Design, Operation, and Maintenance of Controlled-Drainage/Subirrigation (CD-SI) Systems in Humid Areas

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ABSTRACT

THE design, operation, and maintenance of controlled-drainage/subirrigation (CD-SI) systems are covered from the viewpoint of assisting the farmer, practicing engineer, contractor, and SCS personnel. A nomogram is presented for soils, permeability, approximate drain spacings, and ratio of CD-SI system spacing to drainage system spacings. Steps used in the design of a CD-SI system on a farm with sloping fields are covered in this report.

INTRODUCTION

Artificial drainage has been used for many years to lower water table levels and provide aeration for crop roots. Drainage is usually necessary when 6 to 15 cm of rainfall occur over a short period or over a prolonged rainy period if slow natural soil drainage causes the water table levels to rise. It may also be necessary in soils where water seeps to lower elevations in the topography causing water table levels to rise to or near the surface.

Drainage and irrigation may be required in humid areas where rainfall patterns are erratic and soils have low water-holding capacities. In such sandy soils, irrigation may be required several times during the growing season to produce economically viable yields. In these same fields, drainage is required when large rains or seepage causes the water table to rise.

A controlled-drainage/subirrigation (CD-SI) system, a subsurface drainage system with structures to control outflow and inflow, can be used in the drainage mode during wet periods. The same system can furnish water to plants through subirrigation during dry periods. A single system can accomplish both drainage and irrigation (Bordas and Mathieu, 1931; Kalisvaart, 1958; Skaggs et al., 1972; Doty et al., 1975; Doty and Parsons, 1979; Doty, 1980; Wenberg and Gerald, 1982).

The cost of separate irrigation and drainage systems can become prohibitive. Worm et al. (1982) reported the installation in South Carolina of a complete 22-ha CD-SI system including a deep well at a cost of $939/ha compared to a 50-ha center pivot system at a cost of $1,410/ha. They also made an economic evaluation and found that "for the cost and yields observed in this study, the CD-SI system is a more profitable investment than the center pivot system."

The CD-SI systems both improve and decrease the conservation of water in comparison to other irrigation systems. Doty (1980) showed that a CD-SI system in South Carolina furnished adequate water for crop needs over a three-year period except for a few days in 1977. The CD-SI system received 41, 26, and 22 cm of water in 1975, 1976, and 1977, respectively. Irrigation requirements were 38, 26, and 22 cm for these same years. Massey et al. (1983) compared the water supplied to a sprinkler irrigation system and a CD-SI system on three sites and at three locations in the U.S. using simulation models covering 27 years of climatic data. In all cases, more water was supplied to the CD-SI system than to sprinkler irrigation. They reasoned that the water table was within 0.9 m of the soil surface with the CD-SI system, and "this reduced storage available for rainfall and increased drainage and surface runoff over that obtained for sprinkler irrigation." Consequently, storage of water from natural rainfall was less efficient during the growing season with the CD-SI system. Worm et al. (1982) showed that with the CD-SI system, 21 and 13 cm of water were pumped in 1980 and 1981, respectively, while 17 and 13 cm of water were pumped in 1980 and 1981, respectively, for the center pivot system. In general, CD-SI irrigation required about the same or slightly more water than sprinkler irrigation.

The CD-SI system clearly requires less energy. Massey et al. (1983) showed energy requirements for the sprinkler irrigation ranged from 5 to 12 times more than the CD-SI system when the water was pumped from 2 m below the surface and applied at a pressure of 340 kPa. Energy requirements for a center pivot ranged from 0.6 to 2.0 times that of the CD-SI system when the water was pumped from a well 80 m deep. Worm et al. (1982) measured the energy for a center pivot and a CD-SI system, both pumping from a well. Although the pumping level was not shown, the annual energy cost was about 1.6 times more for the high pressure center pivot system than for the CD-SI system in 1980 and 1981.

Initial investment cost and energy savings of the CD-SI system make it advantageous for use as a water management system. The Soil Conservation Service and corrugated tubing manufacturers are recommending installation of these systems throughout the humid region. The purpose of this paper is to give information on the design, operation, and maintenance of CD-SI systems including installation on sloping fields in the humid regions of the U.S.

