20 Water Table Management: Subirrigation and Controlled Drainage

R. WAYNE SKAGGS

North Carolina State University
Raleigh, North Carolina

I. INTRODUCTION

The primary mechanism of water table management discussed in this book is drainage, the removal of excess water to permit farming of poorly drained soils. As discussed in Chapters 2 (Evans & Fausey, 1999) and 3 (Maas & Grattan, 1999), drainage is necessary to provide trafficable conditions for farming operations, to protect the crop from excessive soil water conditions, and to control soil salinity. While excessive soil water conditions are usually the main reason for reduced yields on poorly drained soils, yields may be significantly reduced by lack of adequate rainfall resulting in deficit soil water conditions. In some cases subirrigation can be applied, through the drainage system, to raise the water table and supply crop water needs. The drainage outlet is blocked, or controlled at a preset elevation, and irrigation water is pumped into the drainage system to raise the water table to a depth that will directly supply crop water needs (Fig. 20–1c). The outlet water level elevations may be lowered such that the system functions in the conventional drainage mode during seedbed preparation and harvesting, and during periods of high rainfall.

In cases where an irrigation water supply is not available, soil water may be conserved by installing a weir or other device in the drainage outlet to reduce or "control" the drainage rate (Fig. 20–1b). The maximum drainage intensity provided by subsurface drains is not usually needed at all times during the growing season, so there is opportunity to reduce drainage rates during some periods without compromising objectives of the drainage system. This method of "controlled drainage" can be used to conserve soil water and reduce the loss of nutrients and other pollutants in subsurface drainage water. The objectives, theory, and some aspects of the application of water table management via subirrigation and controlled drainage are discussed in this chapter. Chapter 21 (Fouss et al., 1999a) covers the design of subirrigation and controlled drainage systems while the operation of the systems is the subject of Chapter 22 (Fouss et al., 1999b).

Water table control via controlled drainage and subirrigation is not new. It has been practiced for many years in scattered locations. Fox et al. (1956) discussed the application of subirrigation in California, Idaho, Utah, Colorado, and Florida. Applications in Florida include both the sandy flatwoods soils and the

 Agricultural Drainage, Agronomy Monograph no. 38.

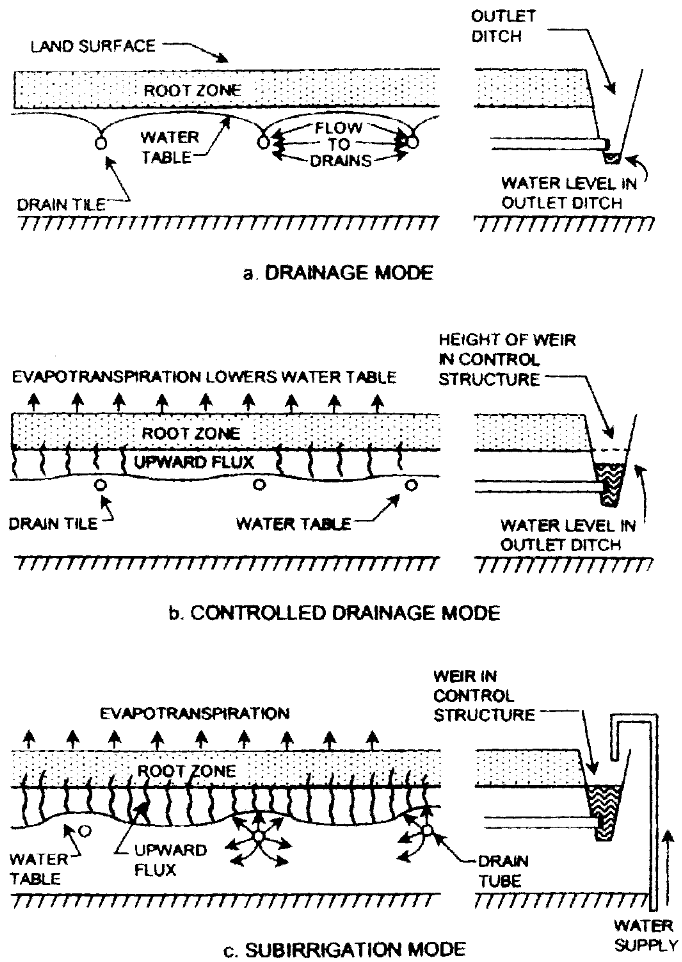

Fig. 20–1. Three modes of water table management.

organic soils near the Everglades (Spencer, 1938). Water table control practices also have been used in the organic soils of the Great Lake States of Michigan, Indiana, Ohio, and Minnesota (Schwab et al., 1966); and in the Sacramento-San Joaquin Delta in Central California (Renfro, 1955). Some of these applications date back to the 1920s (Clinton, 1948). While several hundred thousand hectares were involved, most of the early applications were on very permeable organic or sandy soils. Ditch or subsurface drain spacings were relatively wide (e.g., 50 m or greater) but, because of the high permeability, the water tables responded quickly to raising or lowering drainage outlet water levels.

Feasibility studies in the 1970s (e.g., Skaggs et al., 1972; Skaggs, 1973; Doty et al., 1975) showed that water table control practices could be applied on finer textured soils by fitting the drain spacing and other design parameters to soils and site conditions. Methods to simulate the performance of the system were developed and applied for design and operation (Skaggs, 1999a, see Chapter 13; Skaggs, 1976, 1981; Smith et al., 1985; Fouss, 1985; Fouss & Rogers, 1992). Several studies have shown that controlled drainage can be used to conserve water and significantly reduce pollutant loads from drained agricultural lands (Gilliam et al., 1999, see Chapter 24). Other studies have shown that subirrigation significantly increases yields and profit potential (e.g., Carter et al., 1988; Fausey & Cooper, 1995; Cooper et al., 1991; Broughton, 1995; Madramootoo et al., 1993, 1995; Belcher & D'Itri, 1995). These factors led to a rapid increase in the design, installation, and use of water table control practices as shown in Table 20–1 for the USA. Research continues at several locations

Table 20–1. Status of conventional and controlled drainage in humid region states with more than 1% of total land area drained.†

State‡ (1)	Total cropland§,# (2)	Drained cropland¶,# (3)	Cropland with potential for controlled drainage†† (4)	Cropland with controlled drainage installed†† (5)
Illinois	10 011 000	3 569 000	400 000	2 000
Indiana	5 579 000	2 782 000	600 000	1 200
Iowa	10 705 000	2 834 000	400 000	8 000
Ohio	5 039 000	2 397 000	1 100 000	100
Arkansas	3 280 000	2 151 000	160 000	400
Louisiana	2 595 000	1 562 000	500 000	400
Minnesota	9 321 000	1 934 000	610 000	400
Florida	1 440 000	1 146 000	1 000 000	610 000
Mississippi	3 002 000	1 440 000	1 000 000	60 000
Texas	13 490 000	1 283 000	225 000	0
Michigan	3 823 000	1 563 000	100 000	12 000
North Carolina	2 710 000	984 000	500 000	100 000
Missouri	6 072 000	1 202 000	850 000	0
North Dakota	10 947 000	910 000	10 000	2 000
Wisconsin	4 638 000	409 000	325 000	800
South Carolina	1 449 000	426 000	175 000	1 200
Georgia	2 659 000	219 000	80 000	200
Maryland	726 000	367 000	200 000	600
Tennessee	2 264 000	256 000	120 000	00
New York	2 394 000	333 000	40 000	100
Delaware	210 000	130 000	100 000	800
Total	102 356 000	27 868 000	8 475 000	800 200

† See ASCE J. Irrigation and Drainage Engineering, Special Issue: *Water Quality in Humid Regions*, Vol. 121(4), 1995.
‡ Only states in humid/semihumid regions with more than 1% of total land area drained.
§ Values from 1982 National Resources Inventory.
¶ Values from Pavelis (1987).
# Values rounded to the nearest 1000 ha after conversion from English units.
†† Values estimated by Cooperative Extension, Land Grant Univ. Faculty, and/or Soil Conserv. Service personnel in each state.

(Belcher & D'Itri, 1995; Fouss & Willis, 1990; Munster et al., 1995) to develop technology to integrate the management of water table depth and the application of agrochemicals (pesticides and fertilizers).

Reports in the literature indicate that subirrigation and controlled drainage have been applied around the world, but only on an experimental basis in many countries. Van Bakel (1988) reported that, while the practice of using drain tubing for subirrigation is very limited in The Netherlands, the use of open water drainage systems for controlled drainage and subirrigation has become widespread. Most of the growth of this type of water management has apparently occurred since about 1979 (van Bakel, 1986). Visser (1995) described the application and response to subirrigation for several locations in The Netherlands. Use of subirrigation and controlled drainage in the region near Venice, Italy to increase yields and reduce N losses in drainable waters was discussed by Giardini and Borin (1995), Borin and Lazzaro (1995) and Borin et al. (1997). Results of studies and practical experience with water table management systems in China, Finland, and The Netherlands, as well as the USA and Canada, were reported in an international meeting on the subject in East Lansing, Michigan in 1991 (Belcher & D'Itri, 1995). The author has personally observed the operation of subirrigation and controlled drainage systems in the Bordeaux area of France, in Malaysia and in New Zealand.

