Agricultural Drainage Effects on Water Quality in Southeastern U.S.

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Abstract: A review of literature and summary of research results are presented on the effects of drainage on water quality in North Carolina, South Carolina, Georgia, and Florida. Principal findings from the predominate coarse-textured soils of the Atlantic Coastal Plain include increased nitrate-nitrogen losses associated with improved subsurface drainage. Benefits of drainage include potential reductions in organic nitrogen (N) and phosphorus (P) losses from these mineral soils. Results of drainage investigations on organic soils in the Everglades Agricultural Area of Florida indicate that phosphorus is the primary limiting factor for eutrophication problems in Lake Okeechobee. P losses can be potentially reduced by using slow versus fast drainage, retaining drainage water from vegetable and sugarcane fields (on sugarcane or fallow areas), and minimizing water-table fluctuations. Some of these potential practices and their resultant effects need additional verification for application to other areas and conditions.

INTRODUCTION

In the Southeastern United States, as in other humid regions, adequate surface drainage is required for field activities and to reduce the potential of surface water ponding during crop production. The need for improved subsurface drainage for agricultural purposes is, of course, an economic consideration based on the cost of installation versus the loss of land to surface ditches and the reduced convenience of operating around ditches. If no crop-production benefit is realized by improved drainage (either surface or subsurface), these practices are not likely to be adopted by farmers. The ability to enter the field at the optimum time, perform needed cultural practices, and improve the temperature, aeration, and soil water regime for crop growth are factors that influence the profitability of an agricultural production system (Pavelis 1987; Baker and Johnson 1976). In addition, reductions in erosion and surface water pollution are side benefits of improved subsurface drainage.

The need for drainage (both subsurface and surface) in the southeastern United States is primarily because of the significant rainfall received (average of about 1,100 mm/yr) and the poor natural drainage. Table 1 describes the areal extent of drainage practices in North Carolina, South Carolina, Georgia, and Florida. In North Carolina, South Carolina, and Georgia, the Atlantic Coastal Plain is the primary zone of agricultural production and drainage (Fig. 1). The agricultural soils, in general, are coarse textured with low water-holding capacities and a high potential for chemical leaching. Most soils have relatively low natural fertility and require the application of major and minor nutrients. These soils have relatively high hydraulic conductivities and are subject to chemical leaching.

A section of the Atlantic Coastal Plain extends into Florida, but most drainage associated with agricultural production in Florida is in the Everglades Agricultural Area (EAA), an intensively cropped area located southeast of Lake Okeechobee. The soils in this region are primarily organic in nature and are widely represented by the term "muck" (Snyder 1993). These soils also have relatively high hydraulic conductivities and a high potential for leaching. However, the primary sources of chemical leaching are the nutrients (nitrogen and phosphorus) released during the soil organic-matter decomposition process as the drained soils subside.

Evans et al. (1989b) noted that drainage use in North Carolina began as early as the 1700s. Today, more than 40% of cropland in production in North Carolina requires artificial drainage. Drainage developments in South Carolina and Georgia followed those in North Carolina as the population expanded and land was cleared for agricultural production. Drainage developments in the EAA were planned in the mid-1800s and the first attempt at draining the area was made around 1883 (Izuno and Bottcher 1993a). Drainage installation for crop production was not successfully implemented until the early 1900s. As these organic soils were drained and used for continuous crop production, the soils continued to subside from oxidation. This diminished the effectiveness of gravity drainage, increasing the development of pump and canal networks to remove excess water and to supply irrigation water from Lake Okeechobee. Currently, the water pumped in and out of the EAA is managed by the South Florida Water Management District.

Although the Atlantic Coastal Plain and the EAA are vastly different in soil characteristics and function, similarities do exist. Each region discharges into environmentally sensitive and ecologically important receiving waters. Sensitive receiving waters include the estuaries along the Atlantic coast and Lake Okeechobee and the Water Conservation Areas (WCAs) adjacent to the EAA. Drainage waters pose two problems for salt water estuaries: (1) saltwater concentration is diluted by the freshwater; and (2) contamination results from nutrients, pesticides, and sediment in the runoff. The receiving waters of the EAA are especially sensitive because regulatory action has resulted in proposed limitations on nutrient loadings to Lake Okeechobee (Izuno and Bottcher 1993a).