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DESIGN OF THE SYSTEM

The CD-SI system is designed using the same soil and water principles as a subsurface drainage system, but the system will also be used for subirrigation, i.e., a dual purpose system. There are several items that should be considered prior to designing the system:

1. Does the field need irrigation, drainage, or both?
   (a) Irrigation is needed if any of these conditions affect plant growth and yield:
      1. Available water capacity is less than about 0.12 cm/cm.
      2. Soil type limits the rooting depth to 30 cm.
      3. The water table is deeper than 1.3 m from the surface during the major period of water use by the crop.
   (b) Drainage is needed if:
      1. The water table is less than 60 cm from the soil surface or observations indicate that low yields are a result of wet soils during the growing season.
      2. Planting or harvesting crops is a problem because the water table comes close to the surface.
   (c) Both irrigation and drainage may be needed intermittently or continuously for combinations of a. and b.
2. Is the water supply adequate to support a CD-SI system?
   (a) Water supply can include the following sources.
      1. Water stored in the profile.
      2. Water stored in surface supplies such as lakes, ponds, or streams with dependable flow.
      3. Water in wells.
   (b) Our experience has shown that about 50 L/min/ha (5 gpm/A) of pumped water is adequate in areas where seepage losses are minimal. Where water may be lost to deep seepage and lateral flow, the system's water supply should be adjusted to 65 L/m/ha (7 gpm/A).
3. Are site conditions conducive to the installation of a CD-SI system?
   (a) An impermeable layer or natural water table is close enough to the surface so that a perched water table can be built close enough to the surface to supply water for crop needs.
   (b) The topography is relatively flat.
   (c) Soils are relatively permeable.

Topography, soils, drainage needs, drainage outlets, and water supplies are important features to be considered for water table management or CD-SI systems. The designer should plan water management systems for the entire drainage area, then install the portion of the system that the farmer designates. Then, future system expansion will not overload outlets, water supplies, etc. An example of this is shown later in this paper.

Topographic and Soils Maps

After determining that a CD-SI system is applicable for the area, a topographic survey should be done. This should show normal drainage patterns and the possible need for land leveling or shaping. It is also used to locate control structures and areas to be irrigated by each control structure. A contour interval of 0.3 m is recommended for the map. To develop a topographic map, a grid spacing of 60 m may be used on land slopes of less than one percent, but if land slopes are greater than one percent or irregularities would otherwise be missed, 30-m grid spacings should be used.

The standard soils map can be used in connection with the contour map in laying out the system. A soil survey map with mapping units of about 2 ha in size will be helpful in planning the CD-SI system. The soil survey map, although variable within series, is helpful in deciding where special design attention should be placed. Soils may limit depth of cut, and this limitation may require an area be broken into smaller units to provide water close to the surface for crop needs.

Hydraulic Conductivity and Soil Water Characteristics

Saturated soil hydraulic conductivity and the soil-water characteristic curves must be known before a technically-sound plan can be developed using methods such as DRAINMOD (Skaggs, 1978), a computer simulation design procedure. The saturated hydraulic conductivity should be determined in the field for each soil series. The effective hydraulic conductivity is measured using the auger hole method (van Beers, 1970) or can be calculated from the hydraulic conductivity of the various layers by:

$$K_e = \frac{K_1D_1 + K_2D_2 + \ldots K_nD_n}{D}$$

where:

K_e = effective hydraulic conductivity,
K_1,K_2,K_n = hydraulic conductivity for the respective soil layers,
D_1,D_2,D_n = thickness of the respective soil layers, and
D = total depth of soil where the effective hydraulic conductivity is to be determined.

Permeabilities listed in the Soil Survey interpretation sheets (SCS, 1983) may be helpful, but a wide range of values are usually reported. Peele et al. (1970) reported hydraulic conductivities and other physical characteristics for 35 soils in South Carolina. Hydraulic conductivities in some soils in the Southeast U.S. where field measurements have been made are shown in Table 1. There is a wide variation in the effective hydraulic conductivity of these soils. Similar publications may be available in other states. Since the hydraulic conductivity is so variable, personal knowledge about usual spacings of subsurface drainage systems may be more reliable.