II. MODES OF WATER TABLE MANAGEMENT

Water table management systems may be operated in drainage (D), controlled drainage (CD) or subirrigation (SI) modes. The three modes are shown schematically in Fig. 20–1 for a system consisting of drain tube laterals connecting with an outlet ditch at the field edge. There are many alternatives for the layout of the system. Drain tubes may be used for the mains as well as the laterals, or both the laterals and the mains may be open ditches. The systems shown in Fig. 20–1 are typical in the Carolina's (Evans & Skaggs, 1985). Systems in the Midwest and Canada more typically have drain tube mains rather than open ditches (Belcher et al., 1993). A control structure, normally a flash-board riser, is placed in the outlet drain. By inserting or removing flash-boards, the threshold or weir elevation can be raised or lowered to adjust the outlet water level elevation and thereby change subsurface drainage rates. When the weir is below the outlets for the lateral drains, the system operates in **conventional drainage** mode (Fig. 20–1a).

When the weir is raised to an elevation above the outlets of the laterals, drainage from the system will not occur until the water level in the outlet rises above the weir (Fig. 20–1b). Drainage rates are reduced in this **controlled drainage** mode. Water that would drain out of the profile under conventional drainage is conserved and available to supply evapotranspiration (ET) requirements of the crop. As ET occurs the water table is lowered and water stored in the outlet ditch flows back through the drain tubes into the profile. Hence the water level in the outlet varies from just above the weir, when the water table is high and drainage is occurring, to below the bottom of the ditch after the water table has been lowered by ET. The amount of water stored in the outlet obviously depends on the dimensions of the outlet ditch. If a drain tube is used for the main, very little water will be stored in the drainage system. However, the major storage of water conserved by controlled drainage is in the soil profile and results from holding the water table higher than would occur under conventional drainage. The elevated water table will delay, and for some periods, eliminate the onset of deficit soil water conditions, and thereby reduce drought stresses. The same action may increase stresses caused by too much water if excessive rainfall occurs and if the timing and elevation of weir levels are not properly selected and managed.

Water table and outlet conditions for the **subirrigation** mode of operation are shown in Fig. 20–1c. In this case irrigation water is pumped into the drainage outlet to supply water through the subsurface drainage systems to maintain the water table at a depth that will satisfy the ET requirements of the crop. Water may be pumped continuously or controlled automatically to maintain the water level in the outlet at a constant elevation, or the water table may be allowed to fluctuate by pumping irrigation water to raise the water level in the outlet periodically. More sophisticated methods of managing the system, including feedback control and the use of weather forecasts, have been investigated by Fouss and others (Fouss, 1985; Cooper & Fouss, 1988) and are discussed in Chapter 22 (Fouss et al., 1999b).

Subirrigation systems should be designed and operated such that an adequate amount of water is supplied to the crop during periods of drought, while satisfying drainage requirements during wet periods. A subirrigation system would typically be operated in the D mode during the seedbed preparation and planting or seeding period and in the SI mode during the growing season. Depending on the crop and current weather conditions, the system may be operated in the CD mode during a part of the growing season. Controlled drainage also may be used during the nongrowing season to reduce drainage intensity and the loss of plant nutrients and other pollutants via drainage waters (Gilliam et al., 1999, see Chapter 24). Thus a subirrigation system may be operated in all three modes, SI, CD, and D, while only two modes may be used for a controlled drainage system, CD and D. An exception occurs when controlled drainage is applied on a watershed scale. Controls on the main canal or stream draining a watershed may, in some cases, allow drainage water from the upper reaches of the watershed to supply a constant source of irrigation water for the lower part of the watershed. In such cases controlled drainage may actually provide subirrigation to a significant part of the watershed (Parsons et al., 1990).

While the mode of a water table management system depends on how the drain outlet and the water level therein are controlled, water may drain from the system in all three modes and either drainage or subirrigation may occur in the CD and SI modes. The transition in water table position that occurs after rainfall in systems operated in CD and SI is shown in Fig. 20–2. The elliptical water table profile at time t_1 represents conditions directly after rainfall. As water is removed by ET and drainage, the water table is lowered and becomes horizontal (time t_2 in Fig. 20–2) at the elevation of the control setting in the drain. Drainage ceases at that point but water continues to be removed from the profile by ET. If the water level is maintained at a constant elevation in the drain by SI (Fig. 20–2a) the water table profile will assume a reverse curvature but will continue to recede as indicated for times t_3 and t_4, until the subirrigation rate becomes equal to the ET

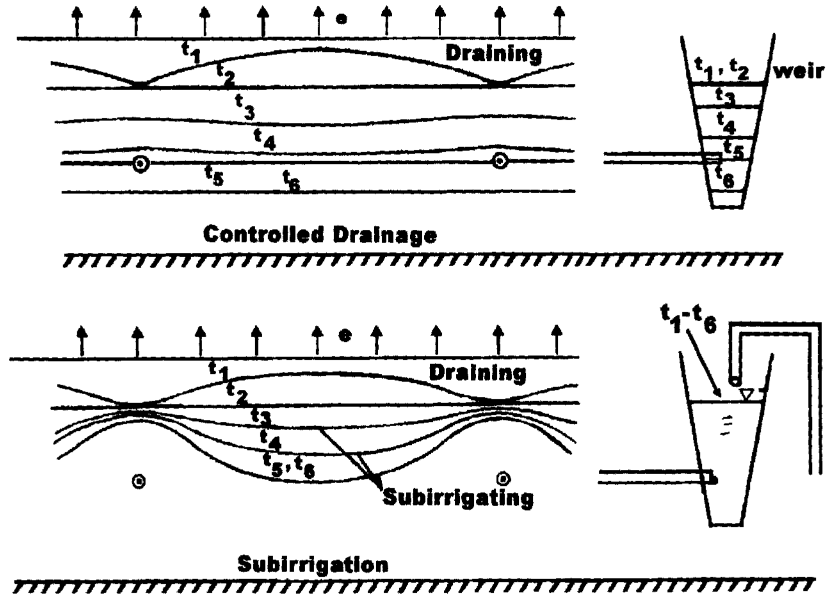

Fig. 20–2. Transition of water table in subirrigation and controlled drainage modes following rainfall. Time after rainfall ceases is denoted by t_1, t_2, . . . on the water table profiles and outlet water levels.

rate and a relatively steady position is attained at time t_5. Actually the water table will continue to adjust as ET rates change from day-to-day, and in response to the diurnal changes in ET. Under so-called steady operating conditions, the water table will recede a few centimeters during the day when ET is high, and rise during the night (Skaggs et al., 1972). For controlled drainage, the water level in the drain outlet is not controlled after the water table falls to a horizontal position at time, t_2, and drainage ceases. As with SI, the water table continues to recede due to ET. This results in a reverse gradient so that water moves back into the profile lowering the water level in the outlet as shown by the water levels at times t_3, t_4, . . . corresponding to the water table profiles at the same times (Fig. 20–2b). The amount of reverse curvature of the water table profile for CD depends on the ratio of the ditch size to the field area, but it is much flatter than profiles for SI and becomes essentially horizontal as the water table approaches the drain level. The performance of these systems under transitional conditions should be considered in their design and operation.

III. OBJECTIVES

The objectives of a water table management system generally include all of the traditional objectives of conventional drainage systems plus additional objectives of conserving soil water, increasing yields by reducing or eliminating stresses caused by deficit soil water conditions, and reducing losses of nutrients and other pollutants via drainage water. The relative importance of these additional objectives depends on the nature of the system. For example, a subirrigation system could be expected to supply irrigation water during long drought periods and significantly increase yields when those conditions occur. A controlled drainage system, on the other hand, would not normally include a water supply. It could be used to conserve drainage water and thereby reduce the length of periods of deficit soil water conditions, but would not protect the crop from periods of long drought.

IV. WATER MOVEMENT DURING SUBIRRIGATION

A major objective of a subirrigation system is to deliver sufficient water to the crop root zone to satisfy ET demands. The systems may be designed to operate in either steady-state or transient modes. Under steady-state conditions, water is maintained at a constant elevation in the drains, which are spaced such that lateral flow will be sufficient to satisfy ET requirements. The constraints are that the range in water table depth from the drain to the midplane between drains should not be excessive so that water availability to the crop is relatively uniform across the field. This method of operation is relatively easy to manage, but it may not take full advantage of water available from rainfall. Thus the steady-state method of operating SI systems may require more irrigation water (Smith et al., 1985) and result in increased drainage compared to other methods of operation.

In the transient mode, water is pumped into the drains and maintained at a relatively high elevation until the water table is raised, usually close to, or even within, the root zone. Then the irrigation water supply is turned off and the water table allowed to be drawn down by ET. If rainfall occurs when the water table is relatively deep, some or perhaps all, of this water is conserved and used by the crop. After the water table recedes to a threshold depth, the irrigation process is repeated. Thus steady-state SI involves a constant irrigation process while the transient mode consists of a series of events. There are many methods for controlling these systems as will be discussed in Chapter 22 (Fouss et al., 1999b).

