

UIIU-WRC-84-189
RESEARCH REPORT 189



UNIVERSITY OF ILLINOIS
AT URBANA-CHAMPAIGN
WATER RESOURCES
CENTER

SEPTEMBER 1984

The Feasibility of Subirrigation Systems on Claypan Soils in the Midwest

By Saied Mostaghimi
DEPARTMENT OF AGRICULTURAL ENGINEERING

Walter D. Lembke
DEPARTMENT OF AGRICULTURAL ENGINEERING

Charles W. Boast
DEPARTMENT OF AGRONOMY

UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

Grant Agreement G-84004

Loan Copy # 2
PLEASE RETURN TO
2535 HYDROSYSTEMS LAB.

WATER RESOURCES CENTER - UIUC
2535 HYDROSYSTEMS LABORATORY
208 NORTH ROMINE
URBANA, ILLINOIS 61801

Project Completion Report
to
U.S. Department of the Interior
Washington, D.C. 20240

WRC RESEARCH REPORT NO. 189

THE FEASIBILITY OF SUBIRRIGATION ON
CLAYPAN SOILS IN THE MIDWEST

By Saied Mostaghimi
Department of Agricultural Engineering
Virginia Polytechnic Institute and State University
Blacksburg, Virginia 24060

Walter D. Lembke
Department of Agricultural Engineering
University of Illinois at Urbana-Champaign
Urbana, Illinois 61801

Charles W. Boast
Department of Agronomy
University of Illinois at Urbana-Champaign
Urbana, Illinois 61801

The research on which this report is based was financed in part by the U.S. Department of the Interior, as authorized by the Water Research and Development Act of 1978. (P.L. 95-467).

Grant Number G-84004

September 1984

Project Completion Report

U.S. Department of the Interior
Washington, D.C. 20240

Contents of this publication do not necessarily reflect the views and policies of the U.S. Department of the Interior, nor does mention of trade names or commercial products constitute their endorsement by the U.S.

ABSTRACT

This was a study to evaluate the suitability of subirrigation along with alternative soil and water management practices on claypan soil. Crop yields on these soils are usually low because of limited water management for crop production. Several years of crops, soil and weather data collected on a claypan soil in Illinois were used to study performance of subirrigation and conventional irrigation on these soils. Various drain spacings and depth combinations for both good and poor quality surface drainage were simulated. Results indicated that optimum drain spacing for subirrigation on these soils would be 6 m under good surface drainage, and a weir setting depth of 35 cm on a 5-year recurrence interval basis. However, such a close drain spacing may not be economically feasible.

Mostaghimi, Saied; Lembke, Walter D.; Boast, Charles W.

THE FEASIBILITY OF SUBIRRIGATION ON CLAYPAN SOILS IN THE MIDWEST
Final Report to Department of the Interior, September 1984, Washington, D.C.
50 p.

KEYWORDS--claypan soils/ corn/ drain depth/ drain spacing/ dry days/
Midwest/ simulation model/ subirrigation/ subsurface drainage/ surface
drainage/ trafficability/ water table depth/ weir depth

ACKNOWLEDGMENTS

This research was accomplished through a grant from the U.S. Department of the Interior. Support was also provided by the Water Resources Center, University of Illinois at Urbana-Champaign, Illinois Agricultural Experiment Station, and USDA Soil Conservation Service.