In deciding on drain spacings in fields or areas within fields with soils of different permeability classes or recommended drain spacings, the system should be planned by agreement between the landowner and engineer based on the dominant soil texture or least permeable soil. If the system is planned for the least permeable soil, cost will be more because more drains are required than for the higher permeable soils. It may be preferable to vary the spacing in the area according to the permeability or recommended drain spacings where

TABLE 1. HYDRAULIC CONDUCTIVITIES FOR SOME SOILS IN THE SOUTHEAST

Soil series	Range of effective hydraulic conductivity, Ke		
	Soil survey interpretation sheet	Field measurements	Technical bulletin No. 1037*
	meters/day		
Goldsboro	0.60 - 1.95	1.95 - 3.29	6.12
Paxville	0.75 - 4.15	2.5	
Exum	0.12 - 0.37	1.4	
Coxville	0.12 - 0.37	3.41 - 5.22	1.49 - 5.22
Duplin	0.12 - 0.37	2.44	
Portsmouth	1.21 - 4.93	1.66 - 98.90	8.24
Altavista	0.37 - 1.22	8.05 - 27.11	
Roanoke	0.04 - 0.12	1.95 - 5.89	
Wahee	0.05 - 0.17	5.36 - 6.79	

*Peele et al., 1970

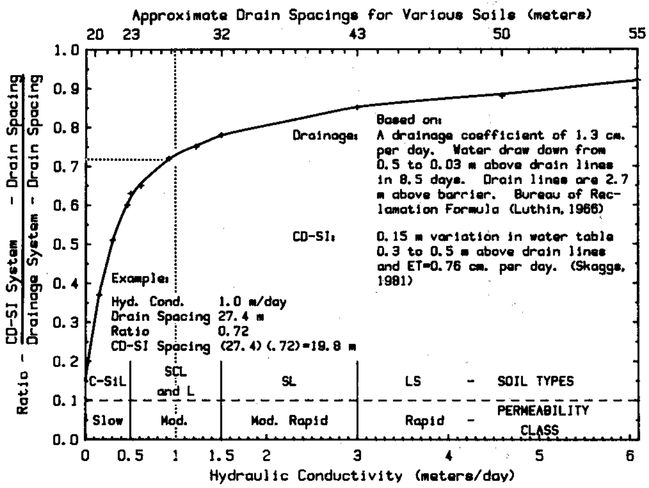

Fig. 1—Nomogram of soils, permeability, approximate drain spacings and ratio of CD-SI system spacing to drainage system spacings.

feasible.

Reliable soil-water suction release curves are often unavailable. Soil water characteristics have been determined on several soils and are now in the SCS State Offices for use with the DRAINMOD Program (Skaggs, 1978). Other soil-water characteristics have been published (Doty, 1980; Carlisle et al., 1978, 1981). Other sources of information for soil-water characteristics are state experiment stations, cooperative extension service publications, and USDA bulletins. Models have been developed to calculate soil water characteristics from the particle size distributions found on the soil survey interpretation sheets (SCS, 1983) for various soil series (Gupta and Larson, 1970; Rawls and Brakensiek, 1982).

Nomogram for Drainage/Subirrigation Line Spacings

In order to develop a drain spacing for design of a CD-SI system, there must be some knowledge of the soils. A thorough knowledge of the soil hydraulic conductivity must be developed, or the engineer or technician must know the drain spacing which has satisfactorily subsurface drained the soil previously. Since CD-SI systems are intended to control the water table at 1.0 m or less from the surface, the depth of the drains are set at the 1.0-m depth. Although DRAINMOD (Skaggs, 1978) was developed to design CD-SI systems, it requires handling the variable soil hydraulic conductivity and soil water characteristics in a computer. The nomogram is an alternative to this.

The nomogram (Fig. 1) was developed to determine drain spacings with the knowledge of soil hydraulic conductivity and/or technician knowledge of soil drainage. The nomogram was developed using two well-known formulas for subsurface drainage (Bureau of Reclamation Formula, Luthin, 1966) and for controlled drainage/subirrigation (CD-SI) (Skaggs, 1981). The spacings for subsurface drainage system and for a CD-SI system were determined using the various hydraulic conductivities using the criteria shown on the nomogram for drainage and CD-SI. Their ratio was then plotted in relation to hydraulic conductivity. These hydraulic conductivities were then divided into soil types and permeability classes as shown by Hantzsche et al. (1982) and the Soil Conservation Service (1951).

