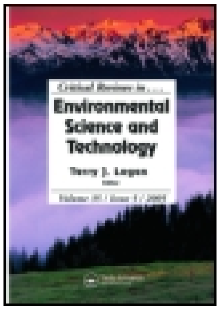

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Hydrologic and water quality impacts of agricultural drainage*

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Hydrologic and Water Quality Impacts of Agricultural Drainage*

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ABSTRACT: While some of the world's most productive agriculture is on artificially drained soils, drainage is increasingly perceived as a major contributor to detrimental off-site environmental impacts. However, the environmental impacts of artificial or improved agricultural drainage cannot be simply and clearly stated. The mechanisms governing the hydrology and loss of pollutants from artificially drained soils are complex and vary with conditions prior to drainage improvements and other factors: land use, management practices, soils, site conditions, and climate. The purpose of this paper is to present a review of research on the hydrologic and water quality effects of agricultural drainage and to discuss design and management strategies that reduce negative environmental impacts.

Although research results are not totally consistent, a great majority of studies indicate that, compared to natural conditions, drainage improvements in combination with a change in land use to agriculture increase peak runoff rates, sediment losses, and nutrient losses. Nevertheless, sediment and nutrient losses from artificially drained croplands are usually small compared to cropland on naturally well-drained uplands.

Increasing drainage intensity on lands already in agricultural production may have positive, as well as negative, impacts on hydrology and water quality. For example, increasing the intensity of subsurface drainage generally reduces loss of phosphorus and organic nitrogen, whereas it increases loss of nitrate-nitrogen and soluble salts. Conversely, increasing surface drainage intensity tends to increase phosphorus loss and reduce nitrate-nitrogen outflows.

Improved drainage is required on many irrigated, arid lands to prevent the rise of the water table, waterlogging, and salinity buildup in the soil. Although salt accumulation in receiving waters is the most prevalent problem affecting downstream users, the effect of irrigation and improved drainage on loss of trace elements to the environment has had the greatest impact in the U.S. These detrimental effects often can be avoided by identifying a reliable drainage outlet prior to construction of irrigation projects.

Research has shown that management strategies can be used to minimize pollutant loads from drained lands. These strategies range from the water table management practices of controlled drainage and subirrigation, to cultural and structural measures. For example,

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controlled drainage has been found to reduce nitrate-nitrogen and phosphorus losses by 45 and 35%, respectively, in North Carolina.

It is becoming increasingly clear that drainage and related water management systems must be designed and managed to consider both agricultural and environmental objectives. While significant advances in our knowledge of environmental impacts and methods for managing these systems have improved in the last 20 years, there is much yet to be learned about the complex mechanisms governing losses of pollutants from drained soils.

KEY WORDS: agricultural drainage, hydrology, nutrients, pesticides, sediment, water quality.

I. INTRODUCTION

Nearly all agricultural soils require drainage for production. Natural drainage processes are not sufficient for agricultural production on about 25% of the croplands in the U.S. and Canada. Artificial or improved drainage is necessary to produce crops on these lands. In some states and provinces, improved drainage is needed on over 50% of the croplands. Although some of the world's most productive agriculture is on these soils, improved drainage is increasingly perceived as a major contributor to detrimental off-site environmental impacts.

Extensive research has documented the effects of improved drainage on hydrology and water quality. When compared to uncleared land under natural conditions, improved drainage and change in land use to agriculture usually increase peak runoff rates and the loss of sediment and other pollutants. However, once land has been converted to agricultural uses and drainage outlets are in place, improved subsurface drainage has been found to reduce runoff, peak outflow rates, and sediment losses, while decreasing losses of some agrichemical pollutants and increasing the losses of others. Thus, the environmental impacts of improved drainage cannot be simply and clearly stated. They depend on conditions prior to drainage improvements and other factors. The mechanisms governing the hydrology and loss of pollutants from drained soils are complex and vary with land use, management practices, soils, site conditions, and climate.

Management strategies that minimize pollutant loads from drained lands range from cultural and structural practices to water table management practices related to subsurface drainage (controlled drainage and subirrigation). Our hypothesis is that drainage systems can be designed and managed to consider both agricultural and environmental objectives. The purpose of this paper is to present the results of a comprehensive review of research on the hydrologic and water quality effects of improved agricultural drainage and to discuss design and management strategies that reduce negative environmental impacts.

II. DRAINAGE STATUS, PURPOSES, AND METHODS

A. Status of Drainage

The status of drainage in the U.S. was documented by Pavelis.[1] As of 1985, 43 million ha, or 25% of the 170 million ha of cropland in the U.S., were designated as wet soils. A total of 31 million ha (28 million nonirrigated and 3 million irrigated) of these soils had been artificially drained to the extent that they are classified as prime farmland. When pastureland, rangeland, and forestland are included, it is estimated that a total of 45 million ha have benefited from drainage improvements. In Canada, 16 million ha of cropland, or 23% of the 68 million ha total, require improved drainage for efficient agricultural production.[2]

Van Schilfgaarde[3] reviewed the role of agricultural drainage as part of the "developmental ethos" in the U.S., i.e., the drive to develop the land and make it more productive. Much of the productive farmland of Illinois, Indiana, Iowa, and Ohio was originally swamp. Not only was it too wet to farm, it provided an environment for mosquitoes, with their subsequent threat of malaria and other diseases. Without artificial drainage, farming or human habitation would not be possible on these lands; with drainage improvement, this area is the epitome of modern U.S. agriculture. In the western U.S., drainage permitted the development of large areas of irrigated land. Without improved drainage, this development would have failed because of waterlogging and salination, as is happening in some areas at present.

The image of drainage has changed in many quarters during the past 20 years. Some who are concerned about the environment see drainage as an evil practice that has destroyed over half the original wetlands in the U.S. They point to the reduction in habitat for wildlife and the disruption of flyways for migrating birds. Of perhaps even greater concern is evidence that artificial drainage may have severe adverse effects off-site. High concentrations of toxic elements in the Kesterson Reservoir in California have been caused by the irrigation and drainage of farmlands.[4,5] The result has been a legally mandated blockage of drainage outlets from the largest irrigation district in the U.S. In humid areas, drainage has been blamed for eutrophication of streams,[6,7] and in a case where freshwater is considered a pollutant, the reduction of salinity and fish production in estuarine nursery areas has been attributed to agricultural drainage.[8,9] Although the actual adverse impacts may be considerably less severe than the perceived impacts in some cases, it is clear that improved drainage does have impacts and that they should be considered in the design and operation of agricultural water management systems.

B. Purpose of Drainage

Agricultural drainage systems are installed primarily to: (1) provide trafficable conditions so that seedbed preparation, planting, harvesting, and other field operations can be conducted in a timely manner; (2) protect the plant from excessive soil water conditions; and (3) control salinity in irrigated arid and semi-arid areas.[10–12] Drainage improvements also have been used for insect control and to reduce the risk of disease that harm people, crops, and livestock.[11]

C. Drainage Development and Methods

The first stage of drainage improvement includes the construction or modification of outlets, canal networks, roads, etc., and it usually takes place during development of the agricultural infrastructure. This stage is usually accompanied by changes in land use from native vegetation to agricultural crops or to silviculture. While construction of outlet canals, clearing and development of new lands for agriculture continued on a relatively large scale through the 1970s in some regions of the U.S., it is essentially nonexistent today. Present regulations to protect wetlands, including the swampbuster provisions of the 1985 Food Security Act (Public Law 99-198) and the 1990 Food, Agriculture, Conservation and Trade Act (Public Law 101-624), have caused drainage for conversion of new lands to agriculture to essentially cease. However, further drainage improvements are needed and will probably continue to be made on agricultural lands, most of which have been farmed for decades.

Clearly, the environmental impacts of drainage depend on the stage of the drainage improvements, and are different between the first stage, where outlets are constructed and land use changes may take place, and succeeding stages, where field scale drainage is improved to increase or sustain crop yields and efficiency of production. It is very important to recognize the starting point when evaluating the environmental impact of drainage improvement. In Section III, we discuss the environmental effects of the first stage of improved drainage, including certain aspects of land conversion to agricultural uses.

Another important factor influencing environmental impacts is the method of improving drainage. Drainage may be provided by surface or subsurface modifications, or a combination of the two.[13,14] Although most of the advancement in drainage technology has been in materials and methods for installing subsurface drainage systems (e.g., plastic drain tubing, trenchers, plows, synthetic filters), surface drainage is more frequently used in some states in the U.S. About 66% of the total rural area drained (45 million ha) in the U.S. has improved surface drainage only, as compared to 34% that has improved subsurface drainage.[1] Surface drainage improvements may consist of land smoothing, grading, precision land forming, and/or bedding to remove depressional areas and establish a slight grade on the land surface. A network of field ditches, laterals, and main canals also may be an integral part of a surface drainage system. Surface improvements are generally less expensive than subsurface improvements[15] and tend to be emphasized in the initial stages during land clearing and development for agriculture. Surface improvements also may be used where furrow, flood, or other methods of surface irrigation are implemented because the necessary land shaping and forming is necessary for irrigation, as well as for drainage. However, surface drainage alone is not effective in removing excess water from the soil profile, and subsurface drainage via buried drainage tubes is favored in many locations. This is particularly true where the growing season is short and trafficable conditions for timely planting and harvesting operations are critical.

The route that drainage water takes as it is removed from agricultural land has an important effect on environmental impacts. Surface drainage water travels primarily over the soil surface to the outlet, whereas subsurface drainage water travels more slowly through the soil profile, then to an outlet. It also is important to note that the present drainage status of many agricultural lands is not adequate, resulting in large losses of crop yields and profits. Future drainage improvements on these lands may consist of either surface or subsurface components, or combinations thereof, and may be dictated by the environmental impacts of the alternative methods.

III. DRAINAGE IMPROVEMENT AND LAND CONVERSION FOR AGRICULTURE

Worldwide public concern in recent years has pointed to agricultural drainage as a contributor to nonpoint source pollution.[3,5,7,16–20] Research has been done to compare the hydrology and water quality of artificially and naturally drained lands.[21–34] Much of the work has concentrated on comparisons of the environmental impacts caused by improved surface and subsurface drainage. Nevertheless, changes in land use usually accompany initial drainage improvements on natural lands. This makes it difficult to separate environmental impacts of drainage from those caused by changes in land use, accompanied by the application of fertilizers, and the production of crops. Certainly changes in land use from natural vegetation to agricultural crop production would be expected to increase losses of sediment and agrichemicals, even in the absence of drainage. Research findings on the hydrology and water quality effects of draining undeveloped lands are summarized below.

A. Hydrology

In most cases, conversion from natural drainage to improved drainage for agriculture or forestry has resulted in increased peak runoff rates.[16,18,21–27] Opposite results also have been reported.[28–34]

Hill[16] discussed the effects of improved drainage on stream discharge in a 1976 review of the environmental impacts of land drainage. He recognized that the general view in the U.S., Canada, and Europe was that improved drainage results in increases in downstream peak flows. However, he emphasized that an accurate assessment of the impacts of artificial drainage on downstream hydrology was precluded by limited information.

In the late 1970s, Skaggs and associates[22] evaluated the hydrologic effects of clearing and draining flat, poorly drained soils in North Carolina for agricultural purposes. The open-ditch drainage system provided primarily surface drainage, although considerable subsurface drainage improvements occurred in one treatment. Results showed that drainage improvement plus land conversion from natural vegetation to corn, soybean, and pasture increased peak runoff rates at the field edge by a factor of 2 to 4. Improved drainage also decreased time to runoff peaks, but did not affect total outflow substantially. In a later summary of their work, it was concluded that the increased magnitude of runoff peak will depend on soil properties and drainage system design.[25] Similarly, in Canada, Irwin and Whiteley[23] studied the effects of improved drainage on stream flow. Although they found that improved agricultural drainage may increase stream flow, they recognized that outflow rates and magnitudes from artificially drained lands will depend on such factors as antecedent soil moisture, rainfall intensity, and the location of drainage improvements in relation to the point of impact assessment.

