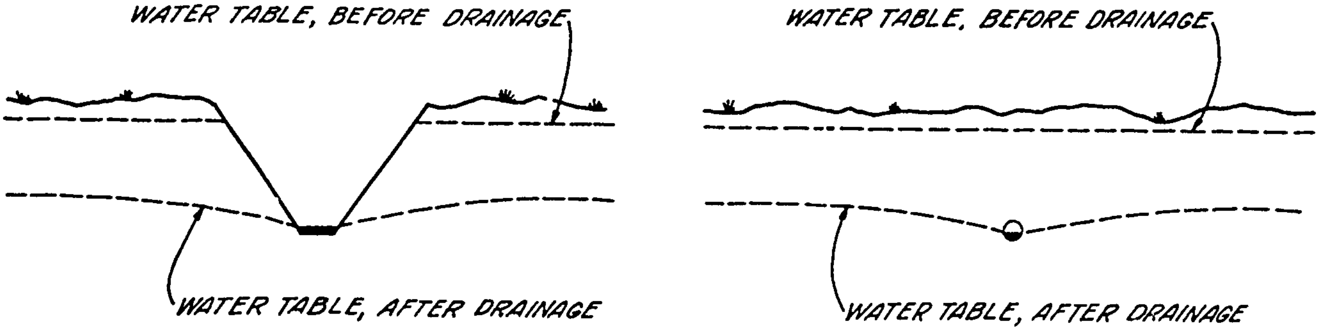


Figure 7-10—Relief drains.

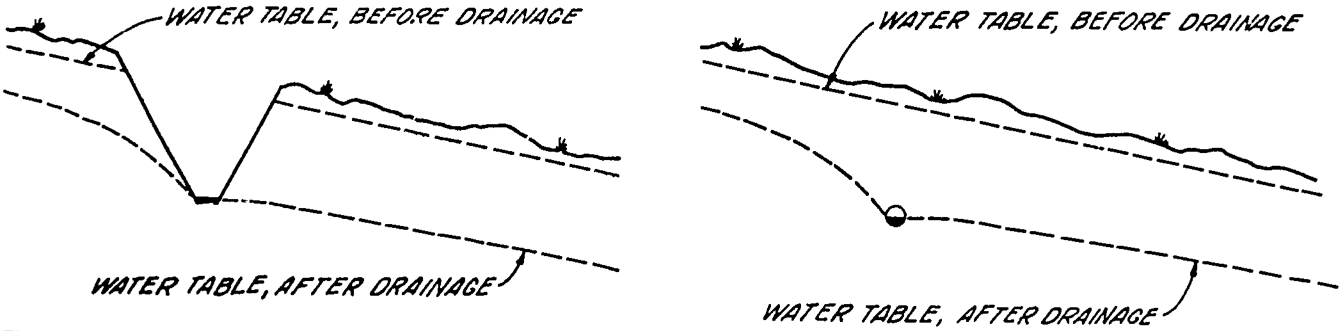


Figure 7-11—Inteception drains.

drainage system (fig. 7-16). Farmers normally use land grading for higher value crops because this treatment can be expensive. Excavations, fills, and land smoothing are all required to prepare the continuous surface grades.

Leaching

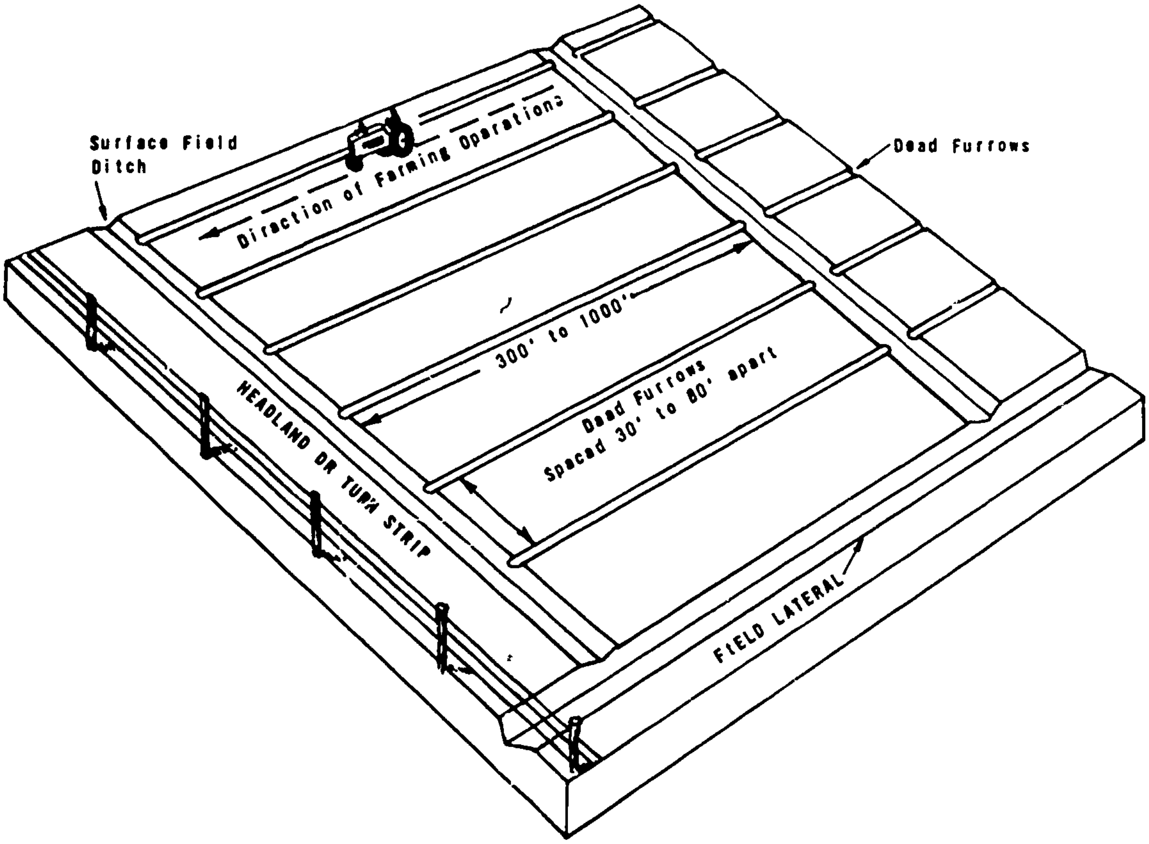
Many drainage systems are installed in arid-region soil to control water-table problems or excessive soil wetness, to remove accumulated salts (leaching), and to prevent excess accumulation of salts in the root zone. Such leaching is accomplished by applying water beyond crop needs so that water and salts may be flushed out.

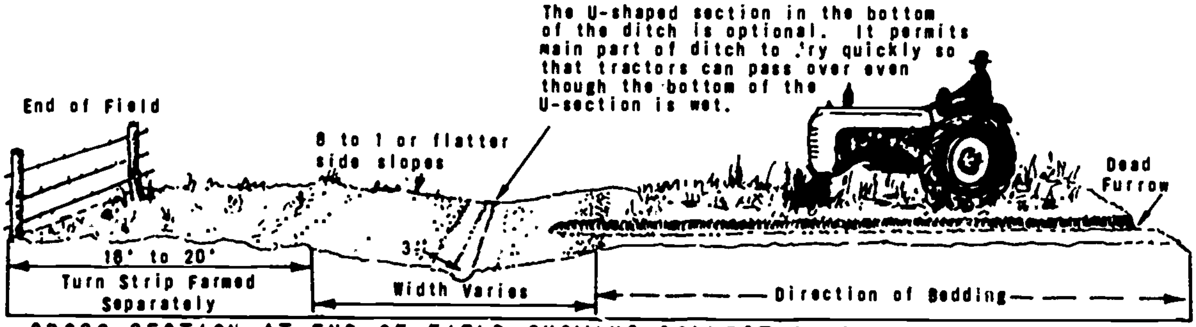
The amount of water required for preventing salinization may vary from 10 to 30 percent of that used for irrigating a crop. When soils need to be reclaimed, however, substantially larger amounts of water may be needed. As much as 3 or 4 feet of water may need to be applied for such reclamation leaching.

The leach water moves downward through the soil profile, taking the salts with it. Some of this water and some of the salts dissolved in it will be removed from the field through the drainage system. An adequate subsurface drainage system is a prerequisite for a leaching program on saline soils.

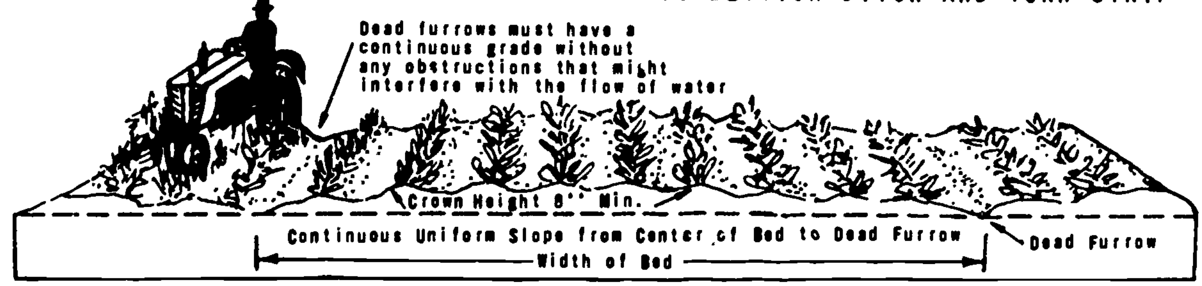
Figure 7-12—Maintaining drainage ditches is important for proper conveyance of excess water. Here, a slope mower with a hydraulic rotary blade cuts grass in Sussex County, Delaware.

Figure 7-13—Water hyacinth impedes free flow of water in Indian River County, Florida.





CROSS SECTION AT END OF FIELD SHOWING COLLECTION DITCH AND TURN STRIP



CROSS SECTION OF BED SHOWING CROWN EFFECT AND PROPER SPACING OF CROP ROWS

Figure 7-14—By bedding flat cropland, farmers can quickly channel excess water to field drains.

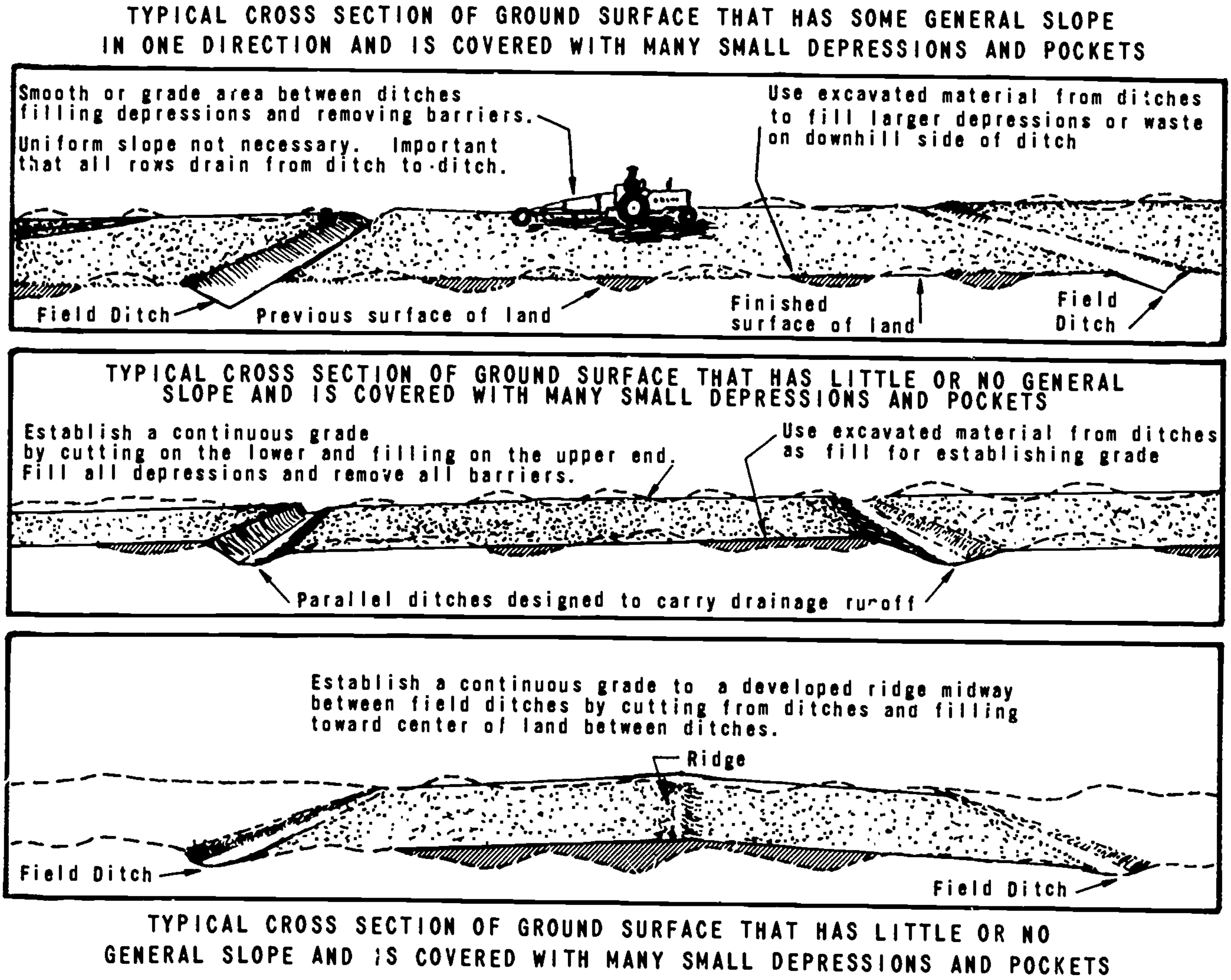


Figure 7-15—Land surface irregularities can be overcome by the procedures shown above.

Figure 7-16—A tractor pulls a land plane to precision-grade a sugarcane field in Edgard, Louisiana.

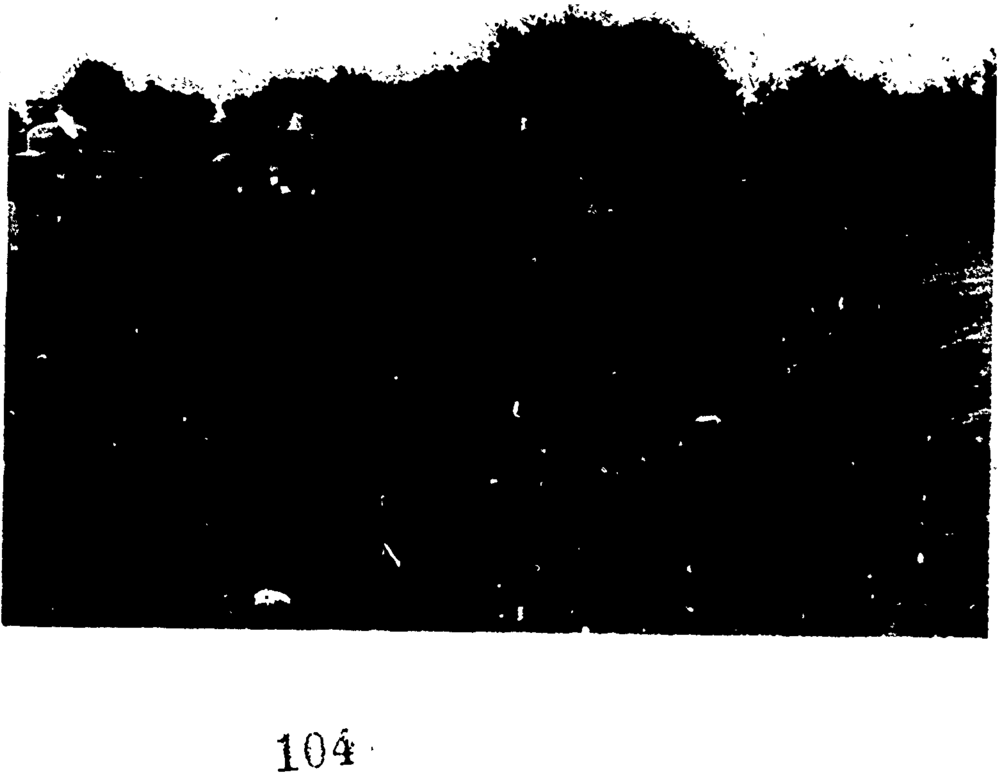
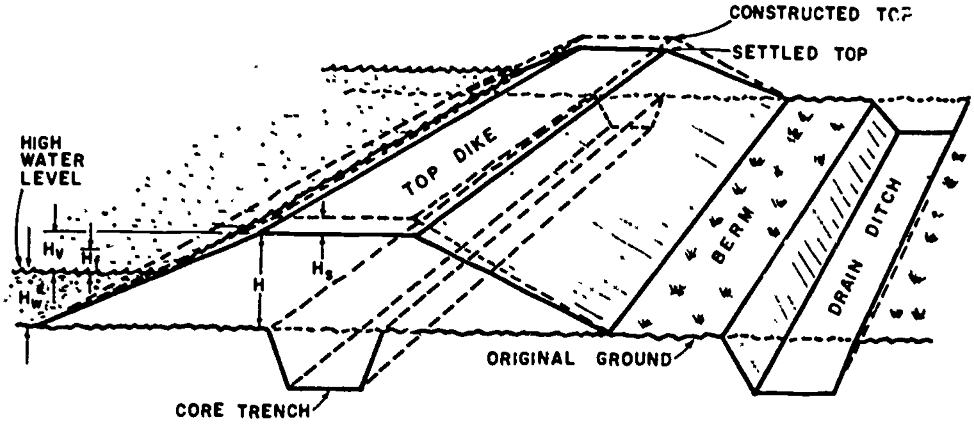


Figure 7-17—A typical dike section.



Land Protection Practices

Various practices can protect land after a drainage system has been installed. Although these practices are not a part of the drainage system, they may be critical to protect the land and enhance the value of the drainage component.

Conservation tillage is a cultural practice which keeps crop residues on the field surface to protect the soil from wind or water erosion. Without this protection, soil surfaces and ditch banks may erode or previously wet soils may dry and suffer wind erosion. Many soil conservation tillage systems require adequate drainage to be fully effective. As higher percentages of rainfall move through the soil profile, such soils require drainage intensities greater than previously used with conventional tillage.

Windbreaks are often needed in large, open areas of drained land, especially on organic soils where they may be closely spaced to prevent severe wind erosion. Windbreaks may be either a strip of perennial or annual vegetation or a constructed barrier or fence placed across the direction of prevailing wind.

Flooding of farmland by surface waters may limit the effectiveness of a drainage system or increase the cost of the system needed to remove the additional flood water. Diversions that intercept flows from higher land and divert them to a safe outlet are usually channels with a supporting ridge on the lower side built across the slope on a nonerosive grade.

Dikes usually protect drained areas by preventing flooding from adjacent streams (fig. 7-17). Caution must be used in the design of dikes to avoid damage from flooding of other areas by unduly restricting or increasing natural stream flows.

Drainage System Combinations

The drainage system is an integral part of a water management system in the farm operation. For example, subsurface field drains provide an essential element of irrigation water management to control salinity in arid and semiarid regions.

Water table control systems that use either a surface or subsurface drainage system to supply irrigation water during dry periods are also becoming more prevalent in humid regions (fig. 7-18). They are used mostly on porous high water-table soils or on organic soils, and are likely to expand to other soils. Computerized simulation and design procedures particularly suit these more complex systems. The

Figure 7-18—Carrots flourish on this 400-acre tract of organic soils in Highlands, Florida, because water control ditches at 100-foot intervals both drain and irrigate.

Figure 7-19—A contracting officer in the Celeryville Conservancy District, Ohio, observes water table control while perched on a Fabridam in the Marsh Run Watershed; these rubberized fabric dams automatically inflate and deflate.

water-table control systems provide an outstanding opportunity for improving water and energy conservation on farms in many watershed areas (fig. 7-19). Generally, costs are considerably lower than the combined cost of separate drainage and irrigation systems.

Waste-water disposal systems often require subsurface drainage to provide time and space in the soil profile for natural biodegradation to take place. The subsurface drainage system also provides an opportunity to monitor the water-quality condition after movement through surface soils and before discharge into public waters.

Detailed design procedures for drainage systems are included in USDA'S SCS Engineering *Field Manual*, drainage guides, technical guides, and in the *National Engineering Handbook*, section 16 titled "Drainage of Agricultural Land." These documents can be examined in SCS field offices.

References

American Society of Agricultural Engineers, Surface Drainage Committee (SW 233). 1979. "Design and Construction of Surface Drainage Systems on Farms in Humid Areas," Engineering *Practices*. ASAE EP 302.2.

Ochs, W. J., W. R. Johnston, and others. 1980. "Drainage Requirements and Systems," *Design and Operation of Farm Irrigation Systems* (ed. Marvin Jensen). Monograph No. 3, Am. Soc. Agri. Eng., St. Joseph, Mich.

U.S. Department of Agriculture, Soil Conservation Service. 1971. "Drainage of Agricultural Land," *National Engineering Handbook*, section 16.

Chapter 8

Planning Farm and Project Drainage

Thomas C. G. Hodges and Douglas A. Christensen
Soil Conservation Service, USDA
Fort Worth, Texas

Because drainage usually involves substantial long-term investments of capital and other costs, the proper planning of farm and project drainage systems is essential. Successful farm drainage results in higher average and more stable farm income since well-planned drainage systems ensure a more efficient use of resources.

General Design and Economic Considerations

Soils needing improved drainage usually have the greatest wetness problems during spring and fall. which cause planting and harvesting delays that reduce crop yields. Even when crops are planted on time, a high water table restricts root development and plant growth. As drier summer months approach, the water table level drops quickly and plants become susceptible to drought stress because the root system cannot reach the water table level.

Plants tend to respond to improved drainage quickly, so crop yields usually jump the first year after drainage systems are installed. However, a number of years of improved yields are necessary to recover the initial investment. Farm drainage systems sometimes cost as much as or more than the land itself, especially when major outlet systems are needed. Further, regular maintenance expenditures are necessary to keep subsurface and surface drainage systems functioning well.

Farm drainage systems cannot function properly without adequate outlets or disposal works such as streams, rivers, bays, or pumps. Drainage improvement may be as minor as installing a short field drain to improve a wet spot on a farm field, or as complex as enlarging major channels and tributaries with tile or open drainage ditches to remove excess water from entire fields. The areas to be drained may range from less than an acre to thousands of acres.

Drainage improvements are technically complex and must meet proper design standards to be effective. In many cases, entire communities help plan and develop adequate drainage systems. Besides improving farm systems, existing farm drain outlet systems may need to be enlarged and deepened. Major systems may require that highway and railroad culverts and bridges be reorganized or modified. Many States have passed laws that permit drainage districts or similar organizations to develop, plan, and install appropriate drainage works and systems (see chapter 10).

Proper drainage systems can improve the local economy and environment of entire communities, with initial farm benefits spreading to agribusinesses and financial institutions.

In planning farm and project drainage systems, existing problems must be correctly identified before appropriate solutions can be designed. Some problems involve excessive water seepage from adjacent hillsides. Other areas have pothole problems where surface water is trapped in dish-shaped depressions. Irrigation may aggravate drainage problems when excess runoff and percolated water must be carried away. In delta and coastal areas, drainage is essential to carry floodwaters caused by heavy rainfall from flatlands with fine textured soils, or from areas with perched water tables where water cannot move freely.

Various drainage problems and the damages they cause are prime economic considerations in the design of drainage systems. These damages on cropland are reflected in increases in production costs and reduced crop yields from excessive wetness. The design of the system takes into account cost efficiency as well as maintenance of crop productivity and farm income. Important design factors are proper ditch, tile, or channel depth and capacity, road culvert and bridge openings, geologic conditions, and downstream outlets which receive runoff water while minimally affecting environmental and economic resources.

In a sound drainage design, installation and maintenance costs need to be balanced to ensure that the system will function properly through its expected lifespan. Careful operation and maintenance of the system are necessary to attain the expected beneficial effects that justify the investment.

Drainage engineers have worked to balance field drain depth and capacity to fit the needs of crop production. As farming practices change, design criteria also change. For example, when farming progressed from animal power to machine power, better drainage became necessary to support heavy equipment and provide proper traction. Tile or other pipe drains were buried deeper to avoid being damaged by heavy equipment, and surface drains were designed to permit crossing by large machinery.

Drainage systems must remove large volumes of water quickly for plant survival and steady crop growth. Plant requirements dictate the degree of drainage that is justified. Field crops can usually sustain wetter conditions than some specialty crops such as vegetables. Removing runoff from moderate rainfall episodes may suffice for field crops, but for vegetable crops, quick removal may be necessary. SCS has established design standards for various resource areas and cropping systems within each State.

Total water management requires sophisticated design and operation; this provides better use of resources and higher crop yields. Subirrigation helps moderate water-table fluctuations during low-water periods from spring to fall. Engineers channel and tile grade and install water control devices in onfarm systems [illegible] channels. Such intensive water manag[illegible] more maintenance to monitor soil [illegible], and runoff conditions and to opera[illegible]es. Water control structures are inst[illegible]rm drainage systems to reduce drainage when soils are dry. Sometimes farmers pump water into the blocked off channels to increase flow into the fields. Vegetation control is easier because water in the ditches inhibits plant growth.

Planning Farm Drainage

As a principle, the net economic benefit from improved onfarm drainage is the amount by which net income with the drainage system exceeds net income without the system. The net income change may come from increased crop production, reduced production costs, or both. Net income is the computed value of production less all associated costs of production, including cost of the drainage system itself. The latter also includes the value of any land required by ditches or other improvements. The gross value of crop production is the crop yield times the price per unit of yield. Crop production costs include the cost of seed, labor, power, water, chemicals, and other materials plus prorated land, machinery, or management charges. Crop production costs with and without drainage systems may be obtained from nearby farmers and local agricultural leaders.

Feasibility Calculations

Benefit-cost ratios are a relative measure of annual benefits of a proposed improvement compared with its costs. Average annual installation cost is determined by amortizing the initial cost of a drainage system at a current interest or other specified rate over the life of the investment. In SCS, farm drainage systems are usually amortized over an expected life of 25 years and project systems for 50 years, assuming reasonable maintenance. The annual cost of operation and maintenance, plus any other recurring costs, are then added to amortized installation costs to get total annual costs. The average benefit-cost ratio, total annual benefit divided by total annual cost, shows the benefits expected for each dollar of cost.

Many farmers encounter times when equipment gets stuck in wet areas during farming operations, resulting in lost time or the need to keep an extra tractor nearby to pull the equipment out. Crops frequently need to be replanted, requiring more production inputs. Also, farmers may need to wait until the ground freezes before they can harvest crops. If the ground does not freeze, the crop may be lost if it is wet at harvesttime. The extent to which these drainage problems are reduced or eliminated is a clear economic benefit of drainage systems.

Reliable information about changes in crop yield with and without drainage is not as available as that for production inputs. Farmers' experience is one good source, although many do not keep individual field records, and yield differences are more varied than production inputs. Information from farmers, supplemented by data from research and agricultural leaders, can be used to estimate expected changes in yields and costs under various conditions. Computer simulation models are also used for estimating yield differentials.

Optimum Drainage Design

Drainage design decisions can be guided more efficiently by referring to research than by making field-by-field calculations. Farm operators can make a partial comparison of open or surface versus subsurface drainage themselves when the soils and other conditions permit either method. The costs of each method and effects of open drains or reducing land in production can also be determined fairly easily. However, data are not always available for assessing the effect of alternative degrees of drainage on crop yields.

Researchers have more access to data, methods, and computer models to determine optimum drain spacings and types of drainage. For example, USDA scientists have developed an "Erosion-Productivity Impact Calculator" (EPIC), a comprehensive mathematical model for determining the relationship between rates of water-induced soil erosion and soil productivity in different U.S. regions (Williams and others, 1983). Drainage conditions are one element of the hydrology submodel of EPIC, along with rainfall, runoff, evapotranspiration, percolation, lateral subsurface water flow, and irrigation. Other submodels consider weather, erosion, nutrients, soil temperature, tillage practices, and economics. The EPIC model thus permits a simultaneous analysis of how crop yields, gross farm income, production costs, and net income may be affected by numerous physical and economic variables, including drainage.

A planning and optimizing model more specific to questions of drainage system design is DRAINMOD, developed by agricultural engineers at North Carolina State University. This model encompasses multicomponent water management systems involving surface drainage, subsurface drainage, subirrigation, and sprinkler irrigation. It considers the effects of alternative system designs involving different depths and spacing of subsurface drains on crop yields, production and investment costs, and farm profits. (See the Skaggs segment for a detailed description and illustrated uses of DRAINMOD.)

A third model, combining a simulation model with an optimizing routine to minimize costs, has been developed at Colorado State University (Durnford, 1982). Its object is to identify economically optimum drainage systems using open and closed relief drainage systems for arid irrigated areas. The drains facilitate proper leaching, thus limiting the net buildup of the water table and reducing the accumulation of salts in the root zone, especially if the ground water is saline. Durnford's model is adaptable to planning irrigation drainage in various regions of the United States and other nations. One application has been to the Beni Magdoul area in Middle Egypt.

Economic evaluations for project systems are basically similar to those used for planning farm drainage but naturally require a broader perspective. Yield and production input data need to be representative, not site-specific. Alternative drainage scenarios considering costs, production inputs, and outputs are developed for each different project area. Net returns with and without improved drainage are compared to determine net benefits. The costs of the project and associated improvements are compared with all benefits in determining net benefits and benefit-cost ratios.

A final point to mention for farm drainage planning is that it often involves only one or a few decisionmakers—the owner, manager, or renter. They make capital investments considering their individual interests in the farm and its operations, accounting for needs, costs, and effects. Detailed soil, cropping system, and engineering data are used to determine the type and extent of the problems and needed treatment measures. All decisionmakers fit the cost and expected benefits of drainage systems into their overall financial or management plans.

Planning Project Drainage

The proper functioning of farm drainage systems depends upon proper outlets. When several farms have inadequate outlets, farmers need to plan a satisfactory outlet system together. Project drainage plans involve much the same basic information as farm plans, but because many farmers and other interests can be involved, quick agreements are frequently difficult.

Information Needs

As the characteristics of decisionmakers in project planning are diverse, inventory data can be more general and less site-specific. Project planning must also consider onfarm drainage needs. Reliable soils and crop system data are necessary for both levels of planning.

Engineering data ordinarily deal more with the hydraulics of stream systems rather than with single streams or specific farm situations. Engineers estimate costs for the main and tributary channelwork providing outlets for farm drainage. They study alternate channel sizes to determine which will produce the most net benefits. Tributaries are evaluated separately to determine if improvements within them are justified in terms of producing net benefits. Instream water control devices are examined for any possible complementary irrigation benefits.

Environmental considerations also become more critical in project planning because outlet improvements may disturb environmental resources, especially if they impinge on fish and wildlife habitat. SCS and the Fish and Wildlife Service (FWS) have jointly developed and adopted uniform Channel Modification Guidelines to assist their personnel in identifying when and where channel modifications may be used as a technique for implementing drainage and other land and water resource projects. These standards require efforts to maintain or restore streams, riparian vegetation, and wetlands as viable ecosystems for fish and wildlife.

Moving water in main and tributary streams and channels to areas where discharge water can move freely without causing downstream damages can be a different design problem. Proper planning of project drainage must include the analyses of floodwater from high direct precipitation which must be carried by the project systems. This is one respect in which project drainage is more complex than onfarm drainage. Road and railroad bridges and culverts may be modified, and utilities may need to be altered or moved. Drainage water from one farm is channeled across another farm, sometimes from one county to another county, and sometimes from one State to another.

SCS provides technical assistance for farm and project drainage planning, which must conform to State and local laws and follow approval standards and specifications. SCS project drainage assistance is authorized under the Watershed Protection and Flood Prevention Act (P.L. 83-566), which calls for a comprehensive approach toward solving flood protection, water supply, drainage, and other watershed problems. SCS investigates hydraulic systems, hydrologic effects downstream, economic and social impacts, and project feasibility. Studies are made to evaluate environmental resources and their protection. Similar studies are undertaken by SCS in Resource Conservation and Development (RC&D) Projects involving drainage.

Cooperation in Drainage Planning

The Marshyhope Creek Watershed (100,600 acres) spanning the Delaware-Maryland boundary is a good example of how diverse environmental, political, and economic interests can be brought together to solve serious resource management problems. The project sponsors include the Delaware State Soil Conservation Commission, the Caroline County (Md.) Commissioners, the Caroline Soil Conservation District, and the town of Federalsburg, Md. The headwaters are in Kent County, Del. The main channel flows southwestwardly into Sussex County, Del., then across the State border into Caroline County, and outlets at Federalsburg.

For more than 30 years, Kent County farmers had tried to develop a drainage outlet system but had faced political and legal opposition by other municipal, county, and State interests. Federalsburg, subject to floodwater damage during large storms, feared additional damages if major upstream channelworks were installed. Planning investigations revealed that 25 subareas in the watershed needed channelwork. Each had adequate drainage outlets above Federalsburg. Hydrologic studies showed that 24 of the 25 subareas could be drained without additional damage to Federalsburg. The largest subarea that drained all of the Kent County portion of the watershed would cause a slight increase in flood stage at Federalsburg (in the event of a 1-percent chance flood event). Such an event has a statistical probability of recurring once in 100 years. It may actually recur more or less frequently than this.

Federalsburg rejected proposals for flood protection other than channel enlargement to carry induced flood flows caused by the upstream work. The final watershed plan included channelwork in the 25 subareas and through Federalsburg. State and Federal agencies also helped protect fish habitats in Smithville Lake, Caroline County.

After reviewing several alternative solutions to flood problems, Federalsburg agreed to the enlargement of the channel through town to carry increased flows (assuming a storm equal to the 1935 storm) caused by channelwork upstream. The sponsors and fish and wildlife interests agreed to include a filter strip and sediment trap above Smithville Lake. The cost of the Federalsburg channel was included as part of the cost of the work in the subarea, mostly upstream, because hydrologic studies indicated that this area was the primary source of the Smithville subarea channel cost.

The general watershed plan was completed January 1964 and subsequently approved for construction by Congress. It included 468 miles of channelwork in 25 subareas and 9,000 feet of channel enlargement in Federalsburg. The sediment control devices were included as part of the channelwork in the Smithville subarea.

Drainage in Irrigation Project Planning

The protection of irrigated soils from excessive accumulation of water (waterlogging) and salts is a major initial consideration in planning irrigation projects. Historic and probable declines in the productivity of irrigated soils in arid regions can be attributed to soil properties that inhibit downward drainage, high rates of evapotranspiration, and poor water quality. Proper recognition of these problems and alternatives for preventing them with artificial drainage systems is indispensable to the project planning process. Correcting them later can be expected to be much more costly than initial avoidance. Moreover, the adverse effects of rising water tables and soil salinity on irrigated land are not just long-term problems; they can become serious after only a few irrigation seasons. The project's economic justification weakens in two major respects: additional capital is needed to solve the problem and/or losses in productivity mean reduced benefits.

Strzepek, Wilson, and Marks (1982) indicate that drainage planning for irrigated areas involves three interacting planning levels: the overall feasibility determination level (general economic justification and essential irrigation and drainage facilities), the infrastructural or collector drain level, and the field drain level. The field drains (surface or buried) control soil water conditions, while the collectors remove the drained water to the main drainage channels. Strzepek and coworkers found, for example, that the location, size, and type of collectors are economically interrelated with the spacing, size, and type of field drains. The design problem is to determine the particular characteristics of collectors and field drains that will minimize total cost of providing required drainage, considering locational variations in soil permeability, uncertain crop yields, cropping patterns, and other factors.

Drainage planning for irrigated areas will increasingly require a fourth planning level and cost element—one of designing project drainage systems and arrangements that minimize or eliminate the adverse effects of chemical-laden waters on crops, wildlife, and human habitats, either within project areas or on offsite areas. In this larger social context, the total project cost would be the sum of within-project investment and operating costs plus offsite damages or disbenefits. Adverse effects and alternatives for minimizing them are considered at more length in the next segment.

References

Durnford, D. 1982. *Optimal Drain Design: An Incremental Net Benefit Approach.* Ph.D. dissertation. Colorado State Univ., Fort Collins.

Strzepek, Kenneth M., John L. Wilson, and David H. Marks. 1982. *Planning and Design of Agricultural Drainage Under Uncertainty: A Dynamic Multi-Level Approach.* Rpt. No. 21, Dept of Civil Engineering, Massachusetts Institute of Technology, Cambridge.

U.S. Department of Agriculture, Soil Conservation Service and Forest Service. 1964. *Watershed Work Plan for the Marshyhope Creek Watershed.* (Cooperative report with the Delaware State Soil Conservation Commission and local sponsors in Caroline County, Dorchester County, and the town of Federalsburg, Maryland.)

Williams, J. R., K. G. Renard, and P. T. Dyke. 1983. "EPIC: A New Method for Assessing Erosion's Effect on Productivity," *Journal of Soil and Water Conservation.* Vol. 38, No. 5, pp. 381-383.

Chapter 9

Drainage for Irrigation: Managing Soil Salinity and Drain-Water Quality

Glenn J. Hoffman
Agricultural Research Service, USDA
Fresno, California

Jan van Schilfgaarde
Agricultural Research Service
Fort Collins, Colorado

Salinity control and the removal of excess water are the major objectives of drainage in irrigated agriculture. These objectives are related. Excess water may induce high water tables which, if saline, contribute to the salination of soils. In humid regions, salinity control is of limited concern because rainwater is almost free of dissolved salts; thus, excess salinity occurs in rainfed areas where there is brine spillage, waste disposal, excess fertilization, or seawater intrusion in coastal regions. As supplemental irrigation increases in humid regions, soil salinity and water-quality problems like those in arid regions may become more prevalent.