The drain spacing scale was then placed on the graph by soil types and permeability classes according to SCS and ASAE recommendations (ASAE EP260.3, 1983-1984; Soil Conservation Service, 1951). Since the drain depth is fixed at about 1 m for water table control, because of controlling the water table of less than 1 m from the surface, the nomogram does not consider drain depth.

The nomogram was checked using soils data found in the literature and the present drain spacing of operating CD-SI systems in those soil series. Many of the drain spacings were determined using DRAINMOD (Skaggs, 1976, 1981; Massey et al., 1983). In the majority of the cases, the present operating CD-SI system spacings are within the limits of the nomogram.

For the Bladen, Raines, Goldsboro, Wagram, and Portsmouth soils, DRAINMOD was used to determine the present CD-SI spacings of 5-7, 13-20, 16-32, 30 and 37 meters, respectively. The nomogram (Fig. 1) shows spacings, Table 2, or 3-10, 17-22, 16-30, 29-37, and 23-37 m, respectively for these soils. Systems have operated satisfactorily in Ocilla, Coxville, Portsmouth, and Goldsboro soils at maximum spacings of 40, 18, 37, 32 m, respectively. The nomogram (Fig. 1, Table 2) gives a range of drain spacings for CD-SI systems 23-55,

TABLE 2. CHECKS FOR DRAIN SPACING WHERE CD-SI SYSTEMS HAVE BEEN PLANNED OR INSTALLED BASED ON RECOMMENDED DRAINAGE SYSTEM SPACING AND MEASURED HYDRAULIC CONDUCTIVITY

Soil series	Measured effective hyd. cond., Ke	Recommended drain system spacing	CD-SI system spacing			
			present	nomogram		
				H.C.	Min.	Max.
	m/day	m				
Ocilla	33.54	30-40	40	55	23	33
Portsmouth	3.04	30-37*	37†	37	23	30
Coxville	1.43	24-30*	18‖	24	16	23
Wagram	1.43	43*	30‡	24	37	—
Goldsboro	1.19	24-37*	16-32	22	16	30
Rains	1.19	25§	13-20§	22	17	—
Lynchburg	0.85	24-37*	30	19	16	30
Lynchburg	0.55	24-37*	30	15	16	30
Portsmouth	0.49	30-37*	30	14	23	30
Bladen	0.24	12.20‡	5-7‡	10	3	7

*South Carolina SCS Drainage Guide
†Massey et al., 1983
‡Skaggs, 1976
§Skaggs, 1981
‖Britton Farm

16-24, 23-37, and 16-30 m, respectively for these soils. Therefore, the use of the nomogram gives CD-SI spacings within the range of those determined with DRAINMOD and matches even more closely to present systems now operating satisfactorily.

The nomogram can be used by the design technician who knows the subsurface drain spacing for a particular soil to determine the CD-SI system spacings. For example, if the soil on which the CD-SI system is to be placed is a silty clay loam soil and the subsurface drains have been spaced at 27.4 m for years, the technician uses the nomogram and finds where a 27.4 m drain spacing crosses the ratio line (See example on Fig. 1). At this intersection, the ratio is 0.72, therefore, the CD-SI system spacing should be 19.8 m. From the same nomogram, if the effective hydraulic conductivity of the field was determined to be 1.0 m/day, the soil should be classified as silty clay loam or loam soil type with a moderate permeability class with an approximate drain spacing of 27.4 m and the CD-SI system spacing of 19.8 m (See example, Fig. 1).

In the example given later, the farmer, Mr. Phil Britton, chose 18.3 m (60 ft) which is on the low side of the range of 15-23 m (52-75 ft). Although there were several soil types on the farm, Mr. Britton chose the drain spacings for the predominant lower hydraulic conductivity soil series, Coxville. This system is on sloping land and is used to show the techniques used for laying out a system on sloping or undulating fields.