Researchers in Iowa studied the hydrological effects of channelizing riparian lands.[21] Using flood-routing simulation methods, they found that channelization resulted in substantial increases in peak discharges. In a study of the hydrologic impacts of peat mining in North Carolina, researchers reported greater peak runoff flows as a result of artificial drainage.[24] Runoff volumes were larger and the runoff duration was longer from the mined sites than from those with natural vegetation. This result was attributed to the removal of vegetation and the grading and sloping of the land surface. Using computer simulation, Konyha and associates[35] showed that the magnitude of the peak runoff rate is dependent on the size of the watershed, characteristics of the canals or natural channels, and the respective locations of the outlet and the drainage improvements. They showed that an increase in peak outflow rate by a factor of 4 (400% increase) at the field edge may be modulated by the canal network so that the resulting increase at the outlet of the watershed is on the order of 10 to 50%.

Increased runoff peaks also have been related to improved drainage of forestland in England,[36] Finland,[37–40] and New Zealand.[41] However, results indicating reduced runoff peaks from artificially drained peatlands also have been documented in Finland,[32–34] Germany,[28] Great Britain,[30] Ireland,[29] and the former U.S.S.R.[31] In a study that discussed these two schools of thought,[26] it was concluded that improved drainage of forestland increases the potential for greater runoff rates, but that the actual effect is influenced by drainage method and intensity, rainfall characteristics, and forest stand.

Gregory[18] indicated that the public perception is that improving forestland drainage increases runoff, and thus increases flooding and salinity problems downstream. He noted that, as a result of conflicting research results, conclusions about the effects of improved drainage of forestland are still controversial. He attributed the conflicting results to widely differing conditions among studies and to different interpretations of the term "drainage."

B. Sediment Losses

The effects of improved drainage on sediment losses depend on the type of drainage improvement, site characteristics such as slope and landscape position, soil type, land use before and after drainage improvements, and cultural practice.

Sediment losses have been reported to increase when natural lands receive drainage improvements.[16,22,24,40,42–46] In some studies, the increase in sediment loss has been temporary, but in most cases the impacts are attributed to increased runoff rates.

Hill[16] concluded that improved drainage generally increases sediment loads. He suggested that this effect could be minimized if appropriate measures were taken upon land development. For instance, reseeding drainage ditches immediately after excavation was recommended to minimize bank erosion, a major contributor of sediment.

Outflows from artificially drained organic and high organic mineral soils in the North Carolina tidewater region had greater sediment loads than outflows from undeveloped sites.[22] Sediment losses were increased by a factor of 1.6 to 10, depending on soil and land use after drainage. Nevertheless, the maximum rate of sediment loss was <600 kg/ha/year, which is small compared to most agricultural lands with good natural drainage (uplands) where erosion rates are usually measured in megagrams per hectare per year. Turbidity also increased during drainage construction, clearing, and land grading. It was concluded, however, that once initial drainage and land development are completed, erosion and turbidity are not likely to cause water quality problems in the flat soils of this region.

Drainage system construction increased water turbidity and outflow loads of suspended and dissolved solids in three agricultural watersheds in Delaware.[45] However, sediment losses decreased once construction was completed because of stabilization of the stream channels.

Ice[42] presented an overview of international research that focused on the hydrologic impacts of improved drainage of forestland. He reported that the increased sedimentation caused by improving forestland drainage was of short term and was related to ditch construction. This conclusion is generally supported by studies on forest drainage in Michigan,[46] South Carolina,[43,44] New Zealand,[41] and Finland.[40]

C. Nutrient Losses

It is widely recognized that artificial drainage of naturally drained lands and conversion to agriculture results in increases in nutrient loadings, mainly nitrate-nitrogen (NO_3-N) and phosphorus (P).[16,22,24,25,27,47–54] This is to be expected inasmuch as drainage improvement allows agricultural production and subsequent increases in nutrient loads as a result of changes in land use, application of fertilizers where none had been used before, and changes in the route and rate by which water is removed from the field. As a result of the wide range of land use changes, drainage methods, crops, soils, and fertilizer amounts, the magnitude and duration of increased nutrient losses vary widely among studies.

Hortenstine and Forbes[47] studied nutrient levels in drainage waters from cultivated peat soils in central Florida. They reported large increases in nutrient levels as a result of fertilizer applications. Nicholls and MacCrimmon[48] compared nitrate-nitrogen and phosphorus losses from cultivated and uncultivated muck soils in Ontario. They found that the combined effects of fertilization and artificial drainage increased the loss of P by 4 to 5 times and NO_3-N by 40 to 50 times as compared to uncultivated conditions.

In North Carolina, Kuenzler and colleagues[50] reported that channelization increased nitrate-nitrogen and phosphorus concentrations in streams draining agricultural lands. Skaggs, Gilliam, and associates[22,25] found that improved drainage increased nitrate-nitrogen and phosphorus losses as compared to natural drainage. They concluded that the magnitude of the increase in nutrient losses will depend on the type of soil and drainage system because these influence denitrification.[25] Gambrell and colleagues[49] found that undisturbed poorly drained soils with relatively high water tables lose less nitrate-nitrogen in drainage water than naturally well-drained soils as a result of denitrification. Nitrate-nitrogen loss was found to increase with improved drainage in two other agricultural watersheds in North Carolina.[51] The NO_3-N loss was reduced when subsurface drainage water passed through riparian buffer zones before reaching a stream.

Lowrance and associates[52] compared nutrient levels in streamflow and artificial drainflow on an agricultural watershed in the Georgia Coastal Plain. Compared to streamflow, they observed greater concentrations of nitrate-nitrogen, calcium, potassium, magnesium, and chloride in subsurface drainage, especially during the growing season and after fertilizer applications. This was attributed to excessive applications of plant nutrients. No differences in levels of phosphorus, ammonium-nitrogen, organic nitrogen, and sulfide were found. More recently, Thomas and colleagues[55] observed that NO_3-N concentrations in shallow groundwater of a drained field were greater than those in shallow groundwater of adjacent, undrained forestland and grassland.

In British Columbia, Richard and associates[53] observed that draining and cultivating a field previously in pasture or untended yielded greater NO_3-N levels as a result of an increase in the rate of mineralization of organic matter. However, nitrate-nitrogen loss decreased with time as a result of the transient effects of enhanced drainage and cultural practices. Furthermore, phosphorus loads from drained fields did not increase, except when preferential flow was thought to occur. They concluded that soil aeration and preferential flow were important factors influencing nutrient movement. Similar results were observed in England,[54] where studies showed a temporary increase of NO_3-N levels in outflows from soils with improved drainage, as compared to naturally drained soils. This was mainly attributed to tillage operations, but no increases were noticed in other nutrients.

D. Drainage of Irrigated Lands

A special category of land conversion for agriculture is irrigation of arid or semi-arid lands. Here artificial drainage is not required, at least initially, to lower the water table to permit farming. Rather, it is essential to prevent the rise of water tables, waterlogging, and salinity buildup in the soil, and to sustain agricultural production.[56–62] As in humid regions, natural drainage rates are adequate to meet the needs of irrigated agriculture in many areas. In others, natural rates are too slow and drainage improvements are required. Drainage and land use changes affect the hydrology and the loss of sediment and plant nutrients to receiving waters.

The major environmental impact of improved drainage on irrigated lands is salt loading via the drainage waters. Salt added in the irrigation water becomes concentrated in the soil-water solution as water is lost by evapotranspiration. Adequate drainage to leach salts from the profile is necessary to maintain irrigated agriculture over time. Without drainage to remove the leaching water, the water table will rise and soil salinity will become great enough to prevent crops from absorbing water. The end result will be a saline, waterlogged soil.

As water is drained toward the outlet, it displaces groundwater that may contain dissolved salts of geologic origin. Thus, salts in the drainage water may originate from both irrigation water and from the soil. The removal of salts from the profile is a natural process as water moves to streams and finally to the oceans. Irrigation and drainage of these soils may dramatically increase the rate of salt removal. The environmental impact of increased salt loading depends on the status of the receiving waters, as well as the concentration and amount from a specific site. At the headwaters of a river, salt loadings from drained irrigated lands may have little impact on river water quality. As the water moving downstream is used for irrigation, and a portion of it returned with increased salinity, stream water quality is degraded. An example is the Colorado River. The total dissolved solids (TDS) concentration of <200 mg/L in the upper reaches increases to 800 to 900 mg/L where the river enters Mexico. Over one third of the increased salt load is contributed by irrigated agriculture in the Colorado River basin.[63]

Drainage systems designed to control salinity are, by definition, intended to remove salt, and usually will lower the quality of the receiving waters. The amount of salt removed depends on irrigation methods and management as much as on the drainage system.[3,57,64] Thus, the design of irrigation and drainage systems should be considered as a unit to satisfy both agricultural production and environmental objectives.

The dominant salts in drainage outflows are carbonates, bicarbonates, sulfates, and chlorides. The negative effects of these salts on both the soil and receiving waters have long been recognized. However, trace elements have had the greatest impact in the U.S. The most famous case involves the Kesterson Reservoir in California's San Joaquin Valley.[4,5] In 1982, scientists discovered that irrigation drainage water was increasing selenium concentrations in the reservoir, which served as a drainage outlet for a large area of agricultural land. The selenium was responsible for the death of certain aquatic organisms and waterfowl.[19,65–71] Other potentially harmful trace elements that were concentrated in the closed-outlet reservoir were molybdenum and arsenic. These elements were not brought into the area by irrigation water but were leached from geologic deposits on site.[69]

Significant actions resulted from these findings. Outlets for the Westlands irrigation district, the largest irrigation district in the U.S. at the time, were blocked under court order. Numerous scientific investigations were conducted to determine the nature of the problem and develop methods to reduce the impacts, as indicated in several proceedings of meetings of the Unites States Committee on Irrigation and Drainage (USCID) and of the International Commission on Irrigation and Drainage (ICID).[72–76] Among these studies were surveys that identified at least four other sites that may have similar problems. The National Research Council appointed a committee and sponsored a study of the overall problem of irrigation-induced water quality problems. Their report noted that drainage systems must now be designed and managed not only to reduce salt accumulation in the root zone and salt disposal in streams, but also to limit toxic effects of selected trace elements contributed by the local geology.[19]

In nearly all cases, the concentration of trace elements in drainage waters would be too small to cause environmental problems. The problem in Kesterson was greatly exacerbated because the concentrations were increased by evaporation of water from the closed-outlet reservoir. Such detrimental effects often can be avoided by making sure that a reliable drainage outlet exists prior to construction of irrigation projects. Nevertheless, it must be recognized that drainage waters from irrigated lands carry constituents that may pollute receiving streams.

> . . . irrigated agriculture over time cannot avoid causing an adverse offsite effect. This effect must be acknowledged: it can be minimized, internalized or rejected, but it cannot be ignored. If irrigation is a desirable use of water, then its waste waters must be treated and/or disposal provided for.[19]

IV. IMPROVED AGRICULTURAL DRAINAGE

Drainage works are needed to sustain production on lands that have already been artificially drained. Drainage systems have a useful life of 20 to 40 years and major renovation or replacement will be necessary on a continuing basis to sustain productivity of drained lands. Of the 43 million ha in cropland on wet soils in the U.S., 31 million ha have been drained sufficiently to eliminate excess wetness as the major factor limiting crop production.[1] Improved drainage is needed on the remaining 12 million ha. In addition, drainage is less than optimum on some of the 31 million ha already drained. Statistics on the percentage of croplands having surface and subsurface drainage improvements are not directly available. However, it has been shown that there were 15 million ha of subsurface drainage in all uses.[1] Assuming that all of those hectares were in cropland, there are at least 16 million ha of drained cropland with surface drainage only. Although generally less expensive, surface drainage is not as effective as subsurface drainage in satisfying the drainage needs of most soils. Productivity could be increased by providing better subsurface drainage on these lands.