Elements in Salinity Control

The key to salinity control is a net downward movement of soil water through the root zone. All soils and irrigation waters contain a mixture of soluble salts, with the concentration of these salts in the soil solution usually higher than that in the applied water. This increase in salinity results from plant transpiration and evaporation from the soil surface, which selectively remove water, thus concentrating the salts in the remaining soil solution. To prevent soil salinity from reaching harmful levels, one must drain (leach) a portion of this concentrated soil solution below the crop root zone. Salt will be leached from the soil whenever water applications exceed evapotranspiration, provided soil infiltration and drainage rates are adequate. Even in well-managed, high-yielding fields, however, the soil water may be several times more saline than the irrigation water. With insufficient leaching, this ratio can easily increase at least 10 times and damage crops. The amount of leaching required depends on the quality of the irrigation water, the crop grown, and the uniformity of irrigation. Subsurface drainage is essential for sustained irrigated agriculture where salinity is a hazard.

In areas where the ground water is deep or nonexistent, salts accumulated in the root zone can be forced downward by irrigating if the substrata are permeable. Of course, this leaching process can continue only until the level of the ground water extends up into the crop root zone. In some irrigated areas, rainfall is sufficient to leach the salts below the root zone. In this case, extra irrigation water for leaching is not required and in fact will cause the water table to rise unnecessarily. Without proper drainage, the water table may remain in the root zone too long and reduce crop productivity.

Leaching

The amount of leaching required to maintain a viable irrigated agriculture depends upon several factors: the salt content of the irrigation water, soil, and ground water; the salt tolerance of the crop; climatic conditions; and soil and water management. If leaching is inadequate, harmful salt accumulations can develop within a few cropping seasons. The fraction of the applied water that must pass through the root zone to prevent harmful salt accumulations in the soil is the leaching requirement. Once salts have accumulated to the maximum tolerable limit for the crop under a given set of conditions, any added salt from subsequent irrigations must be balanced by a similar amount removed by leaching to prevent a loss in yield.

The optimum management strategy is to apply no more water than is necessary for full crop production and leaching of salts. This leaching requirement has been established for irrigation water of various levels of salinity and for irrigated crops of major importance (see fig. 9-1 and Hoffman, 1985). The salinity level of the applied water can be estimated by multiplying the salt concentration of the irrigation water times the amount of irrigation water applied, and then dividing this product by the sum of irrigation and rainfall minus surface runoff.[1] This is shown as follows:

$$C_a = (C_i I) / (I + P - R),$$

where C_a is the average salinity of the applied water that enters the root zone, C_i is the salinity of the irrigation water (I), P is precipitation, and R is surface runoff. The amount of salt the crop can tolerate in the soil profile is the salt tolerance threshold (Maas and Hoffman, 1977). The threshold (C_t) is the maximum soil salinity permitted without crop yield reduction.

Table 9-1 shows threshold values for a number of crops. As an example, if farmers use Colorado River water for irrigation (C_i = 1.3 dS/m) and no rain falls, a tomato crop (C_t = 2.5 dS/m) would require an additional portion of water to be applied above that needed for evapotranspiration. If rainfall was 250 mm, the depth of irrigation with Colorado River water was 600 mm, and about 100 mm of the applied water was surface runoff, then the average salinity of the applied water would be 1.1 dS/m (according to the equation) and the leaching requirement (L_r) for tomatoes would be 0.08 (fig. 9-1). This means that 60 mm of the net amount of water applied must drain below the root zone to avoid losses in tomato yields from excess salinity.

Additional Drainage

Not all the water requiring removal by drainage may originate from onfarm irrigation. In fact, a significant part of the water input to the drainage system often results from seepage from irrigation

Table 9-1—Salt tolerance of crops as a function of the electrical conductivity of the soil saturation extract (C), where relative yield (Y) in percent = $100 - S (C - C_t)$, $C \geq C_t$.

Crop	Salt tolerance threshold (A) (C_t)[1]	Percent yield decline (B) (S)[2]	Qualitative salt tolerance ratings[3]
	dS/m[4]	*Percent/(dS/m)*	
Alfalfa	2.0	7.3	MS
Almond	1.5	19.0	S
Apricot	1.6	24.0	S
Barley	8.0	5.0	T
Bean	1.0	19.0	S
Beet, red	4.0	9.0	MT
Broccoli	2.8	9.2	MS
Cabbage	1.8	9.7	MS
Clover, red	1.5	12.0	MS
Corn	1.7	12.0	MS
Carrot	1.0	14.0	S
Cotton	7.7	5.2	T
Cowpea	1.3	14.0	MS
Cucumber	2.5	13.0	MS
Date palm	4.0	3.6	T
Grape	1.5	9.6	MS
Grapefruit	1.8	16.0	S
Lettuce	1.3	13.0	MS
Onion	1.2	16.0	S
Orange	1.7	16.0	S
Peach	1.7	21.0	S
Peanut	3.2	29.0	MS
Pepper	1.5	14.0	MS
Plum	1.5	18.0	S
Potato	1.7	12.0	MS
Radish	1.2	13.0	MS
Sorghum	6.8	16.0	MT
Soybean	5.0	20.0	MT
Spinach	2.0	7.6	MS
Strawberry	1.0	33.0	S
Sugar beet	7.0	5.9	T
Sugarcane	1.7	5.9	MS
Sweetpotato	1.5	11.0	MS
Tomato	2.5	9.9	MS
Wheat	6.0	7.1	MT

[1]Salt tolerance threshold is the mean soil salinity at initial yield decline.

[2]Percent yield decline is the rate of yield reduction per unit increase in salinity beyond the threshold.

[3]Qualitative salt tolerance ratings are sensitive (S), moderately sensitive (MS), moderately tolerant (MT), and tolerant (T).

[4]dS/m = decisiemens per meter = 1 millimho per cm, referenced to 25° C.

Source: Haas and Hoffman, 1977.

---

[1] For convenience, salt concentration in water is normally measured as the electrical conductivity of the water and reported in units of decisiemens per meter (dS/m). The units of dS/m are numerically equal to millimhos per centimeter (mmho/cm).

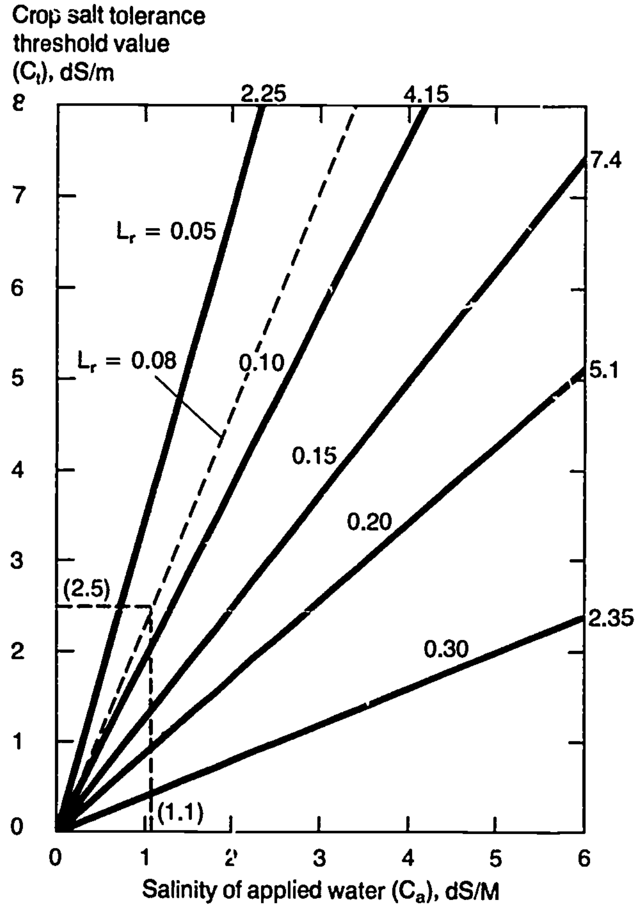


Figure 9-1—Solving for the leaching requirement from the salinity of the applied water and the salt tolerance threshold value for the crop.

canals or from areas irrigated some distance from the area under consideration, such as the desert area west of the Nile Delta (Kirkham and Prunty, 1977). However, water may leave the area through avenues other than the drains. When Chang and others (1983) attempted to match their computed water table heights with measured ones for various fields in California, they obtained their best match when the assumed seepage rate was several times the rate of water removal through the drains.

The dominance of this deep seepage called attention to the important difference between the natural drainage rate and the rate of drainage through installed systems. When a new irrigation project is contemplated for an area, the natural water table may be tens of meters deep, making the potential rate of water removal from such a region difficult to estimate. The requirements of any drainage system, however, are obviously reduced by the amount of natural drainage. If water supplies are relatively expensive, and the spatial variation of soils, terrain, and water applications are minimal, applying less leaching water permits crop yields to drop below the maximum achievable yields, which may be an economic optimal decision. The economic criteria for optimal water application for leaching is to apply the amount of water where the cost of the last unit of water applied equals the value of the additional crop yield. If maximum possible yield is sought, the cost of the last unit of water applied may exceed the value of the additional yield, and profits may not be maximized (Fitz and others, 1980).

Drain Depth

Relatively deep drains are customary in irrigated areas with arid climates. The U.S. Bureau of Reclamation, for example, typically specifies depths between 2 and 3 meters. Such deep installations are costly, and the question arises whether they are needed. Doering and others (1982) concluded from studies in North Dakota that water table depths of approximately 1 meter provided maximum crop yield with minimal supplemental irrigation for several crops. In an evaluation of extensive field data from Pakistan, Oosterbaan (1982) found that the water table depth required to prevent reduced yields of sorghum and cotton was 60 centimeters. Such data support the contention (based on reasoning with limited evidence) that the drain depth typically recommended may be deeper than necessary. Recent changes in installation techniques may support this contention. The equipment needed to install drains to a depth of 1.5 meters by trenching is less cumbersome and less expensive than that needed for greater depths. Trenchless installations may be practical at the shallower depths with significant cost reduction.

Drain-Water Disposal

Besides the benefits to the land being drained, one needs to consider disposal of drainage water. This can be a matter of serious concern and high cost as illustrated by the as yet unresolved drainage problems in California's San Joaquin Valley. An excellent onfarm drainage system has no value unless an adequate outlet exists for drainage water disposal. Depending on its quality, drainage water may be a total or partial substitute source of irrigation water.

Drainage waters collected by tile lines and ditches or removed by the pumping of wells can, in some cases, be disposed of in ways that do not reduce the quality of surface and ground waters. For example, the highly saline drainage water collected in ditches from the San Juan irrigation project in Mexico and formerly discharged to the Rio Grande River is now being conveyed directly to the Gulf of Mexico in a separate channel. Also, a special channel has been constructed for conveying the highly saline, drainage water from the Wellton-Mohawk irrigation project in southwestern Arizona to a point on the Colorado River below the last place where water is taken from the river for beneficial use. Conveyance to sumps for evaporation or reclamation by desalination are other possibilities for disposal. In many cases, however, the disposal of drainage water in a way that does not harm stream and ground water is not practical or possible. There may be several reasons for this: the cost is prohibitive; the drainage water is neither collected nor pumped but moves by underground flow to streams and ground-water basins; or the quality of the drainage water, though somewhat diminished, is such that it still has value for irrigation or other purposes.

Where the flow of agriculture drainage water to bodies of surface and ground water cannot be eliminated, quality degradation can be reduced by minimizing the amount of salt leaving the root zone. That amount can be reduced by decreasing evapotranspiration or by removing accumulated salts in the smallest volume of water compatible with the leaching requirement. Simultaneously reducing evapotranspiration and the amount of water applied decreases the amount of salt that must be removed from the drainage water. This can be achieved in a variety of ways, such as using closed water conveyance systems, eliminating nonbeneficial vegetation, and growing crops with lower evapotranspiration requirements as a consequence of the season or length of their growth period. Removal of excess dissolved salts consistent with the leaching requirement maximizes the salt concentration of the soil solution and drainage waters, and helps produce harmless, slightly soluble salts, such as lime and gypsum, in the soil. It also minimizes the solution of soil minerals and fossil salt deposits which commonly occur in geologic materials below the root zone.

Unusually high and nonuniform soil permeability, and an excessive and nonuniform application of irrigation water are the chief causes of excessive leaching. Minimizing the amount of salt leaving the root zone in drainage water is, therefore, strongly influenced by irrigation efficiency. The leaching of dissolved salts is more efficient and the problems of excessively high and nonuniform soil permeability are reduced when applied water moves through the soil by unsaturated flow. Irrigation by sprinkler and trickle systems permits uniform and controlled rates of water application.

Agricultural drainage waters sometimes contain nutrients and chemicals in sufficient concentrations to help or harm users of the water or the aquatic environment. Aside from the salts associated with salinity, subsurface drainage may contain nitrates and trace elements that harm the environment.

Nitrogen in drainage effluent is normally in the form of nitrate because it is not adsorbed on soil particles. After reaching surface waters, these nitrates may contribute to eutrophication (a situation where minerals and certain nutrients rob water of oxygen, and thus favor plants over animal life). In high concentrations, nitrates may cause or at least contribute to methemoglobinemia (a poisoning of the blood) in infants and certain disorders in ruminant animals. High nitrate concentrations in subsurface drainage can originate from a number of sources: excessive fertilizer, geologic deposits, natural organic matter, decomposition of human or animal wastes, or possibly by deep percolation of nitrates because of a lack of complete efficiency of the root system in absorption. The management goal in drainage and fertilizer practice is to minimize the nitrate concentration of drainage waters.

Minimizing Adverse Effects

In recent years, experts have become increasingly concerned with the significance of the degradation of irrigation return flows due to leaching of trace elements. These elements have accumulated in the soils, and the drainage waters have injured fish and wildlife and could potentially affect human health. As an example, the west side of the San Joaquin Valley has serious drainage and salt management problems because the disposed drainage water is damaging valley waterfowl, agricultural lands, and the San Joaquin River. The original plan called for the drainage water to be diverted from the valley through the San Luis Drain to the Sacramento-San Joaquin Delta, and then into the San Francisco Bay and the Pacific Ocean. Construction of the drain began but it was not completed because of environmentally based objections and lack of construction funds in the mid-1970's. As a result, no acceptable receiving water was identified, and most drainage was discharged through the incomplete drain to the Kesterson National Wildlife Refuge, where it was expected to evaporate. Deformities in waterfowl observed at Kesterson have called attention to high levels of selenium and other trace metals, such as boron, in drainage water from the valley.

Although continued operation of the current system appears unacceptable, shutting down the system appears equally untenable. Estimates indicate that possibly 500,000 acres (200,000 hectares) of agricultural land could be lost over the next 30 years if drainage effluent containing salt or trace elements is not controlled, a loss that could cost the California economy $1.5 billion per year. The Department of the Interior and the State of California have initiated the San Joaquin Valley Drainage Program to identify the magnitude and sources of the problem; the potential alternative bodies of receiving water; and options (including modification of agricultural practices) available for resolving the issue without unacceptable effects on the environment, agriculture, and the economy.

The potential damage from trace elements in drainage effluent is illustrated in table 9-2, where typical concentrations of a number of trace elements in the San Luis drain are compared with the maximum recommended concentrations for irrigating sensitive crops (Pratt, 1973). The criteria on which these recommendations are based include: toxicities in crops grown in nutrient solutions; short-term soil culture experiments in which the amount of an element required to produce toxicities was observed; and soil-plant-animal relationships for elements that are toxic to animals through the food chain at levels lower than those that produce toxicities in plants. The levels of boron and selenium are of paramount concern. This points up how the concentrations of trace elements in drainage effluent is the most pressing new issue in drainage for irrigated agriculture.

Table 9-2—Recommended maximum concentration of trace elements in waters used to irrigate sensitive crops on soils with low capacity to retain these elements in unavailable forms compared with typical values from the San Luis drain

Element	Typical concentrations in San Luis drain[1]	Recommended concentration of irrigation[2]
	mg/m^3, (ppb)	*mg/m^3, (ppb)*
Aluminum	100	5,000
Arsenic	10	100
Boron	14,000	750
Cadmium	10	10
Chromium	18	100
Copper	10	200
Iron	80	5,000
Lead	10	5,000
Lithium	—	2,500[3]
Molybdenum	—	10
Nickel	10	200
Selenium	310	20
Zinc	10	2,000

— = not available.

[1] Values reported by California Department of Water Resources during first half of 1984 near Mendota, Calif.

[2] Recommendations from Pratt, 1973.

[3] Recommended maximum concentration for irrigated citrus in 75 mg/m^3.

References

Chang, A. C., R. W. Skaggs, L. F. Hermsmeier, and W. R. Johnston. 1983. *Evaluation of a Water Management Model for Irrigated Agriculture.* Transactions of the ASAE. Vol. 26, pp. 412-418, 422.

Doering, E. J., L. C. Benz, and G. I. Reichman. 1982. *Shallow-water-table Concept for Drainage Design in Semi-arid and Sub-humid Regions.* Proceedings of Fourth National ASAE Drainage Symposium, Chicago, Ill., December 13-14, 1982. pp. 34-41.

Fitz, Joseph C., Gerald L. Horner, and J. Herbert Snyder. 1980. *The Economic Feasibility of Installing Subsurface Tile Drainage in the Panoche Water District, San Joaquin Valley, California.* University of California, Div. of Agricultural Sciences Bul. No. 1897.

Hoffman, G. J. 1985. "Drainage Required to Manage Salinity," *Journal of the Irrigation and Drainage Division.* Am. Soc. Civ. Engr. Vol. 111, pp. 199-206.

Kirkham, D., and L. Prunty. 1977. *Upslope Recharge, Downslope Waterlogging, and Interceptor Drains.* Proceedings of Third National ASAE Drainage Symposium. ASAE Pub. No. 1-77, pp. 40-50, 54.

Maas, E. V., and G. J. Hoffman. 1977. "Crop Salt Tolerance—Current Assessment." *Journal of The Irrigation and Drainage Division,* Am. Soc. Civ. Engr. Vol. 103, pp. 115-134.

Oosterbaan, O. J. 1982. *Crop Yield, Soil Salinity, and Water Table Depth in Pakistan.* Wageningen, The Netherlands: Annual Report, International Institute for Land Reclamation and Improvement. pp. 50-54.

Pratt, P. F. 1973. *Quality Criteria for Trace Elements in Irrigation Waters.* Station Bulletin, California Agricultural Experiment Station, Davis.

Chapter 10

Drainage Institutions

Carmen Sandretto
Economic Research Service, USDA
East Lansing, Michigan

Early in the development of American agriculture, when good land was abundant and available for cultivation, areas with wet soils and natural wetlands were often bypassed. Many farms contained tracts of land too wet for use even as pasture except during dry seasons, and large areas were too swampy or frequently flooded to make regular cultivation practical. As tillable land became scarcer and higher in price, farmers began to explore ways of reclaiming lands with wetness problems through improved drainage.

Drainage for agriculture has traditionally been recognized as an endeavor beneficial to the public because excess water can influence public health, farm production, farm income, and real estate values. A number of the States recognized early the right of every landowner to a drainage outlet, permitting an owner intending to drain to apply to a designated official, pay any damages, and if the necessity were proved, secure an easement to construct and maintain a private outlet for the drain across a neighbor's land.

Agricultural drainage often needs an artificial drain constructed or a natural watercourse improved, which in turn, may affect the land of other individuals. Efforts to improve drainage outlets often benefit more than one farm and the cost is greater than any one individual wants to assume. These circumstances have encouraged legislation permitting the organization of public corporations or local improvement districts to facilitate artificial drainage activities.

Elements of Drainage Law

Drainage law focused historically on promoting drainage for two purposes: removing excess water from the land so it could be cultivated or otherwise developed, and enhancing public health because swamps and low-lying areas were potential breeding places for malaria-carrying mosquitoes. These considerations were the basis for allowing private individuals to drain their lands (Beck, 1972).

The issues associated with drainage law deal with repelling water at the boundaries of one's land as well as with disposing of excess water once it has entered. Because remedial actions taken by individual landowners interfere with the natural processes of water arriving on or leaving their land, what landowners do will likely affect someone else's land.

Over the years, the courts have molded a substantial portion of the common law of drainage and have frequently quoted three Latin maxims in their deliberations (Beck, 1972). Translated, they are:

1. Water runs and ought to run, as it has used to run.
2. Whose is the soil, his it is even to the skies and to the depths below.
3. Use your own property in such a manner as not to injure that of another.

Basic Drainage Law Doctrines

Given the background provided by the common law of drainage and the modifications resulting from court action, three rules concerning drainage of diffused surface waters have been identified. Following is a brief summary of them as drawn from Beck (1972).

The common enemy rule, or, as it is sometimes mistakenly called, the common-law rule, recognizes surface water as a common enemy which each landowner may try to control by retention, diversion, repulsion, or altered transmission. The focus is on two points: the necessity of improving lands, recognizing that some injury results from even minor improvements, and a philosophical preference for the freedom of landowners to deal with their own land essentially as they see fit.

The common enemy rule permits landowners to drain or repel diffused surface water if they act reasonably under the circumstances. Collecting and discharging large or unusual quantities of diffused surface water onto adjoining land where it may cause damage is considered unreasonable.

The natural flow rule, or, as it is sometimes called, the civil law rule, places a natural easement upon the lower land for the drainage of surface water in its natural course. The natural flow of the water cannot be obstructed by the owner of the lower land to the detriment of the owner of the higher land.

Because there has to be some drainage rule, looking to the law of nature for the rule is reasonable. The Supreme Court of Illinois in 1869 stated:

> The right of the owner of the higher land to drainage is based simply on the principle that nature has ordained such drainage. . . . As water must flow, and some rule in regard to it must be established . . . there can clearly be no other rule at once so equitable and so easy of application as that which enforces natural laws. There is no surprise or hardship in this, for each successive owner takes whatever advantages or inconveniences nature has stamped upon his land.

The need to drain land in order to develop it certainly does not mean that a landowner should be able to force a neighbor or the public to pay for it. In the early development of this country, a presumption in favor of drainage existed because it was viewed as a public benefit, but today policy may favor the retention of natural areas and wetlands. This policy consideration would reject the common enemy rule and tend to support the natural flow rule.

The reasonable use modification in applying the natural flow rule has been to promote drainage. However, the basic principle generally applicable to landownership should apply: landowners should be able to use their property as they see fit as long as they do not unreasonably injure someone else's property. Certainly natural flow can be altered in many instances without doing any injury or damage to another tract.

Under the reasonable use rule, landowners are legally privileged to make reasonable use of their land even though the flow of surface waters is altered and causes some harm to others. Those landowners incur liability when harmful interference with the flow of surface waters becomes unreasonable. The underlying philosophy of this approach is dissatisfaction with rules that either favor the upper landowner, as does the natural flow rule, or that envision conflict between adjoining landowners, as does the common enemy rule.

Beck (1972) has identified the following questions as basic to an analysis of a situation under the reasonable use rule:

> (1) Was there a reasonable necessity for altering the drainage pattern to make use of the land?
>
> (2) Was the altering done in a reasonable manner? That is, was due care taken to prevent injury to another's land? Was the natural drainage pattern followed as much as possible? Is the artificial system reasonably feasible?
>
> (3) Does the benefit from the actor's conduct reasonably outweigh the gravity of the harm to others? This test is the traditional nuisance balancing approach, which has the distinct advantage of keeping up to date.

All of the common-law rules concerning drainage of diffused surface waters involve elements of uncertainty. Under the natural flow rule, dominant owners must show that they are dominant and that the lower owner(s) obstructed the natural drainage pattern. The common enemy rule is uncertain because to permit one set of owners to get rid of diffused surface water as best they can may not be an overall benefit if their action brings them into conflict with neighbors who have the same rights. The reasonable use test is uncertain because it depends upon not only whether landowners make reasonable use of their land but also whether it is reasonable in the larger setting.

The modifications of the common enemy and natural flow rules have done much to alleviate the early attendant injustices. The reasonable use rule seems the most just because it considers the individual circumstances of each case.

An inevitable consequence of a complex society is the diminution in control that landowners have over their land. The public interest concept appears to be expanding. In attempting to resolve problems among individuals, the reasonable use test seems best because it analyzes the gravity of harm versus the utility of the benefit. An element of public interest is interjected in these cases in ascertaining not just the utility to the individual but to the public as well.

The question arises whether there is really any difference between the independent reasonable use rule and the reasonable use modifications of the common enemy and natural flow rules. In a growing number of jurisdictions, all conduct of a landowner with reference to diffused surface waters is subject to the reasonable use rule, whether as a modification of one of the other rules or as an independent test (Beck, 1972).

The general rules formulated from a composite of the basic rules and their modifications with respect to the law of drainage of diffused surface waters can be summarized as follows:

1. A landowner may not obstruct the natural flow in a watercourse (liberally defined in some jurisdictions) to the injury of another.
2. A landowner may not collect unusual amounts of diffused surface waters and discharge them onto adjoining land to its injury.
3. A landowner may not divert onto another's land, to its injury, diffused surface waters from an area that did not naturally drain that way.
4. A landowner may drain diffused surface water into a watercourse (liberally defined in some jurisdictions) subject to the overtaxing capacity, the anticollecting-and-discharging, and the antidiversion rules.
5. In all other respects concerning their conduct with diffused surface waters, landowners are subject to a rule of reasonable use of their land, whether it relates to acceleration or repulsion of flow.

Drainage Rights

Easements for a landowner to drain excess water across the land of another may be obtained the way any other easement is, through grant, express or implied, or through prescription. A number of States provide for use of eminent domain power by private individuals to drain land. This individual exercise of eminent domain is distinct and separate from the use of the power by entities such as drainage districts. Eminent domain is limited to a public use or public purpose, which may create some difficulties in use of the power for draining private lands. However, some State constitutions authorize use of eminent domain for this purpose, and some courts construe the benefit to the public health or economy arising from drainage as a sufficient public purpose. Also, it is possible to create a license for drainage purposes (Beck, 1972).

Public Drainage Organizations

The expansion of agricultural development in many parts of the Nation was accomplished through cooperation among groups of landowners with common drainage interests engaging in community undertakings to remove excess water from their holdings. These efforts eventually resulted in the creation of public organizations to improve off-farm drainage facilities.

Early attempts at drainage improvement by individual landowners were often unsatisfactory because outlets were inadequate to carry off the excess water. Individual efforts to improve drainage were followed by cooperation between groups of adjacent landowners to obtain effective drainage at lower cost. However, these attempts at cooperation in the construction of drains and the distribution of costs often failed because of inherent weaknesses in such voluntary associations. Also, cooperating groups did not possess the power to compel all landowners who benefited from the drainage works to pay their fair share of the costs, nor did they have a mechanism to permit construction of drains across the lands of an owner who refused to consent when circumstances made such construction necessary to secure adequate outlets.

Types of Drainage Organizations

The failure of individual and voluntary cooperative efforts to establish economic drainage improvements led to legislation authorizing the formation of public organizations with certain powers to allow improved drainage of agricultural lands. Legislative authority for the creation of drainage districts as it exists today dates back to the 19th century.

The formation of public drainage organizations usually involves a multistage process which varies in detail from State to State, but which contains elements common to all. Enabling legislation sets out the procedure for the formation of a drainage district, indicates the powers it has, and imposes a duty on the district to keep drainage systems adequately repaired. Appendix B is a synopsis of laws and regulations pertaining to drainage in selected States.

Drainage organizations have generally been referred to as public corporations or as quasimunicipal corporations. Drainage districts or close approximations of them are authorized in 45 States. In 39 States, entities actually denominated "drainage districts" may be formed for various drainage purposes (Beck, 1972). In some States, several types of drainage districts may be created. Many States also authorize multipurpose districts to engage in drainage projects. One factor accounting for the diversity in public organizations has been the tendency to move from single-purpose to multipurpose districts without doing away with the old districts.

The administrative structure established to provide unified action for handling a drainage problem is commonly referred to as its organization; all drainage activities under the direct management and supervision of one organization constitute one project. Drainage projects are those activities undertaken to provide new construction or replacement construction or to provide maintenance and operation of existing drainage works, and are usually classified into three groups:

1. Drains owned by one landowner; the landowner may be an individual, a partnership, an estate, a private corporation, or an institution.

2. Cooperative or mutual drains that represent undertakings by two or more landowners cooperating without special organization under State drainage laws for the construction or operation of drainage works benefiting their lands. Many cooperative or group drainage projects have received assistance and guidance from SCS.

3. Legally organized public drains that represent community or public drainage undertakings accomplished through some form of governmental organization. These organizations can be administered by public officials of a county, a township, a State, an agency of the Federal Government, or by specially elected or appointed officials or boards. General or special State laws provide for equitable cooperation among landowners who will benefit by a particular drainage undertaking.

A variety of drainage organizations have been authorized in nearly all States, with the corporate district and the county drain constituting the two principal types. A system of county drainage districts has been created in some States, whereas in others, special drainage districts have been formed.

Besides the two principal types of drainage organizations, some minor types exist: (1) township drains, which are generally similar in form to county drains but are controlled by officers of the townships; (2) State drainage projects controlled by State officials, usually embracing some State land; (3) irrigation districts, similar to drainage districts, that have drained land within the irrigation districts; (4) commercial companies reclaiming and improving poorly drained land for future sale; (5) cooperative or mutual undertakings without formal corporate organization; and (6) individual landowners including farm partnerships and farm corporations (Bureau of the Census, 1961).

In several States, some difficulty exists in distinguishing between drainage districts and county drains. Many of the organizations classified as county drains were named "drainage districts" in the law. District organizations, under the management of their own officials, were generally considered better suited to larger and more costly undertakings because they provided landowners with a greater degree of local control. County drains administered by county officials were generally more economical for administering small enterprises with relatively simple engineering and financing problems and were most commonly adopted in States where drainage improvements were being provided to land already in farms. Drainage districts were generally confined to areas where reclamation and development of unimproved lands for new farms had been an important consideration in establishing drainage organizations.

The 1950 Census of Drainage treated the drained lands of each county in States having predominantly county drains as a single drainage organization. The States were designated as "county-drain" States: Delaware, Indiana, Iowa, Kentucky, Michigan, Minnesota, Ohio, Oklahoma, North Dakota, and South Dakota. Delaware's predominant form of drainage organization, however, is the drainage district. Thirty other States were identified as "drainage-district" States. The six New England States, Pennsylvania, and West Virginia were determined, for the purpose of the Census, not to have drainage organizations (Bureau of the Census, 1952).

The geographic distribution of agricultural lands served by organized drainage projects of 500 acres or more is presented in figure 10-1. The greatest concentration of agricultural land within drainage project boundaries is found in the Great Lakes, Upper Midwest, Lower Mississippi Valley, Gulf, and Delmarva regions. California's drainage enterprises are typically associated with irrigation projects.

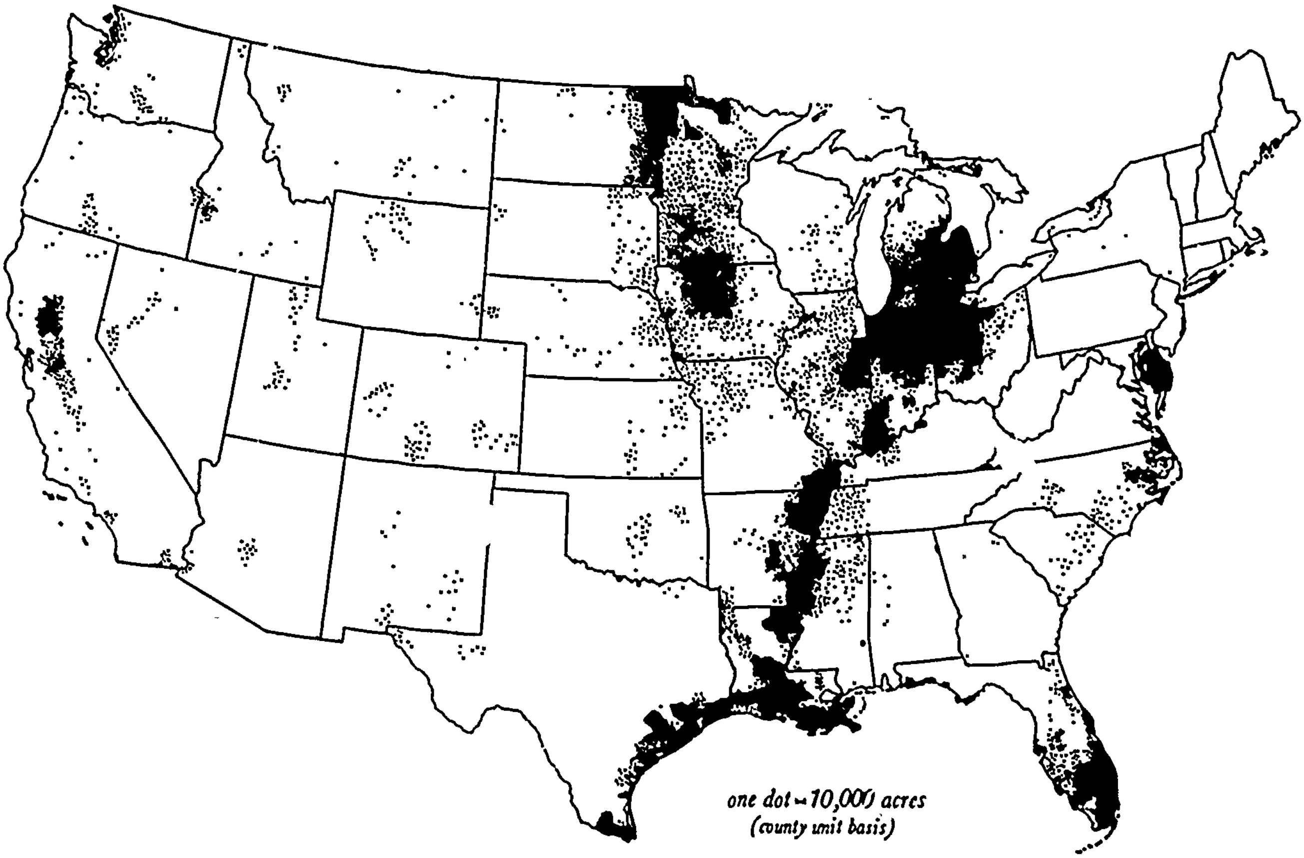


Figure 10-1—Land in organized drainage enterprises.

Creation of a drainage district begins with a petition containing certain specified information, signed by the required number of people, and addressed to a designated court, board, or authorizing official. Frequently, a bond must be filed with the petition to cover the costs and expenses of the proceedings if the district is not established. Sometimes a map must accompany the petition.

The petition is usually referred to an engineer, surveyor, designated board, or some combination of these. A preliminary report is prepared that gives a general idea of the location, character, cost, and potential feasibility of the proposed drainage project and indicates what lands would benefit.

Notice to interested persons or affected landowners is required, usually followed by a hearing and a declaration of the establishment or nonestablishment of the district. In its declaration, the court or board determines the technical sufficiency of the petition and proceedings; it considers whether any benefits will accrue, whether those benefits outweigh the costs, and whether public health or welfare would be enhanced.

The procedure usually includes a provision for appeal from the board to a court or from the organizing court to a higher court. Many State codes have provisions for voting by designated parties as an alternative method of forming districts or as a veto on any district formation. Sometimes the process is concluded with an assessment upon those to be benefited; but, in many States, the organizational procedure is distinct from the assessment procedure.

The enabling legislation indicates the powers possessed by a properly organized drainage district. These generally include the following powers: to acquire and own interests in real and personal property; to construct various works necessary to accomplish the drainage improvements and any other purposes for which the district is organized; to condemn property needed for carrying out the purposes of the district (eminent domain); to make contracts; to borrow money and issue bonds; to pay debts; to sue and be sued; to make an equitable distribution of costs in proportion to benefits conferred; to levy and collect taxes against benefited lands; to employ the necessary personnel; and to adopt regulations for administration of the completed project or projects (Beck, 1972; Yohe, 1927). The codes usually impose on the district a duty to keep the drainage and related works in repair.

What can be drained through the auspices of drainage districts varies from State to State. The focus is usually on either the nature of the land, the purpose to be accomplished, or the nature of the water. In some States, combinations of the foregoing are stated; a few States make no specific statements. The area of a drainage project is usually defined as the area benefited by the drainage works. The area improved or benefited for agriculture as a result of the drainage facilities is what is considered in projects undertaken by landowners, either individually or cooperatively (Beck, 1972).

Drainage district statutes normally do not specify any particular geographic area to be included, but they do require the petition to contain some description of the proposed boundaries. Various governmental bodies with final creative approval of districts, or governmental officials such as State engineers, have differing degrees of control over the boundaries. In any case, the legal document establishing the district defines its boundaries. In most States, if public drains are administered countywide or on the basis of established political boundaries, the boundaries are determined by the area directly benefited. In special districts organized primarily for purposes other than drainage, the entire area in the district defines the boundaries, even though only part may be benefited (Bureau of the Census, 1961).

Several States require the district land to be contiguous, while others specifically allow noncontiguous areas, and some States do not permit districts to cross county lines. Several States have language relating to natural drainage basins, and many States provide for mergers of two or more districts and for subdistricts or interstate districts (Beck, 1972).