TABLE OF CONTENTS

	Page
Introduction - - - - -	1
Previous Work - - - - -	5
Model Description - - - - -	7
Model Components - - - - -	9
Precipitation - - - - -	9
Infiltration - - - - -	9
Surface Drainage - - - - -	10
Subsurface Drainage and Subirrigation - - - - -	11
Evapotranspiration - - - - -	12
Objective Functions - - - - -	13
Working Days - - - - -	13
Dry Days - - - - -	14
SEW ₃₀ - - - - -	14
Simulation Input Data and Procedure - - - - -	15
Soil Information and Input - - - - -	15
Crop Input Data - - - - -	21
Drainage System and Climatological Input Data - - - - -	21
Results and Discussion - - - - -	23
Model Performance - - - - -	23
Simulations - - - - -	24
Effects of Subirrigation on SEW ₃₀ , Working Days and Dry Days -	26
Effects of Combined Surface and Subsurface Drainage on SEW ₃₀ , Working Days and Dry Days - - - - -	39
Summary and Conclusions - - - - -	45
References - - - - -	48

FIGURES

	Page
1. Schematic of the water management system considered by DRAINMOD; subsurface drains can be used for both sub-irrigation and drainage (Skaggs, 1978). - - - - -	8
2. Soil moisture characteristics curve for Cisne silt loam soil.	18
3. Drainage volume or air volume (mm^3/mm^2) as a function of water table depth for Cisne silt loam soil. - - - - -	19
4. Simulated and measured weekly cumulative SEW_{30} values for a combination of surface and subsurface drainage treatments during the 1982 growing season. - - - - -	25
5. Working days versus drain spacing for four weir depths on Cisne silt loam soil under subirrigation. - - - - -	27
6. SEW_{30} versus drain spacing for four weir depths on Cisne silt loam soil with poor surface drainage ($S = 30$ mm) and subirrigation.- - - - -	28
7. SEW_{30} versus drain spacing for four weir depths on Cisne silt loam soil with good surface drainage ($S = 3$ mm) and subirrigation.- - - - -	29
8. Dry days versus drain spacing for four weir depths on Cisne silt loam soil under subirrigation. - - - - -	31
9. SEW_{30} versus drain spacing for both good ($S = 3$ mm) and poor ($S = 30$ mm) surface drainage with subirrigation control weir located at 35-cm depth. - - - - -	33
10. The effect of depth to the impermeable layer on SEW_{30} for good surface drainage ($S = 3$ mm) and subirrigation with an assumed drain depth of 35 cm. - - - - -	34
11. The effect of depth to the impermeable layer on working days for good surface drainage and subirrigation with an assumed weir depth of 35 cm.- - - - -	36
12. The effect of depth to the impermeable layer on dry days, for good surface drainage and subirrigation with an assumed weir depth of 35 cm.- - - - -	38
13. Working days versus drain spacing for both good ($S = 3$ mm) and poor ($S = 30$ mm) surface drainage and conventional subsurface drainage. - - - - -	40
14. SEW_{30} versus drain spacing for both good ($S = 3$ mm) and poor ($S = 30$ mm) surface drainage and conventional subsurface drainage. - - - - -	42

FIGURES Cont.

	Page
15. Dry days versus drain spacing for both good ($S = 3$ mm) and poor ($S = 30$ mm) surface drainage and conventional sub-surface drainage. - - - - -	43

TABLES

	Page
1. Summary of input data for soil properties and crop parameters for Cisne silt loam soil. - - - - -	17
2. Coefficients for the Green-Ampt infiltration equation as a function of initial water table depth. - - - - -	20
3. Summary of drainage input parameters used in simulation for Cisne silt loam soil. - - - - -	22

INTRODUCTION

The design of efficient agricultural water management systems is becoming more critical as production costs and farm prices climb. Water is essential for the permanence and stability of agriculture and demand for water is increasing due to the competition of domestic, municipal, recreational and industrial uses; excessive water quality deterioration; losses through seepage, runoff and evaporation; and increasing tendency towards irrigation.