The application of controlled drainage and subirrigation will influence the need for drainage works.[25,77–86] These water table management practices have the potential to both substantially improve agricultural productivity and reduce off-site environmental impacts.

It may be concluded that drainage improvements will continue to be needed on existing croplands to sustain and improve agricultural productivity. Economic conditions will determine whether such improvements will be profitable to the farmer. Based on existing and historical conditions, and on the potential of the broader concept of water table management, it seems likely that economic forces will support the continuation of drainage improvements and related water management practices. The application of these practices will almost certainly be affected, probably controlled, by their environmental impacts. These impacts are discussed in this section.

A. Hydrology

Results of research on a wide variety of soils, crops, and site conditions show that the design and management of drainage systems have a tremendous effect on the rate and quality of water leaving the field. In general, systems with improved subsurface drainage have less runoff and lower peak outflow rates than do systems that depend primarily on surface drainage.[17,23–25,27,28,35,87–97] Conversely, systems that emphasize improved surface drainage have greater runoff rates and greater losses of sediment and adsorbed constituents such as phosphorus and some pesticides. Subsurface drainage lowers water tables thus increasing the pore space available for infiltration of rainfall. This reduces the proportion of the total outflow occurring as runoff, which is rapid, and increases the proportion that is removed slowly by subsurface drainage over a longer period of time.

Differences in total annual outflows between systems that primarily provide surface drainage and those that are primarily subsurface systems have been small. Use of simulation models has shown that subsurface drainage improvements will increase total outflow slightly (on the order of 10% or less) for some situations.[17,25,27,98–100] These differences have been predicted, not measured experimentally. Such differences would be difficult to measure because they are insignificant compared to the natural variation in outflow rates from year-to-year and season-to-season as a result of the temporal variation in rainfall.

Baker and Johnson[87] summarized the existing research on the effect of subsurface drainage improvements on the hydrology of croplands. They concluded that the hydrologic effects were as follows: shorter surface ponding duration, increased infiltration and percolation, lower water tables, reduced antecedent soil moisture, and thus less runoff.

Similar results have been found in North Carolina.[25,27,35,90,91,100] These studies showed that improved subsurface drainage tends to decrease peak runoff rates as compared to improved surface drainage. Both modeling and field studies showed that the effect of improved subsurface drainage is to lower the water table, increase infiltration and storage, and thereby reduce runoff.[35,100] Results from North Carolina also showed that adding subsurface drainage to lands formerly dependent on surface drainage alone decreased runoff by as much as threefold and reduced peak runoff rates and the frequency of flooding on poorly drained soils.[25,35]

Bottcher and associates[89] reported that a site in Indiana with improved subsurface drainage yielded less runoff than an adjacent field with less intensive subsurface drainage improvements. Field experiments in Louisiana have produced findings consistent with these results.[92–95] As compared to improved surface drainage, subsurface drainage improvements decreased runoff by 34%.[94,95] Furthermore, Istok and Kling[96] found that improved subsurface drainage decreased runoff by 55% on an Oregon watershed. Similar results have been reported for Colorado and Montana,[97] Ontario,[23,88] Quebec,[101] and Germany.[28]

Robinson[102] conducted a comprehensive study of the impact of improved drainage on river flows in the U.K. Data from field experiments were analyzed and simulation studies conducted for five sites. The results showed that improved subsurface drainage reduced peak outflow rates for soils prone to prolonged surface saturation and high water tables in their undrained state, but increased outflow rates on more permeable soils where subsurface flows predominate. These results showed that improved subsurface drainage is most likely to increase peak outflow rates in areas where rainfall is low and there is little runoff under natural conditions.

B. Sediment Losses

Sediment, the product of erosion, is widely regarded as the major pollutant entering our streams, lakes, and estuaries. The mass of sediment far exceeds that of any other pollutant, and it is clearly the single biggest pollutant from agricultural lands, as well as from other sources such as construction sites, mining, and logging operations. For example, in 1977, erosion rates in the U.S. exceeded 22 Mg/ha on 19% of the land used for row crops in the midwest and on 32% of row cropland in the southeast.[103] Wider use of conservation tillage and the sodbuster provisions in the 1985 Food Security Act (Public Law 99-198) have helped reduce these excessive rates, but average losses are still measured in megagrams per hectare. In addition to its direct effects, sediment affects water quality by the phosphorus and pesticides carried with it and the salts that may be dissolved from it.

Extensive research in the U.S., Canada, and Europe has shown that subsurface drainage improvements reduce sediment loss from agricultural watersheds.[25,87,89,91–97,104–108] A field experiment in Indiana showed that subsurface drainage decreased sediment losses by as much as 97%.[89] Results of 7 years of field data from Louisiana showed that improved subsurface drainage reduced annual soil losses by 42% on the average.[95] Similarly, a 6-year monitoring study on an Ohio watershed showed that sediment loadings in runoff were substantially greater than in subsurface drainage.[104,105] Based on a 6-year record, Schwab and colleagues in Ohio reported that average annual soil losses were reduced by 36% with improved subsurface drainage.[107] When an additional treatment, i.e., shallow drains, was added to the Ohio experiment, results showed that the reduction in sediment loss was more marked with shallow than with deep drains.[108] Losses from the plots with deep drains were greater than expected because of suspended sediment in the subsurface drainage effluent. The high sediment content was probably due to swelling and shrinking of the clay soil at the study site. Large soil cracks could have allowed some surface water to flow directly to the drain lines, dislodging soil particles along the way and carrying them into the drain lines as suspended sediment, although this hypothesis was rejected by Schwab and associates.[107,108] It should be noted that the effect of improved subsurface drainage on runoff and erosion is dependent on the intensity of the drainage system. Placing the drains closer together or deeper would increase the subsurface drainage intensity and, in most cases, would further reduce runoff and sediment losses.

Based on research results from a study in Oregon, Istok and Kling[96] suggested that improved subsurface drainage could be an effective management practice for erosion control. The study showed that, on average, sediment yield from relatively steep watersheds (slopes up to 15%) was reduced by 55% with improved subsurface drainage. Subsurface drainage is accepted as a best management practice for erosion control and is cost-shared by the State of Oregon for that purpose.[165]

In Canada, Culley and co-workers[109,110] monitored the concentrations of suspended solids in subsurface drainage on both the field and watershed scales. Substantial amounts of suspended solids in subsurface drainage waters were attributed to cultural practices because greater concentrations were found in subsurface discharge water from continuously cultivated plots, as compared to plots with permanent sod.[109] Watershed-scale studies showed low sediment yields from artificially drained lands.[110]

Skaggs and associates[91] simulated the effects of improved subsurface drainage on erosion. They coupled two computer models, DRAINMOD and CREAMS, and found that predicted erosion on land with a 2% slope could be decreased by up to a factor of 10 by changing the drainage system from one with primarily surface drainage to one with intensive subsurface drainage. This agreed with field studies that showed that because improved subsurface drainage reduced runoff, it could have a significant impact on sediment losses.[17,25]

C. Nutrient Losses

A good understanding of the effects of improved drainage on hydrology is essential to the understanding of its effects on outflow water quality. As discussed in the section on hydrology, intensive subsurface drainage will cause most of the outflow to drain through the soil profile and move from the field through the subsurface drains, especially if surface drainage is poor. If the surface drainage is good (i.e., no potholes and small depressional storage) and/or subsurface drainage is of low intensity, a larger percentage of the outflow will leave the system as surface runoff. It follows that the fractions of the total outflow that leave the field by runoff and by subsurface flow are dependent on the relative intensities of surface and subsurface drainage. The proportions of surface runoff and subsurface drainage also may be affected by the use of controlled drainage and the management of that practice. Thus, the route and rate by which water is drained from a field are controlled by the design and operation of drainage and related water management systems. It follows that the choices made in the design and operation of the system may have a profound effect on the constituents carried by the drainage water.

In general, intensive subsurface drainage will increase outflows of mobile constituents, such as nitrate-nitrogen and certain salts, while decreasing runoff and the loss of sediment, phosphorus, organic nitrogen, and other pollutants, such as certain pesticides, that are attached to the sediment. This general conclusion is supported by the results of many studies. The finding that improved subsurface drainage increases nitrate-nitrogen losses has been reported in California[111–113] Illinois,[114] Vermont,[115] Iowa,[87,116,117] North Carolina,[7,25,27,49,51,90,118] Indiana,[89] Georgia,[119] Maine,[120] Michigan,[121] Minnesota,[122] and Ohio.[104,105,108,123] Similar results have been reported in British Columbia,[53] Ontario,[124,125] Quebec,[126] England,[127] and Sweden.[128] Most studies have attributed the increased loss of NO_3-N to increases in nitrification, and decreases in denitrification caused by deeper water table depths with subsurface drainage and to the fact that subsurface drainage provides an outlet for mobile constituents after they have entered the soil profile. Several researchers also have concluded that improved subsurface drainage decreases phosphorus loss.[7,17,25,87,89,104–106,108,111,121,126] Because most phosphorus losses are sediment-bound, investigators have explained the reduction in P losses by the marked decrease in runoff and thus sediment losses when subsurface drainage intensity is increased.

Evans and associates[129] summarized results from several studies on nutrient losses in North Carolina. Based on a total of approximately 125 site-years of data collected at 14 sites in eastern North Carolina, it was concluded that: (1) outflow from surface drainage systems contains greater concentrations of phosphorus, organic nitrogen, and sediment than that from subsurface drainage systems; (2) subsurface drainage systems contain greater concentrations of nitrate-nitrogen than surface drainage systems. Gilliam and Skaggs[25] found that nitrate-nitrogen losses, from similarly cropped soils, varied from 3.7 kg/ha/year for low intensity subsurface drainage to 15.7 kg/ha/year for medium intensity subsurface drainage, to 32.4 kg/ha/year for high intensity subsurface drainage. Phosphorus losses were 0.53, 0.33, and 0.21 kg/ha/year for the three treatments, respectively, decreasing with increasing subsurface drainage intensity. Organic nitrogen losses decreased with improved subsurface drainage, but the decrease was not as great as the increase in NO_3-N. Thus, total N losses were 13.6, 20.0, and 42.1 kg/ha/year for low, medium, and high subsurface drainage intensities, respectively. Simulation studies on a similar soil showed that NO_3-N losses could be reduced by a factor of two by improving surface drainage and increasing the drain spacing to reduce subsurface drainage intensity.[90] Both drainage treatments satisfied agricultural drainage needs.

There are exceptions. In Ohio, Schwab and co-workers[108] found that annual losses for nitrate-nitrogen and phosphorus were less for shallow pipe drains than for surface drainage. However, plots with deep pipe drains had greater nitrate-nitrogen and less phosphorus loss than those with surface drainage. In Louisiana, field data showed that improved subsurface drainage reduced the annual losses for NO_3-N and P by 20 and 36%, respectively, as compared to improved surface drainage.[94] Nevertheless, on a storm-by-storm basis, differences in NO_3-N losses were not statistically significant. The lack of increase in nitrate-nitrogen loss with improved subsurface drainage could have resulted from the relatively low intensity of subsurface drainage and to the timing of heavy rainfall events with respect to fertilization. Most of the nitrate-nitrogen loss in the Louisiana study was in the runoff, even for the plots with subsurface drainage.[94] Subsurface drainage reduced the amount of runoff, but runoff still occurred. Apparently, the reduction in runoff due to subsurface drainage reduced nitrate-nitrogen losses in runoff in about the same amount that it increased losses through the subsurface drains. This may occur where subsurface drainage is installed but is not intense enough to substantially increase nitrification and/or decrease denitrification in the soil profile.