After a drainage district is formed and certain land is included, the drainage activities of individual landowners may be restricted. Essentially all jurisdictions give drainage districts the power of eminent domain to foster their purposes, but its exercise is usually limited in some way (Beck, 1972).

A project need not provide complete drainage for the area served. Many projects, especially public drains, provide only the principal channel or outlet drain. The construction of laterals and field drains required to provide optimum drainage may be left to individual landowners. These drains and other water-control works installed by farmowners on their own farms, either inside or outside the boundaries of an organized drainage district, are probably either supplemental to or entirely independent of the drainage works installed by a district organized to improve lands for agriculture.

Administration and Financing

Public drainage projects are administered by a board of drainage commissioners who are either elected by the residents or landowners of the district (in some States, voting power is based on acreage), or are appointed by the organization's creative authority. In many States, board members must be real property owners in, and residents of, the county or district involved. In a few States, existing local officials supervise drainage projects. Courts generally hold that a majority of the board can act to bind the district. Although commissioners may usually exercise great discretion in carrying out the governing function, they can be challenged for such improper activity as misapplication of funds (Beck, 1972).

Drainage improvements may be financed in several ways. An assessment against benefited land is most common, but much discretion is often given to the assessing authorities in determining what constitutes a benefit and the procedures involved in the assessment process.

Many States have specific provisions dealing with organizational costs, construction costs, and maintenance costs. A uniform tax on all property within the district is often used to cover organizational costs, but construction and maintenance costs are generally recovered from tax levies based on assessed benefits to the respective tracts of land. Frequently, separate funds are maintained for each cost category. Because expensive drainage projects cannot be financed through a single year's levy, provisions usually exist for a variety of borrowing and repayment methods (Beck, 1972).

As custodians of the project, the drainage commissioners are responsible for maintenance and repair of the drainage system. Deterioration of facilities and subsequent loss of efficiency in removing excess water can occur rapidly if regular inspections and maintenance are neglected. Proper maintenance can yield substantial benefits through increased efficiency and extended life of the project (Yohe, 1927).

Many public drainage organizations are established for a specific purpose, such as to construct new drainage facilities or to enlarge or renovate facilities built by an earlier organization. After accomplishing their immediate objectives, many of these organizations become inactive or dissolve, so when further work is needed, a new drainage organization must be formed. Over the years, drainage organizations have overlapped, and only a small number of organizations may be currently active. Usually the functions of an inactive organization are assumed by a new organization, although control sometimes passes from one organization to another through court action.

Many cases exist in which drainage districts have failed, bonds have not been refunded, and owners of assessed lands have not paid their assessments. The drainage codes of most States provide steps for dissolving defunct drainage districts which specify who can initiate the procedure, where the dissolving power lies, and what conditions must exist before it can be exercised. Lack of dissolution, however, has been more of a problem than dissolution. Districts have simply withered away, the commissioners or directors have disappeared, and projects have been left uncompleted and/or unmaintained (Beck, 1972).

The substantial amount of litigation in the courts over the years demonstrates that many of the drainage districts established years ago were ill-conceived; land was forfeited for failure to pay assessments, and many bondholders could not recover the full face value of their bonds. Recent trends indicate a preference for multipurpose districts (conservancy and water management, for example). The result may be improved natural resource management through emphasis on better planning and coordinating than occurred historically with the single-purpose districts.

Multipurpose Districts[1]

Several States have enacted legislation in recent years authorizing the creation of general multipurpose districts which are permitted to perform many functions, including draining wetlands. Most of these have retained their statutes permitting the creation and operation of separate drainage districts. Multipurpose districts have no primary purpose except the very general one of promoting public welfare as it relates to the total water resources. This differs from special-purpose districts with a primary purpose. For example, most irrigation districts can engage in some drainage; however, drainage is only incidental to the primary purpose of irrigation.

Multipurpose districts that provide for wetland drainage as one function have different names in different States. For example, they are known as conservancy districts in Indiana, New Mexico, Montana, Ohio, and Oklahoma; as water conservancy districts in Nevada and Utah; as watershed conservancy districts in Kentucky; and as river conservancy districts in Illinois. Kansas and South Dakota have watershed districts, Alabama has water management and drainage districts, North Dakota has water resources districts, and Wyoming has watershed improvement districts. Nebraska's natural resources districts probably have the broadest powers of any multipurose districts. Minnesota has both conservancy and watershed districts that may perform drainage functions. The relevant State codes are listed with other references to this volume.

Multipurpose districts generally perform several functions, which may include preventing and controlling floods; constructing flood prevention structures, including levees; improving stream channels; preventing and controlling erosion and sedimentation; regulating stream flows and lake levels and conserving water; improving drainage and reclaiming or filling wet or overflowed lands; diverting or changing water courses; promoting recreation; providing, developing, and conserving water supply for domestic, industrial, recreational, and other public uses; providing for sanitation and public health, and regulating the use of streams, ditches, or water courses for the disposition of waste; relocating, extending, replacing, modifying, consolidating, or abandoning drainage systems within a multipurpose district; and operating and maintaining drainage systems.

Multipurpose districts are generally initiated with a petition signed by a requisite number of landowners which is submitted to the county board of supervisors or county agency, officer, or court. After a public hearing to determine the necessity of establishing a district, the governmental authority will establish a district. Sometimes a referendum is held. A board of directors, usually appointed by the same authority that established the district, governs the district. Areas included in a district do not have to coincide necessarily with county boundaries. Areas can be smaller or larger than a county.

---

[1] This section on multipurpose districts was prepared by Dean T. Massey.

Multipurpose districts may purchase, lease, and own land, and, if necessary, may acquire such interests by eminent domain. They may enter into contracts and construct and maintain structures and facilities. Districts generally have power to levy taxes, borrow money, issue bonds, and levy special assessment of lands benefited.

References

Beck, Robert E. 1972. "The Law of Drainage," In *Waters and Water Rights*. Vol. 5. (ed. Robert Emmet Clark). Indianapolis, Ind.: The Allen Smith Company.

Hannah, H. W., N. G. P. Krausz, and D. L. Uchtmann. 1979. *Illinois Farm Drainage Law*. Coop. Ext. Serv. Circular 751, Univ. of Illinois, Urbana.

Indiana Farm Bureau, Inc. 1981. *The County Drainage Board, Recodified 1981*. Indianapolis, Ind.

Michigan Department of Agriculture, Division of Intercounty Drains. 1984. Personal communication.

Nolte, Byron H. 1981. *The Ohio Drainage Laws Petition Procedure*. Coop. Ext. Serv. Bulletin 482, Ohio State Univ. and County Engineers Association of Ohio, Columbus.

Nolte, Byron H., and Eugene H. Derickson. 1976. *Conservation Improvement Projects Through Soil and Water Conservation Districts*. Coop. Ext. Serv. Bulletin 606, Ohio State Univ., Columbus.

North Carolina Department of Natural Resources and Community Development, Division of Soil and Water Conservation. 1984. Personal communication.

U.S. Congress, Office of Technology Assessment. 1984. *Wetlands: Their Use and Regulation*. Report OTA-O-206, March.

U.S. Department of Commerce, Bureau of the Census. 1932. *Drainage of Agricultural Lands, 1930*.

__________. 1952. "Drainage of Agricultural Lands," Census *of Agriculture, 1950*, Vol. IV.

__________. 1961. "Drainage of Agricultural Lands," Census *of Agriculture, 1960*, Vol. IV.

__________. 1981. "Drainage of Agricultural Lands," Census *of Agriculture, 1978*, Vol. 5, Special Reports, Part 5.

Yohe, H. D. 1927. *Organization, Financing and Administration of Drainage Districts*. Farmers' Bulletin No. 815., U.S. Dept. Agr.

State statutory references:

California Water Code, Secs. 8502, 8550, 8551, 8750, 8751, 8758 (West 1971 and Cumulative Supplement 1984), Secs. 20700, 22095 (West 1984), Secs. 50110, 50300, 50932, 56010 to -014, 56018 to -020, 56030, 56041 to -042, 56050, 56055, 56070 to -071, 56074 to -076, 56083 to -084, 56095, 56104, 56110 to -117 (West 1966 and Cumulative Supplement 1984), and Secs. 70150, 74522 to -525 (West 1966).

Alabama Code, Secs. 9-9-1 to 9-9-80 (1980).

Illinois Annotated Statutes, Ch. 42, Secs. 383 to 410.1 (Smith-Hurd 1976 and Cumulative Supplement 1984-1985).

Indiana Code Annotated, Secs. 13-3-3-1 to 13-3-3-102 (Burns 1981 and Cumulative Supplement 1984).

Kansas Statutes Annotated, Secs. 24-1237 (1981 and Cumulative Supplement 1983).

Kentucky Revised Statutes, Secs. 262.700 to 262.990 (1981 and Cumulative Supplement 1984).

Minnesota Statutes Annotated, Secs. 111.01 to 111.82 and 112.34 to 112.86 (West 1977 and Cumulative Supplement 1984).

Montana Code Annotated, Secs. 85-9-101 to 85-9-632 (1983).

Nebraska Revised Statutes, Secs. 2-3201 to 2-3275 (1977 and Cumulative Supplement 1982).

Nevada Revised Statutes, Secs. 541.010 to 541.420 (1983).

New Mexico Statutes Annotated, Secs. 73-14-1 to 73-14-88 (1978 and Cumulative Supplement 1983).

North Dakota Century Code, Sec. 61-16.1-01 to 61-16.1-63 (Supplement 1983).

Ohio Revised Code Annotated, Secs. 1515.01 to 1515.30 (Page 1978 and Supplement 1983) and Chs. 6131, 6133, 6135, 6137 (Page 1977 and Supplement 1983).

Oklahoma Statutes Annotated, Title 82, Secs. 531 to 688.1 (West 1970 and Cumulative Supplement 1983-1984).

South Dakota Codified Laws Annotated, Secs. 46A-2-1 to 46A-2-37 (1983).

Utah Code Annotated, Secs. 73-9-1 to 73-9-43 (1980 and Supplement 1983).

Wyoming Statutes Annotated, Secs. 41-8-101 to 41-8-126 (1977 and Cumulative Supplement 1983).

Chapter 11

Economic Survey of Farm Drainage

George A. Pavelis
Economic Research Service, USDA
Washington, DC

This overview briefly addresses a series of drainage development and economic questions: At what rate have drainage organizations and individual farmers in the United States improved land by drainage? How has the cost of drainage changed over time? How have past investments in drainage added to the Nation's agricultural capital and wealth? How does drainage capital relate to land and its value in different States and regions? How does drainage contribute to farm production, and what is the significance of maintaining a productive irrigated agriculture through proper drainage and related water management strategies?

The density map in figure 11-1 indicates the general distribution of drained agricultural land in the United States. The total area drained in 1985 was around 110 million acres, of which about 70 percent was cropped and 12 percent grazed. Woodlands accounted for 16 percent, with the balance (2 percent) in farmsteads and other miscellaneous uses.

Areas and Uses of Drained Land

Although poor drainage and its effects are evident even to the untrained eye, good natural drainage and functioning drain systems often go unnoticed. This unseen attribute of drainage is one reason why reliable information on this important land improvement is difficult to obtain from landowners or farm operators.

Another reason is that in its primary developmental period, 1870-1920, and again in a secondary period during 1945-60, much new drainage occurred within organized drainage districts, or county and township drains. These came to be called drainage "enterprises" (U.S. Dept. Commerce, 1961). They can be organized in several ways and can have multiple functions. They may engage in drainage only or in both irrigation and drainage. According to the Bureau of the Census, 20 percent of the 840 or more U.S. irrigation districts maintain about 14,000 miles of drains. Most of the drains serve projects originally constructed by the Bureau of Reclamation but paid for and now operated by water users. Also, about 15,000 miles (13 percent) of the irrigation canals and ditches in the United States are lined to minimize conveyance losses and drainage problems connected with seepage (U.S. Dept. Commerce, 1982).

The connection between organized drainage and the difficulty of obtaining reliable current information is that many organizations have kept few records on project activity within their areas and these may pertain only to the construction period. Organization officials may not have been replaced as they retired or moved away, so it is difficult to locate responsible individuals or otherwise gain access to available records.

The estimates on drainage compiled for this survey are based on Bureau of the Census information, supplemented with data available from USDA agencies and drainage specialists. The Bureau of the Census completed a Census of Drainage Organizations about every 10 years between 1920 and 1978 (13 U.S. Code 142). It also collected some drainage information from farmers in its regular Censuses of Agriculture for 1920, 1930, 1969, and 1974. The References section contains numerous Department of Commerce publications on drainage and related agricultural topics dating from 1930 to 1985.

In 1978, the Bureau of the Census did not request information on land drained from either drainage organizations or farmers but rather compiled county-level estimates provided by local offices of SCS (U.S. Dept. Commerce, 1981). Also, no specific questions

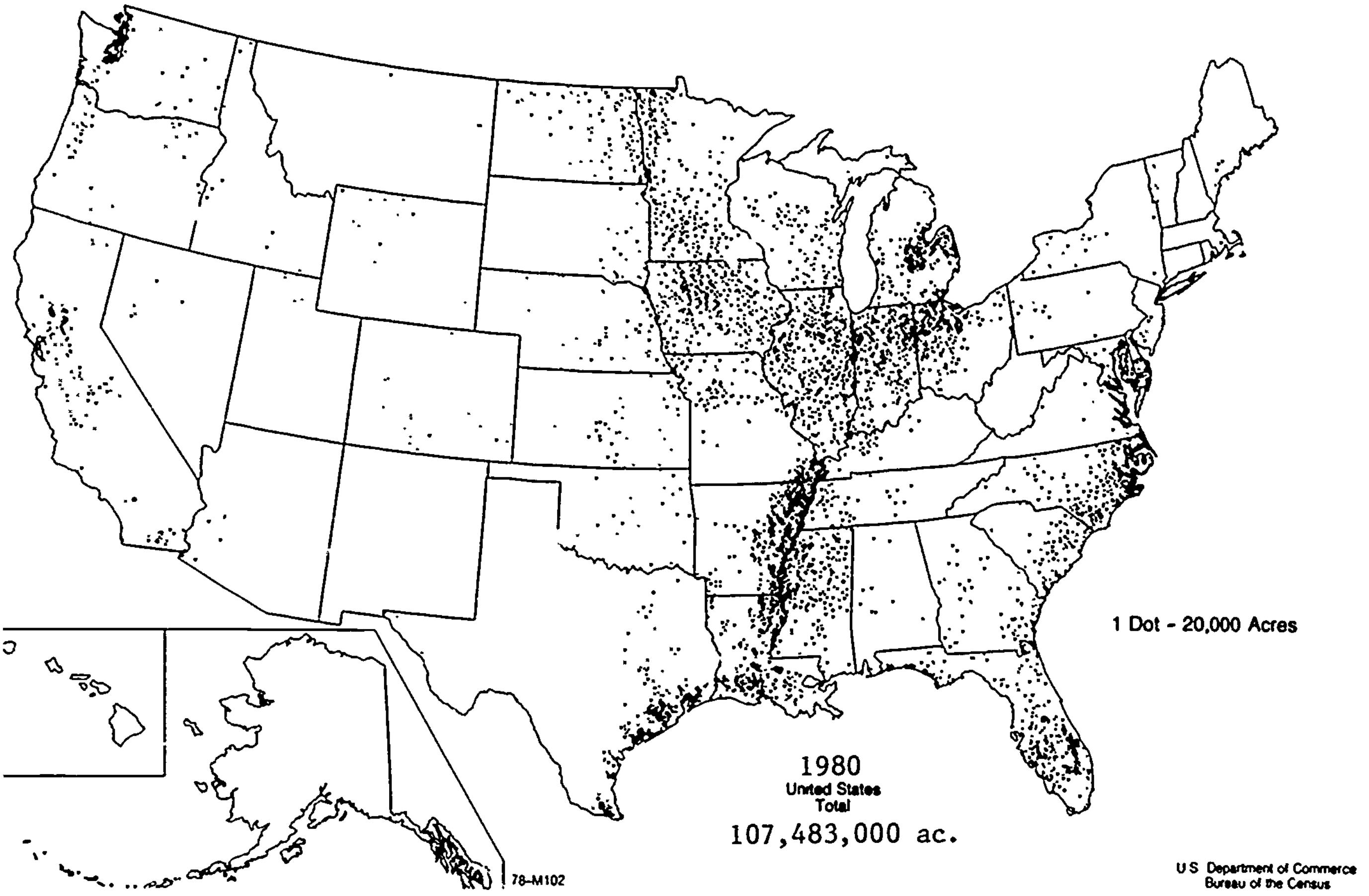


Figure 11-1—Artificially drained agricultural land in the United States, 1985.

on drainage were asked of farmers or others in the most recent (1982) Census of Agriculture.

Procedures and General Estimates

A three-step approach was used to develop estimates of rural land drained in the United States from 1855 to 1985. The total area for which drainage improvements had been installed at least once was determined first. As of 1985, the cumulative total since 1855 had grown to at least 150 million acres. Useful information on drainage back to colonial times is available in books by Harrison (1961) and Weaver (1964).

Determined next was the amount of land actually drained as of given years, using the above cumulative figures in conjunction with areas reported drained in various censuses of agriculture and drainage and other available sources.

The third step was an effort to assess the condition of farm drains, applying some simple assumptions as to their expected service life. Average service lives were assumed to be 20 years for field ditches and other practices for improving surface drainage. A service life of 40 years was assumed for tile and other subsurface drains installed since 1940 (30 years if installed before 1940).

In the case of drainage organization facilities, gross and net capital values in a given period were considered equal to accumulated investment. The yearly investments were allowed to hypothetically "decline" over a period of 60 years to 50 percent of the original cost, the decline being an approximation of maintenance allowances. This does not imply that all organization outlets or other facilities, which served 65 million acres of drained land in 1985, were being maintained as needed. By 1920, maintenance allowances represented 20 percent of cumulative expenditures by drainage organizations. Comparable percentages for years since then were 32 percent for 1940, and 55 percent for 1985. Most current organization expenditures are for maintenance and replacement.

The approximate areas of farm and other rural land drained by 5-year or annual intervals between 1900 and 1985 are in table 11-1. The areas are divided between the land provided and not provided organization service. The areas are also divided between the land drained with open ditches or other surface improvements and that improved with subsurface

Table 11-1—Rural land drained with and without drainage organization service, United States, 1900-85

Year	Net area drained			Area shares	
	Land area drained[1]	Drainage organization service[2]	Independent farm systems	Drainage organization service	Independent farm systems
	Million acres			*Percent*	
1900	6.295	6.265	0.030	99	1
1905	11.677	11.620	.057	99	1
1910	22.305	22.190	.115	99	1
1915	35.045	34.830	.215	99	1
1920	49.445	48.154	1.291	97	3
1925	47.563	45.185	2.378	95	5
1930	49.363	45.414	3.949	92	8
1935	45.850	41.265	4.585	90	10
1940	45.437	39.985	5.452	88	12
1945	50.324	39.203	11.121	78	22
1950	69.929	52.867	17.062	76	24
1955	78.865	57.809	21.056	78	22
1960	86.607	61.491	25.116	71	29
1965	93.643	64.333	29.310	69	31
1970	99.084	65.792	33.292	66	34
1975	103.400	66.279	37.121	64	36
1978	105.278	66.009	39.269	63	37
1980	106.286	65.685	40.601	62	38
1981	106.743	65.538	41.205	61	39
1982	107.200	65.392	41.808	61	39
1983	108.101	65.395	42.705	61	39
1984	109.002	65.401	43.601	60	40
1985	109.681	65.260	44.421	59	41

[1] The net areas of farmland drained are rounded to the nearest 1,000 acres. They are not estimates of wetlands drained but rather refer to the area of farm or other rural land benefited to some extent by water removal to improve the soil environment for plant growth (Bureau of Census definition). Both surface and subsurface drainage improvements are included, such as ditches, swales, tile or other subsurface drains, dikes, pumping plants, and land grading.

[2] The net area with organization or project service includes lands drained within organized drainage districts, county drains, other drainage enterprises, and irrigation enterprises active in special drainage, less those nonagricultural lands drained within enterprises, and also farmsteads, roads, wasteland, and timber or brushlands within the farms serviced by drainage enterprises. As the censuses of agriculture and drainage were not the only sources of required information on drainage, particularly for years since 1959, the areas given may not agree completely with census data.

drains plus associated surface improvements (table 11-2, fig. 11-2).

Beginning with 1950, the estimates of drained area include irrigated land where special drainage was necessary to control soil salinity and temporary high water tables. In 1950, about 5.4 million acres had been reported drained by irrigation enterprises or by drainage enterprises organized specifically for controlling salinity and seepage on irrigated land (U.S. Dept. Commerce, 1961).

The total area of rural land drained in 1985 was about 110 million acres, of which 75 million acres (70 percent) was cropland. About 20 percent of the Nation's total cropland area is drained (for cropland statistics, see Frey and Hexem, 1985). At least 1 million acres of farm or other non-Federal rural land were drained in 22 States. In decreasing order of the approximate area of land drained, counting special drainage needs in irrigated areas, these States were: Illinois (9.8 million acres), Indiana (8.1), Iowa (7.8), Ohio (7.4), Arkansas (7.0), Louisiana (7.0), Minnesota (6.4), Florida (6.3), Mississippi (5.8), Texas (5.8). Michigan (5.5), North Carolina (5.4), Missouri (4.2), California (3.0), North Dakota (2.4), Wisconsin (2.2), South Carolina (1.8), Georgia (1.5), Maryland (1.2), Tennessee (1.2), and Nebraska (1.0). New York and Delaware followed with 915,000 acres and 460,000 acres, respectively.

These 23 States had about 96 percent of all cropland drained in the United States in 1985 and averaged about 25 percent of their cropland drained. However, such general figures obscure the factor of dependence on drainage. About 65 percent of all cropland in Arkansas and 60 percent in Louisiana was drained. Roughly 55 percent of the cropland in

Table 11-2—Rural land drained with surface and subsurface drainage systems, and drainage for systems not fully depreciated, United States, 1900-85

Year	Land area drained: Surface drainage only	Land area drained: Subsurface drainage systems	Area shares: Surface drainage only	Area shares: Subsurface drainage systems	Undepreciated drainage[1]: Surface drainage	Undepreciated drainage[1]: Subsurface drains
	Million acres	Million acres	Percent	Percent	Million acres	Million acres
1900	5.271	1.024	84	16	3.975	1.014
1905	9.775	1.902	84	16	7.447	1.877
1910	18.673	3.632	84	16	15.313	3.572
1915	29.344	5.701	84	16	25.029	5.541
1920	43.452	5.993	88	12	38.131	5.573
1925	41.420	6.143	87	13	41.412	6.143
1930	42.676	6.687	87	13	42.676	6.687
1935	38.606	7.244	84	16	32.697	6.118
1940	36.532	8.905	80	20	19.298	4.711
1945	40.769	9.555	81	19	15.800	3.291
1950	54.041	15.888	77	23	22.849	9.332
1955	60.736	18.129	77	23	29.172	10.768
1960	65.921	20.686	76	24	34.252	12.412
1965	70.039	23.604	75	25	35.244	15.021
1970	72.151	26.933	73	27	21.773	18.022
1975	72.668	30.732	70	30	17.588	21.326
1978	72.015	33.263	68	32	15.394	23.557
1980	71.386	34.900	67	33	15.941	24.994
1981	71.202	35.541	67	33	14.508	25.505
1982	71.165	36.039	66	34	13.786	25.873
1983	71.617	36.484	66	34	13.030	26.188
1984	72.118	36.884	66	34	12.240	26.458
1985	72.397	37.284	66	34	11.450	26.728

[1] Surface drainage improvement less than 20 years old; subsurface drains less than 30 years old if installed before 1940, and less than 40 years old if installed in 1940 or later.

Mississippi and 50 percent in Indiana and Ohio was drained. Other States with at least 25 percent of their cropland drained included Florida (45 percent), Illinois (35 percent), and Michigan (30 percent). Iowa, North Carolina, Missouri, South Carolina, and Delaware followed with around 25 percent of their cropland drained.

Uses of Wet Soils and Drained Soils

Information on the particular uses of wet soils and drained wet soils on non-Federal rural land in the United States was available from a National Resources Inventory completed by SCS in 1982. It is reviewed briefly because its distribution patterns of drained land use in 1982 were the basis for developing comparable estimates for 1985.

A similar but less intensive sample inventory was completed by SCS in 1977. Field personnel of SCS had made county estimates of drained land for the Bureau of the Census in the 1978 Census of Drainage, but in the 1982 inventory they completed

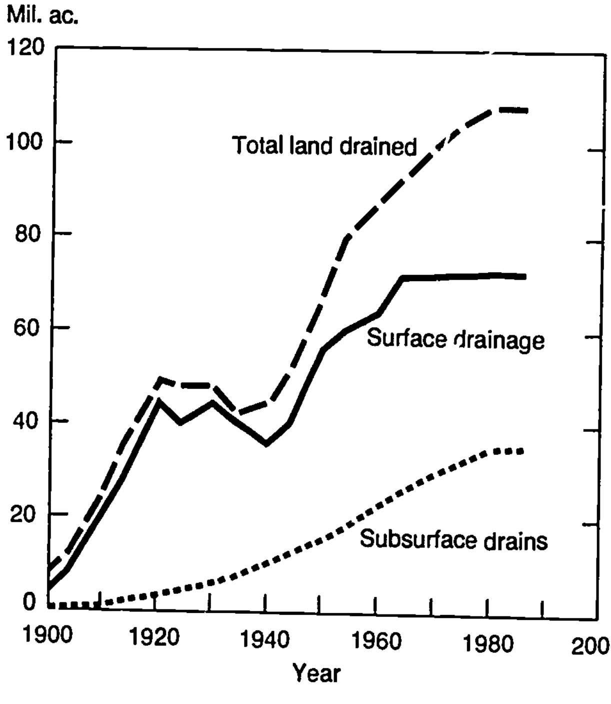


Figure 11-2—Artificially drained land on U.S. farms, 1900-85.

worksheets for about 1 million random sample points within about 350,000 primary sample units. The latter ranged between 40 and 640 acres; most were 100 to 160 acres. Observations for the 1 million sample points covered land use, soil types, flood-prone areas, wetlands, irrigation, erosion rates, and conservation needs. Needs for drainage were determined for nonirrigated cropland, irrigated cropland, pastureland, and rangeland.

The inventory sample points were also assigned a land capability class and subclass designation. Soils having a primary management problem of wetness were designated subclass "w." This designation applies to several major capability classes, for example, IIw, IIIw, IVw, VIw, and VIIw (USDA, 1982). The non-Federal rural land in the United States having wet soils totaled over 233 million acres, of which 45 percent was cropped and 30 percent forested. About 20 percent was in grazing uses.

In the 1982 as in the 1977 inventory, an effort was made to identify prime farmland. With respect to drainage, these are "not saturated with water or flooded during the growing season" (USDA, 1982, p.10).

For sample points designated subclass "w" and also considered prime farmland, one may reason that the basic wetness problem did not seriously inhibit production, because it was removed or controlled by drainage. The 1982 inventory identified about 107 million acres (46 percent) of the wet soils as being prime or adequately drained, of which 72 percent was then cropland (table 11-3). Such an indirect national estimate for the area of land drained in 1982 was about 2 percent higher than the 105 million acres local SCS offices had reported to the Bureau of the Census in 1978.

Dideriksen and others (1978) showed that "w" soils are not equivalent to wetlands as defined by the Fish and Wildlife Service (FWS) and accepted by USDA (Shaw and Fredine, 1956). FWS classes include all wetlands, regardless of their agricultural potential. In 1982, USDA inventoried 78 million acres of remaining non-Federal wetland (Heimlich and Langner, 1986), but 233 million acres of wet soils existed, of which 107 million acres were drained as noted above. The 126 million acres of undrained wet soils in 1982 (233 less 107) exceeded the remaining area of wetlands (78 million acres) by 48 million acres.

A special tabulation by Heimlich indicates that about 40 percent of the wet soils not cropland in 1982 could also be classed as wetlands. Excess water was the dominant restriction on crop use for about 93 percent (65 million acres) of the 78 million acres of wetlands remaining in 1982.

The 1982 inventory also provided information on the uses of drained soils that was not available in either the 1978 or earlier drainage censuses. In the

Table 11-3—Major rural land uses, wet soils on farms, and prime or drained wet soils by land uses, United States, 1982

Land use	Total area	Area having wet soils[1]	Prime or drained wet soils[2]	Share of total acres drained	Proportion drained each use
	Million acres			Percent	
Cropland in crops	421.4	106.9	77.0	71.7	72.0
Irrigated	60.5[3]	14.4	8.4	7.7	58.3
Not irrigated	360.9	92.5	68.6	64.0	74.1
Pastureland	133.3	26.2	11.4	10.7	43.5
Rangeland	405.9	17.7	2.2	2.1	12.4
Forestland[4]	393.7	70.0	15.0	14.0	21.4
Other rural land	59.6	12.7	1.6	1.5	[5]
Total	1,413.9	233.5	107.2	100.0	45.9

[1] Wet soils include land within major land capability classes II, III, IV, VI, VII designated subclass "w," as having a predominant wetness problem.

[2] Prime wet soils include prime farmland only in major land capability classes II, III, and IV designated subclass "w." Among other favorable features prime wet soils are not saturated with water during the growing season and have low salt and sodium content.

[3] The 60 million acres included some land not irrigated in 1982 but irrigated in at least two of the years during 1979-81. The total actually irrigated in 1982 was 49 million acres according to the Bureau of the Census.

[4] Forested wet soils include rural non-Federal land both in and not in farms in 1982, of which 6.5 million acres were grazed and 63.5 million acres were not grazed. Forested wet soils drained, however, are estimated according to note[2].

[5] Not estimated because this land drained was only 0.1 percent of total rural land inventoried in 1982.

1982 inventory, about 77 million acres (72 percent) of the 107 million acres of drained (prime) wet soils in rural areas were in crops. Another 11.4 million acres (11 percent) were in pasture and 2.2 million acres (2.1 percent) in range. About 15 million acres (14 percent) were forestland.

About 75 percent of the wet soils in nonirrigated crops in 1982 were considered adequately drained. On the same basis, 8.4 million acres (70 percent) of the wet soils used for irrigated crops posed no drainage problems (table 11-3). Census sources indicate that another 10.9 million acres of irrigated cropland not having wet soils were also drained (U.S. Dept. Commerce, 1973, 1982). The total area of irrigated cropland artificially drained in 1982 (19.3 million acres) represented 43 percent of all irrigated cropland (44.4 million acres). At least 2.5 million acres of the balance (25.1 million acres) of undrained irrigated cropland need drainage.

Because such statistics are subject to error, the inventory was designed to permit evaluation of their reliability. For example, the 234 million acres of wet soils and the 107 million acres of such soils drained in the United States according to the 1982 inventory are single-valued estimates. The true figures can be either lower or higher than these estimates.

With about a 95-percent chance of being correct, the true figure for all wet soils on farms or other non-Federal rural land can be estimated from the 1982 inventory to be somewhere between 232 million and 235 million acres. The true figure for the fraction of wet soils drained lies somewhere between 106 million and 108 million acres. This and other range estimates of how wet soils and areas drained were used in 1982 are also in table 11-4.

In extrapolating 1982 inventory data on the uses of drained land and making State estimates to 1985, prime wet soils were regarded as a first approximation of the total area drained, because other wet soils, while not prime farmland, may also be drained. For cropland, the land likely drained in a State in 1985 generally was taken as either (a) the prime wet soils in crops, or (b) the wet soils in crops considered to not need drainage in the 1982 inventory, whichever was greater. For pasture, forest, and other uses, the land likely drained was taken as the average of (a) prime wet soils in that noncrop use and (b) half the wet soils in that use not requiring special conservation treatment including but not limited to drainage. This procedure recognizes, for example, that many areas in the Southeast and Delta States have been drained as part of a permanent timber management program.

This procedure showed that the 109.7 million acres drained in 1985 were distributed among land uses as follows: cropland, 75.5 million acres (69 percent); pasture or rangeland, 12.8 million acres (12 percent); woodlands or forest, 17.9 million acres (16 percent); and miscellaneous uses, 3.5 million acres (3 percent).

Table 11-4—Ninety-five (95) percent confidence interval estimates for all wet soils and drained wet soils in rural areas, by different land uses, United States, 1982

Land uses	All wet soils: Wet soils by use[1]	All wet soils: Share of inventory[2]	All wet soils: Interval estimate[3]	Drained wet soils: Area drained	Drained wet soils: Share of inventory[2]	Drained wet soils: Interval estimate[3]
	Million acres	*Percent*	*Million acres*	*Million acres*	*Percent*	*Million acres*
Cropland in crops	106.9	7.1	106.1-107.8	77.0	5.1	75.6-78.0
Irrigated	14.4	1.0	14.1-14.7	8.4	.6	8.1-8.7
Not irrigated	92.5	6.2	91.7-93.2	68.6	4.6	67.9-69.4
Pastureland	26.2	1.7	25.8-26.7	11.4	.8	11.1-11.4
Rangeland	17.7	1.2	17.4-18.0	2.2	.1	2.1-2.4
Forestland	70.0	4.7	69.2-70.7	15.0	1.0	14.7-15.3
Other rural land	12.7	.8	12.3-12.8	1.6[4]	[4]	[4]
Total	233.5	15.6	232.5-234.9	107.2	7.2	106.4-108.2

[1] Wet soils include land within major land capability classes II, III, IV, VI, and VII designated subclass "w," or as having a predominant wetness problem.

[2] Area in col. 1 as percent of all rural non-Federal land and small water areas (1.5 billion acres) sampled in the 1982 National Resources Inventory. The larger (smaller) the percent of the total inventory acreage represented by the areas for each land use in data cols. 1 and 4, the narrower (wider) will be the range estimates in cols. 3 and 6.

[3] Ranges are for a 95-percent statistical confidence interval; that is, based on the inventory sampling procedures, there is a 95-percent probability that the true figures for wet soils or drained wet soils are within the interval given. Because each item in this column is estimated separately, totals may not be the exact sum of individual items.

[4] Share of total inventory area only 0.1 percent; interval not estimated.

Organized and Independent Drainage

Since about 1960, two major shifts appear to have occurred in drainage: one is a trend away from organizing new projects toward farmers independently installing their own systems (Gain, 1967), and the other is that the area with subsurface drains has increased more rapidly than that improved through open or surface drainage (table 11-1, table 11-2, fig. 11-2). The changing condition of drainage systems on farms and possible needs for redrainage were approximated by analyzing these changes.

A rapid developmental period for organized project drainage began about 1870 and ended about 1920, by which time 48 million acres had been drained within organization service areas. This area was over 97 percent of all land then drained in the United States (table 11-1). The true organization share was likely less than this, however, because 1920 was the first time farmers were asked to report how much of their land was artificially drained. Before 1920, the Bureau of the Census and USDA had cooperated in collecting drainage statistics but only from drainage districts and other public organizations.

A new surge of organized project drainage followed World War II and continued until the early 1960's. By 1965, the area of drained land served by organizations had grown to 64 million acres, but had fallen to about 70 percent of all drained land. This was because independent farm systems had expanded even more rapidly during the same period. For example, between 1945 and 1965, nearly 42 percent, or 18 million acres of the 43 million acres of newly drained land, did not rely on organization facilities. Since 1965, new drainage has primarily involved independent farm installations. The area served by drainage organizations within projects apparently peaked in 1978 at about 66 million acres.

Despite these changes, about 60 percent of the farmland drained in the United States in 1985 still relied on arterial drains installed by townships, counties, special drainage districts, and other organizations. The proportion of drained land served by drainage organizations is 80-85 percent in leading drainage States like Indiana, Ohio, Minnesota, Michigan, and California. Group or organized efforts are required for successful drainage of large areas, especially if irrigated.

Another factor to consider is that much of the new investment in farm drainage will replace existing systems using organization facilities. Also, while larger and fewer farms imply more freedom for owners and operators to drain independently of other farms, that implication can be misleading. Enlarged farm units may encompass land already drained and requiring group outlets. Also, what is reported as a large farm operating unit for census purposes may not be a single block of land but a number of separated owned and/or rented tracts.

The need for cooperation in drainage tends to increase with the intensity of drainage development within an area. Its success is determined by climate, soils, topography, and other field conditions, as well as by economics. Any significant future expansion of project drainage may occur in connection with new conversions of wetland forests and other low-lying areas to agricultural, urban, or industrial uses (U.S. Dept. Commerce, 1981, p. vi). But significant new organized activity may also be stimulated by an increasing concern with salinity and seepage in irrigated areas and the modernization of existing drainage systems on farms, including those not now using organization outlets.

Drainage Methods

Surface improvements are still the predominant form of drainage on U.S. farms or other rural land. In 1985, at least 72 million acres (66 percent) were drained with bedding, open ditches, or other surface improvements. Complete data are not available, but up to 37 million acres (35 percent of the total) were possibly drained with underground tile or the newer types of plastic tube drains (table 11-2, fig. 11-2). Gains in subsurface systems in relation to surface drainage since 1960 can be attributed to much improved equipment and material, lower maintenance costs, and minimal land loss for underground drainage. Other technological advances, like laser-beam grade-control devices, have made both methods of drainage and other land-shaping activities more cost-efficient (van Schilfgaarde, 1971; Donnan and Schwab, 1974).