CD-SI Systems Design for Sloping Land

Figure 2 shows a typical contour map of a portion of the Phil Britton Farm* in Florence County, South Carolina, which is used to illustrate system design and installation principles. This contour map shows a wide range in soil surface elevations. Consequently, it is impossible to irrigate this farm by water table management without control of the water level at multiple elevations. The drainage outlet from the farm is near the railroad at the SE corner of the farm, but the outlet for that portion of the farm considered for the first installation was two 0.6-m diameter highway culverts located about 450 m west of the railroad with outlet elevations of 15.27 m. From this outlet to the upper end of the farm considered for a CD-SI system, there is a 1.25-m change in surface elevation. Water table control structures were selected at about 0.4-m increments for a total of four structures on the first portion of the farm. The drainage-irrigation main ran from the highway culverts north and parallel to the road on the east side of the farm.

Most control structures allow excess water to overflow downstream; so does Mr. Brittons. Therefore, water for subirrigation was introduced above the structure of highest elevation and flow by gravity to the structures downstream. This was easily done since Mr. Britton had to install a well (Fig. 3) at the upper portion of the farm to supply water. If surface water supplies had been available, design around the water supply may have

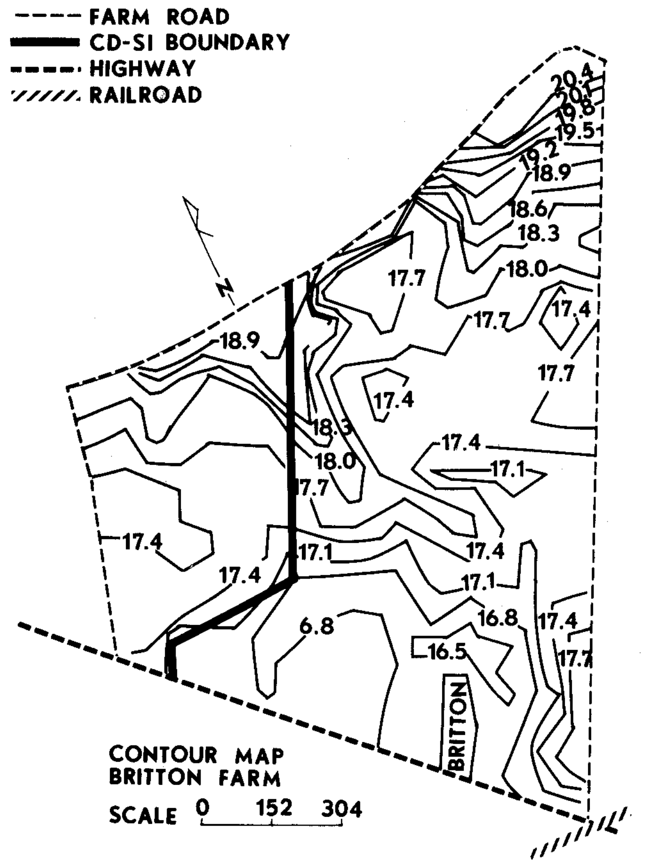

Fig. 2—Contour map for design of CD-SI systems on Phil Britton Farm. The CD-SI system the farmer chose to be installed is east of the boundary shown and north of the highway.