A Florida study reported that subsurface drainage decreased nitrate-nitrogen losses.[130] They compared NO_3-N and P losses from a furrow irrigation system with surface drainage to losses from a subsurface drainage-subirrigation system. They concluded that the high water table held in the subsurface drainage-subirrigation system may have influenced the results. The high water table could have promoted denitrification, thus reducing NO_3-N losses compared to the surface drainage system.

Another exception to the general trend is research showing that improved subsurface drainage can increase phosphorus and nitrate-nitrogen losses, as compared to improved surface drainage. Several researchers have reported such findings.[109,110,131–133] These reported effects of drainage on phosphorus losses have often been coupled with cultural practices. A study to evaluate the water quality from a subsurface-drained citrus grove in Florida concluded that subsurface drainage from sandy soils can lead to substantial losses of nitrate-nitrogen and phosphorus if heavy water applications occur soon after fertilization.[131] Such effects would occur more readily in sandy soils than in soils with higher clay contents. However, watershed-scale studies on Brookston clay soil in Ontario have reported that at least 25% of the total P and 50% of the Ortho-P leaving the watershed was lost via subsurface drainage.[110] About 18% of the sediment (suspended solids) lost from the watershed was removed by subsurface drainage. Another 32% of the sediment was estimated to have been lost via ditch bank erosion. Plot studies on the same soil type showed that 50% of the total P lost was removed by subsurface drainage and 34% of that loss was sediment associated.[109] Furthermore, the losses were substantially affected by P fertilization rate, crop cover, and drain depth. Dissolved P in drainage effluent from permanent sod exceeded those from continuous corn, whereas subsurface sediment and sediment-associated P losses were greatest for continuous corn. Increasing the drain depth from 0.6 to 1.0 m decreased sediment, sediment-associated P, and total dissolved P loads by 49, 54, and 60%, respectively.

The above results from soils in the Great Lakes basin, which includes parts of the U.S. and Canada, are in contrast to results from other studies in the same region.[89,134,135] They are even somewhat in contrast to earlier results from one of the same watersheds for a period of lower subsurface flows.[124] Nevertheless, the results are in agreement with results reported for a similar Lake Erie basin soil (Toledo) with shallow drain depths in Ohio.[108] Discussion of the Ohio experiment given in the previous section on sediment loss is pertinent here.[107,108] In that section, we speculated that the relatively high sediment losses through drain lines may have been due to large cracks and macropores that form in the swelling and shrinking clay soils. This could allow surface water to flow rapidly to the drain lines carrying both sediment and dissolved constituents, including P. The proportion of macropore flow should be greater for permanent sod than for a tilled crop such as corn. These observations are consistent with the conclusion of Culley and associates[109] that P export in subsurface drains is dependent on soil type, drain depth, soil and crop management practices, and antecedent weather conditions.

One other exception to the general trend was reported in Ontario. Thornley and Bos[132] observed unacceptable bacterial and nutrient levels in effluent from a subsurface drainage system and concluded that subsurface drainage was a contributor to poor water quality. However, they suspected that illegal actions from municipal and agricultural communities caused the observed large pollutant loads. In a more recent monitoring study of a watershed in Ontario, Flemming[133] reported that sites with subsurface drainage systems had greater levels of most chemicals and smaller levels of bacterial parameters than fields with open-ditch systems. High nitrate-nitrogen and phosphorus levels were related to excessive fertilizer use, and in some cases, there was a direct connection of milkhouse drains to the field subsurface drainage system.

Several experiments have studied the movement of pesticides in drainage systems,[106,128,136,137–143] but only limited or inconclusive results on the effect of drainage system on pesticide losses have been obtained.[144] In Georgia, Leonard and co-workers[137] found that some pesticides are transported in subsurface outflow, but others degrade rapidly in the soil. They concluded that the fate and movement of pesticides in shallow groundwater is controlled by the pesticide properties. Results from a 4-year study in Ohio indicated that losses of atrazine in runoff were greater than in subsurface drainage.[142] In addition, they observed no differences between runoff and subsurface drainage losses of three other herbicides (alachlor, metolachlor, and metribuzin). A singular experiment in Louisiana reported that improved subsurface drainage reduced losses of atrazine and metolachlor by over 50%, as compared to improved surface drainage.[138] However, the experiment is based on results from only one growing season. Another study in Louisiana found that pesticide concentrations in subsurface drainage decrease quickly after pesticide application.[139] Pesticide transport was found to occur more rapidly and through preferential pathways when conservation tillage was used, as compared to conventional tillage, in a drainage study in New York.[140] In Indiana, Kladivko and associates[141] reported that pesticide losses in subsurface drainage decrease with wider drain spacings, which is directly related to decreases in subsurface drainage rates. Munster and associates[143] in North Carolina found that controlled drainage and subirrigation reduced losses of aldicarb through subsurface drains, but that maximum losses were $<0.05\%$ of the amount applied to a poorly drained coastal plain soil. Parsons and colleagues[145] coupled the models DRAINMOD and CREAMS to simulate pesticide runoff losses from drainage systems. They concluded that surface drainage improvements could increase losses of sediment-bound chemicals. They also concluded that improved subsurface drainage can reduce those surface losses, but it also can increase subsurface losses of mobile, nonadsorbed contaminants.

It is obvious that the mechanisms governing the loss of pollutants from soils with improved drainage are complex and vary with management practice, soil, climate, and characteristics of the pollutants. This is reflected in a consistent conclusion from most studies: there is a significant need for additional research to fully quantify the water quality effects of drainage system design and operation, cultural practice, soil type, climate, and, most importantly, their interactions.

V. MANAGEMENT PRACTICES TO MINIMIZE OFF-SITE IMPACTS

A. Controlled Drainage

Based on experimental results from Meek and associates in California,[146–148] the Committee on Research of the Irrigation and Drainage Division of the American Society of Civil Engineers (ASCE) concluded that nitrate-nitrogen concentrations in drainage waters could be reduced by subjecting the nitrogen pool to anaerobic conditions.[149] This implied the possibility of designing drainage systems specifically to take advantage of denitrification, which was demonstrated with a field experiment in California that utilized submerged drain lines.[146] Similarly, in Israel, nitrate-nitrogen losses in drainage waters were reduced by adding sufficient water to flood fields prior to the release of water.[150]

The concept of controlled drainage to promote denitrification has been extensively researched and implemented in North Carolina.[7,25,27,90,99,118,129] Nitrate-nitrogen loss in drainage waters was reduced by about 50% by using flashboard risers to raise the water level in ditches during the fallow winter months.[118] Control during the growing season further reduced NO_3-N losses. Similar results were observed in five farmer-operated controlled drainage systems for a range of soil types and conditions.[27] Controlled drainage clearly increased denitrification as determined by the dramatically reduced nitrate-nitrogen concentrations in the saturated, reduced zones. However, drainage control had little effect on total nitrogen concentrations in drainage outlet ditches.[27,118] Nitrate-nitrogen concentrations were reduced by up to 20%, compared to no control, but TKN concentrations were somewhat increased. The big impact on nitrate-nitrogen loading is the effect of controlled drainage on total outflow. Evans and associates[129] reviewed results from 125 site-years of North Carolina data and found that controlled drainage reduced total drainage outflows by about 30%. They concluded that controlled drainage reduced both nitrate-nitrogen and phosphorus losses compared to subsurface drainage with no control. An analysis of results from 14 studies showed that drainage control reduced annual total nitrogen losses at the field edge by an average of 45% (10 kg/ha) and total phosphorus by 35% (0.12 kg/ha). Reductions at individual sites were influenced by rainfall, soil type, type of drainage system, and drainage or cropping management intensity. Evans and co-workers[151] concluded that controlled drainage also may reduce nutrient losses on a watershed scale.

In a review of the water quality effects of water table management, Thomas and associates[144] stated controlled drainage does have a beneficial impact on water quality, but this can be maximized only by proper design and management. The effects of soil properties, site parameters, drainage system design, and control strategy on nitrate-nitrogen and phosphorus losses can be evaluated with simulation models.[90,99] Wright and co-workers[152] combined the CREAMS and DRAINMOD simulation models to study the effect of water table management practices on water quality. Their simulations predicted that controlled drainage-subirrigation practices will increase denitrification and decrease nitrate-nitrogen losses in subsurface drainage, a result also obtained by Skaggs and Gilliam.[90] Although controlled drainage is very effective in reducing nitrate-nitrogen outflows, simulations usually predict increased P losses because predicted runoff increases with drainage control compared to subsurface drainage with no control.[99] This is contrary to results of field studies discussed previously that found that drainage control reduced both NO_3-N and P outflows. This discrepancy is believed to be related to the fact that the simulation models usually assume that deep and lateral seepage are negligible. Seepage from a field with an elevated water table can be substantial. Because the seepage water passes through reduced zones with negligible NO_3-N concentration, and because P movement through those zones also is negligible, seepage transports little NO_3-N and P to the environment. Consequently, the simulation models usually predict smaller effects of controlled drainage than measured in the field. The percentage of total loss attributable to lateral seepage per unit area will decrease as the size of the controlled area increases. Therefore, increased runoff and P losses as a result of controlled drainage may occur if the practice is uniformly implemented on very large tracts of land. Results of simulation studies and experience with systems in the field clearly show that the management of controlled drainage systems plays a big role in providing water quality benefits. Used improperly, however, these systems could produce negative water quality effects.[5,7,90]

Because of the potential environmental benefits of controlled drainage, it has been accepted as a "best management practice" by the regulatory agencies in North Carolina.[129,153] Structures to achieve control have been cost-shared by the State of North Carolina in nutrient-sensitive watersheds since 1983. Farmers have readily accepted controlled drainage because it conserves water and increases yields.[129] Control structures have been placed in ditches draining over 100,000 ha in North Carolina, with another 10,000 ha expected to be added in 1993. Based on results of field experiments on several soils, it is estimated that nitrate-nitrogen outflows from the controlled areas have been reduced by over 0.7 million kg annually. Frequent enquiries from both regulatory and agricultural agency personnel in other Atlantic Coast states indicate that interest in this practice is widespread.

B. Cultural Practices

1. Fertilizers

A study in Florida found that improved subsurface drainage from sandy soils can lead to significant nutrient losses if heavy water applications occur soon after fertilization.[130] Similarly, a study in Indiana concluded that nutrient losses from subsurface drainage systems could be intensified if heavy rainfall occurs soon after fertilizers are applied.[89] This implies that fertilizer nutrient losses can be reduced by split applications, soil testing, and fertilizing to achieve goals for reasonable yields.

Researchers in Georgia,[52] Minnesota,[122] Ohio,[123] Vermont,[115] and Ontario[133] observed that nitrate-nitrogen losses increased with increased rate of fertilization. Culley and associates[109] in Ontario reported the same effect for P fertilization. Simulations by Kanwar and co-workers[154] in Iowa showed that greatest nitrate-nitrogen losses were associated with the largest N-application rates. They also found that split fertilizer applications increased N-plant uptake and decreased predicted NO_3-N losses. This result was observed experimentally in a later study.[155]

Clearly, excessive rates of N-fertilization result in larger losses of nitrate-nitrogen to drainage waters. Nevertheless, even the lowest rates required for economic production may result in substantial losses of nitrate-nitrogen to surface and/or groundwaters.