Information was inadequate to permit a breakdown of surface drainage improvements by whether they are intended to simply dispose of excess precipitation and runoff or, as subsurface systems are usually designed, to regulate water tables as well as improve surface drainage. Program data from USDA agencies going back to 1940 combined with general trends noted in historical census statistics were the main basis for separating and analyzing surface and subsurface systems (USDA, 1981a,b,c). For this survey, deep ditches used for water table control, as in the Mississippi Delta and coastal areas where tiling is not feasible, were regarded as surface drains.

Condition and Redrainage Potentials

Knowledge of the age and changing condition of drainage systems is as important as of the total area drained. The changing condition of artificial surface and subsurface drainage was determined in terms of "undepreciated drainage." That term refers to surface systems (12 million acres in 1985) installed or reinstalled during the previous 20 years, the assumed average useful life for surface drainage improvements. Undepreciated underground (subsurface) drains were regarded as those installed in the previous 40 years, the assumed average life for subsurface drains installed since 1940. These benefited about 27 million acres in 1985 (table 11-2).

One should not conclude that surface drainage more than 20 years old and subsurface systems more than 40 years old are no longer effective and thus of no value to farmers or other landowners. For example, the area drained in 1985 with surface systems was nearly 72 million acres. This had two parts: the 12 million acres with relatively new or only partly depreciated surface improvements (those made since 1965), plus another 60 million acres of fully depreciated improvements, or those made before 1965 (table 11-2).

Likewise, the area with subsurface drains in 1985 was nearly 38 million acres, of which 27 million acres represented systems installed since 1945. The remaining 11 million acres with subsurface drains had been drained before 1945. From the standpoint of condition, therefore, the relatively new drainage systems on U.S. farms are weighted more than 2:1 in favor of subsurface drains (27 million acres versus 12 million acres).

Potential redrainage needs and opportunities for redesign change continuously over time (fig. 11-3). As of 1985, potential redrainage included 61 million acres drained by surface improvements installed before 1965, plus the 11 million acres with subsurface drains installed before 1945. Redrainage introduces additional questions, of course, such as how to improve total water management on existing wet soils now in farms, as contrasted with natural wetlands, with joint consideration of erosion control, irrigation, and drainage and their economic benefits and costs.

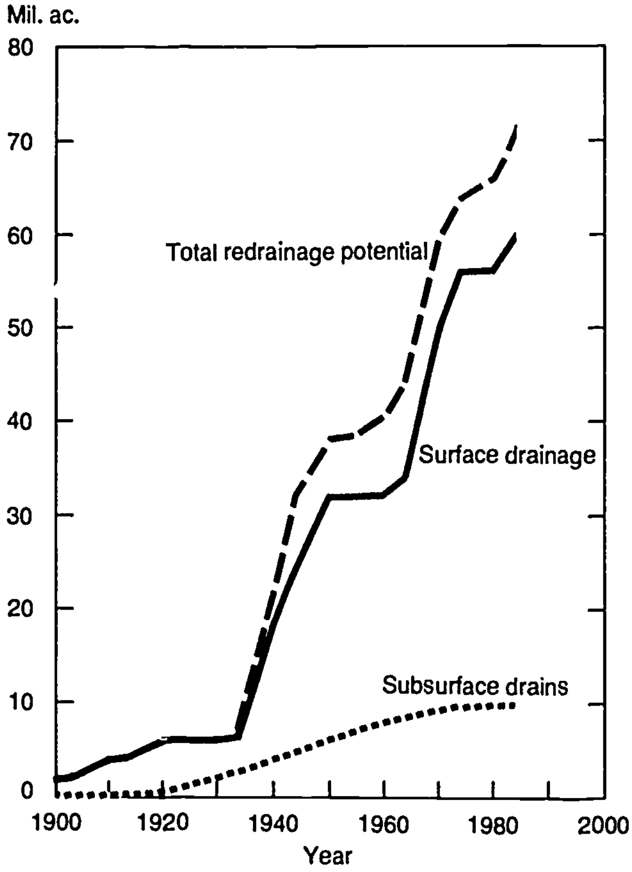


Figure 11-3—Land potentially redrained on U.S. farms, 1900-85.

Investment and Drainage Cost

Tangibly and economically, drainage investments include: (a) depreciable land improvements made to facilitate the removal of excess water from fields, either to simplify tillage operations or increase productivity, and with surface bedding, ditches, or buried concrete pipe, clay tile, or plastic and other tube drains; (b) durable equipment needed for drainage, such as pumps and power units; and (c) any other durable collection and disposal works like sumps, outlet ditches, main channels, and other facilities, regardless of where located or by whom financed and operated.

In examining capital growth, investments in drainage were confined to initial equipment purchases, construction expenses, and other immediate costs. Future investments required along with maintenance and operating costs should be included in determining economic feasibility. The economic implications of "investment" applied to agriculture go far beyond individual farms and localities and can be explained in general terms.

Investment from both an overall economic viewpoint and the viewpoint of a farmer draining land can be expressed in terms of national production during a given year or other period of time. This production consists of all the newly available goods and services for which participants and production factors in the provisioning process earn some income. The value of the total output is represented by the total income thereby earned. Subtracting from the total output and income the goods and services purchased by consumers and government leaves three important items: net exports, newly available but unsold consumer goods, and newly available business goods not intended for individual personal consumption. In agriculture, the latter include farm buildings, machinery or other durable equipment assets, and land improvements like drainage systems. The income-yielding or other benefits inherent in these assets are deferred. They thus constitute investment (Stonier and Hague, 1956; Fox, 1964).

New buildings, equipment, and drainage improvements cause the net stock of agricultural capital to increase if they more than make up for depreciation or the wearing out or using up of existing capital. Thus, depreciation is sometimes called capital consumption (Fisher, 1930).

An example of a governmental drainage activity contributing to national income is a county's or public drainage district's acceptance of a contractor's bid to rehabilitate drainage channels serving agricultural lands. This is an agricultural investment, made by the community through its government. Individual farmers who install drains similarly invest. In addition to prospectively increasing farm production, reducing costs, and otherwise benefiting farm operations, investments by farmers immediately contribute to national output and national income.

Drainage cost is the dollar investment or capital expenditure required to install, reinstall, or repair a drainage system. It represents the economic value of the labor, materials, machine work, or other resources expended on drainage rather than some other use. This expenditure is part of the basis for determining economic feasibility and, if made, becomes a capital asset. In the net present value (NPV) appraisal method, drainage is justified economically if installation cost is less than the discounted capitalized value of all expected future benefits of drainage less associated operating and maintenance expenses. The discounting allows for risk as well as time preference considerations. Skaggs illustrated earlier this kind of benefit-cost analysis as applied to maximizing the expected net benefits or profits from farm drainage.

Another way to determine economic feasibility is to find which discount rate makes the expected future benefits of drainage exactly equal to the installation or investment cost. This rate is called the internal rate of return (IRR). If it is higher than known interest rates being earned on savings, paid on borrowed money, or possibly earned in some other investment opportunity for the farmer, then the investment in drainage is considered justified.

Not all investments in drainage meet the test of economic feasibility, especially if expected benefits did or do not materialize (Goldstein, 1971). The historical investments in drainage discussed here refer to actual investment.

Costs of Organization Service

Investment cost was explained above as the value of the resources needed to complete surface or subsurface drainage improvements on a given tract of land or, more exactly, for an added acre of land if the question is how much more land to drain. Investment by a drainage organization was regarded in the same manner, as the value of the resources required to extend project service to a given additional area and number of farms.

Gross new investment in 1985 dollars for each period beginning in 1855 was calculated by taking average investment costs per acre (deflated to 1985 price levels using available cost indexes) times the number of acres newly drained in each period. The deflated cost per acre is the "real" cost of investing in drainage.

The real investment required to provide an added acre of drained land with organized project service did not appear to change much after about 1915. The real service cost in 1985 was $225 per acre. Project cost refers to the added gross investment, by drainage organization, historically associated with a 1-acre net increase in the area reported drained in a given year within project service areas.

In the primary developmental stage of drainage, 1870-1920, the real cost of providing organization service was considerably higher than in 1985. In 1900, it was $345 per acre. Project costs declined because of scale economies and because of improvements in ditching machinery and a more thorough understanding of the physics of drainage (van Schilfgaarde, 1971).

Costs of Drainage on Farms

The average investment cost of open or other surface drainage was about $140 per acre in 1985. About 72.4 million acres were then improved for surface drainage. The real cost of surface drainage improvements appears to have fluctuated over time, ranging from $225 per acre in 1900 to the low of $125 per acre in 1950. It rose to $210 per acre by 1970 but by 1985 had again declined to $140 per acre. These costs exclude timber clearing or other land reclamation activities often associated with drainage development.

The investment needed to install subsurface drains on U.S. farms averaged about $415 per acre in 1985. About 37.3 million acres were then drained this way. This cost was only about half the per-acre real cost estimated for 1965. Notable declines in the real cost of subsurface drains have resulted from such technological advances as continuous corrugated plastic tubing, improved manufacturing methods and materials, improved distribution and marketing, and advances in field installation techniques and construction equipment. Laser-beam grade-control devices on trenching and other drainage equipment are notable examples (Donnan and Schwab, 1974; van Schilfgaarde, 1971).

Investment Trends

For both organized and independent farm drainage activity, long-term trends in investment parallel expansions in the area drained, but only in a general way, because of changes in prices and drainage technology. Nearly 46 million acres of newly drained land were added to organization service areas during 1900-20 (table 11-1). In 1985 dollars, organization investment averaged $320 million per year during this primary development period.

The rate of new investment by drainage organizations peaked at $460 million per year during 1905-10. During 1910-30, it dropped back to around $300 million per year. It was very low during the Depression through World War II. During 1945-60, investment by drainage organizations recovered to about $75 million per year. It continued around this level until 1980. It fell to about $50 million per year during 1981-85.

Rather large areas were newly improved with surface drainage up until 1920 and again between 1940 and 1970 (table 11-2, fig. 11-2). Investments in actual as well as real dollars increased sharply after World War II because of newly stimulated project activity, better yet more costly drainage methods, and higher costs for materials.

Excepting an apparent lull during 1915-25, farmers in the United States have installed new tile, plastic, or other subsurface drains at a steady rate. A sharp increase in both surface and subsurface drainage followed World War II. The area improved because surface drainage increased by 875,000 acres per year during 1945-80, compared with 425,000 acres per year improved with subsurface drains (table 11-2). However, investments in subsurface drains averaged $465 million per year during 1945-80, compared with $190 million per year for surface drainage. This increase occurred despite the much higher per acre cost of subsurface drains. One factor was that subsurface drainage had become more cost-effective, both absolutely and relatively. Absolute gains in cost effectiveness for subsurface drains occurred because their actual installation cost did not rise as rapidly as prices in general. Relative gains for subsurface drains occurred because their real cost per acre declined in relation to the real cost of surface drainage.

Growth of Drainage Capital

The buildup of drainage investments over time becomes a stock of drainage capital, much like an irrigation reservoir creates a stock of water by impounding runoff. Thus, any drainage improvement can be regarded as involving prior investments and sacrifices in consumption in exchange for future production and other benefits.

The accumulated real investments in drainage for the United States were measured as accumulated annual investments indexed (deflated) year by year to a particular base year, chosen here as the year 1985. The indexing was necessary to allow for changes in investment rates due simply to changes in the prices of materials, labor, and other input factors. The indexed or constant-dollar investments recognize that changes have occurred in materials and methods as well as in the area drained.

Drainage works and improvements were also valued terms of the hypothetical cost of replacing them at a particular time, regardless of when they were built or made. This concept of value is not as theoretical as it may appear. It is a common basis for insurance coverage and an important barrier to replacing obsolete or deteriorated improvements.

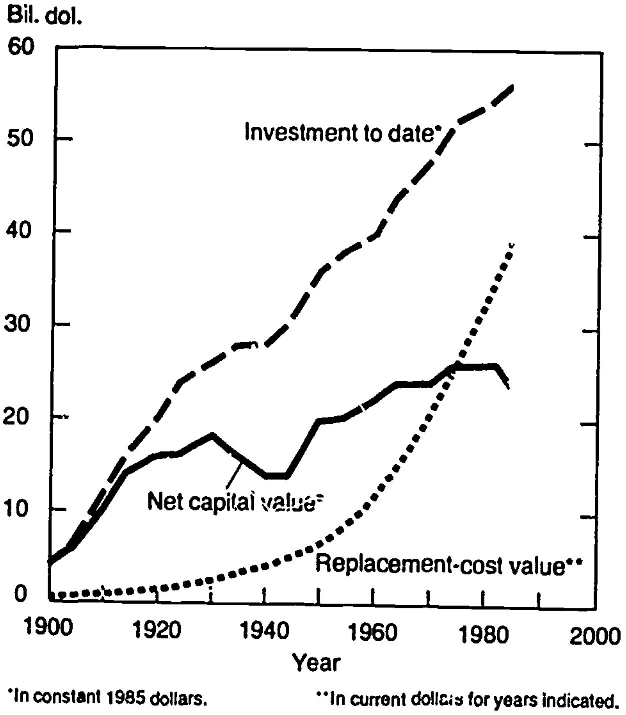


Figure 11-4—Drainage investment and capital in U.S. agriculture, 1900-85.

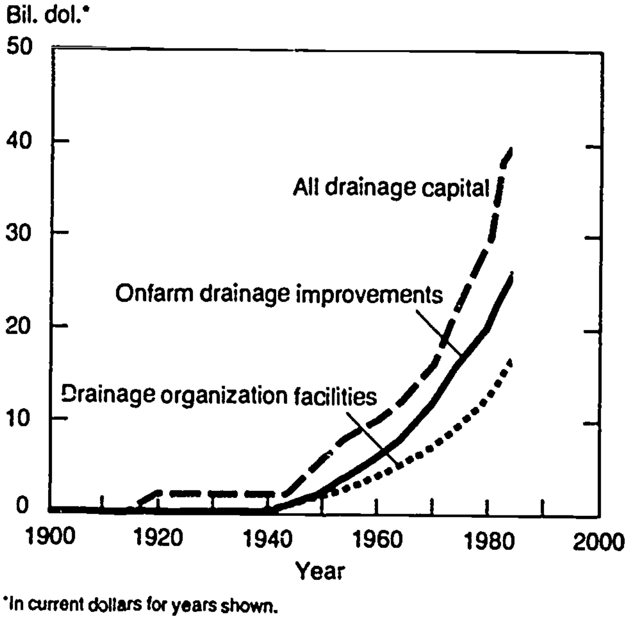


Figure 11-5—The net value of U.S. organization and onfarm drainage facilities, 1900-85.

Net capital value was also estimated. As the sum of all past net investment, it grows or declines with the yearly rate of net investment. The yearly net investment rate is the yearly total investment less depreciation allowances. Calculated net capital values for drainage improvements represent actual market value only to the extent a drainage market exists. In practice, farm drainage improvements are essentially fixed to the land and become an integral component of land value. Organization outlets or other community facilities may also be capitalized into the value of the benefiting private lands.

How historical investment and depreciation have affected the status of drainage capital from 1900 to 1985 is shown in figure 11-4. One curve represents all accumulated U.S. investments in drainage as of 1900 up to 1985, indexed to 1985 dollars. Another curve represents the cost of replacing all existing drainage improvements as of any previous year, and at the costs prevailing in that year.

The third curve shows how aggregate net capital values in constant (1985) dollars have changed during 1900-85. The aggregate net capital value of all drainage capital is the value of organization facilities and farm drainage improvements still in use after deducting all accumulated depreciation on farm improvements from all accumulated investments. Changing net values of organization facilities and onfarm drainage improvements for 1900-85 are in figures 11-5 and 11-6. Figure 11-7 is a similar division of replacement-cost values as of the years indicated.

During 1981-85, gross and net investment in drainage in the United States fell off along with other types of agricultural investment. The area surface-drained increased an average 202,000 acres per year. The average yearly increase for subsurface drains was 475,000 acres. In 1985 dollars, total new investment declined to about $40 million per year for surface systems and $200 million per year for subsurface systems. The average yearly investment from 1981-85 for all new onfarm drainage ($240 million) was less than half the average for 1976-80 ($508 million). For drainage organizations, investment between 1981-85 averaged about $50 million per year. This was assumed to be about the same as the rate between 1976-80 and went mostly for maintenance.

Status of Drainage in 1985

The general status of drainage and capital values for the United States in 1985 was as follows: the net area drained for agriculture and forestry in rural areas was 110 million acres, of which about

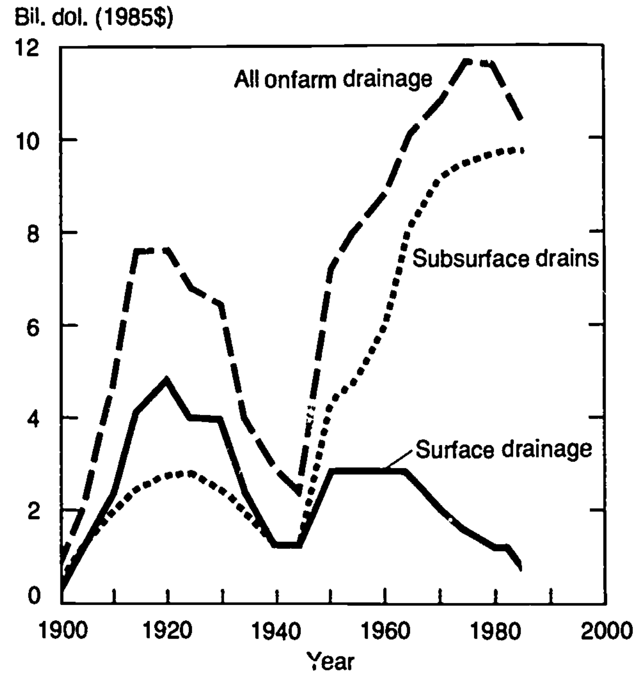


Figure 11-6—Net value of drainage improvements on U.S. farms, 1900-85.

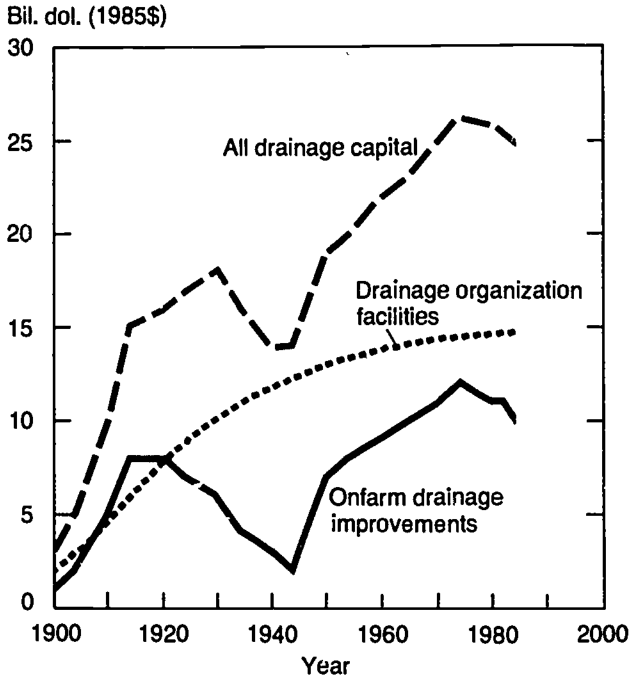


Figure 11-7—Replacement-cost value (current dollars) of drainage capital in U.S. agriculture, 1900-85.

65 million acres were served by drainage organizations and 45 million acres were drained independently. Figure 11-8 shows percentages of all land and cropland drained in the various States.

The accumulated total investments in drainage since 1855 were $56 billion (1985 dollars). The combined net value of all drainage assets in agriculture in 1985 was about $25 billion, $15 billion (60 percent) for organization property and $10 billion (40 percent) for onfarm systems (table 11-5).

Nearly 90 percent of the net value of farm drainage improvements was represented by subsurface drains. They accounted for about 34 percent of all drained land but for 70 percent of the 38 million acres of land having relatively new drainage improvements. The newer systems were on 16 percent of the land with surface drainage and on 72 percent of the land having buried drains. About 11 million acres (28 percent) of the subsurface drains may have needed replacement and modernization while 61 million acres (84 percent) of the surface drainage may have needed redrainage.

Having to replace all drainage works and improvements in the United States in 1985 would have cost about $40.3 billion, $14.7 billion (36 percent) for organization works and facilities and $25.6 billion (64 percent) for farm improvements. The $40-billion cost of reproducing all drainage assets in 1985 was, numerically, nearly equal to the net cash income from farming received by all farmers.

Potential redrainage cost, the cost of replacing fully depreciated drainage improvements was about $12.9 billion in 1985, including $8.5 billion for surface and $4.1 billion for subsurface drainage. As of 1985, fully depreciated improvements included the surface drainage improvements made before 1965 and subsurface drains installed before 1945.

Federal Financial Assistance

While the Federal Government actively aided in the rehabilitation of major outlet ditches and other drainage organization facilities during the 1930's (see Beauchamp segment), the Federal role in financing new drainage improvements on farms has been relatively minor and declining. As of 1985, less than 10 percent of all existing surface or subsurface drainage improvements could be attributed to Federal financing provided under the Agricultural Conservation Program (ACP) starting in 1944. For the years 1944-83, the area benefiting from ACP assistance was divided 80 and 20 percent between surface and subsurface drainage, while financial assistance was divided 40 and 60 percent between surface and subsurface drains (USDA, 1981b,c).

Financial assistance under the ACP as well as technical planning assistance provided by SCS was cur-

Table 11-5—Rural land drainage in the United States, 1985; areas drained, capital values, and potential redrainage costs

Item	Onfarm drainage improvements	Drainage organization facilities	All farm drainage
		Dollars	
Average 1985 costs per acre	235	225	370
Surface drainage on farms	140	—	—
Subsurface farm drains	415	—	—
		Thousand acres	
Area drained or served	109,680	65,260	109,680
Surface drainage	72,400	—	72,400
Subsurface farm drains	37,280	—	37,280
Area potentially redrained	71,500	—	71,500
Surface drainage	60,950	—	60,950
Subsurface farm drains	10,550	—	10,550
		Millions (1985 dollars)	
Total investment, 1855-1985	41,400	14,700[1]	56,100
Surface drainage	17,800	—	17,800
Subsurface farm drains	23,600	—	23,600
Net capital value, 1985	10,000	14,700[1]	24,700
Surface drainage	900	—	(900)
Subsurface farm drains	9,100	—	(9,100)
Replacement-cost value, 1985	25,600	14,700	40,300
Surface drainage	10,100	—	(10,100)
Subsurface farm drains	15,500	—	(15,500)
Potential redrainage costs, 1985	12,900	—	12,900
Surface drainage	8,500	—	8,500
Subsurface farm drains	4,400	—	4,400

— = either not applicable, negligible, or not estimated in this and later tables.

[1] Investment and capital values for organization facilities include $7.9 billion in maintenance allowances up to 1985.

tailed as early as in 1956 if new land was being brought into production. By the 1960's, Congress or USDA agencies had ruled out assistance for draining wetlands considered vital to waterfowl and other wildlife. For the 1975-77 period, U.S. farmers reported that only 4 percent of the cost of installing new or maintaining existing drainage improvements was financed through ACP cost sharing or by FmHA loans. Further, about 82 percent of all drainage expenditures were self-financed by farmers (Lewis, 1982).

In 1983, Federal cost sharing for farm drainage totaled only $75,000, down to 0.05 percent of all cost sharing provided under the ACP. Assistance with drainage in 1983 went to 37 participating farmers in 12 States. Two-thirds of the payments were for underground drainage systems, mostly in New York and Ohio. The remaining one-third was nearly all for land shaping or grading to improve surface drainage in Mississippi, Arkansas, Colorado, and Louisiana (USDA, 1984). Drainage assistance under ACP is now prohibited unless it is a necessary element of an erosion control, water-quality, or environmental system of practices.

Drainage Capital in Land

In 1985, the estimated market or capital value of all U.S. farm real estate was $690 billion, about $90 billion for farm homes or nonresidential buildings and structures and $600 billion for land (Jones and Barnard, 1985). As estimated above, the net capital value in 1985 of all agricultural drainage works and improvements on and off farms was nearly $25 billion. Replacement-cost values totaled over $40 billion, $15 billion for drainage organization facilities and $25 billion for onfarm drainage systems.

Depending on whether investments in drainage are expressed in terms of their net value ($25 billion) or their costs of replacement ($40 billion), they ranged between 4 and 7 percent of the market value of U.S. farmland in 1985. This supposes that sellers of farm or other rural real estate subjectively incorporate in their asking prices at least the net or depreciated

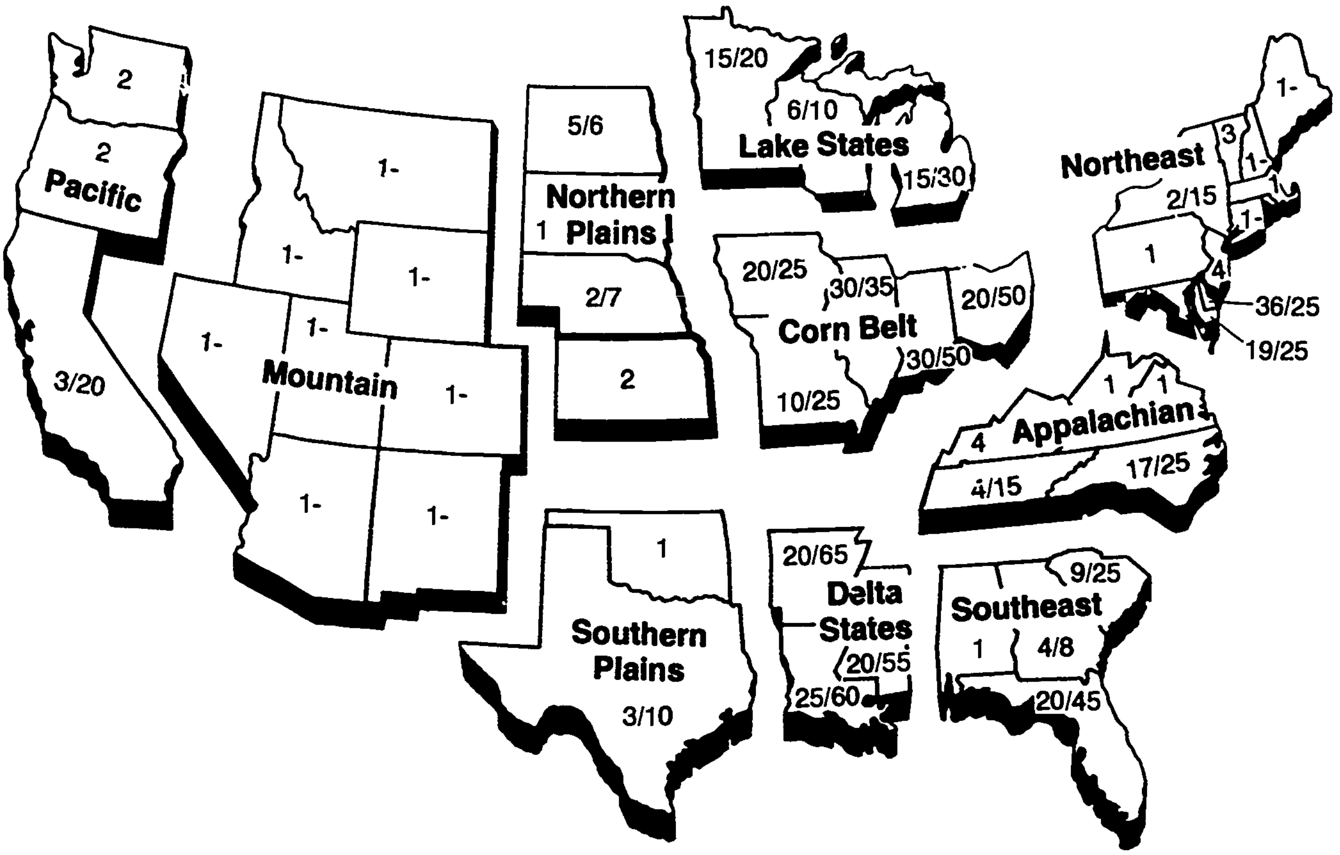


Figure 11-8—About 5 percent of all land and 24 percent of cropland is drained in the 48 contiguous States. The first numeral is the percentage of all land drained in a State. The second numeral is the percentage of all cropland drained in 1985 in the 23 drainage States.

value and perhaps the full replacement-cost value of drainage and other improvements, including accessible drainage outlets or other facilities belonging to drainage organizations.

Drainage needs, drainage methods, and drainage investments vary widely across regions among the States. Accordingly, drainage capital values relative to total land values and related economic data are estimated separately for 23 leading drainage States (table 11-6 and 11-7). These States had about 1 million or more acres of drained land in 1985, or at least 25 percent of their total area of cropland drained. Included are areas drained with open (surface) ditches only, areas having subsurface drains with required surface improvements, and areas benefiting directly from mains and laterals. The total for New York also includes about 50,000 acres of wet cropland soils benefiting from diversion terraces or similar improvements that serve a drainage function (Stamatel, 1986).

Information on organized, independent, and surface and subsurface drainage on farms for the 23 leading drainage States and remaining States as a group is in table 11-6, along with an estimated allocation for 1985 of capital values between surface and subsurface drainage systems. Proportions of cropland drained are also based on data from the 1982 inventory. For example, roughly 50 percent (6.2 million acres) of Ohio's cropland (12.5 million acres) was prime (drained) cropland having wet soils. The inventory also indicated that an additional one-third (4 million acres) of the cropland in Ohio needed drainage improvements (Nolte, 1986). National potentials for additional drainage are not in table 11-6 but are discussed further in the following chapter.

In table 11-7, drainage capital values are estimated and related to the value of farmland in different States. Drainage net capital as a percentage of the total value of farmland (col. 5) appeared to be highest in Michigan (20 percent), followed by Indiana, Ohio, Illinois, Louisiana, Iowa, Delaware, Minnesota, and Mississippi. The drainage improvements were first valued on a net basis and then a replacement basis and compared with farmland values. On a replacement-cost basis, the relative percentages in table 11-7 are greater, but the State rankings are not materially changed.

Table 11-6—Rural land drained in the United States in 1985: Percentages of wet soils and cropland drained and percentages by type of service and drainage methods

States[1]	Total land drained	Cropland drainage		Organized drainage service[4]	Subsurface drains[5]	Subsurface share of onfarm value[6]
		Share of all drainage[2]	Share of all cropland[3]			
	1,000 acres	Percent				
Illinois	9,795	90	35	50	85	95-99
Indiana	8,085	85	50	80	70	85-95
Iowa	7,790	90	25	60	85	95-99
Ohio	7,400	80	50	85	65	80-95
Arkansas	7,085	75	65	45	1	1-1
Louisiana	7,015	55	60	70	1	1
Minnesota	6,370	75	20	80	20	40-80
Florida	6,290	45	45	60	5	20-60
Mississippi	5,805	60	55	55	1	1-1
Texas	5,760	55	10	65	10	25
Michigan	5,515	70	30	85	60	80-95
North Carolina	5,400	45	25	25	15	35-75
Missouri	4,240	70	25	65	10	10-25
California	3,015	90	20	85	80	90-98
North Dakota	2,365	95	6	65	10	15-30
Wisconsin	2,245	45	10	65	30	55-90
South Carolina	1,755	60	25	20	10	15-50
Georgia	1,545	35	8	20	15	40-80
Maryland	1,210	75	30	35	20	40-80
Tennessee	1,150	55	15	25	25	30-70
Nebraska	1,005	80	7	45	10	10-40
New York	915	90	15	10	50	75-95
Delaware	460	70	25	55	10	20-60
Leading States	102,215	70	25	60	35	60-90
Other States	7,465	30	1	40	20	40-80
United States	109,680	70	20	60	34	60-90

---

[1] Leading States are listed separately, in decreasing order of the total land drained as estimated from both the 1978 Census of Drainage and the 1982 National Resources Inventory (NRI) and then adjusted proportionately to the national total for 1985 in tables 11-1 and 11-5.

[2] Cropland drained generally considers the greater of (a) cropland wet soils considered prime cropland or (b) wet soils in crop use not considered to need drainage, as based on State totals in the 1982 NRI. This estimate for drained cropland in a State is then taken as a percentage of all drained land in col. 1.

[3] Cropland drained in relation to all cropland in the 1982 NRI; cropland areas for 1982 closely approximate those also reported for 1982 in Frey and Hexem (1985).

[4] Approximate percentage of the area drained on farms using drainage organization outlets or other disposal facilities; also see note [2], table 11-1.

[5] Estimated as the maximum percentage of drained land having subsurface drains, based on 1982 NRI data for different land uses and wet soils drained. Pasture, forest, and miscellaneous rural land are assumed to be essentially all drained with open (surface) systems; subsurface drainage systems are assumed to be limited largely to cropland, although surface systems are also used on cropland.

[6] The lower percentage is based on 1985 replacement-cost values of subsurface in relation to all onfarm drainage improvements. The higher percentage is based on the net depreciated value of subsurface in relation to all onfarm drainage improvements in 1985.

Table 11-7—Land drained and drainage in the United States in 1985, with net and replacement values in relation to land values

States	Total land drained	Value of drainage capital: Net value[1]	Value of drainage capital: Replacement value[2]	Replacement value per acre[2]	Drainage capital in relation to land value[3]
	1,000 acres	*Million dollars*	*Million dollars*	*Dollars*	*Percent*
Illinois	9,795	3,155	4,775	485	10-15
Indiana	8,085	2,825	4,095	505	15-25
Iowa	7,790	2,655	3,940	505	8-12
Ohio	7,400	2,420	3,540	480	15-25
Arkansas	7,085	815	1,730	245	5-15
Louisiana	7,015	1,230	2,130	305	10-20
Minnesota	6,370	1,490	2,350	370	7-10
Florida	6,290	985	1,795	280	5-10
Mississippi	5,805	805	1,550	265	8-15
Texas	5,760	1,080	1,850	315	1-2
Michigan	5,515	1,880	2,725	495	20-30
North Carolina	5,400	550	1,270	235	5-10
Missouri	4,240	730	1,280	300	4-7
California	3,015	1,120	1,605	530	2-3
North Dakota	2,365	430	735	300	3-5
Wisconsin	2,245	500	815	365	4-7
South Carolina	1,755	150	380	205	3-8
Georgia	1,545	145	350	225	1-3
Maryland	1,210	160	315	245	3-7
Tennessee	1,150	150	305	265	1-3
Nebraska	1,005	130	255	255	1-1
New York	915	185	330	300	2-5
Delaware	460	70	130	285	7-14
Leading States	102,215	23,660	38,250	375	5-9
Other States	7,465	1,040	2,050	275	1-1
United States	109,680	24,700	40,300	370	4-7

---

[1] Includes value of drainage works and facilities provided by drainage districts, county drains, and other organizations, and the net depreciated value of all onfarm drainage improvements.

[2] All onfarm and organization drainage facilities and improvements are included in calculating replacement cost values and average replacement cost values per acre.

[3] Farmland values net of buildings are in Jones and Barnard (1985). The lower percentages are the net depreciated value of all drainage facilities and improvements for the State(s) relative to total farmland value. The higher percentages value drainage capital in terms of its replacement cost.

These indicators of the importance in 1985 of drainage in the farm capital structure of individual States are not claimed to be highly precise, nor should they be taken as measures of drainage benefits as such. They do tend to be higher in States more dependent on public drains and where onfarm subsurface drains predominate, especially if the improvements are valued on a net or depreciated basis.

The dependence on drainage organizations as well as drainage methods used on farms differ by region, and also by States within regions. In terms of area, surface drainage was more common than subsurface drainage in 1985 in all leading drainage States other than Illinois, Indiana, Iowa, Ohio, and Michigan (table 11-6). However, because of their long life and greater installation cost, subsurface drains accounted for most of the capital value of on-farm drainage, nationally and for most States. Notable exceptions are Arkansas, Louisiana, and Mississippi. In these States, open and other forms of surface drainage were still the norm in 1985, in terms of net and replacement values as well as area (table 11-6, col. 6).

Differences in Cost

Variations in capital values based on replacement costs have some practical uses for anticipating the probable cost (marginal cost) of additional drainage in individual States. Costs can be expected to be higher if subsurface drains are involved and/or where organization outlets are necessary than where surface drainage not using public outlets is common (table 11-7, col. 4). The average costs per acre given for various States would approach actual field costs to the extent the probabilities of the additional drainage being surface or subsurface or requiring group outlets correspond to existing patterns of systems and drainage methods, such as those indicated in table 11-6. But however figured, State averages are not substitutes for carefully determining marginal drainage costs in specific cases.

Drainage in the Humid East

Research by Irwin (1979), Skaggs and Nassehzadeh-Tabrizi (1983), van't Woudt and Hagan (1975), Smedema and Rycroft (1984), and numerous other investigators indicates that correcting poor drainage condition improves the yield of nearly all field and fruit crops. Broadly speaking, the expected longrun benefits vary with expected farm prices, production costs, climate, soils, and hydrology. Within a field to be drained, the benefits or installation costs also depend on such design factors as the depth and spacing of the drains and actual rainfall conditions.

Dideriksen and others (1978) have reported that 25 percent of the value of all U.S crops sold comes from artificially drained land. At a regional level, some shares they gave for drained land were 75 percent for cotton and soybeans from the Delta States, 40 percent for corn and soybeans from the Corn Belt, and 40 percent for oats, barley, and hay produced in the Lake States. As these shares are equal to the shares of cropland drained, they presume equal average productivity for drained and other cropland.