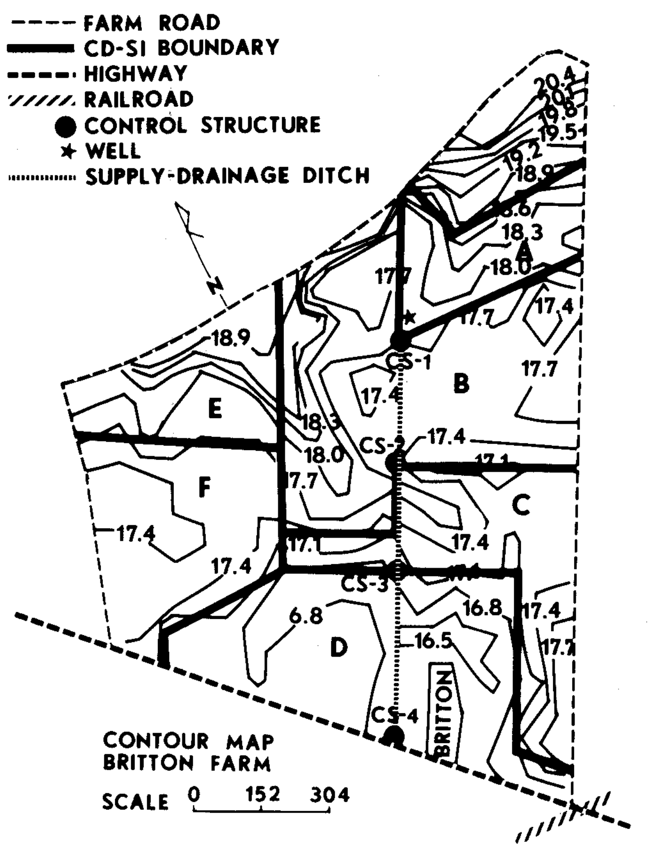

Fig. 3—Contour map showing areas irrigated by different control structure. The farmer plans to install a system in Areas E and F at a later time, therefore, these areas were included in the planned system.

*This system was installed with the combined efforts of the Irri-Drain Division of Advance Drainage Systems, Inc.; the Soil Conservation Service; Dennis Karian, contractor; and Mr. Phil Britton.

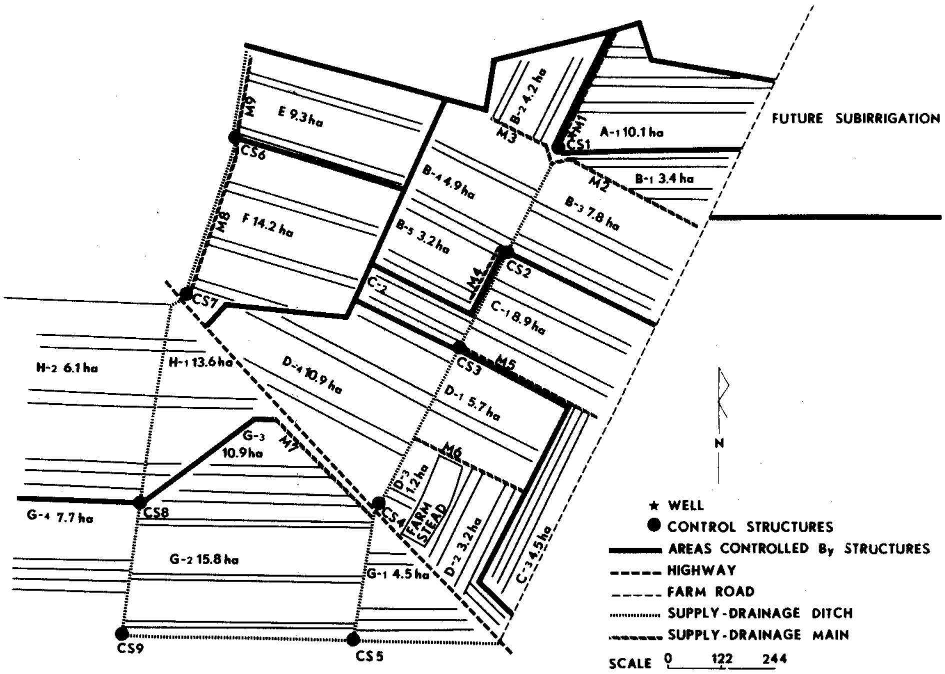

Fig. 4—Subsurface drain layout for a CD-SI system with the variable slopes on the Phil Britton Farm. The drain lines are evenly spaced at 18.3 m (60 ft) over the entire farm, but only Areas A-D were chosen for installation presently. However, the system was designed for all areas.

required pumping to the higher elevations.

Water level control points were then selected along the drainage-irrigation main (Fig. 3). The field was then divided into areas each with the least change in surface elevation. There were wide ranges in elevations within each area which meant that the minimum depth to the water table ranged from 0.3 m to 0.6 m over the farm. This can be adjusted by raising and lowering the water level at the control structure for various crops and cropping conditions.

The decision to use a closed irrigation-drainage main or an open ditch on the CD-SI system was important technically as well as economically. A closed or underground irrigation-drainage main line was used in Area A, Control Structure No. 1. (Fig. 4), and it was necessary to provide surface drainage. Area A's surface was drained by the road ditch along the north-south border and by a shallow, wide waterway along the east-west border that is easily crossed with equipment. To provide a closed system all the way would have required less maintenance, but the cost of the conduit would have been prohibitive. For example, at control structure #2 (Fig. 4), subsurface drainage was required from Areas A, B-1, B-2, B-3, and B-4, totaling about 30 hectares (76 A). Using a minimum removal coefficient of 1.3 cm (0.5 in.) in 24 hrs or 0.045 m^3/s (1.6 CFS), a pipe, 38 cm (15 in.) in diameter, would be required at control structure #2 (Fig. 4). A larger pipe would be required at control structures farther downstream. Therefore, an open ditch was used past control structure No. 1, and standard procedures were used to determine size. This consideration must be made by the engineer in consultation with the landowner.