Pests, both weed and insect, thrive in the subhumid climate of the region creating crop-production pressures. These pests are primarily controlled by chemical methods, which can result in a variety of potential problems due to the wide array

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Note. Discussion open until January 1, 1996. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on May 12, 1994. This paper is part of the *Journal of Irrigation and Drainage Engineering*, Vol. 121, No. 4, July/August, 1995. ©ASCE, ISSN 0733-9437/95/0004-0277–0282/$2.00 + $.25 per page. Paper No. 8454.

TABLE 1 Extent of Drainage in Selected Southeastern States

State (1)	Drained Land Area		
	Total (1,000 ha) (2)	Subsurface (1,000 ha) (3)	As percentage of cropland (4)
North Carolina	2,185	328	25
South Carolina	710	71	25
Georgia	625	94	8
Florida	2,550	128	45

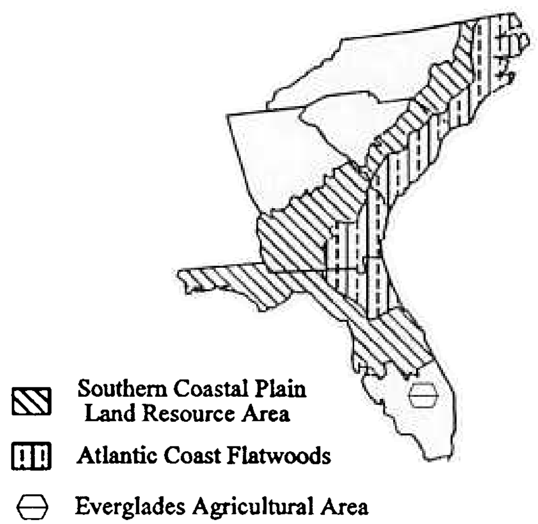

FIG. 1. Primary Areas of Agricultural Drainage in North Carolina, South Carolina, Georgia, and Florida

of crops produced. As a result, subsurface and surface drainage effects on water quality are a major concern throughout this region.

Of course, drainage allows land that would otherwise be minimally (or non) productive to become more productive. Drainage, related to crop-production practices, is perceived to produce poor water quality by many environmental organizations. North Carolina, at least, has achieved a unique position among most states by the designation of controlled drainage as a best management practice (BMP) for reducing nonpoint-source pollution (Evans et al. 1989a). BMPs associated with controlled drainage have also been proposed for the EAA to reduce phosphorus (P) and nitrogen (N) losses to receiving waters (Izuno and Bottcher 1993b; Izuno and Bottcher 1991). These types of approaches with governing and regulatory bodies could be instituted in other states with a concerted cooperative effort.

This paper is designed to consolidate research and results from investigations on the impact of drainage on water quality in North Carolina, South Carolina, Georgia, and Florida. A limited discussion of future needs and directions for drainage and water-quality programs will follow. Evans et al. (1992) and Thomas et al. (1992a) address some of the water-table management effects on water quality on a more general scale, but these will not be reiterated.

LITERATURE REVIEW

Extensive water-table management (WTM) research [primarily controlled drainage (CD), and controlled drainage/subirrigation, e.g. (CD-SI)] has occurred in North Carolina, South Carolina, and Florida, with limited research in Georgia. Most past efforts have centered on rates and amounts of outflows and associated nutrient losses. Studies on conventional drainage effects on water quality are limited in comparison.

Gast et al. (1974) and Devitt et al. (1976) found that soils with fine texture or a restricting horizon have lower quantities of nitrate (NO_3) below surface horizons or when leaving the field than do better-drained soils. Gambrell et al. (1975a) reported that in well-drained soils that were not saturated for extended periods (and lacked sufficient energy sources), denitrification was limited. This limitation allowed fertilizer not taken up by the crop to potentially move to shallow aquifers and then to surface water. Baker and Johnson (1976) showed that artificial drainage increases nitrate movement from agricultural sites whether additional fertilizer was applied or not.