An important related question examined here was whether localities in the generally humid Eastern United States with fairly large fractions of their cropland drained tend to be more productive and exhibit higher real estate values than surrounding areas with smaller proportions of their land drained. Such economic differences cannot be credited entirely to differences in drainage intensity. The differences favoring drainage are believed to be on the conservative side, however, because the comparisons are between different levels of drainage intensity, not between drained land and undrained land with drainage problems. Such ideal comparisons on a broad scale were not feasible for this review.

To recognize various soil and climatic conditions and numerous combinations of farming enterprises, the analysis covered all 2,006 reporting counties in the 31 Eastern States, for which necessary census information was available on drained land, farm production, and land values.

The Census of Drainage for 1978 was used first to identify those counties in the humid East with high concentrations (percentages) of drained land (U.S. Dept. Commerce, 1981). The criterion for "high drainage" varied rather arbitrarily from State to State (fig. 11-9). It ranged from at least 5 percent of a county's land area drained in New England and upper Northeast States like New York and Pennsylvania to 40 percent of the land drained in heavily drained States like Indiana, Ohio, Illinois, Louisiana, and Florida. On this procedure, 307 eastern counties were identified as being highly drained. (See figure 11-9.) A few counties were included where the percentage of land drained was low but where the land drained in a State was most concentrated.

For 1978, an average of 44 percent of the land was drained in the 307 counties highly drained. Some in

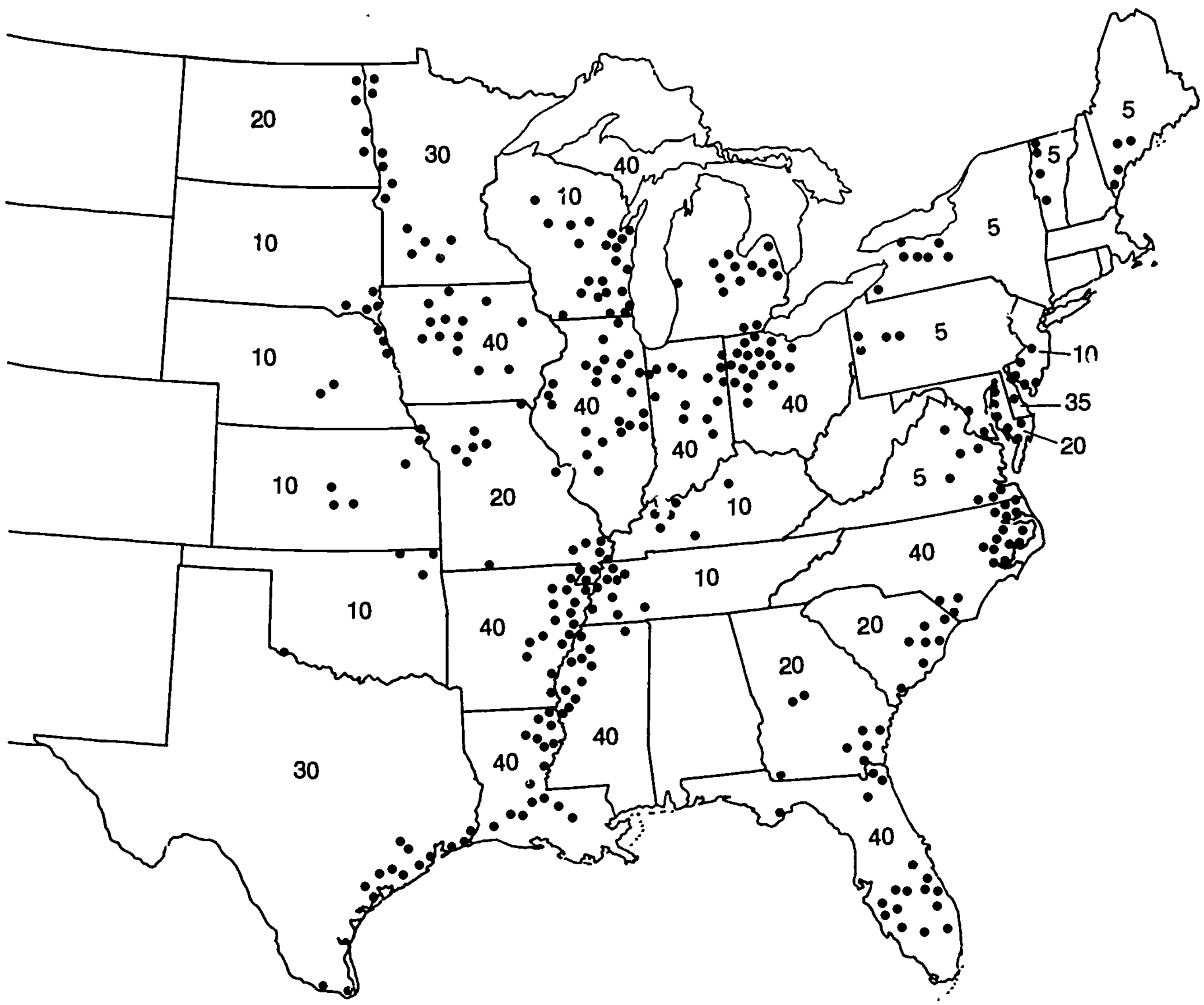


Figure 11-9—More than 300 eastern and Great Plains counties have relatively high concentrations of land drained. Numerals show the minimum percentage of land drained in the counties designated by dots.

the Corn Belt and Delta regions were virtually 100-percent drained. Collectively, the 307 counties had 57 percent of all drained land in the 31 Eastern States, which in turn had 82 percent of all land drained in the United States. The balance was mostly in Texas (5 percent), California (3 percent), and North Dakota (2 percent).

The 1982 Census of Agriculture was then used to examine land use, marketing receipts, and real estate values for the 307 highly drained counties compared with the 1,699 other eastern counties, some of which also have substantial areas drained (U.S. Dept. Commerce, 1984). However, comparisons of real estate values per acre between the highly drained and other counties were restricted to 256 predominantly agricultural counties to minimize the biasing influence of nonagricultural factors on farm real estate values near urban centers.

Crop and Livestock Enterprises

The 307 highly drained eastern counties included 15 percent of the total land area in all the Eastern States. However, they contained 22 percent of the land in farms and 29 percent of the cropland harvested. In 1982, they accounted for 32 percent of the value of all crops sold on eastern farms, and for 19 percent of the livestock or livestock products sold. Crop sales per acre of crops harvested for the 307 highly drained counties averaged 67 percent higher than for the other counties. An average of 44 percent of the farmland was drained in highly drained counties compared with 6 percent in the less-drained counties.

Crop and livestock production indexes for highly drained counties in relation to other counties for different Eastern States and regions were computed

Table 11-8—Production and land values in highly drained counties in relation to other counties, in the Eastern United States, 1982

Regions and States (total reporting counties)[1]	Highly drained counties[2]	Production indexes		Land value indexes[4]	
		Crop sales	Livestock sales	In relation to less highly drained	In relation to State average
	Number	*Percent*[3]		*Percent*[4]	
Northeast (244)	34/28	146	12	128	120
Maine (16)	4/2	64	355	129	124
Vermont (14)	4/4	92	135	88	97
New York (63)	7/7	211	76	124	132
New Jersey (21)	4/0	138	71	—	—
Pennsylvania (67)	4/4	41	49	90	91
Delaware (3)	2/2	83	4,590	—	100
Maryland (23)	9/9	159	198	103	106
Appalachian (469)	47/43	175	79	119	115
Virginia (99)	8/6	237	111	127	124
North Carolina (100)	17/17	151	43	106	105
Kentucky (120)	11/19	—	—	128	124
Tennessee (95)	11/11	195	64	103	103
Southeast (337)	32/23	202	58	138	131
South Carolina (46)	8/6	254	54	126	120
Georgia (159)	8/7	115	74	101	101
Florida (65)	16/10	372	72	114	107
Delta (220)	49/43	288	21	125	114
Mississippi (82)	13/13	316	81	123	116
Arkansas (75)	18/17	420	6	138	119
Louisiana (63)	18/13	166	18	104	102
Lake (240)	48/36	132	107	117	113
Michigan (83)	16/12	116	85	141	121
Wisconsin (71)	21/13	168	136	140	126
Minnesota (86)	11/11	139	48	102	102
Corn Belt (496)	97/36	160	81	132	123
Ohio (88)	19/15	150	92	127	118
Indiana (92)	23/21	113	93	117	111
Illinois (102)	26/20	130	73	126	117
Iowa (99)	14/13	178	38	127	122
Missouri (115)	15/14	323	55	146	136
31 Eastern States (2,006 counties)	307/256	167	78	127	120

— = not available.

[1] Regional totals include data for unlisted States and those with no highly drained counties.

[2] The number before the slash is the total number of highly drained counties in the region or State as of 1978. The number after the slash is the number of highly drained predominantly farm counties; it excludes highly drained counties classed as nonagricultural, urban, or agricultural-urban by the Bureau of the Census.

[3] Crop and livestock product sales per acre of land in farms computed from the 1982 Census of Agriculture. Indexes are per acre sales for the highly drained counties in relation to per acre sales for the less-drained counties in the State and region.

[4] Land values per acre for highly drained farm counties in relation to average values for farm counties not highly drained and then in relation to the average for all farm counties in the State and region.

(table 11-8). The production indexes indicate the extent to which gross farm income was derived from crops and livestock products in the highly drained counties compared with other counties. Average crop and livestock product sales per acre were weighted by total sales volume as well as total areas in farms.

In Arkansas, for example, crop sales for 1982 in 18 highly drained counties averaged $168 per acre of land in farms. The average for the 57 other counties in Arkansas was $40 per acre, giving a ratio of 4.2 ($168/$40) or a 420-percentage index favoring drainage. Sales of livestock and poultry products averaged $10 per acre in the highly drained counties compared with $162 per acre in the other counties, giving an index of 6 percent ($10/$162). Crop production in Arkansas is clearly concentrated in the counties most heavily drained, namely those toward the Mississippi River. Other counties are geared more to livestock and poultry production.

In 12 other Eastern States, crop sales per acre in highly drained counties ranged from 105-370 percent of crop sales for the less-drained counties. These States were Florida, Missouri, Mississippi, South Carolina, Virginia, New York, Tennessee, Iowa, Wisconsin, Louisiana, Maryland, and Ohio (table 11-8).

Crop production in 1982 appeared to be less important in counties with more drained land than in other areas of Maine, Vermont, Pennsylvania, and Delaware. These States are important for dairy, poultry, and other livestock as well as crop production. The extreme livestock product index (4590) for the two highly drained counties in Delaware (Kent and Sussex) can be attributed to their concentrated poultry industry, which depends in part on locally grown feed crops produced on drained land.

States where both crop and livestock production tended to be concentrated in counties that have extensive areas drained were Maryland, Virginia, and Wisconsin. For these States, the crop sales and livestock sales indexes in table 11-8 both exceeded 100 percent.

Total Farm Production

Combined crop and livestock product sales per farm acre are a measure of average resource productivity among different farms and producing areas. Comparisons between highly drained and other counties in the Eastern States suggest that total sales per acre were greater for counties with larger amounts of drained land. Drainage appeared to be most correlated with total farm output in 12 States: Delaware (index = 235), Maine (212), Mississippi (189), Maryland (184), South Carolina (161), Virginia (157), Missouri (146), Wisconsin (142), Vermont (132), and Ohio, Iowa, and Tennessee (122). These indexes express average total farm product sales per acre for the highly drained counties as a percentage of the average for counties with less land drained.

A precaution on these indexes is that they do not fully allow for the fact that, in many localities, agriculture would not be possible without drainage. Wet soils are more productive when drained. They may be either more productive or less productive than other soils with good natural drainage. This factor partly explains the fairly low indexes for leading drainage States like Louisiana, North Carolina, Arkansas, Michigan, and Indiana. The analysis was conducted across regions and States to compensate for limiting the comparisons to a single crop year like 1982.

Land Value Influences

Real estate values are a measure of the capitalized net economic returns expected from land as a factor of production, along with related buildings or other structures. Real estate values in 1982 for 256 highly drained and predominantly agricultural counties in the East averaged 27 percent more (index 127) than values for the 1,422 other agricultural counties (table 11-8).

Real estate values per acre in the 14 most intensively drained farm counties in Missouri ran an average of 46 percent higher than in Missouri's other 93 agricultural counties. Additional States with relatively high land value indexes for the counties most drained included Michigan (141), Wisconsin (140), Arkansas (138), Maine (129), New York (124), Kentucky (128), Virginia, Ohio, and Iowa (all 127), and Illinois and South Carolina (126). These indexes express average real estate values per farm acre for the highly drained and predominantly agricultural counties as a percentage of the average for agricultural counties with less land drained. All averages were weighted according to total areas in farms and total farm real estate values for the two groups of counties in each State.

Drainage appears to strongly influence farm real estate values in the Southeast. Values per acre in 1982 in the 23 highly drained agricultural counties in South Carolina, Georgia, and Florida ran 38 percent more than in their 252 other farm counties, 53 of which are in Alabama. Alabama and some other Eastern States are not listed in table 11-8 because they have no counties with at least 5 percent of the land area drained for agriculture.

Drainage appeared to positively influence land values in all eastern regions and States listed in table 11-8, except Vermont and Pennsylvania. Farm real estate values between highly drained and other counties were not compared in New Jersey, because its four highly drained counties also happen to be highly urbanized.

Average real estate values per farm acre for the highly drained farm counties as a percentage of averages for all farm counties in a State were also computed (table 11-8). Because average land values for States are published at fairly frequent intervals, these indexes would be useful for estimating land value differentials in dollars for highly drained counties under market conditions where their land values per acre tended to change proportionately with those for other counties

Separate values for land and buildings would improve these comparisons but were not available for counties. This was possible earlier in relating drainage investment to farmland values for leading drainage States (table 11-7). Irwin (1979) computed net land values in determining whether Ontario farmers wishing to increase production should acquire additional land or should tile-drain existing wet soils. While the net economic benefits of the expansion or drainage alternatives were not calculated, Irwin found that tile drainage was only 10-60 percent as costly as purchasing additional land in Ontario in 1979, depending on the county.

Changing Feasibility of Drainage

Commodity prices, production costs, drainage costs, and land values change both absolutely and in relation to each other from year to year. The same is true of associated environmental benefits or disbenefits. Thus, the economic feasibility of drainage must be determined on a case-by-case basis at a particular time by farmers and other decisionmakers, with respect to the benefits and disbenefits or other costs of concern to them.

Data on production and land value differences for highly drained counties or other areas are useful for explaining different rates of drainage development among regions. Those data also help identify areas where economic pressures for added drainage may be the greatest. For example, the ratio in 1985 of added onfarm benefits to drainage per dollar of field installation cost (B/C ratio) averaged about 0.90 for the 307 highly drained counties studied in 25 Eastern States. In 1982 the average B/C ratio for the East was near 1.30; in 1978 it was 1.40.

These ratios take as added costs per acre average U.S. surface and subsurface drainage installation costs in table 11-5 adjusted to the average State replacement costs in table 11-7. Added benefits are approximated as average land value differentials from the 1982 census (table 11-8) adjusted according to changes in yearly land values reported by ERS (Jones and Barnard, 1985; USDA, 1986). The drop in the overall eastern B/C ratio from 1.30 in 1982 to 0.90 in 1985, and to 0.75 in 1986 was mainly attributable to falling land values.

Drainage costs increased by 10 percent from 1982-86 while benefits fell by about 35 percent. Farm real estate values in the East had risen from an average of $935 per acre in 1978 to $1,360 per acre in 1982. By 1985, they had fallen by 25 percent and by 1986 by 35 percent (to $920 per acre) from 1982 levels.

In 1985, there were nine Eastern States where the farm-level B/C ratio for added drainage was at least 1.0, including Arkansas (ratio = 1.90), Missouri (1.75), Kentucky (1.65), Virginia (1.37), Mississippi (1.32), South Carolina (1.30), Wisconsin (1.14), Michigan (1.07), and Florida (1.05). Note the predominance of the Mississippi Valley and Southern States in this listing. In 1986 the B/C ratio was 1.0 or more in only seven of these States: Missouri (1.60), Kentucky (1.60), Arkansas (1.55), Virginia (1.45), South Carolina (1.25), Mississippi (1.20), and Florida (1.0).

Between 1982 and 1986, the "average" B/C ratio for drainage in Missouri fell from 2.85 to 1.60. It fell from 1.38 to 0.78 in Ohio, from 1.35 to 0.57 in Iowa, for 1.30 to 0.70 in Illinois, and from near 1.0 to 0.50 in Indiana. Between 1982-86, the average B/C ratio for the Corn Belt region dropped from 1.35 to 0.70, while in the Lake States it fell from 1.20 to 0.75.

Drainage and National Policy

Comparing production and land values for highly drained and other counties in the Eastern States was not an argument for converting remaining wetlands to agricultural uses through drainage and associated clearing or other land reclamation activities. If economically feasible, drainage is still a recommended practice on wet soils, as contrasted with wetlands. As already noted, the preservation of wetlands with their wildlife and other environmental values has been national policy in USDA and other Federal agencies since the 1950's.

The Food Security Act of 1985 denied price support and other farm program benefits to producers who use converted wetlands for producing annual crops. The possible effects of such legislation on conversion decisions by farmers and others were recently examined by USDA in another report (Heimlich and Langner, 198[illegible] An earlier study by Goldstein (1971) dealt with similar questions.

Heimlich and Langner analyzed after-tax net income in representative situations, considering conversion costs, benefits with and without price supports, capital gains, and tax liability. They found, for example, that withholding price supports may discourage decisions of farmers to drain wetlands in some situations, but not if capital gains and other tax advantages are a primary motive for conversion by farmers or other owners of wetlands.

The Food Security Act of 1985 also required USDA to develop plans and give technical assistance to property owners, agencies of State and local governments, and interstate river basin commissions for the protection of both the quality and quantity of subsurface waters and also for the control of salinity in agriculture. The buildup of salts in poorly drained irrigated soils, saline or contaminated drain waters leaving irrigated areas but used again elsewhere for irrigation or wildlife, and rising water tables from irrigation demonstrate that irrigation and drainage are interrelated aspects of water management in agriculture, especially in arid regions.

Drainage and Irrigation

Water management systems that can be used for drainage as well as subirrigation as needed were stressed earlier as an important technological development, especially for organic types of soils common in the Southeast and Mississippi Delta regions.

In addition to containing 57 percent of the drained land in the East in 1982, the 307 highly drained counties discussed above also contained more than half (3.9 million acres, 52 percent) of the 7.6 million acres irrigated in the East. Arkansas, Florida, Louisiana, Missouri, Mississippi, Georgia, and New Jersey have large areas drained and large areas irrigated (compare figs. 11-1 and 11-10). In 1978, the land reported drained plus that reported irrigated easily exceeded all the reported land in farms in 37 of the 92 highly drained counties in these States. Data from the 1982 inventory indicate that 85 percent of the cropland irrigated in Louisiana appears to be land that is also drained (fig. 11-10). Mississippi, Missouri, and Florida follow with 80 percent, 70 percent, and 60 percent, respectively.

The Great Plains States present a contrasting situation. Of the 649 counties in the six central Plains States, 37 are highly drained and comparatively humid (fig. 11-9). Note that 14 are in the gulf coast area in Texas, where average annual rainfall varies between 25-50 inches. Average rainfall is at least 20 inches for all of the 28 other highly drained counties in the Great Plains.

In 1982, crop sales per acre in farms for the 37 highly drained counties in the Great Plains States averaged 3.5 times the average for the 612 other counties. Farm real estate values per acre tended to be about 90 percent higher in Plains counties with substantial areas of drained land compared with other counties. Livestock product sales per acre for the highly drained counties were only 55 percent as much as in the other counties. However, these comparisons involve humid versus semi-arid climates more than different intensities of drainage under uniform climatic conditions.

Drainage and the Irrigated West

The Great Plains States are a transitional region in other respects. In 1985, they had almost 12 million acres of drained land. This was over 10 percent of the national total of 110 million acres. California, North Dakota, Nebraska, and Texas were among the 22 States leading in drainage (table 11-6, fig. 11-8). Drainage is mostly on an organized basis in these and other Western States, especially where it is necessary to prevent or correct soil salinity and rising water tables in irrigated areas. Luthin and Reeve (1957) indicate that the chief causes of salinity and drainage problems in irrigated soils and for affected local and other areas are unfavorable soil conditions restricting percolation, excess water application, and seepage from irrigation canals, ditches, and rivers. They cite studies of the Bureau of Reclamation which indicated that 25 percent of the water entering unlined canals was lost before reaching farmers' fields.

In 1978, about 400 of the 7,360 irrigation organizations in the 17 Western States and Louisiana maintained 17,500 miles of irrigation drains. California led with 4,400 miles, followed by Texas (2,500 mi.), Washington (2,100 mi.), Idaho (1,400 mi.), Montana (1,350 mi.), Wyoming (1,300 mi.), and Oregon (1,000 mi.) (U.S. Dept. Commerce, 1982). About 60 percent of the drains benefited irrigated lands within projects originally constructed by the Bureau of Reclamation but paid for and now operated by water users organized as districts.

Lining irrigation supply canals and ditches can also correct or prevent seepage-related drainage problems, in addition to conserving water and reducing maintenance costs. Water savings result from reductions in canal seepage and transpiration from undesirable vegetation in or adjacent to ditches and canals. In 1978, there were nearly 15,000 miles of lined irrigation canals in the West. This was an increase of nearly 25 percent since 1969 (U.S. Dept. Commerce, 1973, 1982). While 75 percent of the newly lined canals were in California, lining activity increased sharply in Oregon, New Mexico, Nevada, Nebraska, Idaho, and Colorado.

The drainage investment and capital estimates given earlier (table 11-7) could be divided only roughly between drainage associated or not associated with irrigation, based primarily on leading drainage States that also have large areas irrigated. These include California, Nebraska, Texas, Arkansas, Florida, and Louisiana. In 1985, these six States accounted for about 22 percent of all U.S. land drained, and for at least $5.4 billion (22 percent) of the net national investment in drainage (table 11-7). They accounted for 70 percent of the cropland irrigated, and for nearly 85 percent of the 19.3 million acres of irrigated cropland drained (1982 data).

The estimated capital value in 1985 of drains on irrigated farms and those drains managed by irrigation organizations in these six States was at least $2.5 billion; this was around 45 percent of their investment in drainage. The percentage for California was over 90 percent. The U.S. investment in irrigation drainage was at least $2.9 billion. This represented an estimated 10 percent of all drainage capital and an estimated 6 percent of all irrigation capital. These tentative estimates consider the proportion of drainage capital specific to irrigation in a State to be at least equal to the proportion of all drained land in irrigated crops in the 1982 inventory. (Also see tables 11-6, 11-7, and U.S. Dept. Commerce, 1973.)

The percentages of irrigated cropland drained in the leading irrigation and drainage States are in figure 11-10. The average was nearly 25 percent for the 17 Western States and Hawaii. Percentages for the Eastern States refer only to the proportion of all irrigated cropland having wet soils that have been drained.

Drainage, water conservation, and related management needs on irrigated lands are not confined to the States with established irrigation economies. In the 1982 inventory, drainage treatment or other strategies for better water management were considered primary treatment needs on 19.5 million acres of irrigated land in the United States. This was between 32-44 percent of all cropland irrigated on U.S. farms in 1982 (table 11-9). About 16.3 million acres (84 percent) of the irrigated land needing treatment were in the 21 principal irrigation States.

The inventoried additional drainage and other water management needs on irrigated cropland are most reliable for three particular States: California (4.3 million acres), Texas (2.5 million acres), and Nebraska (1.8 million acres). Percentages of the irrigated cropland involved were 55 percent for California, 47 percent for Texas, and 30 percent for Nebraska.

Estimates for the Great Plains, Mountain, and Pacific regions each meet a similar reliability test; that is, the irrigated land requiring better water management, including drainage, equaled or exceeded 0.1 percent (1.5 million acres) of the nearly 1.5 billion acres of U.S. rural land covered by the 1982 inventory. Details for the U.S. production regions are in table 11-9.

Irrigation in Farm Production

Maintaining the productivity advantages of irrigation through proper soil drainage, minimizing the needs for scarce and costly water supplies, and controlling the off-site discharge of chemicals and other harmful agents in drainage effluent from irrigated lands are important economic and environmental goals, within as well as outside of agriculture.

Tradeoffs between these goals are inevitable because in many areas of the West irrigation is indispensable for sustained agricultural production. It is also an important contributor to the overall productivity of U.S. agriculture. To illustrate these points, information on land use and the value of

Table 11-9—Drainage and other water management needs on irrigated cropland in the United States, by regions and selected State groupings, 1982

Regions	Irrigated cropland[1]	Drainage treatment needs[2]	Irrigation water management[2]	Total water management needs on irrigated land	
				Area	Range
	1,000 acres				Percent[3]
Northeast	275	1	34	35	11-12
Appalachian	164	5	40	45	11-27
Southeast	2,086	240	690	930	30-45
Delta	5,695	1,170	535	1,705	30-33
Lake States	845	15	110	125	11-15
Corn Belt	828	175	225	400	32-48
Northern Plains	9,182	40	3,165	3,205	29-35
Southern Plains	5,695	150	2,445	2,595	25-46
Mountain	11,660	100	5,060	5,160	35-44
Pacific	10,885	580	4,755	5,335	43-49
21 irrigation States[4]	41,190	870	15,435	16,305	29-40
Other States (29)	3,243	1,605	1,625	3,230	62-100
United States[5]	44,433	2,475	17,060	19,535	32-44

[1] Irrigated cropland from the 1982 Census of Agriculture.

[2] Regional estimates of drainage and other water management needs on irrigated land developed from data in the 1982 National Resources Inventory.

[3] Except for the Delta region, the lower figures are total water management needs as percentages of irrigated cropland as reported in the 1982 Inventory. The higher figures are total water management needs as percentages of irrigated cropland as reported in the 1982 Census of Agriculture, or col. 4/col. 1. The opposite applies to the Delta region.

[4] The 21 irrigation States include the 17 western mainland States, Hawaii, Arkansas, Florida, and Louisiana.

[5] Includes Hawaii but not Alaska. The 1982 Inventory did not include Alaska.

agricultural products sold in 1982 has been assembled for the United States as a whole, for 29 States where irrigation is relatively less extensive, for the 21 principal irrigation States, and finally for 71 leading producing counties in these States (table 11-10). The 71 counties were among the 100 leading U.S. counties in the total dollar volume of farm products sold in 1978, but all land use and production data in table 11-10 are for the 1982 crop year. County rankings and county-level maps on total irrigated crops are available in special census reports (U.S. Dept. Commerce, 1985a,b).

In 1982, the 71 leading producing U.S. counties in the principal irrigation States accounted for nearly a third of the irrigated crops harvested in the United States. Recall that they were not chosen as leading in the area of irrigated land, yields per acre, or farm product sales per acre. Nevertheless, 73 percent of the cropland harvested in these counties was irrigated. In 1982, their crop sales averaged $625 per acre of crops harvested. This compared with averages of $135 per acre for other counties in the principal irrigation States, and $185 per acre for the 29 Eastern States where irrigation is less extensive. Livestock and livestock product sales per acre of cropland harvested were also generally higher in irrigated areas, as were real estate values.

Livestock product sales per acre of cropland harvested are, of course, biased upward if cropland is limited or the livestock depend primarily on grazing or purchased food. Offsetting this, however, is the fact that tame hays and other harvested feeds are important irrigated crops on many livestock ranches. Wyoming and Nevada are prime examples. In 1982, even the highly irrigated farms (those where all crops were irrigated) in Wyoming obtained 72 percent of their gross income from livestock rather than crop sales. In 1982, farms and ranches with at least some irrigated land accounted for 75 percent of all livestock-related sales in Wyoming and for 60 percent of all livestock sales in Nevada.

Farms or ranches in the principal irrigated and other States as two broad groups appear to be comparable in productivity as measured by crop sales per acre of crops harvested. The mix of livestock and crop enterprises in terms of dollar sales per acre of crops harvested is also about the same under irrigated and nonirrigated conditions, although, as observed above for Wyoming and Nevada, areas can differ widely in this regard.

Table 11-10—Comparative land uses, market values of products sold, and product sales per acre for leading irrigation and other States, United States, 1982

Item	United States	29 selected States[1]	21 Irrigation States: All 21 States[2]	21 Irrigation States: 71 leading counties[3]
		Million acres		
Selected land uses:				
Land in farms	986.8	298.3	688.5	57.2
Harvested cropland	326.3	166.1	160.2	19.4
Irrigated land in farms	49.4	3.4	46.0	16.1
Irrigated crops harvested	44.4	3.3	41.1	14.3
Irrigated pasture and other land	4.6	—	4.6	1.8
Drained land in farms	107.2	78.8	28.4	4.7
Irrigated cropland drained	19.3	2.7	16.6[4]	3.8[5]
		Billion dollars		
Market value of products:				
Total farm products sold	131.9	67.2	64.7	22.9
Crop sales	62.3	31.1	31.2	12.2
Livestock/livestock product sales	69.6	36.1	33.5	10.7
		Percent		
Irrigation and drainage percentages:				
Percentage of land irrigated on farms	5.0	1.1	6.6	28.1
Percentage of harvested cropland irrigated	13.6	2.0	25.7	73.7
Percentage ratio, drained to irrigated cropland	43.4	83.1	40.4	26.4
		Dollars		
Values and product sales per acre in farms:				
Value per acre of farm real estate[6]	825	1,340	595	1,468
Total products sold per farm acre	135	225	95	400
Crops sold per farm acre	65	105	45	215
Livestock products sold per farm acre	70	120	50	185
		Dollars		
Product sales per acre of crops harvested:				
Total products sold per acre	405	405	405[7]	1,180[8]
Crop sales per acre	190	185	195	625
Livestock product sales per acre	215	220	210	555

— = not available.

[1] Includes 29 States with relatively less irrigated land, such as Alaska and Eastern States other than Arkansas, Florida, and Louisiana.

[2] Leading 21 irrigation States include the 17 western conterminous States, Hawaii, Arkansas, Florida, and Louisiana.

[3] Leading counties are those 71 counties within the 21 irrigation States ranking among the 100 leading counties in the United States in 1978 in the total value of farm products sold; however, all census or other statistics are for 1982 (U.S. Dept. Commerce, 1985). Eight of the 71 counties are in Arkansas, Florida, or Louisiana; the other 63 are in the 17 Western States or Hawaii. Data for "nonleading" counties in the 21 irrigation States can be obtained by subtracting col. 4 from col. 3 in the first two sections and then taking similar averages.

[4] 9.1 million acres for the 17 western irrigated States and Hawaii, or 25 percent of the irrigated cropland.

[5] 3.2 million acres for the 63 leading counties in the 17 western irrigated States and Hawaii, or 23 percent of the irrigated cropland.

[6] Real estate values per acre are weighted averages developed from total land values and total land in farms available by States (Jones and Barnard, 1985).

[7] Averages if limited to the 18 western irrigated States are about the same as these.

[8] Respective per-acre averages if limited to 63 leading counties in the 18 Western States are $1,145 for total sales, $590 for crop sales, and $555 for livestock sales.

Concluding Note

This descriptive overview of drainage development, capital growth, and related economic questions does not assume that the factors historically or recently affecting drainage activities will hold in the future. However, the information is useful for several purposes:

- Explaining major changes in technical methods and relating these to the responses of farmers and drainage organizations,
- Estimating the costs and investment requirements associated with the redesign of existing drain systems,
- Discussing the social costs and the role of drainage in agricultural production, as an important element of land water resource management on farms as well as balanced environmental planning,
- Assessing remaining potentials for drainage consistent with public policy, and
- Improving the quality of statistical information about drainage, including the quality of administrative arrangements for collecting it.

References

Donnan, W. W., and G. O. Schwab. 1974. "Current Drainage Methods in the USA," *Drainage for Agriculture.* Monograph No. 17 (ed., Jan van Schilfgaarde). Am. Soc. Agron., Madison, Wisc.

Dideriksen, Raymond I., A. R. Hidlebaugh, and Keith O. Schmude. 1978. "Wet Soils for Crop Production in the United States," *Wetland Functions and Values: The State of Our Understanding.* American Water Resources Assoc.

Fisher, Irving. 1930. The Theory of Interest, New York: Kelly and Milliman.

Fox, Karl. 1965. *Intermediate Economic Statistics.* New York: John Wiley and Sons.

Frey, H. Thomas, and Roger W. Hexem. 1985. *Major Uses of Land in the United States: 1982.* AER-535, U.S. Dept. Agr., Econ. Res. Serv.

Gain, Elmer W. 1967. *Land Drainage for Production of Food and Fiber Crops.* Proceedings, International Conference on Water for Peace, Wash., DC. Vol. 7, pp. 451-461.

Goldstein, Jon H. 1971. *Competition for Wetlands in the Midwest: An Economic Analysis.* Resources for the Future, Inc. Baltimore: Johns Hopkins Press.

Harrison, Robert W. 1961. *Alluvial Empire: A Study of State and Local Efforts Toward Land Development in the Alluvial Valley of the Lower Mississippi River.* Little Rock, Ark.: Pioneer Press.

Heimlich, Ralph E., and Linda L. Langner. 1986. *Swampbusting: Wetland Conversion and Farm Programs.* AER-551. U.S. Dept. Agr., Econ. Res. Serv.

Irwin, Ross W. 1979. *On-Farm Drainage Benefit.* Final Report, OMAF Research Programs 39, Project A-39-742. Univ. of Guelph School of Engineering, Guelph, Ontario.

Jones, John, and Charles H. Barnard. 1985. *Farm Real Estate: Historical Series Data, 1950-85.* SB-738. U.S. Dept. Agr., Econ. Res. Serv.

Lewis, Douglas. 1982. *Land Drainage Investment Survey, 1975-77.* ERS Staff Report No. AGES820525. U.S. Dept. Agr., Econ. Res. Serv.

Luthin, James N., and Ronald C. Reeve. 1957. "Drainage of Irrigated lands," *Drainage of Agricultural Lands.* Monograph No. 7 (ed. James H. Luthin). Am. Soc. Agron., Madison, Wisc.

Nolte, Byron H. 1986. *Cropland Erosion and Drainage Status in Eastern Ohio.* Ohio State University, Columbus. Coop. Ext. Circular AGDEX 751/752. March.

Shaw, Samuel P., and C. Gordon Fredine. 1956. *Wetlands of the United States.* Circular 39, U.S. Dept. Interior, Fish and Wildlife Serv.

Skaggs, R. W., and A. Nassehzadeh-Tabrizi. 1983. *Optimum Drainage for Corn Production.* Technical Bulletin 274. North Carolina Agri. Res. Serv. N.C. State Univ., Raleigh.

Smedema, Lambert, and David W. Rycroft. 1984. *Land Drainage: Planning and Design of Agricultural Drainage Systems.* Ithaca, N.Y.: Cornell Univ. Press.

Stamatel, Henry. 1986. Assistant State Conservationist, SCS/USDA, Syracuse, N.Y. Personal communication, May 7.

Stonier, Alfred W., and Douglas C. Hague. 1956. *A Textbook of Economic Theory.* London: Longmans, Green and Co., Ltd.

U.S. Department of Agriculture. 1981a. Statistical Reporting Service. *Agricultural Statistics*. annual.

____________. 1981b. Agricultural Stabilization and Conservation Service. *Agricultural Conservation Program: 45-year Statistical Summary.*

____________. 1981c. Agricultural Stabilization and Conservation Service. *Practice Cost-Shares by States: 30-year Summary, 1944-74.*

____________. 1982. Soil Conservation Service, and Iowa State University Statistical Laboratory. *Basic Statistics, 1977 National Resources Inventory.* SB-686.

____________. 1984. Agricultural Stabilization and Conservation Service. Agricultural Conservation Program: Statistical Summary, 1983 Fiscal Year.

____________.1986. *Outlook and Situation Summary: Agricultural Resources*. April 9.

U.S. Department of Commerce, Bureau of the Census. 1932. *Drainage of Agricultural Lands, 1930.*

____________. 1942. *Drainage of Agricultural Lands: Land in Drainage Enterprises, Capital Invested, and Drainage Works, 1940.*

____________. 1943. *Drainage of Alluvial Lands: A Comparison of Agriculture Within and Outside of Drainage Enterprises in the Alluvial Lands of the Lower Mississippi Valley.*

____________. 1952. "Drainage of Agricultural Lands," *Census of Agriculture, 1950*. Vol. IV.

____________. 1961. "Drainage of Agricultural Lands. 1960," *Census of Agriculture, 1959*. Vol. IV.

____________. 1973. "Irrigation and Drainage on Farms," *Census of Agriculture, 1969*. Vol. II.

____________. 1973. "Drainage of Agricultural Lands," *Census of Agriculture, 1969*. Vol. II.

____________. 1981. "Drainage of Agricultural Lands," *Census of Agriculture, 1978*. Vol. 5.

____________. 1982., "Irrigation," *Census of Agriculture, 1978*. Vol. 4.

____________. 1984. "Geographic Area Series for States and Outlying Areas," *Census of Agriculture, 1982*. Vol. I, parts 1-54.