A. Steady-State Subirrigation

The water table position during steady-state subirrigation is defined in terms of design and system parameters in Fig. 20–3. The drains are located a distance **d** above the impermeable layer and distance **L** apart. The hydraulic head in the drain is maintained at $\mathbf{h_0}$ above the impermeable layer so that the water level in the ditch (Fig. 20–3b), or the pressure head in the drain tube (Fig. 20–3a) is $\mathbf{y_0}$ above the drain. Water moves laterally from a drain tube or open ditch to replenish water lost vertically from the profile by ET. The zone above the water table is unsaturated except for a small capillary fringe which may exist for some soils. Because the hydraulic conductivity decreases rapidly with water content, there is very little lateral water movement above the water table; most of the lateral water movement occurs in the saturated zone. Thus, from a somewhat simplistic point of view, it may be stated that water moves laterally into the profile by saturated flow, then vertically from the water table by unsaturated flow to the root zone or

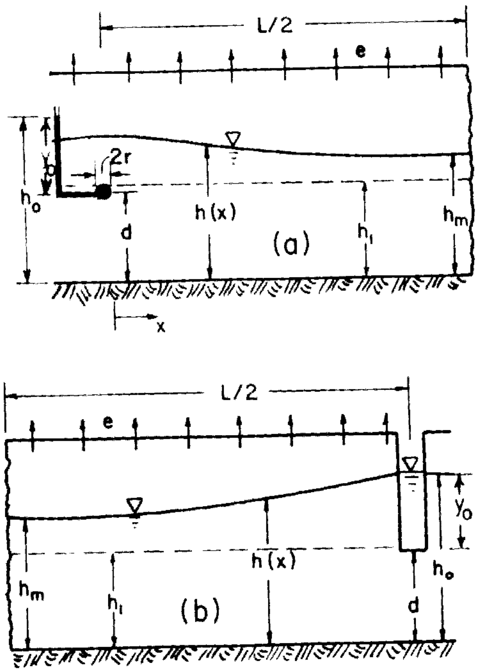

Fig. 20–3. Schematic showing design parameters and water table profiles during subirrigation from (*a*) drain tubes and (*b*) open ditches.

to the surface where it leaves the profile as ET. Note that the elevation of the water table over the drain tube is lower than the water level in the ditch even though water is held in the drain tube outlet at the same elevation (y_o) as that in the ditch. This occurs because of hydraulic head losses due to convergence near the tube. These convergence losses should be accounted for in characterizing water movement during subirrigation (Skaggs, 1991).

The water table elevation that should be maintained during subirrigation depends on the crop rooting depth and the rate that water can be transmitted upward from the water table to the root zone. The depth and distribution of roots depend on many factors (Allmaras et al., 1973). However, for purposes of design, roots are usually assumed to be concentrated in a zone extending to some effective depth which is dependent on crop species. The rate that water can be transferred upward from the water table depends on the unsaturated hydraulic conductivity function, and can be calculated in terms of the pressure head in the root zone and the water table depth by analytical (e.g., Gardner, 1958; Ratts & Gardner, 1974) or numerical methods (Skaggs, 1981). The SI systems are usually operated such that the minimum water table depth (directly over the drain) is a few centimeters below the root zone.

The position and shape of the water table during steady-state subirrigation can be approximated by making the Dupuit-Forchheimer (D-F) assumptions and using the same approach as discussed in Chapter 6 (van der Ploeg et al., 1999) for drainage under steady rainfall (also see Ernst, 1975; Skaggs, 1973, 1981). The result is an elliptical water table shape that may be expressed as

$$h^2 = \frac{-e}{K_s}x^2 + \frac{eL}{K_s}x + h_0^2 \quad [1]$$

where $-e$ is the ET rate (i.e., e is negative for ET and positive for rainfall), K_s is the effective saturated hydraulic conductivity in the horizontal direction, and x is the horizontal distance from the drain. The drains should be placed at a close enough spacing to maintain a minimum water table depth at the midplane ($x = L/2$) during a period of high ET demand. The relationship between steady ET, drain spacing and midplane water table elevation, h_m, can be determined from Eq. [1] as

$$e = 4K_s\left(h_m^2 - h_0^2\right)/L^2 \quad [2]$$

Defining the difference between the water table elevation at the midplane and at the drains as $m = h_m - h_0$, Eq. [2] may be written as

$$e = 4K_s m\left(2h_0 + m\right)/L^2 \quad [3]$$

By defining m to be consistent with the notation used for drainage in this way, the equation has the same form as the Hooghoudt equation. The difference is that, for subirrigation, both m and the steady flux, e, are negative and the depth from the drain to the impermeable layer, d, in the Hooghoudt equation is replaced by h_0 for subirrigation. The drain spacing necessary to maintain a specified e at given h_m and h_0 is

$$L = \left[4K_s m\left(2h_0 + m\right)/e\right]^{1/2} \quad [4]$$

These equations should be reliable for open ditches that penetrate close to the impermeable layer such that the ratio L/d is large and the D-F assumptions hold. However, they do not account for convergence near drain tubes. An approximate method of correcting for convergence losses is to use the Hooghoudt equivalent depth, d_e, as discussed in Chapter 6 (van der Ploeg et al., 1999) for drainage (also see Eqs. [9]-[12] in Chapter 13, see Skaggs, 1999a) for calculating d_e. The equivalent water table elevations at the drain, $h_0' = y_0 + d_e$, and midway between drains, $h_m' = y_m + d_e$, are substituted for h_0 and h_m, respectively, in Eqs. [2] to [4]. That is,

$$e = 4K_s m\left(2h_0' + m\right)/L^2 \quad [5]$$

where $m = h_m - h_0 = h_m' - h_0'$.

A problem arises when Eq. [5] is applied for deep midplane water table depths. The magnitude of e, as predicted by Eq. [5], increases with m, until the water table at the midplane reaches the equivalent depth of the impermeable layer, $h_m' = 0$. For deeper midplane water table depths (which can occur because the actual depth to the impermeable layer is greater than the equivalent depth), Eq. [5] predicts a decrease in q with increasing m. Ernst (1975) observed that this is inconsistent with the physics of flow since the maximum subirrigation rate should occur when the water table at the midpoint is deepest. He derived an equation similar to Eq. [5] to correct these deficiencies. Ernst's equation may be written in the present notation as

$$e = 4K_s m\left(2h_0' + \frac{h_0'}{h_0}m\right)\Big/L^2 \qquad [6]$$

The required drain spacing to maintain a given e is obtained by rewriting Eq. [6] as

$$L = \left[4K_s m\left(2h_0' + \frac{h_0'}{h_0}m\right)\Big/e\right]^{1/2} \qquad [7]$$

Because d_e depends on the drain spacing, L, an iteration process is required to compute L.

One of the disadvantages of using the Hooghoudt equivalent depth concept is that it neglects convergence head losses above the center of the drain. These losses are more important for subirrigation, where a larger portion of the total flow may exit the drain tube through the top half as compared to drainage where most of the flow enters the drain through the bottom half. One method of considering these head losses is to numerically couple equations for radial flow near the drain with solutions based on the D-F assumptions for most of the flow domain (Fipps & Skaggs, 1991; Skaggs, 1991). While these approximate methods require iteration and are somewhat tedious, they can be easily programed for computer solutions.

The K_s value in the above equations is normally assumed to be the equivalent hydraulic conductivity in the horizontal direction. In most cases vertical flow distances are short compared to horizontal flow distances and head losses due to vertical flow are neglected. However this assumption does not hold for profiles consisting of several horizontal layers with alternately large and small K values. Ernst (1975) developed iterative methods for characterizing flow in these relatively complex flow domains.

Equations [3] and [5] predict steady-state subirrigation rates in terms of midplane water table elevation and system parameters. The same equations can be used, without change in form, to predict drainage rates for elevated water table conditions such as shown by the profile for time t_1 in Fig. 20–2. In this case both m and the drainage rate, $e = q$, are positive quantities. Thus the equations are useful for predicting both subirrigation and drainage rates in the CD and SI mode of operation. Although conditions in nature are rarely steady, these equations can be used to calculate water table fluctuations by assuming transient conditions to be a succession of momentarily steady states as described in Chapter 7 (Youngs, 1999). The equations are used in the same way by models such as DRAINMOD to predict water table fluctuations as discussed in Chapter 13 (Skaggs, 1999a).

B. Transient Conditions

Design and management of subirrigation systems require characterization of water movement under various initial and boundary conditions. For example, the response of the water table in the field may lag the rise of the water level in the drain from a few hours to several weeks, depending on the drain spacing and the initial water table depth (Skaggs, 1973). Design parameters would normally be chosen that would allow the water table to be raised in a given time. As with drainage, the most theoretically exact method of describing the process is to solve the Richards equation for the appropriate initial and boundary condition as discussed in Chapter 5 (Nieber & Feddes, 1999) and applied for subirrigation by Tang and Skaggs (1977) and Munster et al. (1994). While this method has been useful for researching the effect of such factors as drain depth in relation to the depth of layers of high permeability (Tang & Skaggs, 1980), it is not practical for routine analysis and design.

Another approach is to employ the D-F assumptions and solve the resulting Boussinesq equation (Nieber & Feddes, 1999; Youngs, 1999; see Chapters 5 and 7) with either analytical or numerical methods. Skaggs (1973, 1981) used numerical methods to solve the nonlinear Boussinesq equation subject to subirrigation conditions for both initially horizontal and initially draining profiles. The solutions can be plotted in nondimensional form, as shown in Fig. 20–4, and used directly for analysis and design. Note $D = h_1/h_0$ where h_1 is the initial water table elevation (Fig. 20–3). The solutions in Fig. 20–4 are for a nondimensional ET rate (e) of $\mu = eL^2/K_sh_0^2 = -1$. Solutions for a range of μ values are given in Skaggs (1981). While the plotted solutions can be used directly, numerical solutions to the Boussinesq equation are relatively easy to obtain with modern personal computers and may be used to obtain solutions for the specific soil properties and dimensions of a given case.