Although the Midwest States receive an ample amount of water as annual precipitation, irrigation in these areas is often economical. Three factors necessitate irrigation in Midwest States: (a) the annual rainfall distribution does not coincide with the evapotranspiration distribution, (b) water holding capacity generally is not sufficient to provide adequate water for crops during the deficit rainfall period and (c) frequently restricted rooting depth limits soil water availability to plants (Lambert et al., 1981). Most of Midwestern states experience frequent periods of hot and dry weather during the growing season. For instance, in East-Central Illinois, the probability of a 5-day or longer dry period (where dry period is defined as less than 0.25 cm precipitation in 24 hours) is approximately 75 percent for the second half of July. When rainfall does occur during the growing season, the low permeability of the heavy soils in some areas and their flat topography result in excessive water in the plant root zone. Therefore, artificial drainage systems are needed to satisfy two specific requirements: (a) to insure trafficable conditions for seedbed preparation, planting, harvesting, and other field operations; and (b) to remove excess water from the root zone during heavy rainfall periods to insure a suitable environment for plant growth during the growing season.

Subirrigation systems are designed to provide total water management for crop production in areas where both irrigation and drainage are needed. During wet periods, the system operates as a drainage system to remove excess water. During dry periods, water is supplied back through the system to the growing crop. In the irrigation mode, water is diverted into the drains and then infiltrates out into the soil. Moisture then reaches the plant roots through lateral and outward movement. The method requires that the depth to water table be subject to rigid control otherwise the depth can become too shallow or too deep and either retard growth or stop it completely.

As with other methods of water management, certain restrictions must be recognized to successfully operate a subirrigation system. Ideally, subirrigation can be practiced in areas with a nearly level and smooth soil surface and a soil profile that includes a highly permeable stratum extending from the surface down to 60 cm or more, underlain by a relatively impermeable substratum (Hoskyn and Bryan, 1969). The impermeable layer insures that water applied will remain where needed, and that a minimum quantity of water will be needed to raise the water table. Subirrigation system effectiveness depends on several soil physical characteristics such as hydraulic conductivity and moisture holding capacity. The soil should be permeable enough so that water will move quickly to supply plants all the water they need in peak consumption periods. Also soil must drain readily enough to remove the excess water which occurs during heavy rainfall. The rate and distance of water movement is dependent primarily upon the texture of the soil. For example, water in the unsaturated state moves more rapidly but for a shorter distance in a sandy loam than in a silt loam soil. Therefore,

drain spacing is directly related to the distance water will move in the soil and still fulfill plant water requirements. Drain spacing is a major factor in total system cost and perhaps the most important single variable in the system design and in the successful functioning of the system. Within limits of available machinery, drain depth has little effect on system cost, but is very important in that sufficient depth is necessary to provide the necessary head differential to move water rapidly from the drain tube and through the soil.

There are several claimed and potential advantages of such a water management system. Foremost are low labor and maintenance requirements when one buried system provides both irrigation and drainage. The method can be used on soils having relatively low water holding capacities and high intake rates. Weed seeds are not carried over the surface of the land by irrigation water to germinate and grow. Thus, weed control is simplified under subirrigation. Another important advantage is that, compared to sprinkler irrigation, soil compaction and erosion is reduced, as is the nutrient leaching from the upper root zone. Soils warm earlier in the spring due to good subsurface drainage and some proof exists that plugging of the tiles may be eliminated by the backflashing effect of subirrigation water (Zetsche, 1964). In contrast to sprinkler irrigation in which water loss from evaporation can amount to as much as 30 percent, subirrigation reduces the problem of surface evaporation, and therefore, higher water-use efficiencies and better crop yields can be obtained.

Subirrigation has some disadvantages though, and ignoring them can be a very serious mistake. The single most important disadvantage is that the system requires an unusual combination of natural conditions to exist

(Criddle and Kalisvaart, 1967). Other disadvantages are that only water supplies of good quality may be used and that choice of crops to be irrigated by this method may be somewhat limited to a narrow range of rooting characteristics. Finally, depending on the tile spacing required for satisfactory crop production, total cost of the system can be a limiting factor.