In their evaluation of the effect of drainage on the fate of unutilized fertilizer N in North Carolina, Gambrell et al. (1975b) found that approximately one-half of the fertilizer applied to both a well-drained and a poorly drained soil was not used by the crop. Most of the N lost by surface runoff from both soils was organic N tied to the sediment. A measurable increase in N loss occurred from fertilized plots as compared with nonfertilized plots. Only 50% of the surface runoff occurred in the poorly drained soil when compared with the well-drained soil. However, the N concentration in runoff from the poorly drained soil was almost twice as great. This resulted in the two soils possessing nearly identical N losses in surface runoff. Nearly three times as much NO_3-N/ha moved from the well-drained soil through subsurface drains as compared with the poorly drained soil. The smaller loss was reported to result from the denitrification of residual NO_3-N in the shallow ground water.

Gilliam et al. (1979) evaluated whether CD could reduce nitrate loss from fields. Flashboard riser control structures were installed in mainlines and outlet ditches to raise water tables and, in turn, to increase denitrification in the soil profile. They found that in a moderately well-drained soil, a large reduction in NO_3-N loss occurred because of the reduced tile effluent, and not because of increased denitrification. In a poorly drained soil, NO_3-N losses were reduced by 50% by adding CD. Outlet control caused increased water movement into and through deeper soil horizons.

DRAINMOD, the water-management model designed to predict the soil water response to rainfall, evapotranspiration, drainage, and water-table control (Skaggs 1980), was used to simulate the effects of drain spacing and surface storage on surface and subsurface runoff (Skaggs and Nassehzadeh-Tabrizi 1981). Ten surface/subsurface drainage combinations were used with corn grown on a continuous basis. Results showed that with good surface drainage, a drain spacing increase from 15 m to 100 m caused three times more surface runoff. With poor surface drainage, surface runoff increased five times for the same spacing increase. Drain spacing and surface drainage conditions significantly affect the amount and rate of surface runoff. They concluded that the drainage system design affects erosion and pollutant transport in drainage outflows from flat or mildly sloping sites.

Skaggs and Gilliam (1981) reported on a North Carolina study to determine the effects of drainage-system design and operation on nitrate transport. Data from the study suggests that poorly drained soils with relatively high water tables lost less nitrate to drainage waters than did naturally well-drained soils. This decrease in nitrate loss was attributed to denitrification in the subsoil of the poorly drained soils. This simulation study (using DRAINMOD) showed that nitrate outflows for soils were very dependent on drainage-system design and operation. The authors stated that nitrate movement from a field can be minimized by using good surface drainage and wide subsurface drain spacings. However, drainage systems must be designed to satisfy trafficability and crop protection requirements.

Evans et al. (1984) conducted a subsurface drainage water-quality monitoring study. Drainage was from small plots receiving 325 kg N/ha/yr, 650 kg N/ha/yr and 1,300 kg N/ha/yr from sprinkler-irrigated swine lagoon effluent. Each plot was covered with Coastal Bermuda grass. The applied N rates represent 1, 2, and 4 times the recommended rate for Coastal Bermuda grass. Nitrogen applications at the medium and high rates resulted in NO_3-N concentrations in subsurface drainage, which were higher than the EPA drinking water standard (10 mg/L). By interpolation, they decided N could be applied at 1.25 times the recommended agronomic rate without exceeding standards.

Jacobs and Gilliam (1985) investigated nitrate losses in drainage outflow from agricultural fields in the North Carolina Coastal Plain. Ten kg/ha/yr to 55 kg/ha/yr NO_3-N were lost to subsurface drainage water in a coastal plain watershed with well-drained to moderately well-drained soils. Fields with forested buffer strips had substantial downslope reductions in N concentration (assumed due to increased denitrification). Subsurface drained fields with ditch outlets apparently moved more N to surface water than nondrained fields.

Gilliam and Skaggs (1986) examined the hydrologic and water-quality effects of clearing, draining, and developing flat, poorly drained soils in the North Carolina Tidewater region in a 3-yr field study (1977–1979). Land development (for agricultural purposes) caused three times the peak runoff rates when compared with areas in native vegetation. However, the total annual outflow varied little. The two developed sites in the study produced low annual losses of NO_3-N, yet the losses were still seven to 10 times greater than NO_3-N losses from the undeveloped sites. A relatively small increase in P loss occurred in a mineral soil, with a larger loss from a shallow organic soil.

Buried subsurface drains are designed to remove excess water from the soil profile. The drains lower the natural water table and provide more storage for infiltration. This reduces surface runoff. Gilliam and Skaggs (1986) noted that higher crop yields resulted with better subsurface drainage. However, the better the subsurface drainage, the more NO_3-N and total N lost and the less P in drainage effluent.