Results in Fig. 20–4 do not consider convergence head losses near the drain so the values of d, h_0, and h must be adjusted by determining the Hooghoudt equivalent depth as discussed above for steady-state conditions. As discussed earlier, use of the Hooghoudt equivalent depth does not consider the effects of convergence at the drain on flow in the plane above the center of the drain. This was considered by using an equation for radial flow near the drain as a boundary condition for numerical solution of the Boussinesq equation (Skaggs, 1991). The results showed that, while head losses in the plane above the drain center can usually be safely neglected for drainage conditions, neglecting those losses can lead to significant error for subirrigation. An example is given below.

C. Analytical Solutions

An analytical solution for a water table rise in response to subirrigation was obtained (Skaggs, 1973) by linearizing the Boussinesq equation and solving by separation of variables in a manner similar to that used by Glover (Dumm, 1954)

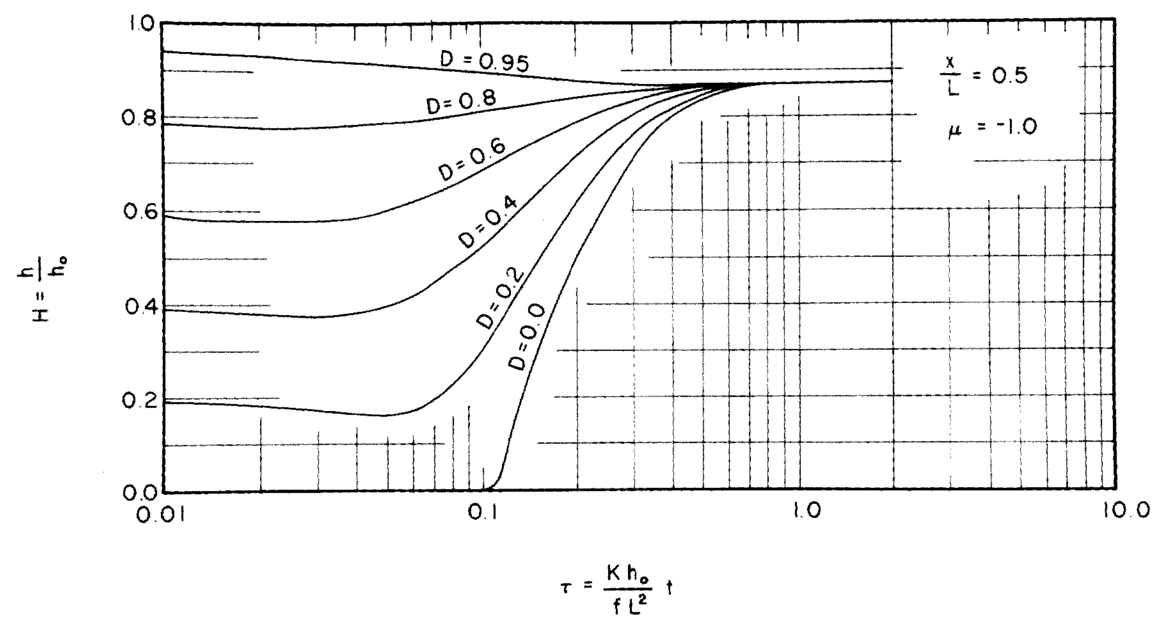

Fig. 20–4. Solutions for water table movement at a point midway between the drains when the water table elevation is raised to h_0 in the drains. The initial water table is horizontal at an elevation of h_1 and $D = h_1/h_0$. The nondimensional vertical loss rate is $\mu = -1.0$ (after Skaggs, 1981).

for a falling water table. The solution may be written for an initially horizontal water table as,

$$h = h_0 - \frac{4(h_0 - h_1)}{\pi} \sum_{n=1,3,5...}^{\infty} \left[\frac{1}{n}\right] e^{-n^2\pi^2\bar{H}\tau} \sin n\pi\xi \qquad [8]$$

where, referring to Fig. 20–3, $\tau = K_s h_0 t / fL^2$, $\bar{H} = (h_1 + h_0)/2h_0$, $\xi = x/L$, and f is drainable porosity. The solution may be written for initially draining profiles by substituting the quantity $[1/n - 8R/n^3\pi^2]$ for [1/n] in Eq. [8], and defining $\bar{H} = (d + m_0 + h_0)/2h_0$, where m_0 is the initial elevation of the midplane water table above the center of the drain, and $R = m_0/(h_0 - d)$. As discussed above, the Hooghoudt equivalent depth should be substituted for d and the quantities h_0, h_1, and h adjusted accordingly to correct for convergence near drain tubes.

D. Comparison of Methods for Predicting Water Table Rise, An Example

A comparison of the methods discussed above for predicting water table response to subirrigation is given in Fig. 20–5 for a uniform soil with parallel drains spaced 15 m apart at a depth of 1.0 m. The effective radius of the drain is 5 mm. The soil is a uniform, isotropic sandy loam with saturated hydraulic conductivity of 0.1 m/h and an impermeable layer 2.0 m below the surface. The unsaturated soil water characteristic is described by the van Genuchten (1980) equation as given in Chapter 38 (Ajuja et al., 1999) with the following values for the equation parameters [see Table 38-2 (Ahuja et al., 1999) for definition of parameters]

$$\alpha = 0.124,\ n = 1.54,\ \theta_s = 0.495,\ \theta_r = 0.245.$$

The drainable porosity, f, was obtained from the soil water characteristic by assuming the unsaturated zone is drained to equilibrium with the water table as

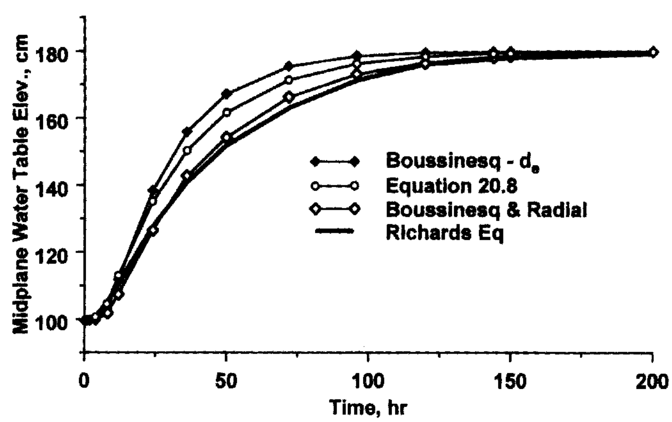

Fig. 20–5. Predicted water table rise for subirrigation in a sandy loam soil with an initially horizontal water table. The water level in the drain outlet was raised at t = 0 to an elevation 80 cm above the drains.

discussed in Amoozegar and Wilson (1999, see Chapter 37, Eqs. [35] and [36]). For this example f increased from 0.114 to 0.185 as water table depth increased from 20 to 100 cm. An average $f = 0.15$ was used in solutions to the Boussinesq equations.

Results plotted in Fig. 20–5 are for an initially horizontal water table at drain depth, 100 cm below the surface, with the unsaturated zone drained to equilibrium (hydrostatic pressure head distribution) with the water table. At time zero the water level in the drainage outlet, and the pressure head in the drains, is raised to an elevation of 180 cm above the impermeable layer, or 80 cm above the drain center. The response of the water table was predicted by four methods:

1. Richards Equation. Numerical solutions to the two-dimensional Richards Equation were obtained with the SWMS_2D model (Simunek et al., 1994, 1995).
2. Boussinesq Equation with radial flow near the drain. Numerical solution to the Boussinesq Equation coupled with an equation for radial flow to predict the water table elevation at the drain (Skaggs, 1991).
3. Boussinesq Equation with d_e. A numerical solution to the Boussinesq Equation with use of Hooghoudt equivalent depth, d_e, to correct for convergence near the drains (Skaggs, 1973, 1981).
4. Analytical solution to the linearized Boussinesq Equation (Eq. [8]).

Results in Fig. 20–5 show that water table rise predicted by a numerical solution of the Boussinesq equation coupled with an equation for radial flow to predict head loss near the drain (Skaggs, 1991) was in much better agreement with solutions to the Richards Equation than were the other methods. Solutions to the Boussinesq equation with the use of the standard equivalent depth, d_e, to correct for convergence near the drain, overpredicted the rate of water table rise, compared to solutions to the Richards equation for this case. Another factor that affects the comparison in Fig. 20–5 is the variable drainable porosity. Only the solution to the Richards equation properly accounts for unsaturated flow processes. The approximate solutions based on the Boussinesq equation would likely be in better agreement with the Richards equation if they accounted for the fact that the drainable porosity increases with water table depth. Effects of a variable drainage porosity can be considered in numerical solutions to the Boussinesq equation (e.g., Parsons et al., 1991) but f was assumed constant in the solutions given in Fig. 20–5.

V. MODELING THE PERFORMANCE OF SUBIRRIGATION SYSTEMS

Solutions presented in the previous section can be used to design subirrigation systems that will satisfy crop ET requirements under steady-state conditions and, under transient conditions, allow the water table to be raised in a specified period of time. In actual operation, however, the effect of subirrigation on crop yields is often more dependent on how well the water table is controlled under variable weather conditions. What happens, for example, when heavy rainfall, or a long period of wet weather, occurs when the system is in subirrigation mode? Are gains in crop yields, due to subirrigation during dry periods, canceled out by increased stresses due to excessive soil water conditions during wet periods? Simulation models discussed in Skaggs (1999a), Parsons (1999), and Skaggs and Chescheir (1999) (see Chapters 13–15) can be used to describe the performance of water table control systems on a continuous basis. By simulating the performance of the system over several years of climatological record, response to different sequences of weather events can be determined and effects of design parameters on yields can be estimated.