2. Conservation Tillage

In a field study in Iowa, Kanwar and associates[155] found that no-till greatly reduced NO_3-N concentrations in subsurface drainage waters as compared to conventional tillage. Gold and Loudon[121] reported that conservation tillage (chisel plow with 20 to 60% residue cover in the winter) markedly reduced sediment and nutrient losses during snowmelt events and early season rainstorms. However, Logan and colleagues[142] found no statistical differences in runoff and subsurface drainage losses of NO_3-N and four herbicides between no-till and moldboard plow. They attributed the lack of tillage effects on water quantity and quality to the low drainage intensity of the site.

The use of conservation tillage may actually increase movement of contaminants to shallow groundwater and losses through subsurface drains. Generally, the goal of water management practices used to control runoff and nonpoint source pollution of surface waters is to increase retention of water on the land and increase infiltration. In some cases, these practices may have negative impacts on groundwater, especially shallow groundwater. Dick and associates[156] presented evidence that no-till farming may increase pesticide transport to groundwater while reducing runoff and pollution of surface waters. Thus, conservation tillage may increase pollutant losses through subsurface drains as evidenced by the data of Culley and co-workers,[109] who found losses of P in subsurface drainage water under sod were greater than those for continuous corn. In addition, Steenhuis and colleagues[140] concluded that conservation tillage may accelerate pesticide transport as a result of preferential flow pathways associated with no-till practices. These results show that it is important to understand the impact of practices designed to control surface processes on groundwater and subsurface drainage outflows.

3. Buffers and Sediment Basins

In many locations of the U.S., including the Atlantic seaboard, riparian zones exist between agricultural fields and streams draining the area. Research in Georgia,[52] Maryland,[157] and North Carolina[51,158] has shown that riparian areas are very effective in removal of NO_3-N, P, and sediment from surface and subsurface drainage waters. Cooper and associates[158] concluded that over half of the sediment leaving agricultural fields in one watershed was deposited in a riparian zone within 100 m of the field edge. The size of the buffer area required for pollutant removal is not known, but Jacobs and Gilliam[51] noted nearly complete removal of nitrate-nitrogen within a 50-m wide riparian zone. Gilliam[7] emphasized the importance of not disturbing riparian areas that currently exist near drained fields. Askew and Williams[43,44] concluded that sedimentation caused by artificial drainage of forestland could be mitigated with proper implementation of sediment control basins.

Gilliam[7] proposed the treatment of pumped agricultural drainage water as another potential practice that could minimize off-site impacts of artificial drainage. He discussed works by Reddy and associates,[159–161] who used aquatic ecosystems to treat agricultural discharge waters. Nutrient losses in drainage waters were reduced by 70 to 90% by pumping the water through a series of reservoirs stocked with aquatic plants. Chescheir and associates[162,163] used wetland buffer areas to treat pumped agricultural drainage waters. The systems removed over 80% of the sediment and nutrients in the drainage water. Similar results were predicted in a modeling study to evaluate the effectiveness of wetland buffer areas for removing pollutants from agricultural drainage waters.[164]

VI. CURRENT DRAINAGE RESEARCH

It is becoming increasingly clear that agricultural drainage systems must be designed and operated to satisfy off-site environmental constraints, as well as to satisfy traditional agricultural objectives. The design and operation of drainage systems impact hydrology and drainage water quality, which, in turn, impact on the downstream environment. The environmental impacts of agricultural drainage activities depend on a large number of factors, including the upstream status of the receiving waters. Those factors involve complex interrelationships between physical, chemical, and biological processes and the parameters and variables that influence them.

In this context, we must recognize that, in evaluating the water quality and hydrologic impacts of drainage, it is not sufficient to consider drainage processes alone. In arid lands, the drainage system performance is largely dependent on the irrigation components: its management, efficiency, and scheduling. In humid areas, the practices of controlled drainage and subirrigation add complexity to the task of selecting options and evaluating and managing hydrologic and water quality impacts. However, the problem is much larger than just determining the impacts of those irrigation and drainage components directly affecting water. It must be assumed that, in general, drainage water quality also is affected by cultural, fertility, and pest management and water management practices.

Past research has provided a fair understanding of the hydrologic impacts of drainage and related water management practices. It also has revealed some general relationships between drainage practices and water quality, but there are many exceptions. Furthermore, it is difficult to quantify many of the qualitative relationships that are known. Research is needed to improve our understanding of the processes governing pollutant movement from agricultural lands before quantification is possible. Methods are needed to quantify the effects of alternative design and operational procedures on crop yields and environmental impacts. The interdependent effects of cultural, fertility, and pest management practices on both agricultural and environmental objectives also must be considered.

An indication of the priority of environmental factors is indicated by the fact that practically all current drainage research is oriented toward determining hydrologic or water quality impacts. The development of computer simulation models is an approach that is being used by many researchers to deal with the complex interactions that must be addressed. However, the development of successful models requires a good understanding of the mechanisms, which we do not have in many cases. A further limiting factor is the lack of good data sets that can be used to test models for the wide range of soil, crop, and climatic conditions that exists.

VII. SUMMARY

Although research results are not totally consistent, a great majority of studies indicate that, compared to natural undrained land, drainage improvements in combination with the change in land use to agriculture increase peak runoff rates, sediment losses, and nutrient losses. Nevertheless, sediment yields from artificially drained croplands are usually small compared to croplands on naturally well-drained uplands. The increased magnitude of the runoff peaks and nutrient loads depend heavily on the land use changes that accompany drainage improvements. They also depend on the type of drainage system, cultural practices, fertilizer usage, crops, soil, and climate.

The most often quoted concern about improved drainage is that it has reduced wetland area in North America by a large percentage. This loss has reduced habitats for birds and wildlife and has removed natural filters that cleanse drainage water from adjacent lands. However, the rate of conversion of lands in the U.S. to agricultural uses has been greatly reduced. Economic forces and regulations to protect wetlands have essentially stopped such land conversions. Thus, water quality impacts of land conversion for agriculture are not critical in the U.S. at the present time. A far more pertinent and important issue is the environmental impact of improved drainage as an agricultural practice. That is, what are the hydrologic and water quality impacts of improving drainage on lands that are already in agricultural production?

Studies on a wide range of soils, crops, and site conditions have shown that increasing drainage intensity on agricultural lands may have both positive and negative impacts on hydrology and water quality. Improved subsurface drainage lowers water tables, increasing the pore space available for infiltration of rainfall. This reduces the proportion of the total outflow occurring as surface runoff, which is rapid, and increases the proportion that is removed slowly by subsurface drainage over long periods of time. Thus, improved subsurface drainage generally reduces peak outflow rate and sediment loss, while decreasing the loss of some pollutants and increasing the loss of others. For example, increasing the intensity of subsurface drainage generally reduces loss of phosphorus and organic nitrogen, whereas it increases the loss of nitrate-nitrogen and soluble salts. Conversely, increasing surface drainage intensity tends to increase phosphorus loss and reduce nitrate-nitrogen outflows. Although exceptions have been reported in the literature for nearly all cases, these general conclusions have been supported by the large majority of investigations.

Improved drainage is required on many irrigated, arid lands to prevent the rise of the water table, waterlogging, and salinity build-up in the soil. The history of irrigated agriculture is replete with failures caused by the lack of adequate drainage to prevent salination of the soils. Drainage to control salinity is, by definition, intended to remove salt, and will usually increase the salinity of receiving waters. The amount of salt removed via artificial drainage depends on irrigation methods and management as much as on the drainage system. Hence, the design of the irrigation and drainage system should be considered as a unit rather than as separate systems.

In irrigated, arid areas, while salt accumulation in receiving waters is the most prevalent problem affecting downstream users, the effect of irrigation and drainage on loss of trace elements to the environment has had the greatest impact in the U.S. The most infamous case involves the Kesterson Reservoir in California's San Joaquin Valley. Selenium, leached from geologic deposits by irrigation drainage water, became concentrated in the reservoir at levels toxic to aquatic organisms and waterfowl. The problems resulted in blockage, under court order, of drainage outlets from the largest irrigation district in the U.S. The problems also resulted in much debate and analysis of the philosophy and strategy of planning irrigation and drainage systems. The problem in Kesterson was greatly exacerbated because the drainage outlet was a closed reservoir and concentrations were increased by evaporation. Such detrimental effects often can be avoided by making sure that a reliable drainage outlet exists prior to construction of irrigation projects.

Research has shown that management strategies can be used to minimize pollutant loads from drained lands. These strategies range from the water table management practices of controlled drainage and subirrigation, to cultural and structural measures. For example, controlled drainage has been found to reduce nitrate-nitrogen and phosphorus losses by 45 and 35%, respectively, in North Carolina.

It is becoming increasingly clear that drainage and related water management systems must be designed and managed to consider agricultural and environmental objectives. There are usually several drainage/water management alternatives that can be used to satisfy agricultural objectives. The challenge is to select those methods that will minimize negative environmental impacts. In some cases, increasing subsurface drainage intensity to reduce surface runoff and sediment losses would be a "best management practice" for controlling nonpoint source pollution. In others, the best management practice may be the use of controlled drainage to reduce nitrate-nitrogen outflows and to conserve water. Past research and field experience has provided a rational basis for selection and design of these systems. While significant advances in our knowledge of environmental impacts and methods for managing these systems have been made in the last 20 years, there is much yet to be learned about the complex mechanisms governing losses of pollutants from drained soils.

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REFERENCES

1. **Pavelis, G. A.,** Economic survey of farm drainage, in *Farm Drainage in the United States: History, Status, and Prospects,* Pavelis, G. A., Ed., USDA Economic Research Service, Misc. Publ. No. 1455, 1987, 110.
2. **Shady, A. M.,** *Irrigation Drainage and Flood Control in Canada,* Canadian International Development Agency, Ottawa, 1989, 309.
3. **van Schilfgaarde, J.,** Trends in water management for agriculture, *Culturtech. Tijdschr.,* 26, 323, 1987.
4. **Letey, J., Roberts, C., Penberth, M., and Vasek, C.,** *An Agricultural Dilemma: Drainage Water and Toxics Disposal in the San Joaquin Valley,* Agric. Exp. Sta., Univ. of California, Riverside, Div. Agric. and Natural Resour., Spec. Publ. No. 3319, 1986.
5. **Hoffman, G. J.,** Environmental impacts of subsurface drainage, in *Land Drainage,* Proc. 4th Int. Drainage Workshop, Lesaffre, B., Ed., ICID, Cairo, Egypt, 1990, 71.
6. **Duda, A. and Klimek, A.,** *Significance of Nonpoint Sources of Nutrients to Eutrophication in the Chowan River,* Workshop on Agrichemicals and Estuarine Productivity, Duke Univ. Marine Lab., Beaufort, NC, 1979.
7. **Gilliam, J. W.,** Drainage water quality and the environment, Keynote Address, Proc. 5th Natl. Drainage Symp., *Am. Soc. Agric. Eng., 7-87, 19,* 1987.
8. **Kirby-Smith, W. W. and Barber, R. T.,** *The Water Quality Ramifications in Estuaries of Converting Forest to Intensive Agriculture,* Water Res. Inst. Rep. No. 148, Univ. of North Carolina, Raleigh, 1979.
9. **Pate, P. P. and Jones, R.,** *Effects of Upland Drainage on Estuarine Nursery Areas of Pamlico Sound, North Carolina,* Working Paper No. 81-10, Univ. of North Carolina Sea Grant Program, 1981.
10. **Reeve, R. C. and Fausey, N.,** Drainage and timeliness of farming operations, in *Drainage for Agriculture,* van Schilfgaarde, J., Ed., Am. Soc. Agron., Monogr. No. 17, Madison, WI, 1974, 55.