Another study was conducted in North Carolina to determine the effects of various artificial drainage treatments on the movement of N and P from poorly drained soils in the coastal plain region (Deal et al. 1986). Computer simulations were used to predict N and P losses over 20 yr from six soils. The results showed that both drainage-system design and management can significantly affect N and P movement in drainage effluent. Systems designed for good subsurface drainage lost 17–35 kg NO_3-N/ha/yr more than systems with poor subsurface drainage. In addition, good subsurface drainage decreased total P losses by 0.2–0.4 kg/ha/yr in mineral soils. The authors suggested using controlled drainage to offset some of the N losses.

Many areas near the North Carolina coast with elevations below 1.5 m mean sea level require drainage water to be pumped to outlets because gravity flow is not sufficient (Gilliam et al. 1988). Pumped areas in North Carolina contain mostly surface-drained fields. Because of the topography, pumps can be placed at any of several outlet locations.

Gilliam et al. (1988) noted that drainage water was being pumped years before concern over the potential adverse environmental consequences to receiving waters surfaced. Usually outlets have been placed at convenient locations with water pumped into estuaries, rivers, and wooded wetland areas. In North Carolina, regulatory agencies now recommend that agricultural drainage water be pumped into wetland areas. This recommendation was made without appropriate documentation of the effectiveness of wetlands for removing pollutants from drainage water.

As a result, studies on the pollutant-removal potential of wetland filter areas below pumped agricultural outlets were instituted (Gilliam et al. 1988; Chescheir et al. 1992). Samples from two wetland filter areas were analyzed for NO_3-N, total kjeldahl nitrogen (TKN), total P, and sediment. These areas effectively removed sediment, P, and N from drainage water. During the drainage events studied, at least 90% of the total sediment and 70% of the P was removed. Less N was removed. TKN concentrations approached background levels and only about 50% of nitrates were removed.

Evans et al. (1989c) investigated the influence of field scale conventional drainage and WTM on drainage water quality at five field locations. Nitrate concentrations at the field edge were reported as being slightly higher and TKN and total P concentrations were slightly lower for good subsurface drainage as compared with surface drainage areas. Total N loss was about 30% higher on subsurface drainage sites when compared with surface drainage sites. Total P transport was 20% higher on surface-drained sites.

Evans et al. (1991) summarized results of 10 studies representing approximately 120 site years of data collected on poorly drained soils in North Carolina. These studies were conducted to evaluate the effects of subsurface drainage, CD, and CD-SI on nutrient and pesticide movement to the surface and ground water. Fertilizer nutrient losses in conventional drainage effluent typically exceeded 20 kg N and 0.25 kg P/ha/yr.

When fields are developed for agricultural production (by removing naturally occurring vegetation such as noncommercial trees and underbrush, grading surfaces, and forming channels), runoff and peak flow increases. Subsurface drainage can reduce peak flows from these areas as compared to areas with only surface drainage. Subsurface drainage systems lower water tables and increase the potential for infiltration and storage during rainfall events, thereby reducing surface runoff.

Evans et al. (1991) concluded the following: (1) peak outflow rates at the field edge are reduced with subsurface drainage systems compared to surface drainage; (2) surface drainage systems typically produce higher concentrations of P and sediment than subsurface drainage systems; and (3) effluents from subsurface drainage systems usually contain higher concentrations of NO_3-N than those from surface drainage systems.

There is limited drainage research in Georgia. Many soils in the Atlantic coast flatwoods region of the state (approximately 2,700,000 ha) require subsurface drainage for economical and consistent crop production. Much of the region is forested or partially cleared, so future uses of subsurface drainage are limited by the Food Security Act of 1985. Studies on water-table management (CD-SI and CD) impact on water quality have been, or are being, performed (Thomas et al. 1991; Thomas et al. 1992b).