Layout of Drain Lines on a Field with Varying Elevations

The CD-SI system should be designed for the entire area which the landowner is considering. Although only Sections A, B, C, and D were installed on Mr. Britton's farm, the entire farm CD-SI system was planned as shown in Fig. 4. The drain line spacings are 18 m over the entire farm. Correct planning and layout of the mains, laterals, and water control structures play an important role in system efficiency as well as cost. The layout of the lateral lines from the irrigation-drainage main line on flat land is straightforward. Laterals are spaced at equal intervals along the main, example Areas B-3 and B-4. At times, it is necessary to run submains in order to supply drainage and irrigation to an area, example Areas B-1 and B-2 (Fig. 4).

In the lateral layout for areas where the slope varies, Areas B-5 and C-3 (See Contour Map, Fig. 3) required additional study. The water table in Area B-5 had to be controlled by control structure No. 2 to bring the water level within 0.6 m of the soil surface. The water level in the ditch along side Area B-5 was controlled by structure No. 3 and was 0.4 m lower in elevations than needed. Therefore, a closed submain, M-4 (Fig. 4), was installed to supply water from the elevation of control structure No. 2.

Area C-3 was at a higher elevation than Area D, but, in this case, one of the last lateral lines in Area C-1, M5, (Fig. 4) was sized to take care of the additional irrigation and drainage in Area C-3. Also, the last lateral line in Area D-1 served as a main, M6, for Area D2. This procedure describes the layout for Mr. Britton's farm but applies in general to any sloping field on which a CD-SI system is to be installed.

OPERATION OF THE SYSTEM

The addition of control structures to a drainage systems converts the system into an irrigation and drainage system. A CD-SI system must be managed continually for irrigation during dry periods and for drainage during wet periods. The system should be operated as a full drainage system during the fall and winter in order to allow the soil to aerate and to clean out the drainage passageways as much as possible.

Management of the water table during wet periods is important since the water table is held from 0.5 to 1.0 m from the surface, and if drainage is not supplied when needed, crops may be damaged. Subirrigation management is just as important. When the water level is allowed to drop below preset conditions, re-establishing a water table level is difficult.

The water table can be managed by at least three modes: constant water table level, irrigation and drainage, and changes in the water table level as needed. At present, most of the existing CD-SI systems in the Southeast operate with a constant water table level control. During dry periods, water is pumped into the supply-drainage main, and the position of the water tables varies only slightly due to diurnal variations in evapotranspiration. Most drainage is accomplished by overflow in the control structure. For high intensity rains and for long extended rainy periods, it becomes necessary to lower the water level in the supply-drainage main to keep the field from becoming too wet. The depth to the water table in the field should be about 75 to 90 cm for corn but may vary by soil type. Desired water depths for other crops are discussed by Wesseling (1974).

Irrigation and drainage modes of control procedure are now under investigation (Smith et al., 1985). To conserve water, the water level is raised to a preset point at the midpoint between drains but allowed to drop a preset distance before more water is applied.

SYSTEM MAINTENANCE

The CD-SI system is mostly underground, but still requires maintenance. Care should be taken in backfilling lines near the ditch to keep the soil from falling or washing into the ditch. Since water is kept in the ditch during the cropping season, the lower portion remain relatively free of weeds, and a mower should control weeds on the portion of the ditch above the drain lines. When the supply-drainage main is an open ditch, banks should be kept free of weeds and bushes. When plastic pipe is used, ditch banks should not be burned because of possible damage to the pipe.

Animal guards should be installed and kept in good repair on all open pipe ends of the system. The system should be kept free of clogging from sediment or chemical deposits. In severe cases, the lines may need flushing with water. Surface drainage outlets should be kept in good repair. Maintenance of the CD-SI system is of utmost importance for successful operation.

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