____________. 1985a. "Ranking of States and Counties," *Census of Agriculture, 1982*. Vol. 2: Subject Series, part 3.

____________. 1985b. "Graphic Summary," *Census of Agriculture, 1982*. Vol. 2: Subject Series, part 1.

van't Woudt, Bessel D., and Robert M. Hagan. 1957 "Crop Responses at Excessively High Moisture Levels," *Drainage of Agricultural Lands* (ed., James N. Luthin). Monograph No. 7. Am. Soc. Agron., Madison, Wisc.

van Schilfgaarde, Jan. 1971. *Drainage Yesterday, Today and Tomorrow*. Paper presented at ASAE National Drainage Symposium, Chicago, Dec. 6-7.

Weaver, M. M. 1964. *History of Tile Drainage in America Prior to 1900*. Waterloo, N.Y.: Private publication.

Chapter 12

Drainage Potential and Information Needs

Arthur B. Daugherty
Natural Resource Economics Division
Economic Research Service
USDA
University Park, Pennsylvania

Douglas G. Lewis*
North Carolina Department of Natural Resources and Community Development
Raleigh, North Carolina

Drainage is an important consideration when examining the quality of the land resource. Prospects for drainage are based on the drainage potentials or "needs" for various agricultural purposes as identified by SCS in its periodic inventories of the Nation's soil and water resources.

Remaining Drainage Potential

Major national data series do not contain a variable representing the continuum of drainage opportunities at a particular location. For the most part, they must be evaluated on a field-by-field basis. However, some information is assembled at the national level which gives an indication of additional drainage potentials on existing and potential cropland, but it is unclear at what points on the water management continuum a drainage system is called for and when agricultural use is considered inappropriate because of the degree of wetness.

The principal sources of information on remaining drainage potential have been SCS's periodic conservation and resource inventories (USDA, 1962 and 1971 and USDA, SCS, 1980). The most recent of these surveys is the 1982 National Resources Inventory (NRI).

Inventories Before 1982

The 1958 Conservation Needs Inventory (CNI) did not report drainage potentials as such. Instead, the area of cropland having excess water as either a dominant or secondary problem was reported. Excess water was defined as a high water table or temporary flooding which prevented or limited the use of conservation cropping systems or practices (USDA, 1962, p. 139). About 15 percent (60 million acres) of nonirrigated cropland had excess water as a dominant problem (table 12-1). Excess water was a secondary problem on an additional 12.5 million acres.

In the 1967 CNI, 43 million acres of nonirrigated cropland in tillage rotation were considered to have drainage problems. This area constituted about 10 percent of all nonirrigated cropland in tillage rotation in the 48 conterminous States and Hawaii.

The 1977 NRI reported 357.2 million acres of nonirrigated cropland in the same 49 States. Of this nonirrigated cropland, 36.5 million acres or about

---

*Formerly with the Economic Research Service, USDA, Raleigh, North Carolina.

10 percent had drainage problems. So, in 1977, the same percentage of nonirrigated cropland had drainage limitations as in 1967, indicating that the relative potential for drainage remained as great in 1977 as it was 10 years earlier.

The simple comparison in table 12-1 of the potential for drainage in 1958, 1967, and 1977 illustrates some of the definitional problems encountered when determining changes in drainage potentials over time. The 1958 CNI reported excess water as the dominant or secondary soil and water problem affecting cropland, but we do not know if excess water was comparable to requirements for a drainage system as assessed in the 1967 and 1977 inventories.

In 1967, the potential for drainage was estimated for nonirrigated cropland in tillage rotation. This definition excludes orchards, vineyards, bush fruits, and open land formerly cropped (USDA, 1971, pp. 10-11). However, the 1977 specification of possibilities for improving drainage on nonirrigated cropland appeared to be related to all cropland, including the categories that were excluded in 1967.

The 1982 National Resources Inventory

In the 1982 NRI, drainage potentials were reported for a wider range of land uses than in earlier inventories. About 25.2 million acres of nonirrigated cropland, 2.5 million acres of irrigated cropland, and 3.4 million acres not in crops had drainage problems. The latter figure included 2.4 million acres of pastureland, 300,000 acres of rangeland, and 700,000 acres of land in other minor uses in rural areas.

Table 12-1—Nonirrigated cropland having drainage problems inventoried in USDA surveys, 1958-77[1]

Survey	Soil and water conservation problem			
	Excess water, dominant problem[2]	Excess water, secondary problem	Drainage potential[3]	Total nonirrigated cropland
		1,000 acres		
1958 CNI	59,918	12,526	—	399,671
1967 CNI[4]	—	—	43,004	420,865
1977 NRI	—	—	36,511	357,166

— = not available.

[1] Data represent 48 conterminous States and Hawaii.

[2] Cropland with an excess water problem was defined as "... land on which excess water caused by a high water table or by temporary flooding prevents or limits the use of conservation cropping systems or practices." (USDA, 1962, p. 139).

[3] Drainage potentials in 1967 were defined as "... cropland on which an adequate drainage system is needed to remove excess surface or internal water" (USDA, 1971, p. 210). In the 1977 NRI, a potential for drainage was indicated where "... an adequate drainage system is needed to control erosion and/or to remove excess surface water or internal water" (USDA, SCS, 1977, p. 14).

[4] Data are for cropland in tillage rotation only (exclude orchards, vineyards, bush fruits, and other land formerly cropped).

Of the total 31.1 million acres of potential new drainage, 27.5 million acres, more than 88 percent were classified as land capability subclass "w" soils, where water in or on the soil interferes with plant growth or cultivation. In some situations, the wetness could be partly corrected by artificial drainage (USDA, Mar. 1981, p. 324). Of the nonirrigated cropland with a drainage problem, 22.5 million acres (89 percent) were subclass "w" soils. About 2.1 million acres (84 percent) of the irrigated cropland with drainage problems were subclass "w" soils. The area of potential drainage treatment made up more than 25 percent of all wet soils in cropland use in 1982.

Besides the 3.4 million acres in noncropland uses with drainage problems in 1982, additional drainage potential may have existed if the land use changed. For example, the NRI did not assess drainage situations for forestland in 1932. However, if forests were cleared and converted to crop use, undoubtedly some conversions would involve drainage of wetlands. More than 14 million acres of forestland with medium or high potential for conversion to cropland were subclass "w" or wet soils, some of which would also be classed as wetlands.

The NRI did not evaluate drainage opportunities as such for potential cropland. However, it considered soil and water problems which would inhibit or prevent the conversion of land to crop uses. Two such problems or limitations were "common flooding" (an NRI term), and also "wetland types 1-20," as defined by Shaw and Fredine (1956).

About 12.2 million acres that have medium or high potential for use as cropland were wetlands and/or had common flooding as the primary or secondary soil and water problem. Table 12-2 presents the combination of these problems of primary and secondary importance. For this discussion, all other soil and water problems were aggregated into one category. Nearly 10 million acres suffered common flooding, and another 2.1 million acres were wetland types 1-20. In addition, 241,000 acres had common flooding as a secondary soil and water problem, and 239,000 acres were classified as wetland types 1-20 as a secondary problem, each with some other primary problem.

About 500,000 acres of the 12.2 million acres of medium- and high-potential cropland, which had either a flooding problem or were wetlands, needed drainage treatment in their present, noncropland use (pasture, range, or other minor uses). This left 11.7 million acres of medium- or high-potential cropland with a possible potential for drainage.

About 1.6 million acres were in 1 of the 20 wetland types but had no secondary soil and water problem affecting conversion to and use as cropland. This area, about 1 percent of the medium- or high-potential cropland, seemed to have the greatest potential for drainage. While land with combinations of problems and/or suffering from flooding may benefit from drainage, the net benefits may be less relative to areas suffering from only a wetness problem.

The NRI showed that the remaining potential for farm drainage in the United States ranged between 31.1 and 42.8 million acres. In the lower range was inventoried land drainable in its use at the time. The upper range included land having medium and high potential for conversion to cropland that was one of the wetland types and/or land that had a common flooding problem but was not identified as requiring drainage in its use at the time.

Table 12-2—Soil and water problems with all land of medium and high potential for cropland inventoried in the 1982 National Resources Inventory

Primary soil and water problem	Secondary soil and water problem				
	None	Wetland types (1-20)	Common flooding	Other problems	Total
			1,000 acres		
None	91,165	0	0	0	91,165
Wetland types (1-20)	1,605	72	211	224	2,112
Common flooding	7,571	1,112[1]	57	868	9,608
Other problems	34,714	239	241	14,644	49,837
Total[2]	135,056	1,422	509	15,736	152,722

[1] This figure indicates that about 12 percent of the 9.6 million acres of convertible land with common (frequent) flooding can also be considered to be 1 of the 20 wetland types. Frequent flooding in itself is not an identifying characteristic of wetlands. The total area of land where a wetland designation is either a primary or secondary problem in conversion is thus about 3.5 million acres (2.112 + 1.422 mil. ac.).

[2] Items may not sum due to rounding.

Achieving new drainage depends on a number of economic and institutional factors. Some of these can be estimated by or for the individual farmowner or operator, such as the benefit from a positive production response or a reduction in production costs. Other factors may not be determined so specifically. These include the necessity for group action for drainage water removal and the acquisition of any permits from Federal or State agencies needed for installing drainage improvements. Any drainage of potential cropland must be consistent with present and prospective public policies concerning production levels and resource conservation, including wetland preservation.

Drainage Information

Examination of drainage accomplishments and prospects is constrained by the availability of reliable data relevant to drainage of agricultural land. Virtually all historical drainage information comes from three primary sources: the Census of Agriculture; program reports of USDA agencies; and periodic special surveys of drainage. Drainage data from the Census of Agriculture reflect two general sources: data collected directly from farm operators and data collected from organized drainage districts. SCS and ASCS publish program reports which summarize their technical assistance and cost-sharing on drainage.

Census of Agriculture Data

Census data on drainage date from 1920. Drainage data were collected from farm operators and from public or private organizations engaged in cooperative drainage enterprises. Drainage enterprises were defined as "... public and private corporations and local improvement districts organized to secure the drainage of land for agricultural purposes...." (U.S. Dept. of Commerce, Bureau of the Census, 1922, p. 348). Drainage enterprises were generally synonomous with drainage districts, a term more commonly used in recent censuses.

In 1920 more than 53 million acres out of a total of 956 million acres of U.S. farmland were provided with some form of drainage. An additional 39 million acres were reported to have drainage problems. Data were also collected on the number of farms reporting drainage, land use on land in drainage enterprises, miles of ditches and tile drains in drainage enterprises, and total capital invested in drainage enterprises.

Data collection in the 1930 Census of Agriculture was comparable to the 1920's except for the change in land use information on drained land. Farm operators reported drainage on 44.5 million acres, a decline from 1920's levels. However, over 66 million acres within drainage enterprises were drained sufficiently to produce a normal crop, more than compensating for the decline reported by farm operators.

The 1940 Census of Drainage was the first which excluded individual farm operators and focused data collection entirely on cooperative drainage enterprises. The number of reported projects declined from 1930 to 1940, but the area within their boundaries increased slightly to 87 million acres. More than 75 million acres received sufficient drainage for a normal crop at a capital investment of $692 million. The slight increase in total investment and the facilities of ditches and tile drains represented by that investment was made despite the general economic depression of the time.

Data on drainage enterprises are relatively consistent regarding method of collection and content from 1920 through 1940. However, several procedural changes began in 1950. The main changes were: drainage enterprises under 500 acres were excluded, drainage enterprises absorbed by a later project were not enumerated, and the data on enterprises under common management were consolidated into one report. The geographic area considered expanded with each Census.

Comparability of data was probably significantly affected by the addition or deletion of States, which can be accounted for, and by excluding enterprises of 500 acres or less, which can only be estimated. About 5 percent of the land in drainage enterprises would have been deleted from the 1940 total had this rule then applied. The number of separate drainage enterprises would have decreased by 53 percent.

Almost 103 million acres were reported as net land drained in 1950 within drainage enterprises. While published on the same line as land in drainage enterprises from the previous three Censuses of Drainage, the reports are not necessarily comparable because not all land within the boundary of a drainage enterprise was artificially drained. The lands may have received some benefit, however, when artificial drainage on adjacent land enhanced the natural drainage patterns.

The 1950 Census marked a change in the financial data collected. In Censuses before 1950, all capital investment accumulated prior to the census date was requested. Investment data for the 1950 Census referred only to investments made during the preceding decade. Annual revenue data were also collected and combined with beginning and ending indebtedness and operation and maintenance costs to construct an approximate equation of the financial status of drainage enterprises for the decade. This was an effort to separate new capital investment from operation and maintenance costs and to identify total tax revenue.

The 1960 Census of Drainage did not include data from projects where land was drained solely because of irrigation. The total area in drainage projects serving agricultural lands was 101.9 million acres in 1960. This total excluded about 3 million acres of drained irrigated land and 6 million acres of swamp and wasteland counted in 1950. Thus, the remaining 92.3 million acres were predominantly agricultural lands benefiting from artificial drainage within drainage projects.

Drainage data collection in the 1970's marked a partial return to earlier procedures. Data were collected from farm operators in the 1969 Census of Agriculture and from drainage projects via the 1972 Census of Governments. Data covered all 50 States for both censuses and were reported as part of the Census of Agriculture. Farm operators responding to the 1969 Census reported draining nearly 60 million acres. Analysts agree that the 1969 and the 1974 estimate (42.8 million acres) greatly understated the total drained. Considerable data available from the Census of Governments detailed the number of project employees, debt, expenditures, and revenues.

The most recent published data on drainage come from the 1978 Census. Data on land drained were collected in yet another manner because of the poor quality of the 1974 Census reports. State and county SCS officials estimated land benefiting from artificial drainage for individual counties which was combined with financial and employment data from drainage districts obtained in the 1977 Census of Government. The 1978 estimates of land drained within each county totaled about 105.3 million acres. Financial data were shown for only one fiscal year in both the 1972 and 1977 Census of Governments.

Table 12-3 summarizes the geographic coverage and data acquisition of the Census Bureau from 1920 to

Table 12-3—Sources of Census Bureau drainage data and States, per selected year

Year	Number of States	Census of drainage enterprises	Census of Governments	Census of Agriculture	Cooperation with SCS
1920	34	X		X	
1930	35	X		X	
1940	38	X			
1950	40	X			
1960	39	X			
	37		X		
1969[1]	50		X	X	
1974	50			X	
	29		X		
1978	50		X		X

X = Drainage data available by year and source.

[1] Census of Governments data are for 1972 but are used in conjunction with data from the 1969 Census of Agriculture.

1978. This is widely regarded as the current best source of data regarding land drained in the United States.

Sources of drainage data and coverage are not consistent nor are methods and procedures of data collection. Another problem is that specific data items have changed from one Census to the next. The total information from these data resembles a mosaic with missing parts. Analysts must use these data with caution because perceptions about the status and trends of artificial drainage of agricultural land are necessarily a function of the data. Poor data can lead to poor perceptions and faulty conclusions.

Agency Program Reports

ASCS has administered the Agricultural Conservation Program (ACP) since 1936. The objective of the ACP had been to encourage adoption of approved conservation practices by providing cost-sharing incentives to landowners. Cost sharing is based on the judgment that the benefits tend to be widely dispersed while the costs are borne by the landowner. Local SCS technicians provided landowners with the technical assistance necessary to install the approved conservation practices.

Each year, ASCS and SCS compile a summary of their cost sharing and technical assistance activities. During 1944-73, the total acreage drained to permit conservation farming under ACP was 54.1 million acres. Funds used for cost sharing for drainage for the same period totaled $356.7 million. These data are incomplete because not all onfarm drainage was installed under the ACP program. Further, the cost share total reflected only an unknown proportion of the total cost of the installation of facilities. Landowners provided the balance of funds necessary to complete the project from their own resources. Cost-sharing proportions were usually unavailable in aggregate form for the period.

SCS data were limited to miles of open ditches and tile drains installed each year. The exception was the cooperation given to the Census of Agriculture in 1978 when local SCS personnel estimated the total land drained in their county. It is difficult to combine miles of tile and ditches with other data to describe in a meaningful way the status of agricultural land drainage because the data do not define quantity, quality, or cost of the investment without making some arguable assumptions.

Periodic Special Surveys

SCS conducted national inventories of soil and water conservation problems and possible treatments in 1958 and 1967. Similar data were collected in the 1977 and 1982 NRI's. ERS used a subsample of the 1977 NRI to estimate the extent of drainage investments during 1975-77.

The objectives of the SCS inventories differed from the previously described data sets. While the Census data and agency reports painted a picture of what had been accomplished regarding agricultural land drainage, the inventories described what remained to be done. Land capability is described in terms of limitations, such as excess water. This limitation has a presumed but not a necessary relationship to drainage, for example, drained lands do not have the limitation of excess water. These data help assess the potential for drainage but cannot describe the current status of agricultural land drainage.

The 1982 NRI will facilitate estimates of subsurface drains, field ditches, and main ditches installed as a conservation practice. Only three practices per point can be listed, so drainage may be deleted in favor of three other practices. It is not clear how the existence of underground drainage is to be detected or if only drainage as a "conservation practice" is counted. No provision is made for the collection of collateral economic data.

ERS's Land Drainage Investment Survey was a follow-on survey to the 1977 NRI. ERS collected data on land drained, type of drainage, and total investment for 1975-77. About 29 million acres were affected by drainage investments in the United States during the 3-year period. Almost 6.5 million acres were drained by new systems and 22.5 million acres were drained by additions to existing drainage during the 3 years.

Conclusions on Drainage Information

Perceptions about the status and trends of artificial drainage of agricultural land are a function of the extent and quality of drainage data. Existing information tends to give an incomplete picture of land drainage. Although Census data are widely used as the authoritative source of drainage information, such information has been based at various times on the Census of Agriculture, the Census of Drainage, the Census of Governments, and SCS estimates. Not all farm operators know what part of their land is drained, nor do drainage district or SCS personnel. Published Census reports acknowledge the double counting of some drainage while some land is overlooked. Although the definition of drainage has changed little over time, specific data items have changed as have definitions of the relevant universe, such as what constitutes a farm, whether to include drained irrigated land, and public versus private drainage enterprises. It is not possible to assess the effectiveness of existing systems so it is implicit in the data that all systems remain equally effective in removing excess water.

Another problem is that new drainage investments cannot be separated from maintenance expenditures. Some data, the number of drainage district employees, for example, are of questionable usefulness in evaluating the status or trends of agricultural drainage.

ASCS and SCS reports are limited to program participants and include only the cost-sharing portion of total investment. Some data are reported in units which cannot be meaningfully integrated with other data sets. The periodic surveys tend to address drainage remaining to be done rather than drainage which has been done. The exceptions are the 1982 NRI and the 1975-77 trend data from the 1978 Resource Economics Survey.

Given these limitations, use agricultural land drainage data with caution. Changes in policies and institutions affecting drainage certainly change the benefits and costs of draining, both to the individual and to society at large. Greater attention to societal interests makes the information needed for decision-making more complex. In short, increased efforts and expenditures to improve data collection are needed to ensure a more accurate "mosaic" describing agricultural land drainage, and thus more rational private drainage investments and public policy decisions.

References

Shaw, Samuel P., and G. Gordon Fredine. 1956. *Wetlands of the United States*. Circular 39. U.S. Dept. Interior, Fish and Wildlife Serv.

U.S. Department of Agriculture, Agricultural Stabilization and Conservation Service. 1981. *Agricultural Conservation Program, 45-year Statistical Summary, 1936-1980.*

___________. 1975. *Practice Cost-shares by States: 30-year Summary, 1944-1974.*

___________. *Agricultural Conservation Program: Statistical Summary*, annual.

___________, Economic Research Service. 1982. *Land Drainage Investment Survey, 1975-77: A Report on Landownership Follow-on Survey*. ERS Staff Report AGES820525.

___________, Soil Conservation Service. 1977. *Erosion Inventory, Instructions for the PSU and Point Data Collection*. June.

___________. 1980. *Basic Statistics-1977 National Resource Inventory.*

___________. 1962. *Basic Statistics—National Inventory of Soil and Water Conservation Needs*. SB-317. August.

___________. 1971. *Basic Statistics—National Inventory of Soil and Water Conservation Needs, 1976.* SB-461. January.

___________. 1981. "Soil and Water Resources Conservation Act, 1980 Appraisal." *Soil, Water and Related Resources in the United States: Status, Condition, and Trends*. March.

U.S. Department of Commerce, Bureau of the Census. 1922. "Irrigation and Drainage," *U.S. Census, 1920*, Vol. VII.

__________. 1930. "Drainage of Agricultural Land," *U.S. Census, 1930.*

__________. 1942. "Drainage of Agricultural Lands," *U.S. Census of Agriculture, 1940.*

__________. 1952. "Drainage of Agricultural Land," *U.S. Census of Agriculture, 1950,* Vol. IV.

__________. 1961. "Drainage of Agricultural Land," *U.S. Census of Agriculture, 1959,* Vol. IV.

__________. 1973. "Drainage of Agricultural Lands," *U.S. Census of Agriculture, 1969,* Vol. IV.

__________. 1977. "Irrigation and Drainage on Farms," *U.S. Census of Agriculture, 1974,* Vol. II, part 9.

__________. 1981. "Drainage of Agricultural Lands," *U.S. Census of Agriculture, 1978,* Vol. 5, special reports, part 5.

Chapter 13

Drainage Challenges and Opportunities

Fred Swader
Extension Service, USDA
Washington, DC

George A. Pavelis
Economic Research Service, USDA
Washington, DC

Land drainage has its roots in antiquity. Its extent and persistence document its relevance to present-day agriculture. Substantial changes and progress in technique have occurred, especially following World War II. Uncertainties exist about the profitability of using drainage to improve existing or to develop new cropland, and these uncertainties are linked primarily to the prevailing cost-price situation for specific commodities, not to the concept or technologies of land drainage.

Drainage challenges and opportunities exist in technical and operational matters as well as in the policy arena. These challenges and opportunities are likely to be perceived differently by different audiences. At the operations levels, concerns of farmers and their related agribusiness institutions may differ from those of other private interests and government. We outline some of these concerns to illustrate the complexity of their mutual accommodation.

Preservation of Wetlands

The preservation of wetlands is an excellent example of the intermixture of views at various levels and by various audiences. This is no longer a debatable issue at the Federal level. Executive Order 11990 issued in 1977 (appendix A) details and codifies policy. This policy directive and similar formal legislation on the preservation of wetlands clearly sets policy at the Federal level. Federal agencies have implemented the necessary administrative procedures to comply. Executive Order 11988 on Flood Plain Management (May 1977) covers wetlands within flood plains. Other pertinent legislation includes the Fish and Wildlife Act of 1958, the Drainage Referral Act of 1962, the National Environmental Policy Act of 1969, the Endangered Species Act of 1972, section 404 of the Clean Water Act of 1972, and the "anti-swamp-busting" provisions of the Food Security Act of 1985. Various State and local policies have similar objectives.

Many people, farmers included, appreciate waterfowl and the recreational and general environmental values of wetlands (figs. 13-1 and 13-2). But also, many people appreciate these values from an abstract rather than personal economic perspective. Those who actually own or manage land must weigh the limited economic and potential nonmonetary benefits of leaving a wetland area undisturbed against the potential economic benefits of adapting it to their operations by draining it. This very practical contrast of values is the point of departure in a major *National Geographic* article on waterfowl protection needs (Madson, 1984).

Wetlands may be considered a liability for a number of reasons. They may impede farming operations and farm expansion. They may be assessed and taxed the same as productive farmland, or even assessed the same as waterfront property. Wetlands may attract waterfowl, which can damage crops, or less desirable blackbirds and muskrats.

In his earlier chapter, Thomas writes ". . . . generally acceptable methods of quantifying wetland values as marketable goods and services have not yet been developed. . . ." In their chapter, Smith and Massey also allude to the level of abstract appreciation of wetlands when they note that ". . . The demands for environmental products of wetlands are largely expressed through governmental organizations."

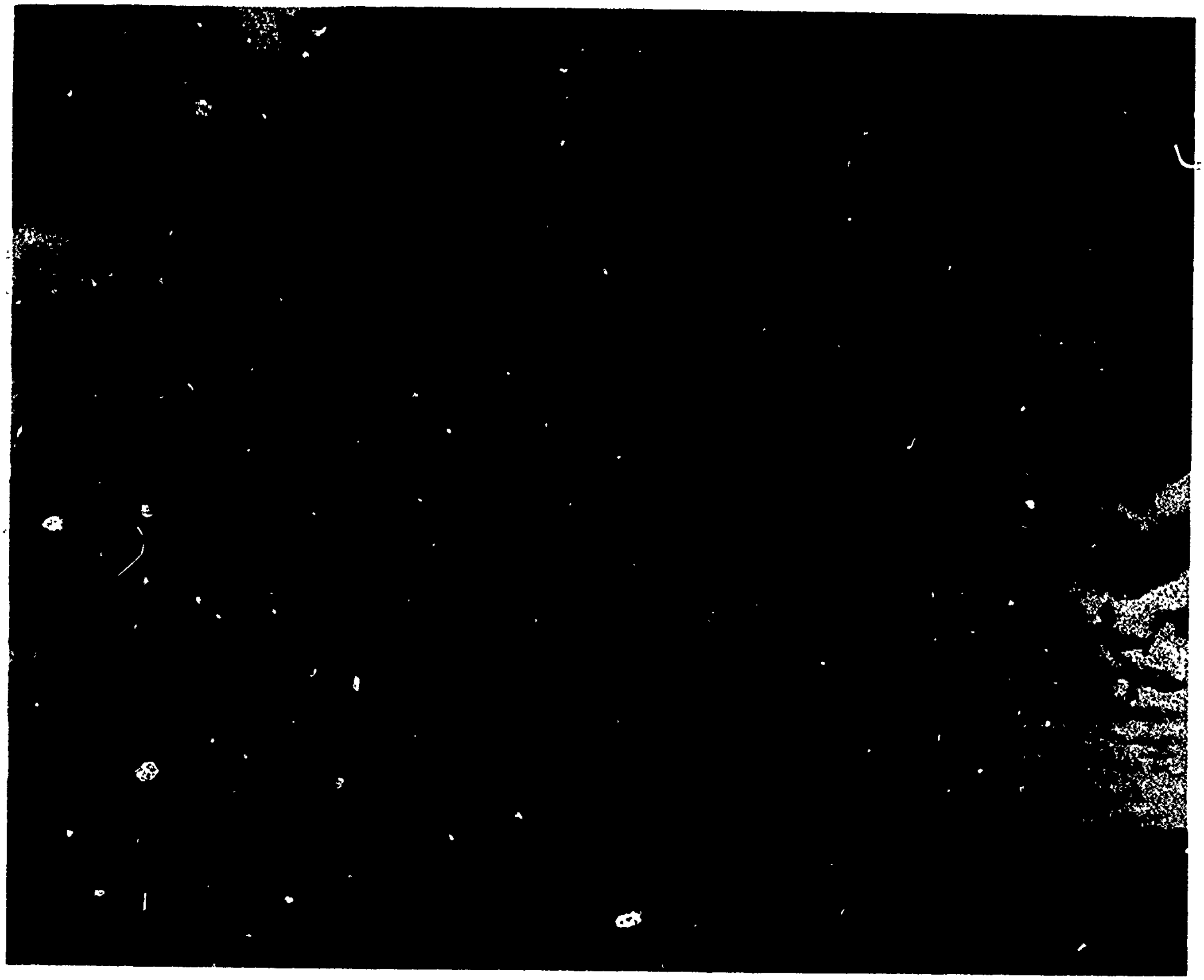


Figure 13-1—Spring migrating geese flock to the 25-acre Wilson Creek Watershed, Otoe County, Nebraska.

These differences in perception can deter the acceptance of Federal and State policies to protect wetlands. Such policies often embrace the ideal of preservation of wetlands without addressing the pragmatic concerns of the landowner.

There have been, and continue to be, Federal, State, and private programs that address these pragmatic concerns. An excellent example is the Federal Water Bank Program, administered by USDA under the Water Bank Act of 1970 (P.L. Law 91-559, as amended). Under this program, wetlands along waterfowl flyways are withheld from farm use under long-term rental agreements with landowners. Financial assistance can also be provided for installing habitat and water-quality improvement measures. As of 1985, USDA had negotiated about 7,500 Water Bank agreements with landowners, covering 720,000 acres of wetlands

An important USDA disaster assistance provision allows CCC grains to be donated to the Department of the Interior for feeding migratory waterfowl when threatened with starvation or for preventing crop damage. Such assistance requires that the Secretary of the Interior finds that an emergency exists.

CCC grain stocks may also be donated by USDA to State agencies for feeding resident wildlife threatened with serious damage or loss from starvation, upon requests of appropriate State agencies and authorization by the Secretary of the Interior (USDA, 1983).

Other Federal agencies also assist and cooperate in the preservation of wetlands and the management of wildlife refuges along the major waterfowl flyways. Flyways are general migration routes. Private organizations, notably Ducks Unlimited,

Figure 13-2—Wild ducks and geese feed on annual rye grass planted for them in Dare County, North Carolina.

have active programs to preserve wetlands as waterfowl breeding areas. Several States have their own programs to encourage farmers to maintain and manage wetlands for waterfowl habitat.

The Function of Wetlands

Wetlands are purported to be and often are wildlife habitat, flood storage areas, ground-water recharge areas, ground-water discharge areas, siltation basins, ecological filters, and unique ecological and educational areas. Except for wildlife production, market values cannot yet be assigned to these functions. If there are no market values or arrangements for compensating landowners for income given up by maintaining wetlands, landowners resist protection by regulation as a "taking" of traditional property rights.

The desirability of expanding current cost-sharing and cost-transferring programs to protect wetlands depends upon one's niche in a spectrum, ranging from detached conceptualist to threatened landowner. The existing programs appear to have been well-received and effective. But, it is not known whether enough wetlands can be purchased to adequately sustain an as yet unspecified optimum waterfowl population. Market values have not been established for wetland functions other than waterfowl production. Other wetland functions are not well understood, much less appreciated. This may help explain why no programs for purchasing or leasing wetlands exist except those associated with waterfowl production.

Increased public education may help landowners accept the importance of wetlands for functions other than waterfowl habitat. If landowners understand that wetlands within their holdings serve some valuable function, such as ground-water recharge, the understanding will translate into wider acceptance of the need to preserve or manage such areas for multiple purposes. This behavior presupposes that ecologic or hydrologic functions are known, or can be reliably identified, and can be related to something of importance to the landowner. Educational programs based on sound, reliable information are beginning to appear in the Southeastern Coastal Plain Region, addressing the problems of Bottomland Hardwoods (Harris and others, and Florida Cooperative Extension Service, 1984).

Note that even such functional information may not be sufficient. A study of farmer attitudes toward soil conservation practices found that "Stewardship of the Soil" (moral) arguments are not perceived to be particularly effective in promoting soil conservation. Economic considerations are significantly more important in this regard, based on farmers' beliefs, perceptions and past behavior (Pioneer, 1982). This is so despite a 50-year effort by USDA agencies to promote conservation. It suggests that cost sharing and technical assistance, coupled with conservation education programs, will probably be more effective promotional devices for preserving wetlands than those based on the premise that farmers have a moral duty to conserve or leave untouched natural resources for the benefit of others.

Rates of Wetland Conversion

Until recent studies of the Fish and Wildlife Service and USDA, there was little data on the area of wetlands or rates of conversion to other uses (Frayer and others, 1983; USDA, 1982). Earlier estimates were largely approximations from independent studies which contained different concepts and baseline data. While the estimates are largely of historic interest, there is no argument that large acreages have been converted from wetlands to other uses, and a primary end use was agriculture. The more important issues are whether such conversions are likely to continue, whether the projections like those of the National Research Council are likely, and whether new policies are needed to limit such conversions.

Little pressure currently exists for additional conversions to produce agricultural products. The current surpluses, the depressed farm economy, and the weakened competitive position of the American farmer in world markets seem to make large-scale conversions unlikely in the short run.

At the same time, however, domestic and world supplies of corn, soybeans, and feed grains may fluctuate greatly. Supply-demand relationships are likely to swing again toward increased demand for the products of U.S. agriculture, including corn, soybeans, and feed grains.With large increases in demand, there is little doubt U.S. farmers would likely respond by increasing their acreages at the extensive margin, including moving into heretofore unprofitable wetlands.

The effects of shifts in world supply/demand relationships may be mitigated by the continued introduction of bio- and other technologies into farming. Clearly, if per acre yields, especially of soybeans, could be doubled by genetic engineering, the necessity of expanding cropland acreage by various means, including drainage, would greatly decrease. At the same time, however, intensive water management, including controlled drainage systems for wet soils, may be a profitable component of using new technologies to their best advantage.

Continued educational programs are needed. Whatever the likelihood of expanded demand and increased prices for agricultural crops, the absence of awareness of the importance of wetlands will make those wetlands situated within the intensive margin vulnerable. When demand is strong and commodity prices are increasing, such areas are more likely to be regarded as obstacles to increasing income.

Supply of Wetland Products

There is a presumption of a shortage of wetland products. Smith and Massey state that "Because of the increasing scarcity of wetland products and the heightened public valuation, private decisions at the extensive margin increasingly face a public choice test." Whether this perception is supported by present inventory data is not clear.

It appears that most presumptions of a shortage of wetland products are based on waterfowl numbers. There have not been detailed estimates of the extent and location of wetlands that perform other specific functions, except perhaps the acres of hardwood bottomlands, which do play a role in floodwater storage.


Figure 13-3—Pines are able to grow because of woodland ditch drainage in Brunswick, Georgia, where once the soil was too waterlogged to support trees.

In its National Wetlands Inventory, the Fish and Wildlife Service is producing detailed wetland maps for the United States. These maps will help quantify the extent and location of wetlands that perform various specific functions.

Do Wetlands Need More Protection?

The present demand for cropland is not likely to require draining large areas of wetlands. The Nation is not in imminent danger of exhausting its available cropland (Crosson, 1982). Farmers who survive the current crisis in agriculture will likely concentrate on intensifying their operations to optimize growing conditions for "hi-tech crops." Their land improvement efforts are likely to focus on existing cropland. Much of this cropland has already been drained; the maintenance of existing drainage systems will be required. There will also be some expansion within partially drained fields. The aggregate impacts of these activities upon wetlands will probably be small.

It is not clear, however, that other primary industries will limit land drainage to the intensive margin. Relatively large acreages of wetlands have been drained in the Southeastern Coastal Plain for subsequent intensive forestry production. Such land treatment changes large acreages from wetlands of some classification and some hydrologic functions to other productive functions.

Such conversions are usually made by large corporations as part of their long-range production plans. These companies have sufficient capital to retain engineering services, to contract for land improvement, to harvest and process existing timber stocks, and to clear the remains in preparation for intensive forestry production. Such conversions are subject to State laws. They may be influenced more by national export policies and by State employment growth policies than by wetland preservation policies at either level of governments.

The purpose of these corporate efforts is sometimes confused by short-term intervening uses. If the prices for farm commodities are relatively high there will be incentives and local pressures to lease or use such newly drained lands to produce high-value cash crops. In the early 1970's, large areas of young pines were cleared by bulldozers, converting eventual pine forests to soybean fields.

The immediate returns from such cash cropping may well recoup the costs of conversion and also return some additional benefits to the land development company. The use of chemicals to produce cash crops discourages forest regrowth and suppresses the populations of subsequent weed species. It may not be good wetland management, but the short-term cropping of cleared coastal plain forestlands may make good economic sense to landowners (fig. 13-4). While agriculture has played a significant role in the drainage of wetlands, this scenario illustrates how the role may sometimes be incidental to the original purposes of drainage. It also challenges a candid consideration of the possible scope of wetland conversion potentials in different regions, and in industries other than agriculture.

National and Regional Wetland Conversions

More information on the extent of wetlands of different types and suitability for wildlife, hydrologic functions, and agricultural use is becoming available from various Federal and State studies. Recent national assessments include the Wetlands Status and Trends Study by FWS in the Department of the Interior, and the 1982 NRI, completed by SCS (Frayer and others, 1983, and USDA, 1982).

The Wetlands Trends Study of FWS photo-interpreted land use changes between the mid-1950's and mid-1970's for about 3,600 randomly selected sample units (each 4 square miles). On the other hand, the 1982 NRI identified land uses along with many other characteristics as of 1982 for about 1 million randomly selected sample points examined in the field.

Agricultural Conversions

According to the Wetlands Trends Study, agriculture was the observed end use of about 87 percent of the wetlands developed between 1954 and 1974 (USDA, 1985, and Frayer and Tiner, 1984). Nearly 98 percent of the conversions to agriculture involved Palustrine wetlands. Broadly speaking, Palustrine wetlands are inland freshwater or water-saturated areas more than 30-percent covered by trees, shrubs, or mosses. If not meeting these conditions, they can be small areas (under 20 acres) with freshwater regimes, with any standing water less than 2 meters (6.6 feet) deep. Complete scientific definitions of Palustrine and other major wetland systems and classes are in Cowardin and others (1979).