In agricultural areas, effluent from artificial drainage can be an important contribution to streamflow nutrient loads. Lowrance et al. (1984) quantified the effects of artificial drainage effluent on streamflow nutrients on an agricultural watershed. Concentrations and loads of NO_3-N, NH_4-N, organic N, dissolved molybdate (reactive P), total P, Ca, Mg, K, Cl, and SO_4-S were measured in streamflow and artificial drain flow on a 1,568 ha agricultural watershed near Tifton, Georgia. Concentrations of NO_3-N, Ca, Mg, K, and Cl were generally higher in drainage water than surface in flow. NO_3-N loads were about 60 times higher (per ha) in row-cropped fields than in a mixed-cover watershed. Organic N loads/ha were lower in the drained fields, but Ca, Mg, K, SO_4-S, and

Cl were lower in the mixed-cover area. They assumed that in-stream and riparian zone processes converted inorganic N to organic and removed N by denitrification.

In South Carolina, watershed-scale controlled drainage has been investigated; however, no direct research results have been reported on conventional drainage and water quality.

In Florida, research has primarily been directed toward water-table-management practice effects on water quality in the EAA in South Florida. However, limited research has occurred in the high water-table region of Northeast Florida, which is associated with the Atlantic Coast flatwoods region of the Coastal Plain. Campbell et al. (1985) investigated the effects of potato production practices on drainage water quality in a 3-yr project. In this study, water-furrow irrigation with surface drainage was compared to a subsurface drainage-irrigation system. Although total water discharge from each system varied by less than 10%, measured inorganic N losses were about 35% less and P losses were about 60% less for the subsurface drainage-irrigation system when compared with the water-furrow irrigation system.

Phosphorus in drainage water leaving the EAA is proclaimed to be contributing to accelerated eutrophication of Lake Okeechobee and to the degradation of the Everglades National Park and the Water Conservation Areas adjacent to the EAA. Izuno et al. (1991) investigated P concentrations in drainage water from muck soils of the EAA to identify critical P-loss problems for the development and implementation of appropriate BMPs. The cropping systems during the study included sugarcane, radish, cabbage, rice, drained fallow, and flooded fallow fields. The flooded fallow component is designed to reduce the subsidence and degradation rate of the organic soils.

Total dissolved P loading rates from the overall cropping system represented from 50% to 80% of the total P (TP) loading rates (Izuno et al. 1991). P losses from the mineralization of soil in the drained fallow fields were a large percentage of overall P losses. In some cases, under less-fertilized crops, the P concentrations in drainage water were lower in comparison to the drained fallow fields. These crops may be responding as P sinks or PO_4 fixation (sorption) by soil colloids may have reduced losses. Overall, recommendations for reducing P losses included the development and implementation of BMPs, which: (1) reduce P fertilization; (2) increase the efficiency of plant available P usage (including both applied and mineralizable sources); and (3) improve drainage practices that reduce outflows, but also maintain flood control and crop protection. Current methods of reducing P loads, which primarily rely on strategic pumping, should not be expected to significantly reduce the total P loading to the canals, Lake Okeechobee, and the WCAs without considerable risk to crops. The combined implementation of pumping and on-farm management practices could significantly reduce the loadings.

The foregoing results are consistent with results developed by other studies in the EAA (CH2M-Hill 1978, 1979; Dickson et al. 1978). Some of these results must be interpreted by the methodology being used and the reader is referred to these references for more detail. Basically, drainage and fertilization practices contributed significantly to the loadings, but questions still remained about which practices would reduce loadings and by how much they would be reduced.

Izuno and Bottcher (1987) implemented a study to evaluate the effects of slow versus fast drainage on N and P losses from sugarcane, along with crop-management alternatives. Their results indicated that basin-wide implementation of BMPs could potentially reduce P loadings by 20–60% (Izuno and Bottcher 1991; Wiggins and Bottcher 1993). In addition, the most significant P loading reductions were attributed to altering farm drainage practices, i.e., the use of slow versus fast drainage reduced P loadings the most.

Additional water-management practices to reduce P losses were proposed by Izuno and Bottcher (1993b). By retaining the drainage water from vegetable production in sugarcane or fallow fields, the potential P reductions are estimated at 20–90%. Retaining drainage water on sugarcane fields is estimated to reduce P losses by 15–60%. Minimizing water-table fluctuations by changing pumping schedules can potentially reduce P loadings by 0–50% when implemented on all crops.

SUMMARY OF RESEARCH

From the aforementioned studies and the wide variety of variables investigated and results obtained, the consolidation of the information is not simple. Table 2 summarizes results on the effects of agricultural drainage on NO_3-N losses. Overall, drainage increased NO_3-N losses when compared with predominately surface-drained, poorly drained, undeveloped, or mixed-cover areas. P losses in the EAA were assumed to be the limiting factor associated with the eutrophication of Lake Okeechobee and drainage practices contributed to the P losses.