There are about 4 million hectares of claypan soil in the Midwest. These soils have a 30- to 75-cm layer of silt loam topsoil with a heavy clay subsoil that is very slowly permeable and severely limits root development and water penetration. The crop yields on these soils are usually low because of limited water management. With proper water management these soils can become very productive. A high percentage of these soils occur on nearly level to gently sloping lands of Illinois.

There are many areas in the Midwest where subirrigation, if properly designed and operated, would give better results than the conventional methods of soil and water management. Climate, topography, subsoil characteristics, and high water table associated with claypan soils in the Midwest may be particularly adaptable to subirrigation. However, very little information is available on subirrigation systems for claypan soils in the Midwest. Their feasibility, and performance compared to commonly practiced irrigation systems have not been studied, nevertheless, investigations show that subirrigation systems do work satisfactorily in some areas, and it has been stated that this system of irrigation, if properly designed and operated, might be the best method available for many areas (Criddle and Kalisvaart, 1967). The extent of claypan soils in the Midwest justifies efforts in studying the suitability of subirrigation in these soils.

The objectives of this study were: (a) to evaluate the suitability of subirrigation along with alternative soil and water management practices on claypan soils, and (b) if subirrigation is suitable, develop design criteria for the Midwest.

PREVIOUS WORK

Walker et al. (1982) investigated the effects of combinations of both irrigation and drainage treatments on corn production on claypan soils in the upper Midwest for five years. The irrigation treatments were sprinkler, furrow, and no irrigation. The drainage treatments were surface, subsurface, and no drainage. The results indicated average corn yield increases of 0.8 and 2.4 t/ha due to drainage and irrigation, respectively. Together, irrigation and drainage acted synergistically to produce an average yield increase of 4.8 t/ha. They concluded that both irrigation and drainage is needed for maximum crop production on the claypan soils. Rausch and Nelson (1984) investigated the benefits of water management systems on claypan soils of Missouri. They reported that subirrigation improved alfalfa yield by 2.5 times over that of non-irrigated plots. However, the slow permeability of the claypan layer restricted the lateral water flow in the soil and subirrigation water moved less than 2 meters away from the trench. It should be noted that they used a 15-m spacing between the drains used for subirrigation and that their results are based on only one year of data collection.

Cole (1971) presented an excellent comprehensive review of knowledge pertaining to subirrigation. He lists 58 references in his literature survey of potential and problems related to subirrigation. Increases in crop yields under subirrigation systems have been reported

by many investigators. These reports have been encouraging. In Arkansas, reports indicate a 340-kg increase in cotton yield with sub-irrigation over the nonirrigated check (Bryan and Baker, 1964). In Texas, studies have shown comparable corn yields for subirrigation and furrow irrigation, while the subirrigation system required 42 percent less water (Zetzsche, 1964). Eldin (1970) reported corn yields of 10.44 and 6.33 t/ha under subirrigation and control system of irrigation, respectively. He also reported that cucumbers with 66.0 cm of water produced 43.9 t/ha of yield in subirrigation, but no yield was obtained using a sprinkler system. Sepaskhah et al. (1976) reported that sub-surface irrigation required 55 percent less water to produce bean yields comparable to that obtained with furrow irrigation.

A restricting layer exists at a depth of less than 75 cm in claypan soils. This layer is very slowly permeable thereby limits natural subsurface drainage and causes a high water table in claypan soils (Goetsch, 1981). Recent studies by Skaggs have demonstrated the feasibility of crop production on an area which has both a high water table and an impermeable layer beneath the soil surface (Skaggs, 1977). The relationship of water table depth to yield of many field crops has been investigated. Doty et al. (1975) found that silage yields of field corn increased by 0.5 t/ha for each additional day the water table was maintained at less than 100 cm from the surface in a sandy soil. Other studies have also shown the best crop response when the water table was maintained between 60 and 100 cm from the soil surface (Follett and Doering, 1974). These findings show that controlling the water table could increase crop production on a variety of soils. Therefore, sub-irrigation, which maintains the water table at some predetermined depth

below the ground surface could be suitable for optimum crop production on claypan soils in the Midwest. It should be noted that previous studies show that the best water table depth for crop production is greater than the claypan depth (Doty et al., 1975).