11. **Fausey, N. R., Doering, E. J., and Palmer, M. L.,** Purposes and benefits of drainage, in *Farm Drainage in the United States: History, Status, and Prospects,* Pavelis, G. A., Ed., USDA Economic Research Service, Misc. Publ. No. 1455, 1987, 48.
12. **Vos, J., Ed.,** Symp. Proc. 25th Int. Course on Land Drainage, International Institute of Land Reclammation and Improvement, Publ. No. 42, Wageningen, 1987.
13. **Ochs, W. J., Wenberg, R. D., and Stroup, G. W.,** Drainage system elements, in *Farm Drainage in the United States: History, Status, and Prospects,* Pavelis, G. A., Ed., USDA Economic Research Service, Misc. Publ. No. 1455, 1987, 79.
14. **Skaggs, R. W.,** Principles of drainage, in *Farm Drainage in the United States: History, Status, and Prospects,* Pavelis, G. A., Ed., USDA Economic Research Service, Misc. Publ. No. 1455, 1987, 62.
15. **Skaggs, R. W. and Nassehzadeh-Tabrizi, A.,** Optimum drainage for corn production, North Carolina Agric. Res. Serv., North Carolina State Univ., Tech. Bull. No. 274, 1983, 41.
16. **Hill, A. R.,** The environmental impacts of agricultural land drainage, *J. Environ. Manage.,* 4, 251, 1976.
17. **Skaggs, R. W.,** Design and management of drainage systems, Keynote Address, Proc. 5th Natl. Drainage Symp., *Am. Soc. Agric. Eng.,* 7-87, 1, 1987.
18. **Gregory, J. D.,** Hydrologic impacts of forest water management, in *The Ecology and Management of Wetlands, Vol. 2, Management, Use, and Value of Wetlands,* Hook, D. D., et al., Eds., Timber Press, Portland, OR, 1988, 137.
19. Committee on Irrigation Induced Water Quality Problems (COIIWQP), *Irrigation-Induced Water Quality Problems, What Can Be Learned from the San Joaquin Valley Experience,* National Research Council, National Academy Press, Washington, D.C., 1989, 157.
20. **Skaggs, R. W.,** Report on sustainability of drainage systems, in *Land Drainage,* Proc. 4th Int. Drainage Workshop, Lesaffre, B., Ed., ICID, Cairo, Egypt, 1990, 39.
21. **Campbell, K. L., Kumar, S., and Johnson, H. P.,** Stream straightening effects on flood-runoff characteristics, *Trans. Am. Soc. Agric. Eng.,* 15, 94, 1972.
22. **Skaggs, R. W., Gilliam, J. W., Sheets, T. J., and Barnes, J. S.,** *Effect of Agricultural Land Development on Drainage Waters in the North Carolina Tidewater Region,* Water Resour. Res. Inst., Rep. No. 159, Univ. of North Carolina, Raleigh, 1980.
23. **Irwin, R. W. and Whiteley, H. R.,** Effects of land drainage on stream flow, *Can. Water Resour. J.,* 8, 88, 1983.
24. **Gregory, J. D., Skaggs, R. W., Broadhead, R. G., Culbreath, R. H., Bailey, J. R., and Foutz, T. L.,** *Hydrologic and Water Quality Impacts of Peat Mining in North Carolina,* Water Resour. Res. Inst., Rep. No. 214, Univ. of North Carolina, Raleigh, 1984.
25. **Gilliam, J. W. and Skaggs, R. W.,** Controlled agricultural drainage to maintain water quality, *J. Irrig. Drain. Eng.,* 112, 254, 1986.
26. **Starr, M. R. and Paivanen, J.,** Runoff response to peatland forest drainage in Finland: a synthesis, in *Forest Site and Productivity,* Gessel, S. P., Ed., Dordrecht, 1986, 43.
27. **Evans, R. O., Gilliam, J. W., and Skaggs, R. W.,** *Effects of Agricultural Water Table Management on Drainage Water Quality,* Water Resour. Res. Inst., Rep. No. 237, Univ. of North Carolina, Raleigh, 1989.
28. **Baden, W. and Eggelsman, R.,** The hydrologic budget of the highbogs in the Atlantic region, in Proc. 3rd Int. Peat Congr., Quebec, 1968, 200.
29. **Burke, W.,** Aspects of the hydrology of blanket peat in Ireland, in Int. Symp. on Hydrology of Marsh-Ridden Areas, Minsk, Byelorussian SSR, 1972, 16.
30. **Green, F. H. W.,** Hydrology in relation to peat sites, in *Peatland Forestry,* NERC, Edinburgh, 1973, 103.
31. **Pereira, H. C.,** *Land Use and Water Resources in Temperate and Tropical Climates,* Cambridge University Press, Cambridge, 1973.
32. **Heikurainen, L.,** Comparison between runoff conditions on a virgin peatland and a forest drainage area, in Proc. 5th Int. Peat Congr., Poznan, 1976, 76.

33. **Heikurainen, L.,** Effect of forest drainage on high discharge, in *The Influence of Man on the Hydrological Regime with Special Reference to Representative and Experimental Basins,* Proc. Helsinki Symp., IAHS-AISH Publ. No. 130, 1980, 89.
34. **Heikurainen, L., Kenttaines, K., and Liane, J.,** The environmental effects of forest drainage, *SUO,* 29, 49, 1978.
35. **Konyha, K. D., Skaggs, R. W., and Gilliam, J. W.,** Effects of drainage and water-management practices on hydrology, *J. Irrig. Drain. Eng.,* 118, 807, 1992.
36. **Conway, V. M. and Miller, A.,** The hydrology of small peat-covered catchments in the Northern Pennines, *J. Inst. Water. Eng.,* 14, 415, 1960.
37. **Mustonen, S. E. and Seuna, P.,** *Influence of Forest Draining on the Hydrology of Peatlands,* National Board of Waters, Water Resour. Inst., Publ. No. 2, Finland, 1971.
38. **Ahti, E.,** Ditch spacing experiments in estimating the effects of peatland drainage on summer runoff, in *The Influence of Man on the Hydrological Regime with Special Reference to Representative and Experimental Basins,* Proc. Helsinki Symposium, IAHS-AISH Publ. No. 130, 1980, 49.
39. **Seuna, P.,** *Long-Term Influence of Forestry Drainage on the Hydrology of an Open Bog in Finland,* National Board of Waters, Water Resour. Inst., Publ. No. 43, Finland, 1981.
40. **Seuna, P.,** Influence of forestry on material transport and runoff, in Wetlands/Peatlands, 1987 Symp., Edmonton, Alberta, 1987, 161.
41. **Jackson, R. J.,** Hydrology of an acid wetland before and after draining for afforestation, Western New Zealand, in *Forest Hydrology and Watershed Management,* Proc.Vancourver Symp., IAHS-AISH Publ. No. 167, 1987.
42. **Ice, G. G.,** International research on the hydrologic impacts of draining forest lands, in *Research on the Effects of Forest Harvesting, Drainage, Mechanical Site Preparation and Prescribed Fire on Water Quality,* NACSI Tech. Bull. No. 442, NY, 1984, 40.
43. **Askey, G. R. and Williams, T. M.,** Sediment concentrations from intensively prepared wetland sites, *S. J. Appl. For.,* 8, 152, 1984.
44. **Askey, G. R. and Williams, T. M.,** Water quality changes due to site conversion in coastal South Carolina, *S. J. Appl. For.,* 10, 134, 1986.
45. **Ritter, W. F., Chirnside, A. E. M., and Scarborough, R. W.,** Effect of agricultural drainage on surface water quality in Delaware, in *Development and Management Aspects of Irrigation and Drainage Systems,* Keyes, C. G., Jr. and Ward, T. J., Eds., American Society of Civil Engineers, 1985, 345.
46. **Trettin, C. C. and Sheets, P. J.,** Impacts of forest drainage on water quality, in Proc. 5th Natl. Drainage Symp., *Am. Soc. Agric. Eng.,* 7-87, 231, 1987.
47. **Hortenstine, C. C. and Forbes, R. B.,** Concentrations of nitrogen, phosphorus, potassium and total soluble salts in soil solution samples from fertilized and unfertilized histosols, *J. Environ. Qual.,* 1, 446, 1972.
48. **Nicholls, K. H. and MacCrimmon, H. R.,** Nutrients in subsurface and runoff waters of the Holland Marsh, Ontario, *J. Environ. Qual.,* 3, 31, 1974.
49. **Gambrell, R. P., Gilliam, J. W., and Weed, S. B.,** Nitrogen losses from soils of the North Carolina coastal plain, *J. Environ. Qual.,* 4, 317, 1975.
50. **Kuenzler, E. J., Mulholland, P. J., and Ruley, L. A.,** *Water Quality in North Carolina Coastal Plain Streams and Effects of Channelization,* Water Resour. Res. Inst., Rep. No. 127, Univ. of North Carolina, Raleigh, 1977.
51. **Jacobs, T. C. and Gilliam, J. W.,** Riparian losses of nitrate from agricultural drainage waters, *J. Environ. Qual.,* 14, 472, 1985.
52. **Lowrance, R. R., Todd, R. L., and Asmussen, L. E.,** Nutrient cycling in an agricultural watershed. II. Streamflow and artificial drainage, *J. Environ. Qual.,* 13, 27, 1984.
53. **Richard, P., Chieng, S. T., and Nagpal, N. K.,** Water and nutrient movement in an agricultural soil under drained and undrained conditions, in *Toxic Substances in Agricultural Water Supply and Drainage, An International Environmental Perspective,* Summers, J. B. and Anderson, S. S., Eds., 2nd Pan-American Regional Conf., ICID, Ottawa, 1989, 281.