Use of DRAINMOD to describe the performance of subirrigation systems will be demonstrated for the Portsmouth soil (fine loamy, mixed, thermic Typic Umbraquults) of Example 2 in Chapter 15 (Skaggs & Chescheir, 1999). The drain spacing required to maximize profit for corn (*Zea mays* L.) production was 50 m for a drain depth of 1.25 m and intensive surface drainage (see Table 15–4, Chapter 15). The 40-yr average predicted yield was 77% of potential, with most of the decrease (below 100%) due to deficit soil water conditions (Table 20–2). Average relative yield was 79% when only deficit soil water conditions were considered vs. 97% for excessive soil water stresses alone. Subirrigation by raising the water level in the drains to within 60 cm of the surface from 15 May to 31 July increased the predicted relative yield to 82%. Stresses due to deficit soil water stresses were reduced but those caused by excessive soil water conditions were increased (Table 20–2). In this case, most of the yield increase achieved by reducing deficit soil water conditions during some periods was lost because of increased stresses due to high water tables during other periods.

The problem of managing the water table to eliminate stresses caused by both deficit and excessive soil water conditions is illustrated in Fig. 20–6a for the year 1975. When the system was operated in the drainage mode with a 50-m drain spacing, dry conditions in the early part of the growing season caused the water table to be greater than 1.4 m deep and reduced yields to 62% of potential (Table 20–2). Heavy rainfall, starting on Day 175, raised the water table into the root zone during the latter part of the season but the 50-m drain spacing was sufficient to hold further yield reductions to only 3% (Table 20–2). Subirrigation raised the

Table 20–2. Predicted relative yields in percentage for corn (*Zea mays* L.) on Portsmouth sandy loam soil at Plymouth, North Carolina. For subirrigation, the water level in the drainage outlet was raised to a 60-cm depth for the period 15 May to July 31. Values given for "excess" and "deficit" represent relative yields that would have been obtained if the only stresses were those due to excessive and deficit soil water conditions, respectively. The "overall yield" considers effects of both deficit and excessive soil water stresses.

Drain spacing	50 m				25 m			
	Excess	Deficit	Overall	SD†	Excess	Deficit	Overall	SD†
40-yr av. (1951–1990)								
Drainage	97	79	77	15	100	78	78	16
Subirrigation	89	93	82	11	94	99	93	5
1975								
Drainage	97	62	60		100	61	61	
Subirrigation	91	80	72		96	96	93	

† SD = standard deviation.

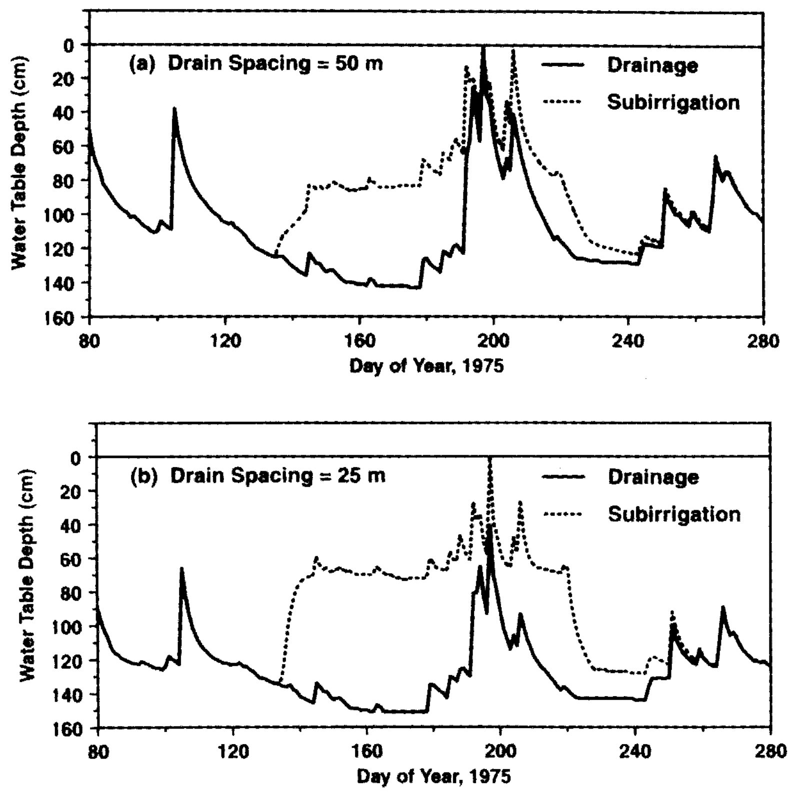

Fig. 20–6. Predicted water table depth for 1975 for a Portsmouth sandy loam soil near Plymouth, North Carolina. Predictions are given for both drainage and subirrigation for drain spacings of (*a*) 50 m (optimum spacing for conventional drainage for this soil) and (*b*) 25 m (optimum spacing for subirrigation).

water table, reduced deficit soil water stresses during the first half of the season and increased yields. However, the effect of subirrigation was negative during the second half of the season as elevated water levels in the drains prolonged the time that the water table was in the root zone (Fig. 20–6a). Some of the gains in yield that would have resulted from the reduction of deficit soil water stresses in the first half of the growing season were lost due to excessive soil water conditions in the second half. The result was an increased yield compared to that predicted for conventional drainage, but the yield was still only 72% of potential. The negative effects of a prolonged high water table could be reduced by switching the system to drainage mode during wet periods (Fouss et al., 1999b, see Chapter 22), but that management intensity may or may not be present for a given situation. The subject of management and control of these systems is discussed in Chapter 22 (Fouss et al., 1999b).

The problem in this example is that drains spaced at 50 m are too far apart to provide either an adequate subirrigation rate during dry periods or sufficient drainage when the drain water level is elevated during wet periods. The 40-yr average relative yield predicted for subirrigation is plotted as a function of drain spacing in Fig. 20–7. Yields for conventional drainage are plotted for comparison. These results show that, by reducing the drain spacing, compared to that required for drainage alone, subirrigation can be used to substantially increase yields. Subirrigation increased average yields, compared to drainage alone, for drain spacings less than 75 m. For larger spacings, predicted yields for subirrigation were somewhat less than for drainage alone. In this range, increased stresses due to high water table conditions had a greater effect on yields than did the reduction in deficit soil water stresses. The spacing required to maximize profits was determined by an economic analysis, following the methods of Evans et al. (1988), to be 25 m for this soil.

The 1975 water table response to subirrigation with a 25-m drain spacing is shown in Fig. 20–6b. In this case subirrigation raised the water table high enough to supply most of the soil water needs during the early (dry) part of the growing season, yet the drains were spaced close enough to prevent the water table from rising into the root zone for an extended time during the wet period, even with the elevated water level in the drains. Predicted relative yield for subirrigation was 93% vs. 61% for drainage alone in 1975 (Table 20–2). The 40-yr average predicted relative yield for subirrigation with a 25-m spacing was 93% compared to 77% for drainage alone at the optimum spacing of 50 m. Another often overlooked, but important benefit of subirrigation, is its effect on reliability of production. The standard deviation of annual relative yield over the 40-yr period was 5% for subirrigation with a 25-m spacing vs. 15% for conventional drainage with drains 50 m apart (Table 20–2).

Another factor affecting the interaction between deficit and excessive soil water stresses is the depth that the water level is maintained in the outlets commonly controlled by the weir depth in an outlet structure. Results illustrating the effects of different weir depths on the previous example with a drain spacing of

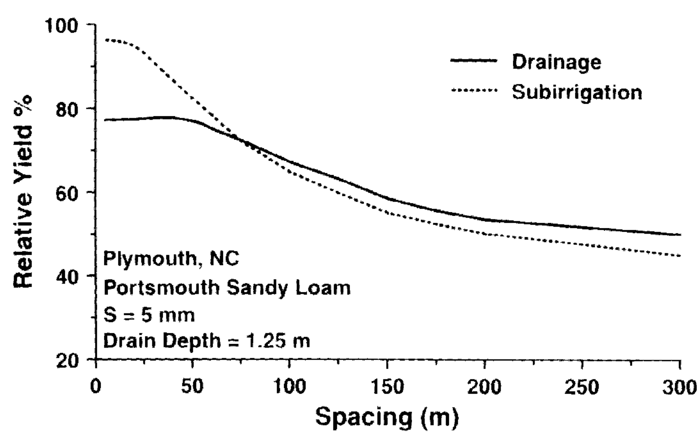

Fig. 20–7. Effect of drain spacing on 40-yr average corn yields predicted by DRAINMOD for subirrigation and drainage of a Portsmouth sandy loam near Plymouth, North Carolina. Results are predicted for good surface drainage and a drain tube depth of 1.25 m.