MODEL DESCRIPTION

The simulation model, DRAINMOD, was developed at North Carolina State University for shallow water table soils and was described in detail by Skaggs (1978, 1980). The model was developed for design and evaluation of multicomponent water management systems which may include facilities for surface drainage, subsurface drainage, sprinkler irrigation and subirrigation. It has been extensively used and its accuracy verified against field data from several locations (including North Carolina, Ohio and Indiana) and it is currently being tested against data from Florida, Louisiana and California (Skaggs, 1982).

A schematic of the water management model is shown in Figure 1. Detailed descriptions of the model logic and examples of its application have been given by Skaggs (1980). Briefly, however, the model is based on a water balance for a thin section of soil of unit surface area which extends from the impermeable layer to the surface and is located midway between the adjacent drains. The water balance is computed on an hourly basis in DRAINMOD by using approximate methods to calculate infiltration, drainage, subirrigation, and evapotranspiration. When rainfall occurs, a water balance is also conducted at the surface with time increments that can be as short as three minutes to describe the infiltration process (Skaggs and Nassehzadeh-Tabrizi, 1983).

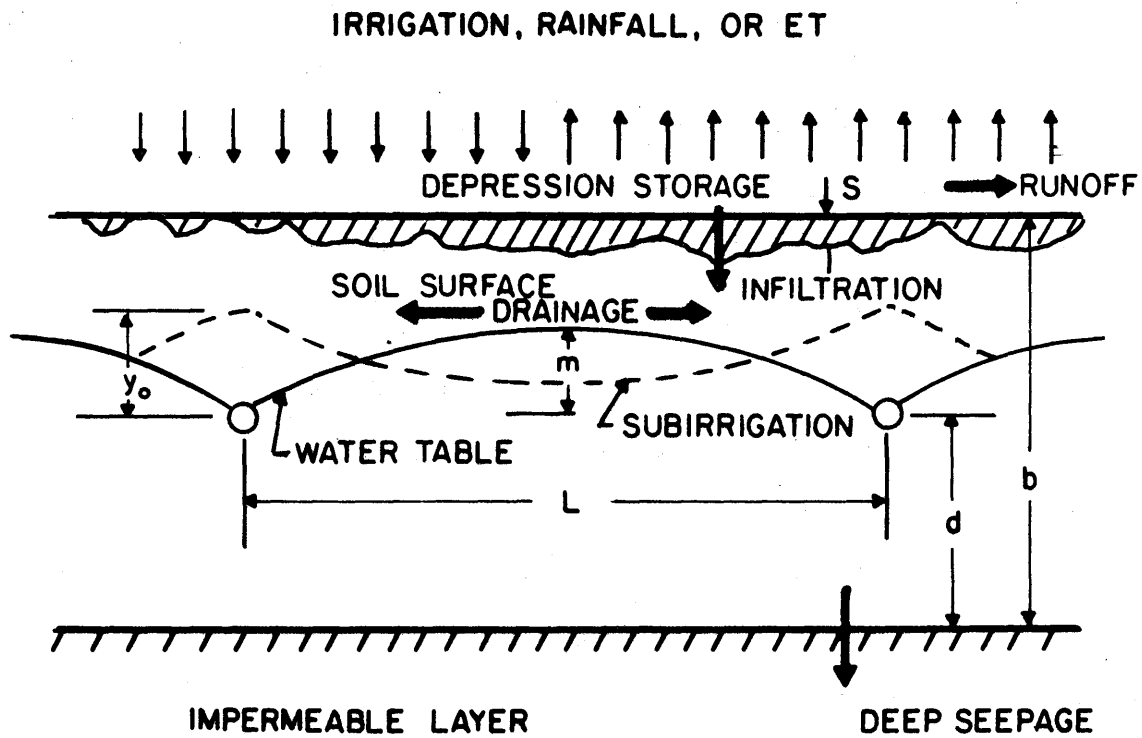


Figure 1. Schematic of the water management system considered by DRAINMOD; subsurface drains can be used for both sub-irrigation and drainage (Skaggs, 1978).