The overall benefits of drainage indicate potential reductions in organic N and P losses in mineral soils (Table 3). In the EAA, under organic soils, P losses can be potentially reduced by using slow versus fast drainage, retaining drainage water from vegetable and sugarcane fields on sugarcane or fallow areas, and minimizing water-table fluctuations. Some of these potential practices and their resulting effects need additional verification for their application to other areas and conditions.

Improved agricultural drainage continues to be an economical method of maintaining the soil water regime for crop production. Improved subsurface drainage (conventional) decreases surface runoff, which, in turn, decreases chemical and sediment losses associated with surface runoff. As the efficiency of subsurface drainage increases, the loss of nitrates via shallow ground water increases result in a need for the

TABLE 2. Subsurface Drainage Effects on Nitrate-Nitrogen Losses

NO_3-N loss (1)	Reference (2)
10–55 kg/ha/yr moved from the field	Jacobs and Gilliam (1985)
7–10 times undeveloped or predominately surface drained areas	Gilliam and Skaggs (1986)
17–35 kg/ha/yr more than poor subsurface drainage	Deal et al. (1986)
30% more than surface drained areas	Evans et al. (1989b)
60 times the per ha No_3-N load from a mixed-cover watershed	Lowrance et al. (1984).

TABLE 3. Water-Quality Benefits Associated with Drainage and Water-Table-Management Practices

Benefits (1)	Reference (2)
Atlantic Coastal Plain	
Reduction in organic N loss	Lowrance et al. (1984)
Decreased total P loss by 0.2–0.4 kg/ha/yr	Deal et al. (1986)
Decreases peak surface runoff	Gilliam and Skaggs (1986)
Everglades Agricultural Area	Izuno and Bottcher (1993b)
Reduce P loadings by 20–60% by using slow versus fast drainage	
15–90% reduction in P losses by retaining vegetable and sugarcane drainage water on sugarcane fields	
0–50% reduction in P loadings by minimizing water-table fluctuations	

better management of these nutrients. Pesticide losses associated with drainage are being investigated and limited results are currently available.

THE FUTURE

Current research programs are filling the gaps in the knowledge base on drainage and WTM effects on water quality. Studies of pesticide degradation and movement processes and improved methods to simulate agricultural chemical losses under high water-table conditions are being conducted. Management modeling systems are slowly being developed as farm decision aids. These model systems will incorporate water quantity and quality, crop growth (variety of models), management alternatives, and economic evaluation. As with most research programs, currently installed drainage, CD, and CD-SI systems provide the impetus for most current research programs, with results directed toward enhancing the current systems.

Many of the water-quality benefits of water-table management are known or are being investigated. However, some benefits may not yet be identified. The negative perceptions of agricultural drainage, or the perception that agricultural drainage implies drainage of wetlands, must be addressed before the application base for WTM can be expanded to its potential. Without expansion to the potential area, national programs providing research support will continue to be limited and the degree of concern about the problems will decrease and new benefits may never be discovered. Addressing these perceptions requires the education and training of the public and agencies so they may better understand the overall benefits of agricultural drainage and water-table management both to the economy and the environment.

Studies have been implemented on the economic importance of agricultural drainage practices for particular areas. Investigations of the EAA have shown that the reduction or elimination of drainage capabilities, due to water-quality constraints, could severely impact the more than $600,000,000 per year in sales (early 1990 data) directly attributable to this area (Alvarez et al. 1993). The economic impact throughout the Atlantic Coastal Plain would also approach these figures.

One other major area that needs research is the overall economic component of developed management systems to reduce water-quality degradation (systems that improve water quality, but do not reduce profit). The costs of water-quality degradation and rehabilitation (both on- and off-site), which can be directly attributed to drainage and water-table management practices must also be determined and factored into the overall economic analysis. Proposed practices, structural modifications, or simulation and control (such as automation) technologies must provide economic considerations in their design and implementation to improve their applicability from the beginning without significantly increasing the complexity of operation.

The future of agricultural drainage requires multidisciplinary investigations with increased socioeconomic and environmental considerations. New methods must be acceptable to the user and the general public.

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