25 m are plotted in Fig. 20–8. Yields were predicted for weir depths from 20 to 95 cm. Predicted relative yield as affected by stresses caused by both deficit and excessive soil water conditions, and by the combination of the two, are plotted in Fig. 20–8. These results show that there are no reductions in yield due to deficit soil water conditions for shallow weir depths (less than 50 cm) for this drain spacing. Yield as affected by deficit stresses decreases with increase in weir depth more than 60 cm. Conversely, excessive soil water conditions do not affect yield for deep weir depths (>90 cm) but reduce yields significantly for depths less than 30 cm. The overall yield as affected by both excessive and deficit soil water conditions is maximum at about a 60-cm weir depth.

This example also illustrates the importance of management on the water used by subirrigation. The results show that, for weir depths greater than 40 cm, average yields are not very sensitive to the depth from the surface that the water level is held at the outlet. However, the amount of water pumped for subirrigation is strongly dependent on the depth water is held in the outlet. For example, the predicted average relative yield for a weir depth of 40 cm is about the same as that for the 95-cm depth, 86%. In contrast, the average amount of water pumped was 23 cm/yr for the 40-cm weir depth, compared to only 8 cm/yr for the 95-cm weir depth. That is, holding the water level 95 cm rather than 40 cm from the surface resulted in the same predicted yields, but required only 35% of the water for subirrigation. As the controlled water level is raised, the volume of pore space available for infiltration decreases, resulting in an increase in surface runoff and subsurface drainage. If the water table were held at the surface, there would be no storage available for infiltration and all rainfall would run off. In this limiting hypothetical case, all the water used by the crop would have to be pumped for subirrigation. Thus, it is clear from Fig. 20–8 that the amount of subirrigation water required can be minimized by holding the outlet water level as deep as possible while still

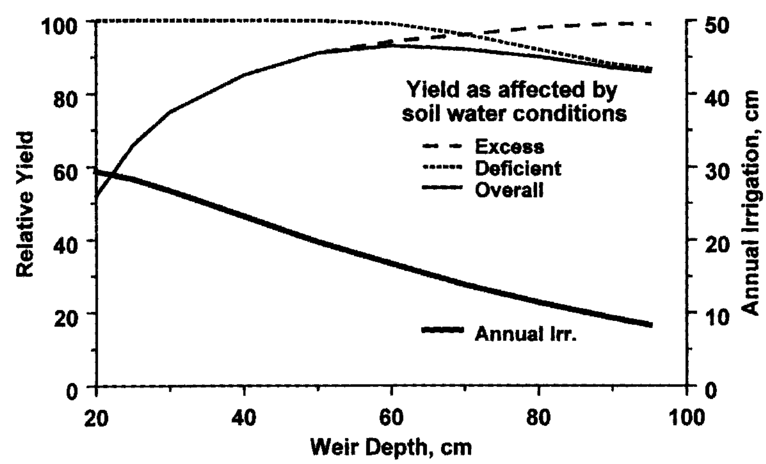

Fig. 20–8. Effect of depth from soil surface to water level in the drain during subirrigation on corn yield as affected by deficit and excessive soil water conditions, overall predicted yield and annual irrigation amount. Results are 40-yr averages for a Portsmouth sandy loam near Plymouth, North Carolina.

maintaining high yields. The deeper water level control will more fully utilize rainfall, reduce drainage volumes, and thereby reduce pollutant loads.

VI. CONTROLLED DRAINAGE

Controlled drainage has been applied on both field and watershed scales to conserve water and increase crop yield (Evans et al., 1992; Doty et al., 1984; Busscher et al., 1992; Parsons et al., 1987). It also has been found to be an effective method of reducing losses of plant nutrients and other pollutants to surface waters (Gilliam et al., 1999, see Chapter 24; Gilliam et al., 1979; Evans et al., 1991) and is currently being promoted for that purpose in nutrient sensitive coastal plains watersheds (Gilliam et al., 1997). Controlled drainage has been used historically to reduce subsidence in drained organic soil (Stevens, 1955). This application continues in places such as the Everglades agricultural area in Florida, the Western Johor area in Malaysia, and many other locations around the world.

Controlled drainage reduces the intensity of subsurface drainage by raising the water level in the drainage outlet. This may be desirable on a field scale when subsurface drainage intensity is greater than is needed. In many areas, drains have been installed at a fixed spacing and depth, without regard for differences in soil properties. In some cases this practice has resulted in excessive drainage of permeable soils, removing water that would otherwise be available to the crop, and increasing drought stresses. Controlled drainage can be used in such cases on a year-round basis. In other cases, because of seasonal weather patterns, differences in crop susceptibility or other factors, drainage requirements vary substantially over the year. This provides opportunity to reduce drainage intensity in accordance with the requirements, in order to satisfy other objectives. A good example is the use of controlled drainage to reduce losses of N in drainage waters in the Atlantic coastal plains. In that location, most of the annual drainage occurs in the winter and early spring when crop drainage needs are low or nonexistent. By using controlled drainage to enhance denitrification during this period, nitrate losses in the drainage waters can be substantially reduced without affecting crop production (Gilliam et al., 1979). The greatest drainage needs for field crop production in this region often occur during seedbed preparation and planting. The application of controlled drainage after the crop is planted, when drainage requirements are somewhat reduced, conserves water, increases yields and further reduces nitrate movement into surface waters. Yield response to controlled drainage varies with subsurface drainage intensity and from year-to-year, because of the variability of rainfall. For example, data presented by Parsons et al. (1990) indicate that 5-yr average predicted corn yields could be increased by 4 to 11% depending on drainage intensity. However, predicted yield increases varied widely from year-to-year.

Controlled drainage on a watershed scale has, in many cases, greater potential than it does on a field scale (Evans et al., 1992). This is especially true where deep drainage outlets have been constructed to provide drainage for the lowest elevations in the watershed. Overdrainage frequently occurs where these channels have been constructed in soils with higher permeabilities and low water holding capabilities.

Doty et al. (1984, 1985, 1987) conducted a watershed scale research and demonstration project to determine the effects of controlled drainage on a channel constructed through poorly drained soils with deep sandy subsoils. Results of the study were summarized by Evans et al. (1992). The controlled water level affected drainage from an 800-ha section of the Conetoe Creek watershed near Tarboro, North Carolina. Controlled drainage raised the water table and increased channel water supplies available for sprinkler irrigation by about threefold. The high permeability of the subsoil provided rapid recharge from the water table aquifer to the channel as it was pumped down for sprinkler irrigation. This permitted water stored in the profile to be used for irrigation. This source of stored water would not have been as readily available from the channel if the surrounding soils had lower permeabilities, or if the channel had been shallow.

Channel water level control increased crop yields on the Conetoe Creek project (Doty et al., 1984; Evans et al., 1992). Corn yields were increased by 25% in nonirrigated fields and by 15% in irrigated fields because of the raised water table (Parsons & Evans, 1990). The effect on yields was greatest near the channel where overdrainage of the deep sandy soils had reduced yields for 30 yr since channelization had occurred. The direct effect of channel control on yields decreased as distance from the channel increased (Doty et al., 1984).

Effects of watershed scale controlled drainage elevations, drainage rates, and crop yields can be evaluated with the simulation model WATRCOM (Parsons et al., 1991). The model (Skaggs, 1999a, see Chapter 13) is capable of considering branched channel networks with multiple soil types and crops. A simulation study for the Conetoe Creek site (Parsons et al., 1987) showed that control on the main channel would substantially increase yields near the channel but would have little effect about 150 m away. The model predicted that, during dry periods, water storage and upstream flows would not be sufficient to prevent channel water levels from declining below the control level. Simulation results were consistent with trends observed in the Conetoe Creek project.

VII. ADVANTAGES AND CONCERNS

The water table management practices of subirrigation and controlled drainage are applicable on many relatively flat, poorly drained lands. Advantages of subirrigation included the fact that both irrigation and drainage requirements can be satisfied by the same system, thereby reducing total costs. Fox et al. (1956) noted that subirrigation is more efficient than other irrigation methods on soils with high permeabilities and low water-holding capacities, labor requirements are low and the practice does not interfere with tillage and other field operations. Another advantage is that energy requirements are only 5 to 25% of that required by sprinkler irrigation (Massey et al., 1983). Advantages of controlled drainage include water conservation, increased yields, and reduced losses of plant nutrients and other pollutants to surface waters.

There also are a number of potential problems and concerns with the application of water table management practices. An inherent disadvantage is that these practices are limited to relatively flat sites with specific conditions (c.f., Fouss et al., 1999a, see Chapter 21). Subirrigation results in saturation of the soil around the drain for relatively long periods of time. This may result in deterioration of soil structure, and/or biological clogging (Martin, 1945; Allison, 1947; Christiansen, 1947) causing reduced hydraulic conductivity and increased hydraulic head losses near the drains in some soils (Susanto & Skaggs, 1995; Bentley & Skaggs, 1993).

Clogging doesn't normally occur when the drain is surrounded by coarse sandy or loamy sands but these materials may attain a "fluid" or "quick" status when the water level in the drain is raised for a long period of time. These conditions are unstable and soil may subsequently move into the drain if the water level in the drain is quickly lowered. A related problem, in the systems with open ditches, is sloughing of the ditch banks due to the water level being elevated and lowered from season to season.