54. **Roberts, G., Hudson, J. A., and Blackie, J. R.,** Effect of upland pasture improvement on nutrient release in flows from a natural lysimeter and a field drain, *Agric. Water Manage.*, 11, 231, 1986.
55. **Thomas, D. L., Shirmohammadi, A., Lowrance, R. R., and Smith, M. C.,** Drainage-subirrigation effect on water quality in the Georgia Flatwoods, *J. Irrig. Drain. Eng.*, 117, 123, 1991.
56. **Skogerboe, G. V., Walker, W. R., and Ayars, J. E.,** Drainage for Reducing Salt Pickup from Grand Valley, in Proc. 3rd Natl. Drainage Symp., *Am. Soc. Agric. Eng.*, 1-77, 87, 1977.
57. **van Schilfgaarde, J. and Hoffman, G. J.,** Managing salt by drainage in irrigated agriculture, in Proc. 3rd Natl. Drainage Symp., *Am. Soc. Agric. Eng.*, 1-77, 84, 1977.
58. **Paterson, B. A. and Harker, D. B.,** Tile drainage of irrigated till soils in Alberta, in *Irrigation and Drainage, Today's Challenges*, Eggleston, J., Ed., American Society of Civil Engineers, 1980, 263.
59. **Johnston, W. R., Steinert, B. C., and Stroh, C. M.,** Benefits from the drainage of heavy irrigated soils, in Proc. 4th Natl. Drainage Symp., *Am. Soc. Agric. Eng.*, 12-82, 171, 1982.
60. **Backlund, V. L. and Hoppes, R. R.,** Status of soil salinity in California, *Calif. Agric.*, 38(10), 8, 1984.
61. **van Schilfgaarde, J.,** Agriculture, irrigation and water quality, in *Toxic Substances in Agricultural Water Supply and Drainage, Defining the Problems*, Summers, J. B. and Anderson, S. S., Eds., USCID, 1986, 173.
62. **Hoffman, G. J. and van Schilfgaarde, J.,** Drainage for irrigation: managing soil salinity and drainage-water quality, in *Farm Drainage in the United States: History, Status, and Prospects*, Pavelis, G. A., Ed., USDA Economic Research Service, Misc. Publ. No. 1455, 1987, 96.
63. **Jonez, A. R.,** Controlling salinity in the Colorado River Basin, the arid west, in *Salinity in Water Courses and Reservoirs*, French, R. H., Ed., Butterworth, Boston, 1983, 337.
64. **Skaggs, R. W.,** Simulation drainage system performance as affected by irrigation management, in *Symp. on Land Drainage for Salinity Control in Arid and Semi-Arid Regions, Vol. 1, Keynotes*, Drainage Research Institute, Water Resource Center, Cairo, Egypt, 1990, 61.
65. **Ohlendorff, H. M., Mothem, R. L., Bunck, C. M., Aldrich, T. W., and Moore, J. F.,** Relationships between selenium concentration and avian reproduction, North Am. Wildlife Natural Resour. Conf., 1986.
66. **Day, M. and Nelson, D. G.,** Irrigation drainage flows, salinity and trace element relationships in Broadview Water District, in *Toxic Substances in Agricultural Water Supply and Drainage, Defining the Problems*, Summers, J. B. and Anderson, S. S., Eds., USCID, 1986, 45.
67. **Johnston, W. R. and Steinert, B. C.,** Agricultural drainage water management problems in Westlands Water District, in *Toxic Substances in Agricultural Water Supply and Drainage, Defining the Problems*, Summers, J. B. and Anderson, S. S., Eds., USCID, 1986, 37.
68. **Groves, G. R., Squires, R. C., and Johnston, W. R.,** Selenium removal from agricultural drainage water, in *Toxic Substances in Agricultural Water Supply and Drainage, Searching for Solutions*, Summers, J. B. and Anderson, S. S., Eds., USCID, 1988, 25.
69. **Deason, J. P.,** Irrigation-induced contamination: how real a problem?, *J. Irrig. Drain. Eng.*, 115, 9, 1989.
70. **Tanji, K. K.,** Chemistry of toxic elements (As, B, Mo, Se) accumulating in agricultural evaporation ponds, in *Toxic Substances in Agricultural Water Supply and Drainage, An International Environmental Perspective*, Summers, J. B. and Anderson, S. S., Eds., ICID, Ottawa, 1989, 109.
71. **Moore, S. B.,** Selenium in agricultural drainage: essential nutrient or toxic threat?, *J. Irrig. Drain. Eng.*, 115, 21, 1989.
72. **Summers, J. B. and Anderson, S. S., Eds.,** *Toxic Substances in Agricultural Water Supply and Drainage, Defining the Problems*, USCID, 1986.

73. **Summers, J. B. and Anderson, S. S., Eds.,** *Toxic Substances in Agricultural Water Supply and Drainage, Searching for Solutions,* USCID, 1988.
74. **Summers, J. B. and Anderson, S. S., Eds.,** *Toxic Substances in Agricultural Water Supply and Drainage, An International Environmental Perspective,* ICID, Ottawa, 1989.
75. **Backstrom, T. E. and Reid, L. J., Eds.,** *Controlling Toxic Substances in Agricultural Drainage, Emerging Technologies and Research Needs,* USCID, 1990.
76. **Holy, M.,** *The Influence of Irrigation and Drainage on the Environment with Particular Emphasis on Impact on the Quality of Surface and Ground Waters,* Vol. 1A, ICID, Ottawa, 1990.
77. **Clinton, F. M.,** Invisible irrigation of Egin Bench, *Reclam. Era,* 34, 182, 1948.
78. **Renfro, G., Jr.,** Applying water under the surface of the ground, *Water: Yearbook of Agriculture,* USDA, 1955, 173.
79. **Kriz, G. J. and Skaggs, R. W.,** Water management using subsurface drains, *J. Soil Water Conserv.,* 28, 216, 1973.
80. **Skaggs, R. W.,** Water table movement during subirrigation, *Trans. Am. Soc. Agric. Eng.,* 16, 988, 1973.
81. **Skaggs, R. W.,** Water movement factors important to the design and operation of subirrigation systems, *Trans. Am. Soc. Agric. Eng.,* 24, 1553, 1981.
82. **Doty, C. W., Parsons, J. E., Badr, A. W., Nassehzadeh-Tabrizi, A., and Skaggs, R. W.,** Water table control for water resource projects on sandy soils, *J. Soil Water Conserv.,* 40, 360, 1985.
83. **Menan, N. A., Broughton, R. S., Madramootoo, C. A., Prasher, S. O., and von Hoeningen Huene, B.,** A method of designing subsurface irrigation/drainage systems to maximize net benefits, *Can. Water Resour. J.,* 2, 46, 1986.
84. **von Bakel, P. J. T.,** Using drainage systems for supplemental irrigation, *Irrig. Drain. Syst.,* 2, 125, 1988.
85. **Evans, R. O. and Skaggs, R. W.,** Design guidelines for water table management systems on coastal plain soils, *Appl. Eng. Agric.,* 5, 539, 1989.
86. **Fouss, J. L., Skaggs, R. W., Ayars, J. E., and Belcher, H. W.,** Water table control and shallow groundwater utilization, in *Management of Farm Irrigation Systems,* Hoffman, G. J., Howel, T. A., and Solomon, K. H., Eds., American Society of Agricultural Engineers, St. Joseph, MI, 1990, 783.
87. **Baker, J. L. and Johnson, H. P.,** Impact of subsurface drainage on water quality, in Proc. 3rd Natl. Drainage Symp., *Am. Soc. Agric. Eng.,* 1-77, 91, 1977.
88. **Whiteley, H. R. and Ghate, S. R.,** Sources and amounts of overland runoff from rain on three small watersheds, *Can. Agric. Eng.,* 21, 1, 1979.
89. **Bottcher, A. B., Monke, E. J., and Huggins, L. F.,** Nutrient and sediment loadings from a subsurface drainage system, *Trans. Am. Soc. Agric. Eng.,* 24, 1221, 1981.
90. **Skaggs, R. W. and Gilliam, J. W.,** Effect of drainage system design and operation on nitrate transport, *Trans. Am. Soc. Agric. Eng.,* 24, 929, 1981.
91. **Skaggs, R. W., Nassehzadeh-Tabrizi, A., and Foster, G. R.,** Subsurface drainage effects on erosion, *J. Soil Water Conserv.,* 37, 167, 1982.
92. **Bengtson, R. L., Carter, C. E., Morris, H. F., and Kowalczuk, J. G.,** Subsurface effectiveness on alluvial soil, *Trans. Am. Soc. Agric. Eng.,* 26, 423, 1983.
93. **Bengtson, R. L., Carter, C. E., Morris, H. F., and Kowalczuk, J. G.,** Reducing water pollution with subsurface drainage, *Trans. Am. Soc. Agric. Eng.,* 7, 80, 1984.
94. **Bengtson, R. L., Carter, C. E., Morris, H. F., and Bartkiewicz, S. A.,** The influence of subsurface drainage practices on nitrogen and phosphorus losses in a warm, humid climate, *Trans. Am. Soc. Agric. Eng.,* 31, 729, 1988.
95. **Bengtson, R. L. and Sabbagh, G.,** USLE P Factors for subsurface drainage on low slopes in a hot, humid climate, *J. Soil Water Conserv.,* 45, 480, 1990.
96. **Istok, J. D. and Kling, G. F.,** Effect of subsurface drainage on runoff and sediment yield from an agricultural watershed in western Oregon, U.S.A., *J. Hydrol.,* 65, 279.

97. **Ross, E. A.,** *Benefits to Surface and Ground Water Quality Resulting from On-Farm Subsurface Drainage Systems,* American Society of Agricultural Engineers, St. Joseph, MI, 1989, paper no. 89-2683.
98. **Skaggs, R. W., Gilliam, J. W., and Evans, R. O.,** A computer simulation study of pocosin hydrology, *Wetlands,* 11, 399, 1991.
99. **Deal, S. C., Gilliam, J. W., Skaggs, R. W., and Konyha, K. D.,** Prediction of nitrogen and phosphorus losses as related to drainage system design, *Agric. Ecosyst. Environ.,* 18, 37, 1986.
100. **Skaggs, R. W. and Nassehzadeh-Tabrizi, A.,** Effect of drainage system on surface and subsurface runoff from artificially drained lands, in *Applied Modeling in Catchment Hydrology,* Mississippi State University, State College, 1981, 337.
101. **Natho-Jina, S., Prasher, S. O., Madramootoo, C. A., and Broughton, R. S.,** Measurements and analysis of runoff from subsurface drained farmlands, *Can. Agric. Eng.,* 29, 123, 1987.
102. **Robinson, M.,** Impact of improved land drainage on river flows, Institute of Hydrology, Rep. No. 113, Crowmarsh Gifford, Wallingford, Oxon, U.K., 1990.
103. U.S. Department of Agriculture (USDA), Appraisal 1980, Soil and Water Resour. Conserv. Act, Washington, D.C.
104. **Logan, T. J. and Stiefel, R. C.,** The Maumee River Basin Pilot, Vol. I, Watershed Study, Watershed Characteristics and Pollutant Loadings, USEPA Rep. No. 905/9-79-005-A, Chicago, IL, 1979.
105. **Logan, T. J.,** The Maumee River Basin Pilot Watershed Study, Vol. III, Continued Watershed Monitoring (1979–80), USEPA Rep. No. 905/9-79-005-C, Chicago, IL, 1981.
106. **Schwab, G. O., McLean, E. O., Waldron, A. C., White, R. K., and Michener, D. W.,** Quality of drainage water from a heavy-textured soil, *Trans. Am. Soc. Agric. Eng.,* 16, 1104, 1973.
107. **Schwab, G. O., Nolte, B. H., and Brehm, R. D.,** Sediment for drainage systems for clay soils, *Trans. Am. Soc. Agric. Eng.,* 20, 866, 1977.
108. **Schwab, G. O., Fausey, N. R., and Kopcak, D. E.,** Sediment and chemical content of agricultural drainage water, *Trans. Am. Soc. Agric. Eng.,* 23, 1446, 1980.
109. **Culley, J. L. B., Bolton, E. F., and Bernyk, V.,** Suspended solids and phosphorus loads from a clay soil. I. Plot studies, *J. Environ. Qual.,* 12, 493, 1983.
110. **Culley, J. L. B. and Bolton, E. F.,** Suspended solids and phosphorus loads from a clay soil. II. Watershed study, *J. Environ. Qual.,* 12, 498, 1983.
111. **Johnston, W. R., Ittihadieh, F., Daum, R. M., and Pillsbury, A. F.,** Nitrogen and phosphorus in tile drainage effluent, *Soil Sci. Soc. Am. Proc.,* 29, 287, 1965.
112. **Carter, D. L., Bondurant, J. A., and Robbins, C. W.,** Water soluble NO_3-nitrogen, PO_4-phosphorus, and total salt balances on a large irrigation tract, *Soil Sci. Soc. Am. Proc.,* 35, 331, 1971.
113. **Devitt, D., Letley, J., Lund, L. J., and Blair, J. W.,** Nitrate-nitrogen movement through soil as affected by soil profile characteristics, *J. Environ. Qual.,* 5, 283, 1976.
114. **Kohl, D. H., Shearer, G. B., and Commoner, B.,** Fertilizer nitrogen: contribution to nitrate in surface water in a corn belt watershed, *Science,* 174, 1331, 1971.
115. **Benoit, G. R.,** Effect of agricultural management of wet sloping soil on nitrate and phosphorus in surface and subsurface water, *Water Resour. Res.,* 9, 1296, 1973.
116. **Baker, J. L., Campbell, K. L., Johnson, H. P., and Hanway, J. J.,** Nitrate, phosphorus and sulfate in subsurface drainage water, *J. Environ. Qual.,* 4, 406, 1975.
117. **Kanwar, R. S., Johnson, H. P., and Baker, J. L.,** Comparison of simulated and measured nitrate losses in tile effluent, *Trans. Am. Soc. Agric. Eng.,* 26, 1451, 1983.
118. **Gilliam, J. W., Skaggs, R. W., and Weed, S. B.,** Drainage control to diminish nitrate loss form agricultural fields, *J. Environ. Qual.,* 8, 137, 1979.
119. **Hubbard, R. K. and Sheridan, J. M.,** Water and nitrate-nitrogen losses from a small, upland, coastal plain watershed, *J. Environ. Qual.,* 12, 291, 1983.