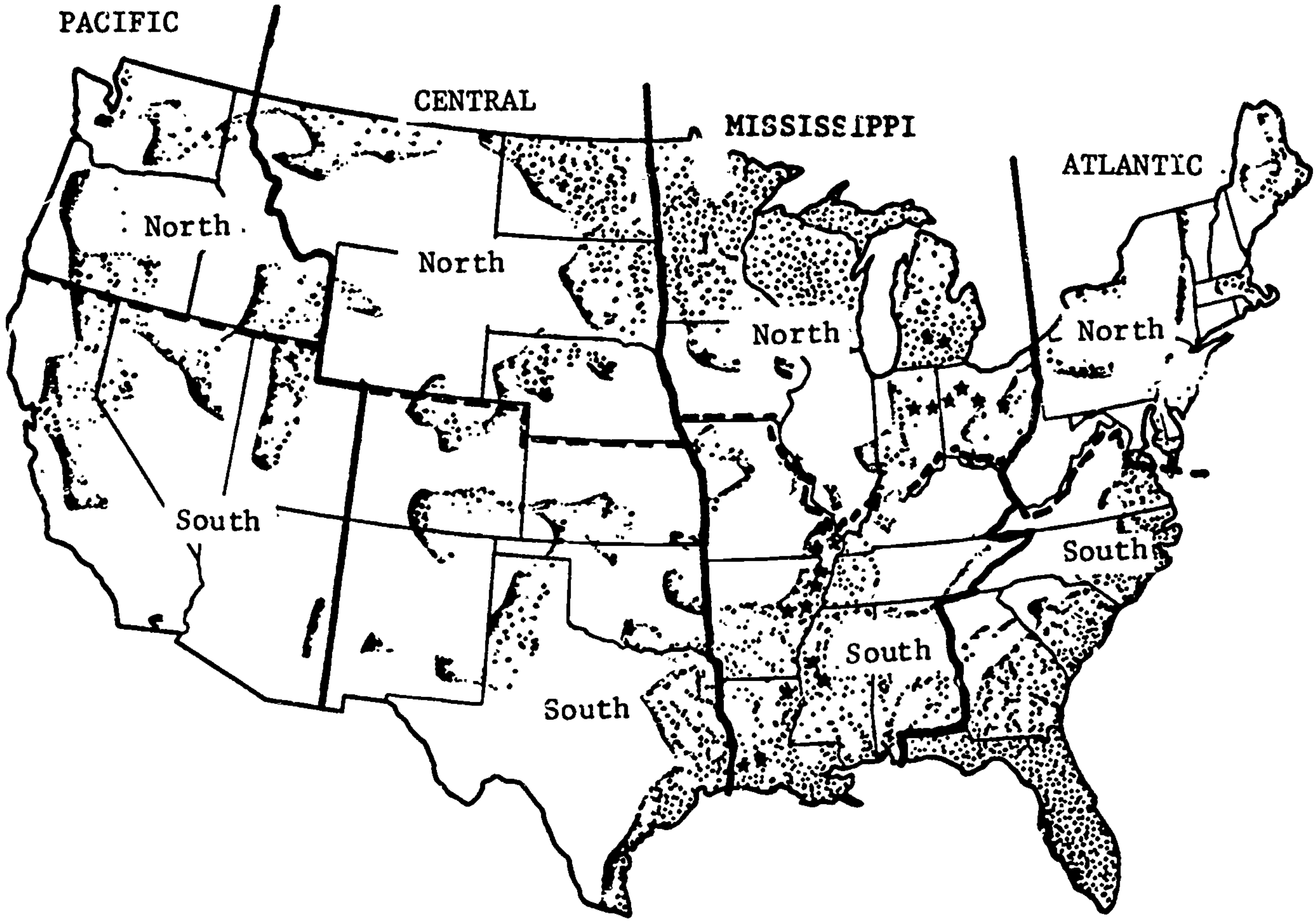
Figure 13-4—Bottomland wetlands are being converted to agricultural use in many areas of the Southeast: channelizing (left) and clearcutting.

The Wetlands Trends Study also indicated that gross conversions of Palustrine wetlands to agriculture were limited almost entirely to only three of six recognized broad classes of Palustrine wetlands. The three classes and their relative importance include: Palustrine Forested (53 percent), Palustrine Emergent (39 percent), and Palustrine Scrub/Shrub (8 percent). Examples are in figures 5-4 to 5-6.

While USDA's 1982 NRI employed a detailed wetlands classification developed earlier by FWS (Shaw and Fredine, 1956), it also broadly classified wetlands as to whether they were in the Palustrine system or the four other major wetland systems now used by FWS: Marine, Estuarine, Lacustrine, and Riverine.

Another important feature of the 1982 NRI was that it encompassed all non-Federal rural land. State, county, municipal, Indian, and private ownership categories were recognized. Privately owned and vegetated Palustrine wetlands not in agricultural use, whether or not now in farms, are the wetlands most relevant to questions of agricultural conversion. This leaves aside conversion costs, other economic factors, and management requirements that determine the actual feasibility of conversion and likely environmental impacts.

Four major waterfowl flyways are recognized by FWS and others for the United States. Each is divided into north and south sections (fig. 13-5). For these flyway areas, table 13-1 contains estimates as of 1982 of all non-Federal wetlands, non-Federal



Note: Shaded portions incorporate general wetland areas. Each dot represents about 10,000 acres.

SOURCE: Adapted from Samuel P. Shaw and C. Gordon Fredine, "Wetlands of the United States: Their Extent and Their Value to Waterfowl and Other Wildlife," Fish and Wildlife Service, U.S. Department of the Interior, Circular 39, 1956.

*Counties in the Mississippi Flyway more than 75 percent drained.

Figure 13-5—Waterfowl flyways and wetlands of the United States.

publicly held wetlands, privately owned wetlands, and the private Palustrine wetlands vegetated and not currently cropped or permanently grazed. Range estimates of the convertibility of such wetlands to cropland through drainage and associated development measures are also included in table 13-1. Our low estimate (2.5 million acres) is based on direct judgments made in the 1982 NRI of medium or high potentials for conversion to cropland of privately owned vegetated Palustrine wetlands not currently in agriculture. Our middle estimate (7.5 million acres) includes all such wetlands fairly easily suitable for crops (land use capability IIw and IIIw). Our high estimate (12.9 million acres) then adds in wetlands marginally suitable for crops (capability class IVw).

In their analysis of the NRI data, Daugherty and Lewis (chapter 12) indicate that the total remaining potential for farm drainage in the United States in 1982 was between 31.1 and 42.8 million acres. The lower figure included land already in crop use or grazed and considered to need drainage. The added 11.7 million acres were noncropland with at least a medium potential for conversion to cropland. For 3.5 million acres was a designation as wetlands (types 1-20) under the Shaw/Fredine system (1956), either a primary or secondary soil and water problem limiting conversion. A later analysis by Heimlich and Langner (1986) indicates that 5.1 million acres of wetlands were rated in the inventory as having at least a medium potential for conversion. Their figure covered all non-Federal

Table 13-1—Non-Federal wetlands in the 48 conterminous United States in 1982, with estimates of wetlands convertible to crop production[1]

Flyways (figure 12-1)	Total non-Federal wetlands[2]	Non-Federal public wetlands[3]	Total private wetlands[4]	Wetlands convertible to crops[5]	Estimates of agricultural conversions		
					Low estimate[6]	Middle estimate[7]	High estimate[8]
				Thousand acres			
Pacific:	4,390	635	3,755	584	35	56	150
North	1,623	73	1,550	301	34	45	109
South	2,767	562	2,205	283	1	11	41
Central:	10,378	799	9,579	2,120	53	250	538
North	6,693	536	6,157	704	13	36	74
South	3,685	263	3,422	1,416	40	214	464
Mississippi:	34,577	7,763	26,814	19,638	1,477	2,657	4,810
North	19,191	6,929	12,262	8,967	556	1,141	1,518
South	15,386	834	14,552	10,671	921	1,516	3,292
Atlantic:	28,884	3,708	25,176	20,425	950	4,544	7,370
North	8,239	1,009	7,230	5,655	262	1,164	1,706
South	20,645	2,699	17,946	14,770	688	3,390	5,664
United States	78,229	12,905	65,324	42,767	2,510	7,517	12,868

[1] Basic data for this table were compiled by Ralph E. Heimlich, ERS, USDA, from the 1982 National Resources Inventory.

[2] Wetland system types with non-Federal U.S. totals include: Palustrine, 70.564 million acres (90.2 percent); Estuarine, 5.985 million acres (7.7 percent); Lacustrine, 1.508 million acres (1.9 percent); Riverine, 144,000 acres (0.2 percent); and Marine, 28,000 acres (less than 0.1 percent).

[3] Non-Federal public ownership categories with U.S. totals include: State, 10.292 million acres (79.7 percent); county, 1.518 million acres (11.8 percent); Indian, 800,000 acres (6.2 percent); and municipal, 295,000 acres (2.3 percent).

[4] Includes all privately owned rural wetlands because wetland conversions to agriculture as the end use are not limited to areas presently in farms. In 1982, about 16.3 million acres (25 percent) of the privately owned U.S. wetlands were used for grazing or crops.

[5] Includes Palustrine wetlands not grazed or cropped in 1982, having either forest, scrub/shrub, or emergent vegetation characteristic of saturated soils. Loosely corresponds to wetland classes 1, 2, 3, 6, and 7, as defined by Shaw and Fredine (1956).

[6] Minimum conversion estimate represented by private Palustrine vegetated wetlands not used for agriculture in 1982 that, in the judgment of conservation specialists completing field observations for the National Resources Inventory, had either a medium or high potential for conversion to cropland.

[7] Middle conversion estimate represented by private Palustrine generally vegetated wetlands not used for agriculture in 1982 that were designated land use capability classes IIw and IIIw in the NRI. These are lands that are suitable for crop production only with appropriate conservation management and if the wetness (w) plus the secondary limitations that restrict the choice of plants are corrected. Acres by class are: Class IIw (2 million acres) and class IIIw (5.5 million acres). Capability classification systems are detailed in Agricultural Handbook 210 (USDA, 1961).

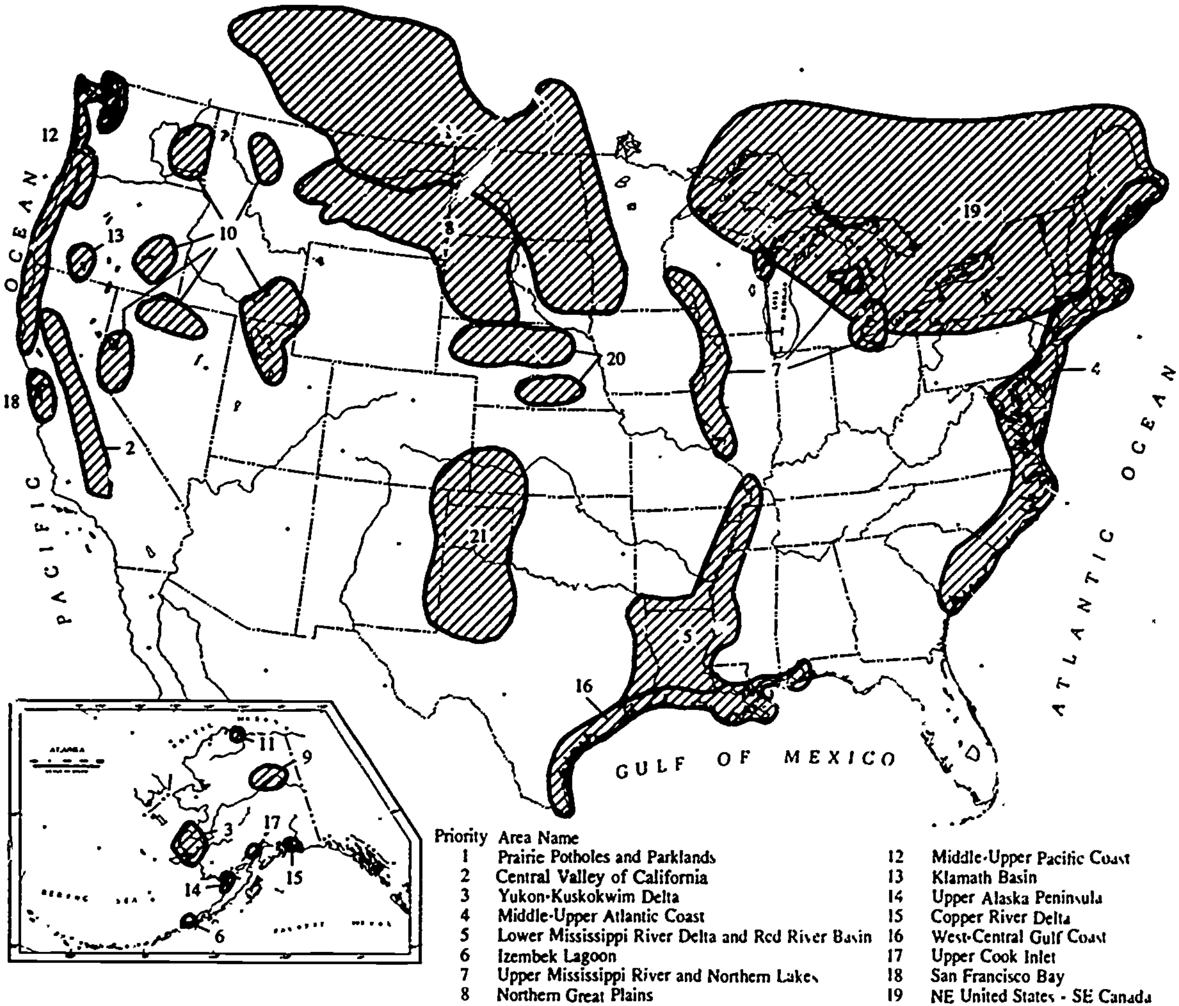
[8] Conversion estimate as in [7] but with land use capability class IIw also added. Class IV lands have severe limitations that restrict the choice of plants and/or require very careful conservation management. Class IVw lands account for about 5.4 million acres (42 percent) of the maximum estimate for agricultural wetland conversions in the United States.

"Palustrine" wetlands as defined by Cowardin and others (1979), including 1.3 million acres of wetlands that could be brought into crop production without drainage. About 95 percent of the 5.1 million acres were Shaw/Fredine wetland types 1, 2, 3, 6, and 7; nearly 80 percent were types 1 and 2.

The Daugherty/Lewis and Heimlich/Langner analyses thus suggest that an estimate of wetlands most feasibly drained and converted to cropland could range from 3.5 to 3.8 million acres. The flyway-based estimates in table 13-1 (total 2.5 million acres) are lower because they are limited to privately owned and to at least partially vegetated Palustrine wetlands not currently cropped or grazed; they are considered the wetland areas most vulnerable to being converted from waterfowl habitat to agriculture by drainage. The middle and upper estimates in table 13-1 (7.5 and 12.4 million acres) apply basic land-use capability considerations rather than convertibility judgments of technicians completing the 1982 NRI.

Waterfowl Values

In their 1956 study, Shaw and Fredine qualitatively determined areas having primary and secondary value to waterfowl, for each of their 20 defined types of wetlands. Waterfowl habitat areas of primary concern are identified in figure 13-6. Weighting the Shaw-Fredine primary value percentages for types 1, 2, 3, 6, and 7 by the area in these types in the 1982 inventory indicates that, for the United States as a whole, about 22 percent (9.4



Priority	Area Name
1	Prairie Potholes and Parklands
2	Central Valley of California
3	Yukon-Kuskokwim Delta
4	Middle-Upper Atlantic Coast
5	Lower Mississippi River Delta and Red River Basin
6	Izembek Lagoon
7	Upper Mississippi River and Northern Lakes
8	Northern Great Plains
9	Yukon Flats
10	Intermountain West (Great Basin)
11	Teshelpuk Lake
12	Middle-Upper Pacific Coast
13	Klamath Basin
14	Upper Alaska Peninsula
15	Copper River Delta
16	West-Central Gulf Coast
17	Upper Cook Inlet
18	San Francisco Bay
19	NE United States - SE Canada
20	Sandhills and Rainwater Basin
21	Playa Lakes

Figure 13-6—Major waterfowl habitats.

million acres) of the 42.7 million acres of remaining private Palustrine vegetated wetlands theoretically convertible to crop production are of primary value to waterfowl, although Shaw and Fredine considered all wetlands to have at least a "lesser" value for waterfowl. Under the minimum conversion estimate in table 13-1, between 550,000 acres and 700,000 acres (22-28 percent) of the wetlands drained and converted to agriculture could be regarded as having primary value to waterfowl. For the middle estimate, the amount would be between 1.6 and 2.1 million of the 7.5 million acres converted. The maximum conversion would involve between 2.8 and 3.6 million acres of wetlands having a primary value to waterfowl.

This brief examination of wetlands from the viewpoint of wildfowl and conversion questions also reveals that States within the Mississippi and Atlantic Flyways contain 81 percent of all non-Federal wetlands, 89 percent of State, county, and other non-Federal publicly owned wetlands, and 80 percent of all privately owned wetlands (table 13-1). More important, these two humid-area flyways apparently contain 92 percent of the vegetated Palustrine wetlands not currently in agriculture.

Smith and Massey observed that pressures for complete evaluation of all wetland benefits for wildlife, hunters, farmers, and other interests will increase with wider public recognition of their alternative uses and their reduction to a remnant level. Some products of wetlands, such as waterfowl hunting, are more readily evaluated than others. Pending the completion of coordinated studies, opportunities for combining information on the value of different uses developed in separate studies and from independent sources should not be overlooked. The next section outlines some of these possibilities.

Balancing Competing Natural Resource Values

Miller and Hay (1981) have studied the relationship between wetland habitat availability, hunter success, and the level of duck hunting in the Mississippi Flyway. This is a 14-State area extending through Minnesota, Wisconsin, and Michigan, the entire Corn Belt, and the Mississippi Delta, plus Kentucky, Tennessee, and Alabama (fig. 13-1). Other approaches to determining waterfowl habitat values in the Upper Midwest were examined earlier by Goldstein (1971). Miller and Hay estimated that in 1975 waterfowl habitat had a value (consumer surplus value) to duck hunters of $29 per day of hunting per year, based on cited earlier work of Hay with Charbonneau. Capitalized into the indefinite future at a 7-3/8-percent discount rate in 1984 prices, this amounted to $160 per acre of lost wildlife habitat.

A similar study for the Pacific Flyway by Hammack and Brown (1971) was based not on days hunted, but on the value hunters placed on a duck bagged, estimated at $9.80 per duck at 1984 prices. This converts to a capitalized value of about $220 per acre of habitat, assuming an average of 1.6 birds per year are bagged per acre of habitat and again capitalizing into the indefinite future at 7-3/8 percent.

These two research studies suggest that an acre of wetlands available for duck hunting in 1984 had a market value ranging from $160 to $220 per acre, for an average of $190 per acre. It is not advisable to relate precisely such wide-area values to the marginal values of particular wetlands if converted to agriculture, so only broad estimates can be made. According to the 1978 Census of Drainage, there were 20 predominantly agricultural counties within the 14-State Mississippi Flyway with 75 percent or more of their land area drained (U.S. Dept. of Commerce, 1981). The 20 counties are listed in table 13-2. Figure 13-5 shows their general location. Five of the 20 counties are more than 90-percent drained: Mississippi County, Arkansas (99 percent); Mississippi County, Missouri (98 percent); Hancock County, Ohio (96 percent); Dunklin County, Missouri (96 percent); and New Madrid County, Missouri (94 percent).

The rationale for looking at counties already intensively drained is that, if not in agriculture, large areas in these localities would have remained as or would revert to wetlands and waterfowl habitat. Their present market values in agricultural use are guides to the market value of an additional acre of wetlands converted to farming, though not necessarily in the same county. This value, less the net cost of conversion, can be related to waterfowl hunting values as an opportunity cost—one of a class of benefits given up when draining wetlands.

Net conversion costs are actual draining and/or associated clearing costs less the value of wood or other products removed in the process. For the nine counties of table 13-2 located in the northern section of the Mississippi Flyway (Michigan, Ohio, Indiana, and Iowa), net conversion costs in 1984 averaged an estimated $550 per acre. Conversion costs for the 11 counties located in the southern section averaged $435 per acre (Herrington and Schulstad, 1978).

The next step is to subtract conversion costs from market values of farmland. According to the most recent Census of Agriculture and USDA sources, in 1984 the market value of farmland without buildings for the 20 high-drainage counties within the Mississippi Flyway averaged $1,105 per acre (U.S. Dept. Commerce, 1983; Jones, 1985). This provides a rough measure of the market value in 1984 of an added acre of remnant wetlands within the Mississippi Flyway converted to agriculture by drainage and/or necessary clearing. Deducting a net conversion cost of $477 per acre, the added net agricultural market value would be $628 per acre. This is a farm use value to compare with the above values of $160 to $220 per acre associated with not converting additional wetlands to agriculture.

For situations similar to those in the 20 Mississippi Flyway counties more than 75-percent drained, waterfowl hunting values in 1984 averaged 25 to 35 percent of net agricultural values, depending on whether the above Miller-Hay waterfowl hunting value of $160 per acre or the Hammack-Brown value of $220 per acre is compared with the net agricultural value of $628 per acre. If the two waterfowl habitat value estimates are given equal weight (averaged to $190 per acre), the 1984 waterfowl values of wetlands within the Mississippi Flyway were about 30 percent of the corresponding agricultural value of drained wetlands (table 13-2). But, this percentage ranged from 63 percent for conditions represented by Sharkey County, Mississippi, to 21 percent for conditions

Table 13-2—Waterfowl hunting values compared with agricultural values for the 20 agricultural counties in the Mississippi Flyway where at least 75 percent of the farmland area is drained

Counties (States)[1]	Farmland area drained	Farmland value, 1984		Relative waterfowl values[4]	
		Sale value[2]	Net value[3]	1984	1986
	Percent	*Dollars per acre*		*Percent*	
Sharkey (Mississippi)	80	735	300	63	124
St. Francis (Arkansas)	85	760	325	58	140
Clinton (Michigan)	88	875	325	58	154
Shiawassee (Michigan)	86	890	340	56	141
Mississippi (Arkansas)	99	960	525	36	67
Dunklin (Missouri)	96	965	530	36	79
Washington (Mississippi)	75	990	555	34	53
Crittenden (Arkansas)	85	1,015	580	33	58
New Madrid (Missouri)	94	1,045	610	31	64
Mississippi (Missouri)	98	1,040	605	31	64
Paulding (Ohio)	86	1,225	675	30	62
Crawford (Ohio)	83	1,250	700	27	58
Hancock (Ohio)	96	1,305	755	25	52
Jefferson Davis (Louisiana)	49	1,190	755	25	42
Henry (Ohio)	86	1,345	795	24	49
East Carroll (Louisiana)	79	1,230	795	24	39
Wells (Indiana)	75	1,385	835	23	50
Adams (Indiana)	82	1,400	850	22	49
Pocahontas (Iowa)	80	1,475	925	21	69
Acadia (Louisiana)	80	1,335	900	21	34
Average, 20 counties[5]	86	1,105	628	30	58

---

[1] Counties listed according to highest waterfowl hunting values relative to agricultural land values in 1984.

[2] Land without buildings, based on Census of Agriculture for 1982 and Jones (1985).

[3] Sale value less average net costs of draining or clearing and draining. Net drainage costs for listed counties in Mississippi, Arkansas, Missouri, and Louisiana averaged $435 per acre. These costs exceed drainage costs in chapter 11, averaged for these four States, by about 60 percent, indicating that substantial clearing and other preparation costs are likely in converting southern wetlands to agriculture. Costs for the remaining listed counties in the Northern States within the Mississippi Flyway (Michigan, Ohio, Indiana, Iowa) averaged $550 per acre. These costs exceed drainage costs in chapter 11, averaged for these four States, by about 10 percent.

[4] Ratio of average waterfowl hunting value per acre ($190) to net farmland values for 1984 or 1986. The $190 per acre is the average of $160 per acre and $220 per acre. See text.

[5] Averages based on 5.7 million acres in farms and 4.9 million acres drained in the 20 counties. Drainage intensities are assumed to be approximately the same in 1984 and 1986 as reported in the 1978 Census of Drainage (U.S. Dept. Commerce, 1981).

represented by Pocahontas County, Iowa, and Acadia County, Louisiana. It is interesting to note that nearly the same fraction (80 percent) of the farmland in these three counties is drained, but agricultural land values differ considerably. Excluding buildings, in 1984 values were $735 per acre in Sharkey County, $1,335 per acre in Acadia County, and $1,475 per acre in Pocahontas County.

Waterfowl habitat values relative to the potential agricultural values of remnant wetlands change as the demands for and supplies of waterfowl habitat and farmland change. Lacking actual data, assume that between 1984-86 habitat values and drainage conversion costs in the Mississippi Flyway were stable. Between 1984 and 1986 average farmland values did fall except in New Jersey, Virginia, and New England (USDA, 1986). Percentage decreases in average farm real estate values per acre for the eight Mississippi Flyway States represented in table 13-2 were: Iowa (-44 percent), Indiana (-34 percent), Ohio (-30 percent), Mississippi (-23 percent), and Mississippi (-20 percent). The relative waterfowl values in table 13-2 were approximated by applying percentage statewide decreases in land values between 1982, 1984, and 1986 to county land values reported in the 1982 Census.

The sensitivity of relative waterfowl values to changing farmland values can be shown by comparing waterfowl value indexes for 1984 and 1986. Between 1984 and 1986, the waterfowl value index rose from 63 to 124 percent for Sharkey County, Mississippi. It rose from 58 to 154 percent for Clinton County, Michigan. The relative value of wetlands for waterfowl habitat increased more in the northern than in the southern States of the Mississippi Flyway because agricultural land values fell more in the northern States. For example, between 1984 and 1986 the relative waterfowl value percentage rose from 21 to 69 percent for Pocahontas County, Iowa, but from 21 to only 34 percent for Acadia County, Louisiana.

The average waterfowl value index for wetlands for the 20 highly drained counties in table 13-2 as a group rose from 30 to 58 percent between 1984 and 1986. For all counties in table 13-2, nonagricultural benefits of wetlands other than waterfowl hunting values would need to be less significant in 1986 than in 1984 to justify wetland preservation. Preservation of waterfowl habitat alone would be justified for the first four county situations in the table, although the situations are not necessarily typical for the entire county.

Under such conditions, the incentive to drain additional wetlands is reduced in two ways: (1) For operators wishing to expand operations, the cost of simply purchasing additonal cropland as against draining wetlands for crop use would fall, and (2) existing landowner options for marketing waterfowl hunting values and/or other beneficial qualities of wetlands to hunters or public agencies, by means of purchase, lease, or easements, would be more attractive. How well the agricultural, nonagricultural, and environmental benefits of wetlands are quantified or otherwise identified will determine the ultimate success of such institutional arrangements for optimum wetland use.

The research opportunity suggested by these possible outcomes is to periodically update information like that in tables 13-1 and 13-2 for all flyways as farmland values and recreational demands change. The fact that State Experiment Stations and USDA already monitor land values on a regular basis for many other purposes would facilitate this work considerably.

Such research would enable environmentalists and public officials to identify localities where lease and purchase of remaining true wetlands to farming interests would likely be the least costly. It would also improve predictions on the future rate of wetland conversions, based on anticipated waterfowl hunting demands as well as anticipated demands for the products of competing industries. These include not only agriculture, but also forestry, resort, and residential community development, and other activities like airport construction. More specific analyses of farm drainage adoption and optimum design decisions have been completed by Goldstein (1971), Irwin (1980), and Skaggs and Nassehzadeh-Tabrizi (1983).

Improving Drainage Information[1]

Perceptions on the status and trends of wetlands depend on the amount and quality of data concerning the current extent of drainage. Government statistics have tended to give an incomplete picture of land drainage. Census-type data have been widely used as the most authoritative source of information. However, they have been based at various times on the Census of Agriculture, the Census of Drainage, the Census of Governments, annual SCS planning assistance progress reports, and ASCS cost-sharing reports. Not all farm operators know what part of their land is drained.

---

[1] Douglas Lewis contributed information for this section.

Although the definition of drainage has changed little over time, specific data items have changed, as have definitions of the relevant universe, such as what constitutes a farm, how drained irrigated land is considered, and what constitutes public versus private drainage enterprises. Moreover, it has not been possible to assess the effectiveness of different drainage improvements in different regions. As a result, in official reports, all systems appear to be equally effective in removing excess water or soil salts in the case of irrigation-associated drainage.

Another problem is that new drainage investments have not been reported separately from expenditures for maintenance. The 1983 Farm Expenditure Survey, conducted by NASS, was a first effort to pick up both kinds of financial information.

ASCS and SCS reports are also limited to program participants and typically give only the cost-sharing portion of total investment. Some information is given in units not easily integrated with other data sources. Periodic agency surveys have tended to address additional drainage needs rather than improvements already in place. The 1982 inventory conducted by SCS and a 1978 Resource Economics Survey conducted by ERS attempted to correct this problem.

Given these limitations, caution is recommended in using historical agricultural land drainage data. Changes in policies and institutions affecting drainage certainly change the benefits and costs of draining, both to individual farmers and society at large. Greater attention to societal interests means that the information needed for decisionmaking becomes more complex. In short, increased efforts and expenditures to improve data collection are needed to ensure a more accurate mosaic of agricultural land drainage, thus permitting more rational private drainage investments and public policy decisions.

USDA's role in farmland development through drainage has diminished considerably since its agricultural conservation and resource improvement started in the 1930's. In 1960, drainage accounted for about 9 percent of all conservation cost-sharing assistance to farmers; about 40 percent of this assistance went for open drains compared with 60 percent for subsurface or pipe drains. By 1983, drainage accounted for only $51,000, or 0.02 percent of all ACP assistance. Also, in 1983, only 8 percent of the ACP assistance was for surface or open drainage systems.

The minor USDA role in current drainage activities was also indicated in a 1978 Resource Economics Survey (Lewis, 1982). During 1975-77, cost sharing and loan programs of USDA represented only about 4 percent of the capital funds spent for onfarm drainage improvements. Nearly 82 percent came from farmers' own funds. The remaining 14 percent was obtained from loans.

The basic drainage information challenge, however, comes from another quarter. Legislation has been passed to discontinue the Census of Drainage Organizations taken every 10 years since 1920 by the Department of Commerce. As already noted, USDA has eliminated drainage as a practice qualifying for cost-sharing assistance. USDA does provide technical assistance for draining wet soils but not for land classified as wetlands.

Governmental agencies unquestionably have been one of the primary users of the information they develop at public expense for public use. But, as an agency's own drainage program activities are scaled back, its capacity to produce and even its interest in statistical information tend to weaken. The challenge, therefore, is to develop plans to acquire coordinated information on farm and other drainage activities, including wetland conversions, without relying on Census-type and other formal data-gathering programs. This is an opportunity for wildlife, agricultural, forestry, and other commercial interests to pool their knowledge and resources for research, management, and policymaking. Such efforts will require the participation of all interested sectors of the economy, including Federal agencies.

Maintenance and Repair Challenges

Open drains traditionally have not been maintained in a timely manner which decreases their effectiveness. This is especially true for open drains used as outlets for numerous onfarm drainage systems. Studies by Burris and others in Ohio (1985) showed that the net benefit of an effective annual maintenance program over periodic reconstruction (15-year cycle) averaged $12.70 per acre.

A good maintenance program for any type of drainage system is just as necessary as proper design and construction. Sound maintenance plans should be developed that consider system effectiveness as well as environmental concerns. When systems involve more than one landowner, the assignment of responsiblility for maintenance should be outlined and agreed upon by the concerned parties in the original plans.

Salinity and Water Quality Control

Drainage systems can help maintain salinity levels in crop root zones within safe limits for crop production. Sound irrigation water management can reduce and, in some cases, eliminate the need for artificial drainage systems. Using drainage water as a supplemental source of irrigation is now receiving special attention. If successful, drainwater use for irrigation will reduce drainwater flow and thus ease discharge problems that now exist or could develop in arid and semiarid climates. Drainwater quality is a growing concern, particularly for trace elements and the salt load. Efforts to handle these problems must be considered in all system designs and farming operations in these climates.

Drainage is Water Management

Agricultural drainage always has been viewed as a process of land conversion, improvement of the soil environment for plants either with or without irrigation, and elimination of operational hazards and nuisances. Drainage is now seen as a key aspect of water management, not as a purpose or activity in itself. Water is the resource basically involved, whether the purpose is to remove or otherwise control it on cropland, to avoid offsite wildlife and other environmental disbenefits from chemically polluted drain waters, to control salinity on irrigated soils, or to limit the intrusion of agriculture and other land uses into wetland areas. No one denies that large areas of former wetlands are now in urban and agricultural uses (Shaw and Fredine (1956), Tiner, (1984), and U.S. Congress,(1984).) But, it is also true that neither surface nor subsurface drainage improvements, nor provisions for proper drainage on irrigated lands, necessarily mean a loss in wetlands as conventionally defined.

The concept of drainage as water management has even stronger support in new drainage systems based on rainfall probabilities and in water control systems usable either for water removal or subirrigation, depending on growing-season variations in soil moisture conditions. Such systems are already viewed as the best context for anticipating the future character of water management on farms and for agriculture generally.

To consider drainage as water management is to advocate a complete analysis of drainage benefits, costs. and environmental impacts in particular cases. Nonagricultural aspects are acknowledged to be very significant and variously include hydrologic, water quality, climatic, recreational, and educational values (Thomas, chap. 5, and Bardecki, 1984). This does not mean such values have an importance overwhelming all others, although they may supersede all others for prescribed areas or wetland types. It may be more meaningful as well as less controversial to quantify these values from a water-resource rather than from a wetland vantage point.

As true wetlands are drained and converted to agricultural or other uses, most of the values said to be lost are associated with a changed or impaired water and aquatic plant environment, not with drained land as such. Similarly, benefits from improved drainage in wet soils not considered wetlands are associated with improved moisture and other soil conditions for crops and more efficient field operations. The result is essentially the same when irrigated lands are adequately drained.

Within these newer concepts, several additional challenges call for policy attention and study of the future of farm drainage.

Agricultural drainage can have positive and negative consequences, both on farms and offsite. The problem is that the consequences are frequently not associated with the original decisionmaker, beneficiary, or loser. Further, some drainage activities on farms are clearly neutral in their consequences. They may involve nonirrigated soils or irrigated soils but not hurt wildlife and wetlands, at least not as generally defined. Separating the neutral from known or potentially controversial situations is one way to simplify matters for policymakers as well as for other scientists.

Fausey and colleagues observed that by increasing moisture storage capacity, good drainage can reduce runoff and erosion damage, thus improving the effectiveness and durability of soil conservation measures like minimum tillage and grassed waterways. Their observations illustrate how water management strategies can have multiple onsite and offsite benefits as well as costs and particular detrimental effects. While many of the various purposes and effects of soil and water management as described by agronomists, soil scientists, and engineers seem readily usable for structuring complete benefit/cost studies, not much economic research of this kind has been done. It is important because farm output-increasing or cost-decreasing strategies like irrigation and drainage are sometimes questioned as perhaps benefiting agriculture at society's expense, especially when water supplies are being diminished and crops are in surplus.

Challenges for Research and Education

A first research and educational challenge is to increase our understanding of how all drainage benefits and costs, in both a direct and opportunity sense, can be related to each other in the same framework in analyzing alternative private decisions and public policies. In effect, this will remove potential market-failure situations as described by Langner (1985). It will also improve predictions on the scope and location of additional drainage and thus on the likely nature of possible controversies, providing a rational basis for actually resolving disputes. It will require cooperation among engineers, biologists, extension specialists, and social scientists throughout the research process, especially in the planning stage.

Surveys and inventories are an important statistical resource in benefit/cost studies, but analysts need to proceed from similar definitions. The economic evaluation of the environmental costs of agricultural activities requires survey data developed on an interdisciplinary basis (Miranowski, 1983). Just as it is possible to define away problems, it is also possible to provoke them by arbitrary definitions and classifications tilting toward a particular but not agreed-upon point of view. Agricultural and environmental advocates can be expected to cooperate in examining drainage if they agree, at least in principle, on the expected costs and benefits of drainage, on the kinds of lands and soil conditions involved, and on the environmental benefits or disutilities created elsewhere.

Another research opportunity is implied in the Smith and Massey observation that past agricultural productivity projections were based on assumptions of competition. This is a situation in which there are many farms, with none individually having an appreciable influence on product prices and input costs. For the most part, this still characterizes American agriculture. A research challenge here is to study technological and marketing activities in the drainage industry itself, given the reduced number of farmers, overcapacity problems in agriculture, and concern over losses of wetlands. The size, location, form of business organization, and probable public agricultural policies for remaining farms, plus any remaining natural limitations to production, will be the keys to anticipating where additional drainage will likely occur.

We close with a few recurring ideas. We do not know enough about most of the real functions of wetlands, especially noncoastal wetlands, to predict the specific effects of either maintaining or draining such wetlands for agriculture and other uses. Draining hardwood bottomlands is an exception, because flood storage capacities of such wetlands can be calculated within reasonable limits of accuracy.

It follows that if the functions are not known and the effects of wetland preservation or drainage are not known, it is difficult to formulate new drainage policies or develop programs to inform farmers, landowners, or policymakers about the value of retaining wetlands. The same difficulties apply in increasing public awareness of the contributions of agricultural drainage to public health, land settlement, and economic development.

Efforts should be made to identify and measure all functional values of wetlands. Meanwhile, real opportunities exist for developing educational programs of more immediate interest to, and effectiveness for, farm operators and wildlife interests.

Many landowners attach no intrinsic value to wetlands but view them as any other pieces of property. If the property has no intrinsic value and no apparent functional value, it must either be written off as having no value or converted to something of value. It follows that, in the absence of existing functional values, or the opportunity to develop such values, conversion to other uses becomes the only rational option. This challenge to researchers and educators can be expressed as a series of frank questions.