Poor-quality irrigation water also may impair the drain performance, in both drainage and subirrigation modes. Davenport and Skaggs (1990) reported that poor-quality subirrigation water, pumped from a drainage canal, was one cause of increased head losses near the drain. Quality of the subirrigation water is important for other reasons. For example, iron-rich subirrigation water may cause or exacerbate the development of ochre that could result in complete blockage of the drains (Armstrong & Castle, 1999, see Chapter 34; Ford, 1979). Rands and Dennis (1995) reported on the failure of a subirrigation system in the Fens in England due to ochre accumulation around the drains. In this case ochre buildup occurred when drains were managed in both drainage and subirrigation modes. Another disadvantage of subirrigation is that it may require slightly more water than sprinkler irrigation (Massey et al., 1983), although the water required is very much a function of how the system is managed (e.g., Fig. 20–8; Fouss et al., 1999b, see Chapter 22).

Evans et al. (1992) discussed management problems and institutional barriers affecting the application of controlled drainage on a watershed scale. Variability of soils, crops, topography and management systems in multifarm watersheds make it nearly impossible to optimize water levels in the main drainage channels to satisfy all objectives. Apart from the technical challenge of managing the outlet water level to satisfy several purposes, legal precedent on management alternatives has not been established. There also are legal questions and institutional barriers regarding assessment of benefits and responsibility for costs on watershed scale controlled drainage projects. Similar questions arise regarding which landowners have rights to withdraw water from the main channel for irrigation or other uses, and the impact of controlled drainage on downstream users. Until methods for dealing with these legal and institutional barriers are worked out, development of watershed scale channel control projects will continue to be slow, and likely limited to watersheds where multiple land uses do not exist (Evans et al., 1992).

REFERENCES

Ahuja, L.R., W.J. Rawls, D.R. Nielsen, and R.D. Williams. 1999. Determining soil hydraulic properties and their field variability from simpler measurements. p. 1207–1233. *In* R.W. Skaggs and J. van Schilfgaarde (ed.) Agricultural drainage. Agron. Monogr. 38. ASA, CSSA, and SSSA, Madison, WI.

Allison, L.E. 1947. Effect of microorganisms on permeability of soil under prolonged submergence. Soil Sci. 63:439–450.

Allmaras, R.R., A.L. Black, and R.W. Richman. 1973. Tillage, soil environment and root growth. p. 62–86. *In* Proc. Natl. Conserv. Tillage Conf., Des Moines, IA. 28–30 March. Soil Conserv. Soc. Am., Ankeny, IA.

Amoozegar, A., and G.V. Wilson. 1999. Methods for measuring hydraulic conductivity and drainable porosity. p. 1149–1205. *In* R.W. Skaggs and J. van Schilfgaarde (ed.) Agricultural drainage. Agron. Monogr. 38. ASA, CSSA, and SSSA, Madison, WI.

Armstrong, A.C., and D.A. Castle. 1999. Drainage of organic soils. p. 1083–1105. *In* R.W. Skaggs and J. van Schilfgaarde (ed.) Agricultural drainage. Agron. Monogr. 38. ASA, CSSA, and SSSA, Madison, WI.

Belcher, H.W., G.E. Merva, and W.H. Shayya. 1993. SI-DESIGN—a simulation model to assist with the design of subirrigation systems. p. 295–308. *In* E. Lorre (ed.) Water management in the next century. Trans. Workshop Subsurface Drain. Models, 15th Int. Congr. ICID, The Hague. 4–5 September. CEMAGREF-DICOVA, Antony Cedex, France.

Belcher, H.W., and F.M. D'Itri (ed.). 1995. Subirrigation and controlled drainage. Lewis Publ., Boca Raton, FL.

Bentley, W.J., and R.W. Skaggs. 1993. Changes in entrance resistance of subsurface drains. J. Irrig. Drain. 119:584–599.

Borin, M., L. Giardini, P. Ceccon, P. Manini, and G. Guidoboni. 1997. Pipe drainage in the Eastern Padano-Veneta plain in north-east Italy. Irrig. Drain. Syst. 11:61–81.

Borin, M., and B. Lazzaro. 1995. Effects of water-table management on nitric nitrogen leaching in lysimeters planted with maize. p. 55–60. *In* Bericht uber die 5. Lysimetertagung "Stofftransport und Stoffbilanz in der ungesattigten Zone." 25–26 April. BAL Grumpenstein, Austria.

Broughton, R.S. 1995. Economic, production and environmental impacts of subirrigation and controlled drainage. p. 183–191. *In* H.W. Belcher and F.M. D'Itri (ed.) Subirrigation and controlled drainage. Lewis Publ., Boca Raton, FL.

Busscher, W.J., E.J. Sadler, and F.S. Wright. 1992. Soil and crop management aspects of water table control practices. J. Soil Water Conserv. 47:71–74.

Carter, C.E., J.L. Fouss, and V. McDaniel. 1988. Water management increases sugarcane yields. Trans. ASAE 31:503–507.

Christiansen, J.E. 1947. Some permeability characteristics of saline and alkali soils. Agric. Eng. 28:147–150

Clinton, F.M. 1948. Invisible irrigation on Egin Bench. Reclam. Era 34:182–184.

Cooper, J.R., and J.L. Fouss. 1988. Rainfall probability forecasts used to manage a subdrainage-subirrigation system for watertable control. Agric. Water Manage. 15:47–59.

Cooper, R.L., N.R. Fausey, and J.G. Streeter. 1991. Yield potential of soybean under a subirrigation/drainage water management system. Agron. J. 83:884–887.

Davenport, M.S., and R.W. Skaggs. 1990. Effects of drain envelope and slope on performance of a drainage-subirrigation system. Trans. ASAE 33:493–500.

Doty C.W., T.S. Currin, and R.E. McLin. 1975. Controlled subsurface drainage for Coastal Plains soils. J. Soil Water Conserv. 30:82–84.

Doty, C.W., J.E. Parsons, A. Nassehzadeh-Tabrizi, R.W. Skaggs, and A.W. Badr. 1984. Stream water levels affect field water tables and corn yields. Trans. ASAE 27:1300–1306.

Doty, C.W., J.E. Parsons, A.W. Badr, A. Nassehzadeh-Tabrizi, and R.W. Skaggs. 1985. Water table control for water resource projects on sandy soils. J. Soil Water Conserv. 40:360–364.

Doty, C.W., J.E. Parsons, and R.W. Skaggs. 1987. Irrigation water supplied by stream water level control. Trans. ASAE 30:1065–1070.

Dumm, L.D. 1954. New formula for determining depth and spacing of subsurface drains in irrigated lands. Agric. Eng. 35:726–730.

Ernst, L.F. 1975. Formulae for the groundwater flow in areas with sub-irrigation by means of open conduits with a raised water level. Misc. Rep. 178. Inst. Land Water Manage. Res., Wageningen, The Netherlands.

Evans, R.O., and N.R. Fausey. 1999. Effects of inadequate drainage on crop growth and yields. p. 13–54. *In* R.W. Skaggs and J. van Shilfgaarde (ed.) Agricultural drainage. Agron. Monogr. 38. ASA, CSSA, and SSSA, Madison, WI.

Evans, R.O., J.W. Gilliam, and R.W. Skaggs. 1991. Controlled drainage management guidelines for improving drainage water quality. North Carolina Coop. Ext. Serv. Publ. AG-443.

Evans, R.O., R.W. Skaggs, and R.E. Sneed. 1988. Economics of controlled drainage and subirrigation systems. North Carolina Coop. Ext. Serv. Publ. AG-397.

Evans, R.O., J.E. Parsons, K. Stone, and W.B. Wells. 1992. Water table management on a watershed scale. J. Soil Water Conserv. 47:58–64.

Evans, R.O., and R.W. Skaggs. 1985. Agricultural water management for Coastal Plain soils. North Carolina Coop. Ext. Serv. Publ. AG-355.

Fausey, N.R., and J.R. Cooper. 1995. Subirrigation response of soybeans grown with high yield potential management. p. 225–230. *In* H.W. Belcher and F.M. D'Itri (ed.) Subirrigation and controlled drainage. Lewis Publ., Boca Raton, FL.

Fipps, G., and R.W. Skaggs. 1991. Simple methods for predicting flow to drains. J. Irrig. Drain. Eng. 117:881–896.

Ford, H.W. 1979. Characteristics of slime and ochre in drainage and irrigation systems. Trans. ASAE 30:1093–1096.

Fouss, J.L. 1985. Simulated feedback-operation of controlled-drainage/subirrigation systems. Trans. ASAE 28:839–847.

Fouss, J.L., R.O. Evans, and H.W. Belcher. 1999a. Design of controlled drainage and subirrigation facilities for water table management. p. 719–742. *In* R.W. Skaggs and J. van Schilfgaarde (ed.) Agricultural drainage. Agron. Monogr. 38. ASA, CSSA, and SSSA, Madison, WI.

Fouss, J.L., R.O. Evans, D.L. Thomas, and H.W. Belcher. 1999b. Operation of controlled-drainage and subirrigation facilitation for water table management. p. 743–763. *In* R.W. Skaggs and J. van Schilfgaarde (ed.) Agricultural drainage. Agron. Monogr. 38. ASA, CSSA, and SSSA, Madison, WI.

Fouss, J.L., and G.H. Willis. 1990. Research need on integrated system for water and pest management to protect groundwater quality. p. 288–296. *In* Proc. 1990 Conf. Irrig. Drain. Div., Durango, CO. 11–13 July. ASCE, New York.

Fouss, J.L., and J.S. Rogers. 1992. Drain outlet water level control: A simulation model. p. 46–61. *In* Proc. 6th Int. Drain. Symp., Nashville, TN. 13–15 December. ASAE, St. Joseph, MI.