120. **Benoit, G. R., Grant, W. J., Bornstein, J., and Hepler, P.,** Carbon and nitrogen levels in subsurface drained silty clay soil, *Trans. Am. Soc. Agric. Eng.*, 32, 559, 1989.
121. **Gold, A. J. and Loudon, T. L.,** Tillage effects on surface runoff water quality from artificially drained cropland, *Trans. Am. Soc. Agric. Eng.*, 32, 1329, 1989.
122. **Gast, R. G., Nelson, W. W., and Randall, G. W.,** Nitrate accumulation in soils and loss in tile drainage following nitrogen applications to continuous corn, *J. Environ. Qual.*, 7, 258, 1978.
123. **Logan, T. J., Randall, G. W., and Timmons, D. R.,** Nutrient content of tile drainage from cropland in the north central region, *Ohio Agric. Res. Dev. Cent. Res. Bull.*, p.1119, 1980.
124. **Bolton, E. F., Aylesworth, J. W., and Hore, F. R.,** Nutrient losses through tile drains under three cropping systems and two fertility levels on a brookston clay soil, *Can. J. Soil Sci.*, 50, 275, 1970.
125. **Hill, A. R. and McCague, W. P.,** Nitrate concentrations in streams near Alliston, Ontario, as influenced by nitrogen fertilization of adjacent fields, *J. Soil Water Conserv.*, 29, 217, 1974.
126. **Wiyo, K., Madramootoo, C. A., Enright, P., and Bastien, C.,** Modeling nutrients in runoff from potato fields using CREAMS, American Society of Agricultural Engineers, St. Joseph, MI, 1990, paper no. 90-2505.
127. **Williams, R. J. B.,** The chemical composition of water from land drains at Saxmundham and Woburn, and the influence of rainfall upon nutrient losses, Rothamsted Exp. Sta. Rep. No. 1970, Pt. 2, Harpenden, England, 1970.
128. **Brink, N.,** Losses of substances from tile drained soils, in *Land Drainage*, Proc. 4th Int. Drainage Workshop, Lesaffre, B., Ed., ICID, Cairo, Egypt, 1990, 209.
129. **Evans, R. O., Gilliam, J. W., and Skaggs, R. W.,** Controlled drainage management guidelines to improve drainage water quality, *N.C. Agric. Ext. Serv. Bull.*, AG-443, 1990.
130. **Campbell, K. L., Rogers, J. S., and Hensel, D. R.,** Drainage water quality from potato production, *Trans. Am. Soc. Agric. Eng.*, 28, 1798, 1985.
131. **Rogers, J. S., Stewart, E. H., Calvert, D. V., and Mansell, R. S.,** Water quality from a subsurface drained citrus grove, in Proc. 3rd Natl. Drainage Symp., *Am. Soc. Agric. Eng.*, 1-77, 99, 1977.
132. **Thornley, S. and Bos, A. W.,** Effects of livestock wastes and agricultural drainage on water quality: an Ontario case study, *J. Soil Water Conserv.*, 40, 173, 1985.
133. **Flemming, R. J.,** Impact of agricultural practices on tile water quality, American Society of Agricultural Engineers, St. Joseph, MI, 1990, paper no. 90-2028.
134. **Hergert, G. W., Klausner, S. D., Bouldin, D. R., and Zwerman, P. J.,** Effects of dairy manure on phosphorus concentrations and losses in tile effluent, *J. Environ. Qual.*, 10, 345, 1981.
135. **Miller, M. H.,** Contribution of nitrogen and phosphorus to subsurface drainage water from intensively cropped mineral and organic soils in Ontario, *J. Environ. Qual.*, 8, 42, 1979.
136. **Muir, D. C. and Baker, B. E.,** Detection of triazine herbicides and their degradation products in tile-drain water from fields under intensive corn (maize) production, *J. Agric. Food Chem.*, 24, 122, 1976.
137. **Leonard, R. A., Shirmohammadi, A., Johnson, A. W., and Marti, L. R.,** Pesticide transport in shallow groundwater, *Trans. Am. Soc. Agric. Eng.*, 31, 776, 1988.
138. **Bengtson, R. L., Southwick, L. M., Willis, G. H., and Carter, C. E.,** The influence of subsurface drainage practices on herbicide losses, *Trans. Am. Soc. Agric. Eng.*, 33, 415, 1990.
139. **Southwick, L. M., Willis, G. H., Bengtson, R. L., and Lormand, T. J.,** Atrazine and metolachlor in subsurface drain water in Louisiana, *J. Irrig. Drain. Eng.*, 116, 16, 1990.
140. **Steenhuis, T. S., Staubitz, W., Andreini, M. S., Surface, J., Richard, T. L., Paulsen, R., Pickering, N. B., Hagerman, J. R., and Geohring, L. D.,** Preferential movement of pesticides and tracers in agricultural soils, *J. Irrig. Drain. Eng.*, 116, 50, 1990.

141. **Kladivko, E. J., van Scoyoc, G. E., Monke, E. J., Oates, K. M., and Pask, W.,** Pesticide and nutrient movement into subsurface tile drains on a silt loam soil in Indiana, *J. Environ. Qual.*, 20, 264, 1991.
142. **Logan, T. J., Eckert, D. J., and Beak, D. G.,** Tillage, crop and climatic effects on runoff and tile drainage losses of nitrate and four herbicides, *Soil Till. Res.*, in press.
143. **Munster, C. L., Skaggs, R. W., Parsons, J. E., Evans, R. O., and Gilliam, J. W.,** Modelling aldicarb transport under drainage, controlled drainage and subirrigation, American Society of Agricultural Engineers, St. Joseph, MI, 1991, paper no. 91-2631.
144. **Thomas, D. L., Hunt, P. G., and Gilliam, J. W.,** Water table management for water quality improvement, *J. Soil Water Conserv.*, 47, 65, 1992.
145. **Parsons, J. E., Skaggs, R. W., and Gilliam, J. W.,** Pesticide fate with DRAINMOD/CREAMS, in *Proc. CREAMS/GLEAMS Symp.*, Beasley, D. B., Knisel, W. G., and Rice, A. P., Eds., Agric. Eng. Dept., Coastal Plain Exp. Sta., University of Georgia, Publ. No. 4, 1989, 123.
146. **Meek, B. D., Grass, L. B., and MacKenzie, A. J.,** Applied nitrogen losses in relation to oxygen status of soils, *Soil Sci. Soc. Am. Proc.*, 33, 575, 1969.
147. **Willardson, L. S., Meek, B. D., Grass, L. B., Dickey, G. L., and Bayley, J. W.,** Drain installation for nitrate reduction, *Grount Water,* 8, 11, 1970.
148. **Willardson, L. S., Meek, B. D., Grass, L. B., Dickey, G. L., and Bailey, J. W.,** Nitrate reduction with submerged drains, *Trans. Am. Soc. Agric. Eng.*, 15, 84, 1972.
149. Committee on Research of the Irrigation and Drainage Division, Water management through irrigation and drainage: progress, problems, and opportunities, *J. Irrig. Drain. Div.*, 100, 153, 1974.
150. **Raveh, A. and Avnimelech, Y.,** Minimizing nitrate seepage from the Hula Valley into Lake Kinneret (Sea of Galilee). I. Enhancement of nitrate reduction by sprinkling and flooding, *J. Environ. Qual.*, 2, 455, 1973.
151. **Evans, R. O., Parsons, J. E., Stone, K., and Wells, W. B.,** Water table management on a watershed scale, *J. Soil Water Conserv.*, 47, 58, 1992.
152. **Wright, J. A., Shirmohammadi, A., Magette, W. L., Fouss, J. L., Bengtson, R. L., and Parsons, J. E.,** Water table management practice effects on water quality, *Trans. Am. Soc. Agric. Eng.*, 35, 823, 1992.
153. **Stone, K. C., Sommers, R. C., Williams, G. H., and Hawkins, D. E.,** Water table management in the eastern coastal plain., *J. Soil Water Conserv.*, 47, 47, 1992.
154. **Kanwar, R. S., Baker, J. L., and Johnson, H. P.,** Simulated effects of fertilizer management on nitrate loss with tile drainage water for continuous corn, *Trans. Am. Soc. Agric. Eng.*, 27, 1396, 1984.
155. **Kanwar, R. S., Baker, J. L., and Baker, D. G.,** Tillage and split N-fertilization effects on subsurface drainage water quality and crop yields, *Trans. Am. Soc. Agric. Eng.*, 31, 453, 1988.
156. **Dick, W. A., Edwards, W. M., and Haghiri, F.,** Water movement through soil to which no-tillage cropping practices have been continuously applied, in *Agricultural Impacts on Ground Water — A Conference,* Water Well Publishing Co., Dublin, OH, 1986, 243.
157. **Peterjohn, W. T. and Correll, D. L.,** The effect of riparian forest on the volume and chemical composition of base flow in an agricultural watershed, in *Watershed Research Perspectives,* Correll, D. L., Ed., Smithsonian Institution Press, Washington, D.C., 1986, 244.
158. **Cooper, J. R., Gilliam, J. W., Daniels, R. B., and Robarge, W. P.,** Riparian areas as filters for agricultural sediment, *Soil Sci. Soc. Am. J.*, 51, 416, 1987.
159. **Reddy, K. R., Campbell, K. L., Graetz, D. A., and Portier, K. M.,** Use of biological filters for treating agricultural drainage effluents, *J. Environ. Qual.*, 11, 591, 1982.
160. **Reddy, K. R., Sacco, P. D., Graetz, D. A., Campbell, K. L., and Sinclair, L. R.,** Water treatment by aquatic ecosystem: nutrient removal by reservoirs and flooded fields, *Environ. Manage.*, 6, 261, 1982.

161. **Reddy, K. R., Sacco, P. D., Graetz, D. A., Campbell, K. L., and Portier, K. M.,** Effect of aquatic macrophytes on physico-chemical parameters of agricultural drainage water, *J. Aquat. Plant Manage.*, 21, 1, 1983.

162. **Chescheir, G. M., Gilliam, J. W., and Skaggs, R. W.,** Nutrient and sediment removal in forested wetlands receiving pumped agricultural drainage water, *Wetlands*, 11, 87, 1991.

163. **Gilliam, J. W., Chescheir, G. M., Skaggs, R. W., and Broadhead, R. G.,** Effects of pumped agricultural drainage water on wetland water quality, in *The Ecology and Management of Wetlands, Vol. 2, Management, Use, and Value of Wetlands*, Hook, D. D., et al., Eds., Timber Press, Portland, OR, 1988, 275.

164. **Chescheir, G. M., Skaggs, R. W., and Gilliam, J. W.,** Evaluation of wetland buffer areas for treatment of pumped agricultural drainage water, *Trans. Am. Soc. Agric. Eng.*, 35, 175, 1992.

165. **Blacklund, V.,** personal communication, 1991.