Can programs be developed to manage wetlands to provide some incentive for wetland retention and to provide some tangible benefits to the farm operator? Are there things that farmers themselves might do to increase the returns from retained wetlands? Can their wetlands and those of other private landowners be managed to produce economic returns in the form of trappable furbearers or leased hunting rights? Can the waterfowl hunting values like those in table 13-2 be converted to landowner income to maintain wetlands? Such programs would take the question of wetland retention, at least in some cases, from the realm of abstract values to tangible returns. The potential for such programs has been acknowledged within various Federal agencies (Tiner, 1984), but there is little identifiable movement toward such programs.

Some recognition is beginning to emerge at the State level (Harris and others, 1984; Malecki, 1985;

Davidson, 1984). But, much of the literature continues to deal with the generalities or potential for drainage impacts on wetlands (Redelfs, 1983; Sullivan, 1985). They do not address the highly technical matters of actual impacts. Other studies discuss the potential for legislative solutions rather than opportunities for enlisting the assistance of landowners in protecting wetlands for their functional values (Kusler, 1983; Bell, 1981). Drainage and wetlands preservation of natural resource management as a stable element of both depends on public policies and private actions that accommodate both landowner and public interests.

References

Bardecki, Michael J. 1984. "What Value Wetlands?," *Journal of Soil and Water Conservation*. Vol. 39, No. 3, May-June, pp. 166-169.

Bell, H. E., II. 1981. *Illinois Wetlands: Their Value and Management*. Illinois Institute of Natural Resources, Chicago.

Burris, Robert L., Dana C. Chapman, and Gary L. Overmein. 1985. *Economics of Ditch Maintenance in Northwestern Ohio*. Presented at Am. Soc. of Civil Engineers Irrigation and Drainage Specialty Conference, San Antonio, Tex., July 16-19.

Cowardin, Lewis F., Francis C. Golet, and Edward T. LaRoe. 1979. *Classification of Wetlands and Deepwater Habitats of the United States*. FWS/OBS-79/31. U.S. Dept. of the Interior, Fish and Wildlife Serv.

Crosson, P. R. 1982. *The Cropland Crisis — Myth or Reality?*. Resources for the Future, Inc., Wash., DC.

Davidson, B. 1984. "Texas Wetlands—A Valuable Resource," *Texas Water Resources*. Vol. 20, No. 1. Texas Water Resources Institute, College Station.

Frayer, W. E., T. J. Monahan, D. C. Bowden, and F. A. Graybill. 1983. *Status and Trends of Wetlands and Deepwater Habitats in the Conterminous United States, 1950's to 1970's*. U.S. Dept. of the Interior, Fish and Wildlife Serv., and Department of Forest and Wood Sciences, Colorado State Univ., Ft. Collins.

Goldstein, Jon H. 1971. *Competition for Wetlands in the Midwest: An Economic Analysis*. Baltimore: Johns Hopkins Press for Resources for the Future, Inc.

Hammack, Judd, and Gardner Mallard Brown, Jr. 1974. *Waterfowl and Wetlands: Toward Bioeconomic Analysis*. Baltimore: Johns Hopkins Press for Resources for the Future, Inc.

Harrington, Billy E., and Robert N. Schulstad. 1978. *Conversion of Delta Woodland and Pasture to Cropland: Economic Feasibility and Implications*. Bulletin 858. Arkansas Agr. Expt. Sta., Fayetteville.

Harris, L. D., R. Sullivan, and L. Badger. 1984. *Bottomland Hardwoods: Valuable, Vanishing, Vulnerable*. Florida Coop. Ext. Serv. SP-28. Univ. Florida, Gainesville.

Heimlich, Ralph E., and Linda L. Langner. 1986. *Swampbusting: Wetland Conversions and Farm Programs*. AER-551. U.S. Dept. of Agr., Econ. Res. Serv.

Irwin, Ross W. 1980. *On-Farm Drainage Benefit*. Final Report Project A-39-742. Univ. of Guelph, School of Engineering, Guelph, Ontario.

Jones, John F. 1985. U.S. Dept. Agr., Econ., Res. Serv. Special data developed for authors.

Kusler, J. A. 1983. *Our National Wetland Heritage: A Protection Guidebook*. The Environmental Law Institute, Wash., DC.

Langner, Linda L. 1985. *Economic Perspective on the Effects of Federal Conservation Policy on Wild-Life Habitat*. Transactions, North American Wildlife and Natural Resources Conferences, Wash., DC. March 18-20.

Lewis, Douglas. 1982. *Land Drainage Investment Survey, 1975-77*. ERS Staff Report No. AGES820505. U.S. Dept. Agr., Econ. Res. Serv.

Madson, John. 1984. "American Waterfowl: Troubles and Triumphs," *National Geographic*. Vol. 166, No. 5, pp. 562-599.

Malecki, R. 1985. "Agriculture and Wetlands: A New Perspective," *New York Food and Life Science Quarterly*. Vol. 15, No. 3, pp. 11-13. New York State Agri. Exp. Sta., Ithaca.

Miller, Jon R., and Michael J. Hay. 1981. "Determinants of Hunter Participation: Duck Hunting in the Mississippi Flyway," *American Journal of Agricultural Economics*. Vol. 63, No. 4, pp. 677-684.

Miranowski, John A. 1983. "Agricultural Impacts on Environmental Quality," *Water Resources Research: Problems and Potentials for Agriculture and Rural Communities.* Ankeny, Iowa: Soil Conservation Society of America.

Pioneer Hi-Bred International, Inc. 1982. *Soil Conservation Attitudes and Practices: The Present and the Future.* Des Moines, Iowa.

Redelfs, A. E. 1983. *Wetlands Values and Losses in the United States.* M.S. thesis, Oklahoma State Univ., Stillwater.

Shaw, Samuel P., and C. Gordon Fredine. 1956. *Wetlands of the United States.* Circular 39. U.S. Dept. Interior, Fish and Wildlife Serv.

Skaggs, R. W., and A. Nassehzadeh-Tabrizi. 1983. *Optimum Drainage for Corn Production.* Technical Bulletin No. 274. North Carolina Agri. Res. Serv., State Univ., Raleigh.

Sullivan, J. D. 1985. *Stream Channelization in New York: Impacts on Agriculture and the Environment.* M.S. thesis. Cornell University, Ithaca, N.Y.

Tiner, R. J., Jr. 1984. *Wetlands of the United States: Current Status and Recent Trends.* U.S. Dept. Interior, Fish and Wildlife Serv.

U.S. Congress, Office of Technology Assessment. 1984. *Wetlands: Their Use and Regulation.* March.

U.S. Department of Agriculture, Economic Research Service. 1986. *Outlook and Situation Summary; Agricultural Resources,* April 9.

U.S. Department of Agriculture, Soil Conservation Service. 1961. *Land Capability Classification.* AH-210.

U.S. Department of Agriculture, Soil Conservation Service and Iowa State University. 1982. *Basic Statistics, 1977 National Resources Inventory* SB-686. (Statistical Bulletin in process for 1986 Inventory; wetland data retrievable from computer files).

U.S. Department of Commerce. 1981. "Drainage of Agricultural Lands," *Census of Agriculture, 1978.* Vol. 5: Special Reports, part 5.

Appendix A

Executive Order 11990: Protection of Wetlands

(Federal Register, Vol. 42, No. 101, Wednesday, May 25, 1977)

By virtue of the authority vested in me by the Constitution and statutes of the United States of America, and as President of the United States of America, in furtherance of the National Environmental Policy Act of 1969, as amended (42 U.S.C. 4321 et seq.), in order to avoid to the extent possible the long and short term adverse impacts associated with the destruction or modification of wetlands and to avoid direct or indirect support of new construction in wetlands wherever there is a practicable alternative, it is hereby ordered as follows:

Section 1. (a) Each agency shall provide leadership and shall take action to minimize the destruction, loss or degradation of wetlands, and to preserve and enhance the natural and beneficial values of wetlands in carrying out the agency's responsibilities for (1) acquiring, managing, and disposing of Federal lands and facilities; and (2) providing Federally undertaken, financed, or assisted construction and improvements; and (3) conducting Federal activities and programs affecting land use, including but not limited to water and related land resources planning, regulating, and licensing activities.

(b) This Order does not apply to the issuance by Federal agencies of permits, licenses, or allocations to private parties for activities involving wetlands on non-Federal property.

Sec. 2. (a) In furtherance of Section 101(b)(3) of the National Environmental Policy Act of 1969 (42 U.S.C. 4331(b)(3) to improve and coordinate Federal plans, functions, programs and resources to the end that the Nation may attain the widest range of beneficial uses of the environment without degradation and risk to health or safety, each agency, to the extent permitted by law, shall avoid undertaking or providing assistance for new construction located in wetlands unless the head of the agency finds (1) that there is no practicable alternative to such construction, and (2) that the proposed action includes all practicable measures to minimize harm to wetlands which may result from such use. In making this finding the head of the agency may take into account economic, environmental and other pertinent factors.

(b) Each agency shall also provide opportunity for early public review of any plans or proposals for new construction in wetlands, in accordance with Section 2(b) of Executive Order No. 11514, as amended, including the development of procedures to accomplish this objective for Federal actions whose impact is not significant enough to require the preparation of an environmental impact statement under Section 102(2)(C) of the National Environmental Policy Act of 1969, as amended.

Sec. 3. Any requests for new authorizations or appropriations transmitted to the Office of Management and Budget shall indicate, if an action to be proposed will be located in wetlands, whether the proposed action is in accord with this Order.

Sec. 4. When Federally-owned wetlands or portions of wetlands are proposed for lease, easement, right-of-way of disposal to non-Federal public or private parties, the Federal agency shall (a) reference in the conveyance those uses that are restricted under identified Federal, State or local wetlands regulations; and (b) attach other appropriate restrictions to the uses of properties by the grantee or purchaser and any successor, except where prohibited by law; or (c) withhold such properties from disposal.

Sec. 5. In carrying out the activities described in Section 1 of this Order, each agency shall consider factors relevant to a proposal's effect on the survival and quality of the wetlands. Among these factors are:

(a) public health, safety, and welfare, including water supply, quality, recharge and discharge; pollution; flood and storm hazards; and sediment and erosion;

(b) maintenance of natural systems, including conservation and long term productivity of existing flora and fauna, species and habitat diversity and stability, hydrologic utility, fish, wildlife, timber, and food and fiber resources; and

(c) other uses of wetlands in the public interest, including recreational, scientific, and cultural uses.

Sec. 6. As allowed by law, agencies shall issue or amend their existing procedures in order to comply with this Order. To the extent possible, existing processes, such as those of the Council on Environmental Quality and the Water Resources Council, shall be utilized to fulfill the requirements of this Order.

Sec. 7. As used in this Order:

(a) The term "agency" shall have the same meaning as the term "Executive agency" in Section 105 of Title 5 of the United States Code and shall include the military departments; the directives contained in this Order, however, are meant to apply only to those agencies which perform the activities described in Section 1 which are located in or affecting wetlands.

(b) The term "new construction" shall include draining, dredging, channelizing, filling, diking, impounding, and related activities and any structures or facilities begun or authorized after the effective date of this Order.

(c) The term "wetlands" means those areas that are inundated by surface or ground water with a frequency sufficient to support and under normal circumstances does or would support a prevalence of vegetative or aquatic life that requires saturated or seasonally saturated soil conditions for growth and reproduction. Wetlands generally include swamps, marshes, bogs, and similar areas such as sloughs, potholes, wet meadows, river overflows, mud flats, and natural ponds.

Sec. 8. This Order does not apply to projects presently under construction, or to projects for which all of the funds have been appropriated through Fiscal Year 1977, or to projects and programs for which a draft or final environmental impact statement will be filed prior to October 1, 1977. The provisions of Section 2 of this Order shall be implemented by each agency not later than October 1, 1977.

Sec. 9. Nothing in this Order shall apply to assistance provided for emergency work, essential to save lives and protect property and public health and safety, performed pursuant to Sections 305 and 306 of the Disaster Relief Act of 1974 (88 Stat. 148, 42 U.S.C. 5145 and 5146).

Sec. 10. To the extent the provisions of Sections 2 and 5 of this Order are applicable to projects covered by Section 104(h) of the Housing and Community Development Act of 1974, as amended (88 Stat. 640, 42 U.S.C. 5304(h)), the responsibilities under those provisions may be assumed by the appropriate applicant, if the applicant has also assumed, with respect to such projects, all of the responsibilities for environmental review, decision-making, and action pursuant to the National Environmental Policy Act of 1969, as amended.

The White House
May 24, 1977

Jimmy Carter

Protection of Wetlands

(Statement by the President Accompanying Executive Order 11990. May 24, 1977)

The Nation's coastal and inland wetlands are vital natural resources of critical importance to the people of this country. Wetlands are areas of great natural productivity, hydrological utility, and environmental diversity, providing natural flood control, improved water quality, recharge of aquifers, flow stabilization of streams and rivers, and habitat for fish and wildlife resources. Wetlands contribute to the production of agricultural products and timber, and provide recreational, scientific, and aesthetic resources of national interest.

The unwise use and development of wetlands will destroy many of their special qualities and important natural functions. Recent estimates indicate that the United States has already lost over 40 percent of our 120 million acres of wetlands inventoried in the 1950's. This piecemeal alteration and destruction of wetlands through draining, dredging, filling, and other means has had an adverse cumulative impact on our natural resource and on the quality of human life.

The problem of loss of wetlands arises mainly from unwise land use practices. The Federal Government can be responsible for or can influence these practices in the construction of projects, in the management of its own properties, and in the provisions of financial or technical assistance.

In order to avoid to the extent possible the long and short term adverse impacts associated with the destruction or modification of wetlands and to avoid direct or indirect support of new construction in wetlands wherever there is a practicable alternative, I have issued an Executive Order on the protection of wetlands.

Appendix B

Selected State Drainage Authorities

Carmen Sandretto and Dean T. Massey

For all States with established public drainage organizations, the basic enabling statutes determine the types of organization permitted. In some States, the authority to establish drainage districts is conferred by the legislature on the governing body of the county in which the largest portion of the affected area is situated. In other States, the authority is vested in counties, or in district or circuit courts. The clerk of the superior court is vested with this authority in some jurisdictions (North Carolina is one example). Boards of drainage commissioners have jurisdiction in others.

Drainage authorities for California, Illinois, Indiana, Michigan, North Carolina, and Ohio are herein summarized and provided as examples of different systems. (References consulted appear at the end of the basic text chapter on Drainage Institutions). These six States account for about one-third of the agricultural land drained in the United States (Bureau of the Census, 1981).[1] While the statutes are somewhat similar for any public drainage organization, they reflect adaptation of general principles to the particular needs of individual States. Several uniform requirements are: (1) the drainage activity must, in addition to improving or reclaiming agricultural land, be beneficial to the public health, utility, or welfare; (2) the cost of the drainage works must not exceed the estimated benefits to be derived by the land affected; and (3) the indebtedness incurred must not exceed the actual assessments levied for the purpose of liquidating such debts.

In some States, a system of county drainage districts has been created; in others, special drainage districts have been formed (Illinois has the largest number of these organizations). Of the six States discussed here, California, Indiana, Michigan, and Ohio have county drainage districts, and also have provisions for intercounty or interstate drainage districts if circumstances warrant such joint ventures. California permits the formation of districts with a primary purpose other than drainage, such as irrigation, but the districts may carry out drainage as a secondary purpose. Illinois, Indiana, and Ohio authorize multipurpose districts that include agricultural drainage as one of their functions. In Indiana, separate funds are employed to finance the various functions carried out by the drainage organization. In Ohio, soil and water conservation districts can also implement drainage improvements. Several types of cost-sharing arrangements are available in Ohio, including provisions for State help in financing.

California

California authorizes the creation and operation of county drainage districts, of special districts with drainage as a secondary purpose, and of the Sacramento and San Joaquin Drainage District.

The creation of a county drainage district is initiated by a petition signed by at least 100 owners or at

---

[1] References cited in appendix B are listed in the References section of chapter 10.

least 50 percent of the owners of real property within the proposed district. This petition is submitted to the county board of supervisors, which then adopts and publishes a resolution stating its intention to create a district and setting a date for a public hearing on the petition.

After the public hearing, the board of supervisors may issue an order forming a district. That order names the district and describes its boundaries, which may be set to include areas within a village or city if the governing boards of those areas approve. However, if 10 percent of the district's registered voters so request, the county board of supervisiors must first submit the creation of a district to a vote.

The governing body of a district is a board of directors consisting of at least five members. If the district does not include any incorporated areas, the county board of supervisors serves as the board of directors. Boards of directors of districts containing incorporated areas are comprised of the presiding officer of each city or village within the district, the chairperson of the county board of supervisors, a member of the governing body of each city or village within the district (other than the presiding officer), and two members of the county board of supervisors (other than the chairperson).

A county drainage district in California has the authority to acquire, hold, and use real and personal property within the district; to exercise powers of eminent domain; to make and accept contracts; to employ personnel; to acquire, construct, and operate all types of land drainage systems; and to sell property. District directors can also adopt ordinances relating to the operation of a district in the same manner as a county board of supervisors.

Before constructing a drainage system or holding a vote on the issuing of bonds, a general survey must be prepared on any problems anticipated in protecting the land within the district from storm, overflow, or waste waters. Survey documents include a general description of the work to be performed, general plan and general specifications of the proposed work, any property to be acquired, and estimated cost for the proposed work. If the general survey is approved, precise plans and specifications are prepared. Work may begin after the final plans are adopted by a four-fifths majority of the board.

District boards are empowered to levy and collect taxes, borrow money and incur indebtedness, and direct payment of all lawful claims against the district. Taxes may be levied on the equalized assessed value of all taxable real property in the district to assist in repaying bonds, as well as the cost of maintaining, operating, extending, or repairing any work or improvements.

Special assessments to cover the costs of drainage construction may be levied against the property in the district benefited if approved by four-fifths of the district board of directors. County drainage districts are also empowered to charge and collect fees for providing and operating storm drainage facilities.

Bonds may be issued after the district board has approved the general survey and after the issuance has been approved by two-thirds of the registered voters in the district casting votes in a special referendum. A district may not incur an indebtedness exceeding 15 percent of the assessed value of all taxable real property in the district. Proceeds from the sale of bonds can only be used for acquiring property and performing construction work.

California also permits the formation of special purpose districts that may have a primary purpose other than drainage, but that can also carry out drainage as a secondary purpose. Irrigation districts, for example, are permitted to provide for drainage made necessary by irrigation. Such districts may be created upon petition by owners of land irrigated from a common source and by the same system of works.

Special purpose districts include reclamation districts empowered to construct, maintain, and operate drains, canals, sluices, water gates, levees, pumping plants, dams, diversion works, or irrigation works. The purpose of these districts is to reclaim land subject to overflow or to incursion from tidal or inland waters. These districts are created upon petition of owners of one-half or more of any lands subject to flood or overflow, susceptible to reclamation and who desire to reclaim the land. Another special purpose district, the levee district, operates to protect land from overflow. Drainage is also one of the several special purposes of water conservation districts.

The Sacramento and San Joaquin Drainage District, located in the 5-million-acre San Joaquin Valley, was formed under California statutes in 1913, and is managed and controlled by a seven-member reclamation board appointed by the governor. The district constructs, maintains, and operates ditches, canals, pumping plants, and other drainage works. The board adopts plans for a project, estimates costs and expenses, and may then levy assessments upon lands benefited within the district for work performed.

Illinois

The civil-law principles of natural drainage apply to all Illinois farmlands, regardless of whether they are in drainage districts. However, natural drainage rules do not adequately meet the needs of landowners in many parts of the State. To cover the inadequacies of natural drainage rules and to provide landowners with a means for securing proper drainage, the legislature passed laws providing for drainage districts based on a system of assessments which permit districts to include only lands benefited (Hannah, Krauz, and Uchtmann, 1979).

All drainage districts in Illinois are subject to the following general principles:

1. Assessments can be levied only against land which is benefited.
2. Assessments on land cannot exceed the benefits which the land will receive.
3. Drainage districts are public corporations charged with specific governmental functions. If necessary, the districts may acquire rights in land by instituting eminent domain proceedings and paying just compensation to the owner.
4. Assessments are not limited to land alone but may be levied against improvements, provided that there are benefits to the improvements.
5. Benefits, or the estimated value of the proposed drainage works to a particular property, are not limited to agricultural or sanitary benefits, but may include other kinds, such as those for a railroad or manufacturing concern. Therefore, assessments may be levied against such property.
6. Landowners are entitled to a hearing on the question of benefits before they can be compelled to pay drainage assessment
7. Drainage districts are dependent solely upon statute, and these statutes must be fulfilled to make their organization legal.

In Illinois, landowners in the proposed drainage districts initiate organization by filing a petition in the circuit court of the county in which most of the proposed district lies. The petition must be signed either by a majority of the landowners who own one-third of the land, or by one-third of the landowners who own a majority of the land. A petition signed by one-tenth of the landowners who own at least one-fifth of the land is also valid, but then a referendum is also required.

Any petition must include the name of the proposed district, a statement showing its necessity, a description of the proposed work, a description of boundaries and approximate area of the lands that would be affected, the names of landowners, and a formal request for the organization of the district and appointment of commissioners.

After the court finds for the petitioners, the county board or chief executive officer appoints three commissioners. These commissioners must examine the land and prepare a report showing the feasibility of the proposed project, its probable annual cost, what lands will be benefited and the aggregate benefits, whether aggregate benefits equal or exceed costs, and whether the proposed district includes all the lands benefited. The commissioners may alter the plan in the petition to secure maximum benefits and minimize damages.

The activities of Illinois drainage districts may be financed through assessments, loans or grants, notes, or bonds (with specific limitations on bonding authority). The scope of activities for drainage districts includes drainage planning as well as the construction and maintenance of improvements for flood control, conservation, regulation, utilization, and disposal of water and water resources.

In carrying out their activities, drainage districts in Illinois may cooperate and enter into agreements with other kinds of districts, proper Federal or State agencies, and municipal corporations. Provisions exist for annexation or detachment of lands and for the consolidation of drainage districts. The dissolution of drainage districts may be initiated by petition from at least three-fourths of the adult landowners who own not less than three-fourths of the land or by a majority of the drainage commissioners. The court may order dissolution after a hearing, provided that the district is free of debt, that no contracts will be impaired, and that the costs of dissolving the district are advanced by the petitioners.

180

Indiana

Indiana has a system of county drainage boards. Each board consists of three appointees who must be resident freeholders of the county and knowledgeable in drainage matters. In addition, the elected county surveyor serves on the board as an ex *officio*, nonvoting member.

Each regulated drain in a county is under the jurisdiction of the board, but private and mutual drains are handled separately. However, land drained by a private or mutual drain is subject to assessment for construction, reconstruction, or maintenance as a regulated drain if any part of the land is drained by a regulated drain.

The county surveyor is the technical authority on the construction, reconstruction, and maintenance of all regulated drains or proposed regulated drains in the county. The county surveyor classifies all regulated drains in the county as drains in need of reconstruction, maintenance, or abandonment, and submits a written report setting forth the classification of regulated drains in order of priority for action by the board.

In determining the benefits of drainage, the surveyor and board may consider a number of factors, including the characteristics of the watershed, soil type, land use and number of acres in each tract, and the increased value accruing to each tract from the construction, reconstruction, or maintenance of drains.

Each county has a general drain improvement fund to pay the cost of constructing or reconstructing a regulated drain. A maintenance fund for each regulated drain is used for the necessary repair or maintenance of that particular drain.

If the board determines that the cost of constructing or reconstructing a particular drain is in excess of the amount that assessed landowners may conveniently pay in installments over a 5-year period, it may authorize the sale of bonds to finance the project. A redemption fund is then established for each project for which the board authorizes the sale of bonds.

Indiana drainage codes also contain provisions for handling situations involving more than one county, municipalities, interstate drains, and cooperative projects with State or Federal agencies.

Michigan

Michigan has a system of drainage organizations based on individual counties plus a number of intercounty drainage districts. Of the 83 counties in the State, approximately 70 have an elected county drain commissioner. In the remaining counties (usually those with small populations, little agriculture, and limited drainage problems), the county road commission handles the drainage matters within its jurisdiction.

Intercounty drainage districts exist in places where drains cross county boundaries. In these cases, a drainage board is organized to administer the intercounty drainage district. The board is composed of a representative from the Michigan Department of Agriculture and of drain commissioners from the affected counties.

County drainage systems in Michigan are supported through special taxes levied on properties that benefit from the drainage facilities. The county drain commissioners assess the tax on the basis of a determination of the beneficial effects to individual properties.

North Carolina

In North Carolina, drainage districts are considered political subdivisions of the State. They are established by petitioning the clerk of court, with the petition specifically identifying the lands involved and the proposed drainage or reclamation activity. All landowners in the district must be notified of the proposal. The clerk, upon receipt of the petition, appoints a disinterested board of viewers to examine the land and project, and to report back to the clerk. The feasibility, benefits, and necessity of the project are all determined.

After the district is formally established, the board of viewers classifies the lands therein according to five types based upon the extent of benefits. After notice and hearing, this report is also subject to clerk of court approval. It may be further appealed to superior court.

After the district is established, it is operated by an elected board of drainage commissioners, with a treasurer appointed by the clerk of court. The board is the central decisionmaking authority, although some items are subject to approval by the clerk of court.

The construction or improvement process is controlled by an appointed superintendent of construction or engineer. The contract-letting is subject to public notice and sealed bidding, with the contract based upon the board of viewers' final report, which is fixed with the clerk. The drainage commissioners have control of the maintenance and repair of the project after completion.

Because the establishment of new districts has decreased over time, organized drainage activities in North Carolina are currently concerned mostly with the improvement, renovation, enlargement, and extension of canals and other existing works. The procedure for improving and enlarging the original project is again a step-by-step process involving the commissioners, the clerk of court, a separate board of viewers, notice of and hearing on any proposal, and the opportunity for appeal to the superior court. The feasibility, benefit, and necessity of the improvement or enlargement is determined only after notices and hearings.

The authority for the collection of costs is specified. Initially, the cost of the projects plus 3 years' maintenance is certified to the clerk, placed in a drainage record, and collected on an annual basis. An assessment roll is to be prepared by the board of drainage commissioners, specifying the owners of land and the amount of assessment.

The commissioners may levy annual maintenance assessments based upon the previous classifications of land. The amount of assessment is subject to clerk of court approval, and collection is the responsibility of the county tax collector.

Ohio

Drainage laws in Ohio are broad in scope and are administered by the boards of county commissioners. A wide variety of drainage-related improvements may be planned, financed, and constructed, using either the petition procedure or the mutual agreement procedure. When drainage improvement affects land in two or more counties, the proceedings are conducted by a joint board of county commmissioners. A representative of the director of the Ohio Department of Natural Resources is an *ex officio* member of the joint board but able to vote only in the case of a tie.

The petitioning procedure may be initiated by any benefiting owner(s) or public body and filed with the board of county commissioners. The board of county commissioners, the county engineer, and other interested parties view the proposed drainage improvement. The first hearing is held after proper notification of affected owners, and the county then files a preliminary report, including an estimate of cost, comments on feasibility of the project, and the engineer's opinion as to whether benefits from the project are likely to exceed the estimated cost.

If the board of county commissioners grants the petition, the county engineer is responsible for making surveys, developing plans, and estimating the cost of construction. The plans must provide for erosion and sediment control measures as part of the permanent improvement. If the land required exceeds specified amounts, the owner(s) shall be compensated by removal of the extra land from the taxable valuation of the property. A schedule of assessments of benefits and damages may be prepared, but as an alternative, the board of county commissioners may pass a resolution to levy a tax on all the property listed and assessed for taxation in the county to cover the construction and maintenance costs of a drainage improvement (Nolte, 1981).

All landowners whose names appear in the county engineer's schedule of assessments and damages must receive proper notice of the final hearing. The board determines when assessments are to be paid and whether bonds are to be issued, and orders the county engineer to let contracts for construction. Upon completion of construction, the assessments are adjusted *pro rata* from the estimated to the final cost. This assessment plus maintenance costs for 1 year are levied upon each parcel of land.

The board of county commissioners establishes and maintains a fund for the repair, upkeep, and permanent maintenance of each drainage improvement, obtained through an annual assessment upon the benefited owners. Any owner may apply for a reduction in the maintenance assessment to allow for work the owner proposes to do on any portion of a public ditch, watercourse, or other improvement. The county engineer recommends the reduction in the maintenance assessment, and the board confirms or rejects the allowances.

The board of county commissioners may grant any owner a reduction of not more than 50 percent of the annual maintenance assessment provided that such owner has filed with the county engineer proper certification from the board of the soil and water conservation district of the county where the land is located. Such an owner must follow certain practices in the cultivation or management of agricultural land, practices that are designed to reduce surface water runoff and erosion of sediment and silt into drainage channels. The county engineer has the right to inspect the premises of any owner claiming assessment reduction and to ask the soil and water conservation district to review any certificate on file. Such a certificate remains in effect until canceled by the board of county commissioners (Nolte, 1981).

The board of county commissioners, with the advice of the county engineer, may also enter into agreements with local soil and water conservation districts for the purpose of planning, constructing, or maintaining drainage improvements. Certain types of drainage improvements are eligible for State financial assistance (Nolte and Derickson, 1976).

The legislature has established a rotary fund to help pay initial expenses, including the costs of surveys, plans, and appraisals for soil and water conservation. Applications for a repayable advance from the rotary fund are submitted to the Ohio Soil and Water Conservation Commission by the board of county commissioners.

Applications for cost-share funds are submitted by the board of county commissioners to the Ohio Soil and Water Conservation Commission. Agreements may be authorized to provide up to 50 percent of the non-Federal cost of construction of an approved improvement.

The mutual agreement procedure applies in Ohio when one or more owners desire to join in the construction of a drainage improvement and are willing to pay the cost of construction. The mutual agreement, with plans approved by a registered professional engineer and with construction schedules, is submitted to the clerk of the board of county commissioners, and is reviewed by the county engineer. The county engineer prepares benefit assessment schedules for maintenance purposes, and the board of county commissioners holds a hearing to approve the schedules.

The landowners contract for and pay the cost of the construction plus the estimated cost of maintenance for 1 year. The construction must be acceptable to the county engineer and certified to be in accordance with the plans. The improvements and maintenance are under the direction of the board of county commissioners and are funded by an annual assessment upon the benefited owners (Nolte, 1981).

Appendix C

Acknowledgments and Contributors

This cooperative publication was planned by an *ad hoc* committee including James L. Fouss, Agricultural Research Service; Walter J. Ochs, Soil Conservaton Service; George A. Pavelis, Economic Research Service; Paul E. Schleusener, Cooperative State Research Service; Fred Swader, Extension Service; and Jan van Schilfgaarde, Agricultural Research Service. Raymond L. Bridge, Division of Information, Economics Management Staff, assisted with early editorial suggestions. James R. Carlin and other staff of the Information Division assisted with editing, design, art preparation, and publication.

The various chapters of this publication were extensively reviewed and discussed by authors and others at a Drainage Workshop in Denver, Colorado, April 11-12, 1984. Workshop Advisors were Professor David J. Allee, Department of Agricultural Economics, Cornell University; Professor Glenn O. Schwab, Department of Agricultural Engineering, Ohio State University; Dr. Gerald B. Welsh, SCS/ARS Research Coordinator, Soil Conservation Service, USDA; and Professor Lyman S. Willardson, Department of Agricultural and Irrigation Engineering, Utah State University.

Courtesy copies of most chapters in draft were informally provided staff from the Fish and Wildlife Service (FWS), U.S. Department of the Interior, who discussed their National Wetlands Inventory and related activities at the workshop in Denver. Gary L. Hickman provided helpful comments on the initial manuscript in June 1984. This USDA project was reviewed further with FWS personnel in Washington, DC, September 1984, and the completed publication was reviewed by Dr. William O. Wilen and other FWS staff. A number of photographs for the work have been generously provided by FWS through Dr. Wilen, Coordinator of its National Wetlands Inventory.

Others providing reviews, information, or editorial support included Professors Robert E. Beck of Southern Illinois University and Byron H. Nolte, Extension Agricultural Engineer, Ohio State University; also Susan Collins, Carla Eakins, Jane Kohlwey, and Marc Robertson of the University of Wisconsin-Madison. Swayne F. Scott, National Irrigation Engineer for the Soil Conservation Service, Henry Stamatel, Assistant State Conservationist for New York (SCS), and Donald McCandless of the Northeast Technical Center, SCS, provided reviews or special information, as did Economic Research Service staff Dwight M. Gadsby, Ralph E. Heimlich, Gerald L. Horner, John E. Hostetler, and Gary C. Taylor.

The present affiliations of authors and others directly involved in the publication follow:

David J. Allee (Advisor)	Professor of Economics Department of Agricultural Economics Cornell University Ithaca, New York
Linda G. Allen (Word-processing assistance)	Bureau of Census U.S. Department of Commerce Washington, DC (Formerly with Economic Research Service, USDA)
Glennis J. Beaird (Word-processing assistance)	Resources and Technology Division Economic Research Service, USDA Washington, DC
Keith H. Beauchamp	Soil Conservation Service Engineer (ret.) and Consulting Drainage Engineer 605 Webster Avenue Jacksonville, Illinois
James R. Carlin (Editorial Advisor)	Division of Information Economics Management Staff, USDA Washington, DC
Douglas A. Christensen	Economist South National Technical Center Soil Conservation Service, USDA Fort Worth, Texas
Ann M. Crowell (Word-processing assistance)	Federal Aviation Agency Washington, DC (Formerly with Economic Research Service, USDA)
Arthur B. Daugherty	Agricultural Economist Resources and Technology Division Economic Research Service, USDA Washington, DC
Eugene T. Doering	Agricultural Engineer Northern Great Plains Research Center Agricultural Research Service, USDA Mandan, North Dakota
William E. Donnan	Consulting Drainage Engineer and former Agricultural Research Service Engineer Pasadena, California
James L. Fouss	Agricultural Engineer Agricultural Research Service, USDA Louisiana State University Baton Rouge, Louisiana
Thomas C. G. Hodges	Head, Economics, Social Sciences and Evaluation Staff South National Technical Center Soil Conservation Service, USDA Fort Worth, Texas
Glen L. Hoffman	Research Leader Water Management Research Laboratory Agricultural Research Service, USDA Fresno, California

Douglas Lewis	Division of Soil and Water Conservation Department of Natural Resources and Community Development State of North Carolina Raleigh, North Carolina
Dean T. Massey	Agricultural Economist and Attorney Law School, University of Wisconsin Madison, Wisconsin
Walter J. Ochs	Agricultural and Rural Development Department The World Bank Washington, DC
Melville L. Palmer	Extension Agricultural Engineer Ohio State University Columbus, Ohio
George A. Pavelis	Resources and Technology Division Economic Research Service, USDA Washington, DC
Ronald C. Reeve	Drainage Consultant Columbus, Ohio
Carmen Sandretto	Agricultural Economist Resources and Technology Division Economic Research Service, USDA Washington, DC
Paul E. Schleusener	Agricultural Engineer (ret.) Cooperative State Research Service, USDA Washington, DC
Glenn O. Schwab (Advisor)	Professor of Soil and Water Engineering Department of Agricultural Engineering Ohio State University Columbus, Ohio
R. Wayne Skaggs	Professor of Soil and Water Engineering Department of Biological and Agricultural Engineering North Carolina State University Raleigh, North Carolina
Stephen C. Smith	Associate Dean School of Natural Resources College of Agricultural and Life Sciences University of Wisconsin Madison, Wisconsin
Gordon W. Stroup	Drainage Engineer Western National Technical Center Soil Conservation Service, USDA Portland, Oregon
Fred Swader	National Program Leader for Water Resources Extension Service, USDA Washington, DC
Jan van Schilfgaarde	Director, Mountain States Area Agricultural Research Service, USDA Fort Collins, Colorado
Carl H. Thomas	Chief Biologist (ret.) Soil Conservation Service, USDA Washington, DC
Gerald B. Welsh (Advisor)	Research Coordinator, SCS/ARS Soil Conservation Service, USDA Washington, DC
Richard Wenberg	National Drainage Engineer Soil Conservation Service, USDA Washington, DC
Lyman S. Willardson (Advisor)	Professor of Irrigation Department of Agricultural and Irrigation Engineering Utah State University Logan, Utah

Appendix D

English and Metric Conversion Equivalents

English or metric units		Multiplied by	Gives
ac	acre	0.4047	ha
ac-ft	acre-feet	0.1233	ha-m
cm	centimeter	0.3937	in
cm^2	sq. centimeter	0.1550	in^2
cm^3	cu. centimeter	0.0610	in^3
cm/hr	cm. per hour	0.3937	in/hr
cm^3/hr	cu. cm. per hour	0.0610	in^3/hr
cm^3/cm^2	cu. cm. per sq. cm.	0.3937	in^3/in^2
ft^3	cu. feet	0.0283	m^3
ft^3/sec	cu. ft. per second	28.32	ltr/sec
gal	gallon (U.S.)	3.7853	ltr
gpm	gallons per minute	3.7853	ltr/min
ha	hectare	2.4710	ac
ha-m	hectare-meters	8.1080	ac-ft
kg	kilogram (1,000 g)	2.2046	lbs
km	kilometer (1,000 m)	0.6214	mi
km^2	sq. kilometer	0.3861	mi^2
ltr	liter (1,000 cu. cm.)	0.2642	gal
m	meter	39.3700	in
m/day	meters per day	39.3700	in/day
m^3	cu. meters	1.3080	yd^3
mm/day	millimeters per day	0.0394	in/day
mi	mile	1.6093	km
mi^2	sq. miles	2.5900	km^2
yd^3	cu. yard	0.7646	m^3