Fox, R.L., J.T. Phelan, and W.D. Criddle. 1956. Design of subirrigation systems. Agric. Eng. 37: 103–108.

Gardner, W.R. 1958. Some steady solutions of the unsaturated moisture flow equation with application to evaporation from a water table. Soil Sci. 85:228–233.

Giardini, L., and M. Borin. 1995. Subirrigation experiments in the Veneto Region (Northeast Italy). A review of the period 1981–1989. p. 207–223. *In* H.W. Belcher and F.M. D'Itri (ed.) Subirrigation and controlled drainage. Lewis Publ., Boca Raton, FL.

Gilliam, J.W., J.L. Baker, and K.R. Reddy. 1999. Water quality effects of drainage in humid regions. p. 801–830. *In* R.W. Skaggs and J. van Schilfgaarde (ed.) Agricultural drainage. Agron. Monogr. 38. ASA, CSSA, and SSSA, Madison, WI.

Gilliam, J.W., R.W. Skaggs and S.B. Weed. 1979. Drainage control to reduce nitrate loss from agricultural fields. J. Environ. Quality 8:137–142.

Gilliam, J.W., D.L. Osmond, and R.O. Evans. 1997. Selected agricultural best management practices to control nitrogen in the Neuse River Basin. North Carolina Agric. Res. Serv. Tech. Bull. 311.

Maas, E.V., and S.R. Grattan. 1999. Crop yields as affected by salinity. p. 55–108. *In* R.W. Skaggs and J. van Schilfgaarde (ed.) Agricultural drainage. Agron. Monogr. 38. ASA, CSSA, and SSSA, Madison, WI.

Madramootoo, C.A., A. Papadopoulos, and G.T. Dodds. 1993. Agronomic and environmental benefits of water table management. J. Irrig. Drain. Eng. 119:1052–1065.

Madramootoo, C.A., S.R. Broughton, and G.T. Dodds. 1995. Water table management for soybean production on a sandy loam soil. Can. Agric. Eng. 37:1–7.

Martin, J.P. 1945. Microorganisms and soil aggregation: II. Influence of bacterial polysaccharides on soil structure. Soil Sci.61:157–166.

Massey, F.C., R.W. Skaggs, and R.E. Sneed. 1983. Energy and water requirements for subirrigation vs. sprinkler irrigation. Trans. ASAE 26:126–133.

Munster, C.L., R.W. Skaggs, J.E. Parsons, R.O. Evans, J.W. Gilliam, and M.A. Breve. 1994. Simulating aldicarb transport in a drained field. Trans. ASAE 37:1817–1824.

Munster, C.L., R.W. Skaggs, J.E. Parsons, R.O. Evans, J.W. Gilliam, and E.W. Harmsen. 1995. Aldicarb transport in drained coastal plain soil. J. Irrig. Drain. Eng. 121:378–384.

Nieber, J.L., and R.A. Feddes. 1999. Solutions for combined saturated and unsaturated flow. p. 145–212. *In* R.W. Skaggs and J. van Schilfgaarde (ed.) Agricultural drainage. Agron. Monogr. 38. ASA, CSSA, and SSSA, Madison, WI.

Parsons, J.E. 1999. Simulation models for drainage water quality. p. 501–535. *In* R.W. Skaggs and J. van Schilfgaarde (ed.) Agricultural drainage. Agron. Monogr. 38. ASA, CSSA, and SSSA, Madison, WI.

Parsons, J.E., and R.O. Evans. 1990. Stream water level control for irrigation supplies. p. 971–981. *In* G.J. Hoffman et al. (ed.) Management of farm irrigation systems. ASAE, St. Joseph, MI.

Parsons, J.E., R.W. Skaggs, and C.W. Doty. 1987. Application of a three-dimensional water management model. Trans. ASAE, 30:960–968.

Parsons, J.E., R.W. Skaggs, and C.W. Doty. 1990. Simulation of controlled drainage in open-ditch drainage systems. Agric. Water Manage. 18:301–316.

Parsons, J.E., R.W. Skaggs, and C.W. Doty. 1991. Development and testing of a water management model (WATRCOM): Development. Trans. ASAE 34:120–128.

Pavelis, G.A. (ed.). 1987. Farm drainage in the United States: History, status, and prospects. USDA Econ. Res. Serv. Misc. Publ. 1455.

Rands, J., and C. Dennis. 1995. Results from an experiment where blocked drains occurred following subirrigation. p. 395–412. *In* H.W. Belcher and F.M. D'Itri (ed.) Subirrigation and controlled drainage. Lewis Publ., Boca Raton. FL.

Ratts, P.A.C., and W.R. Gardner. 1974. Movement of water in the unsaturated zone near a water table. p. 311–358. *In* J. van Schilfgaarde (ed.) Drainage for agriculture. Agron. Monogr. 17. ASA, Madison, WI.

Renfro, G., Jr. 1955. Applying water under the surface of the ground. p. 273–278. Water: The 1955 yearbook of agriculture. U.S. Gov. Print. Office, Washington, DC.

Schwab, G.O., R.F. Frevert, T.W. Edminster, and K.K. Barnes. (ed.). 1966. Soil and water conservation engineering. 2nd ed. John Wiley & Sons, Inc., New York.

Simunek, J.M., T. Vogel, M.Th. van Genuchten. 1994. The SWMS_2D code for simulating water flow and solute transport in two-dimensional variably saturated media. U.S. Salinity Lab. Res. Rep. 132. USDA-ARS, Riverside, CA.

Simunek, J.M., M. Sejna, M.Th. van Genuchten, and D.L. Suarcz. 1995a. The SWMS_2D code with a user-friendly interface in a Windows environment. p. 157–161. *In* L. Ahuja et al. (ed.) Proc. Workshop on Computer Applic. Water Manage., Fort Collins, CO. 23–25 May. Colorado State Univ., Fort Collins.

Skaggs, R.W. 1973. Water table movement during subirrigation. Trans. ASAE 16:988–993.

Skaggs, R.W. 1976. Evaluation of drainage-water table control systems using a water management model. p. 61–68. *In* Proc. 3rd Natl. Drain. Symp., Chicago, Il. 13–14 December. ASAE, St. Joseph, MI.

Skaggs, R.W. 1981. Water movement factors important to the design and operation of subirrigation systems. Trans. ASAE 24:1553–1561.

Skaggs, R.W. 1991. Modeling water table response to subirrigation and drainage. Trans. ASAE 34:1969–175.

Skaggs, R.W. 1999a. Drainage simulation models. p. 469–500. *In* R.W. Skaggs and J. van Schilfgaarde (ed.) Agricultural drainage. Agron. Monogr. 38. ASA, CSSA, and SSSA, Madison, WI.

Skaggs, R.W., and G.M. Chescheir. 1999. Application of drainage simulation models. p. 537–564. *In* R.W. Skaggs and J. van Schilfgaarde (ed.) Agricultural drainage. Agron. Monogr. 38. ASA, CSSA, and SSSA, Madison, WI.

Skaggs, R.W., G.J. Kriz, and R. Bernal. 1972. Irrigation through subsurface drains. J. Irrig. Drain. Div. 98:363–373.

Smith, M.C., R.W. Skaggs, and P.E. Parsons. 1985. Subirrigation system control for water use efficiency. Trans. ASAE 28:489–496.

Spencer, A P. 1938. Subirrigation. Florida Agric. Ext. Bull. 99.

Stevens, J.C. 1955. Drainage of peat and muck lands. p. 539–557. *In* Water: The 1955 yearbook of agriculture. U.S. Gov. Print. Office, Washington, DC.

Susanto, R.H., and R.W. Skaggs. 1995. Hydraulic head losses near agricultural drains: preliminary results and research needs. p. 413–417. *In* H.W. Belcher and F.M. D'Itri (ed.) Subirrigation and controlled drainage. Lewis Publ., Boca Raton, FL.

Tang, Y.K., and R.W. Skaggs. 1977. Experimental evaluation of theoretical solutions for subsurface drainage and irrigation. Water Resour. Res. 13:957–965.

Tang, Y.K., and R.W. Skaggs. 1980. Drain depth and subirrigation in layered soils. J. Irrig. Drain. Eng. 106:113–122.

van Genuchten, R. 1980. Predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J. 44:892–898.

Visser, J. 1995. Some results of subirrigation in the Ijsselmeerpolders in The Netherlands. p. 11–124. *In* H.W. Belcher and F.M. D'Itri (ed.) Subirrigation and controlled drainage. Lewis Publ., Boca Raton, FL.

Van der Ploeg, R.R., R. Horton, and D. Kirkham. 1999. Steady flow to drains and wells. p. 213–263. *In* R.W. Skaggs and J. van Schilfgaarde (ed.) Agricultural drainage. Agron. Monogr. 38. ASA, CSSA, and SSSA, Madison, WI.

van Bakel, P.J.T. 1986. Planning, design, and operation of surface water management systems: A case study. Rep. 13. ICW, Wageningen, The Netherlands.

van Bakel, P.J.T. 1988. Using drainage systems for supplemental irrigation. Irrig. Drain. Syst. 2:125–137.

Youngs, 1999. Non-steady flow to drains. p. 265–296. *In* R.W. Skaggs and J. van Schilfgaarde (ed.) Agricultural drainage. Agron. Monogr. 38. ASA, CSSA, and SSSA, Madison, WI.