Model Components

Precipitation

Precipitation records are one of the major inputs to DRAINMOD. The accuracy of the model prediction for infiltration, runoff and surface storage is dependent on good rainfall data (Skaggs, 1978). Precipitation records are read into the model as hourly values. Skaggs (1982) indicated the precipitation records of shorter time increments can be used, but such data are not normally available, so the model is programmed to read hourly records.

Infiltration

The Green and Ampt (1911) equation is used by DRAINMOD to predict infiltration rates into the soil. The equation was originally derived for deep homogenous soil profiles with a uniform initial water content. Water is assumed to enter the soil as slug flow resulting in a sharply defined wetting front. The Green and Ampt equation, which is a result of the direct application of Darcy's Law to a slug flow regime, may be written as:

$$f = K_s + K_s M S_{av}/F \quad (1)$$

where f is the infiltration rate, F is the accumulated infiltration, K_s is the hydraulic conductivity of the wetted zone, M is the difference between final and initial volumetric soil moisture contents, and S_{av} is the effective suction at the wetting front. For a particular soil with a given moisture content, Equation (1) can be written as:

$$f = A/F + B \quad (2)$$

where A and B are parameters that depend on soil properties, and initial water content and distribution.

In addition to uniform profiles for which Green and Ampt equation was originally developed, Bouwer (1969) and Childs and Bybordi (1969) reported that it may also be used for soils with nonuniform initial water contents and profiles that become denser with depth. The model requires input for infiltration in the form of a Table of A and B versus water table depth. When rainfall occurs, A and B values are interpolated from this table for the appropriate water table depth at the beginning of the rainfall event. Then an iteration procedure is used with Equation (2) to determine the cumulative infiltration at the end of hourly time intervals (Skaggs, 1978).

Surface Drainage

When rainfall occurs, water infiltrates into the soil surface and percolates through the profile and raises the water table. If the rainfall rate is greater than the soil infiltration capacity, then water begins to collect on the surface. Surface drainage is characterized by the average depth of depression storage that must be satisfied before runoff can begin. Gayle and Skaggs (1978) reported that depression storage depth in an eastern North Carolina field varied from about 1 mm for lands that had been smoothed to greater than 30 mm for rough plowed fields. Surface detention storage which depends on the runoff rate, slope, and hydraulic roughness of the surface is neglected in DRAINMOD. Detention storage is the depth of surface water that is accumulated, in addition to the depression storage, before runoff from the surface begins. By neglecting surface detention storage, DRAINMOD assumes that runoff moves immediately from the surface to the outlet.

The effect of improving the surface drainage can be simulated by varying the average depth of depression storage from small values for good surface drainage to large values for poor surface drainage.

Subsurface Drainage and Subirrigation

The rate of subsurface water movement into drain tubes depends on the hydraulic conductivity of the soil, drain depth and spacing, soil profile depth and water table elevation. Water moves toward drains in both the saturated and unsaturated zones. However, in DRAINMOD it is assumed that lateral water movement occurs mainly in the saturated zone. Hooghoudt's steady state equation as used by Bouwer and Van Schilfgaarde (1963) is used in DRAINMOD for subsurface drainage. This equation can be written as:

$$q = \frac{8Kd_e m + 4Km^2}{L^2} \quad (3)$$

where q is the flux, m is the midpoint water table height above the drain, K is the effective lateral hydraulic conductivity, L is the distance between the drains, and d_e is the equivalent depth of the impermeable layer below the drain which is used in this equation to correct for convergence near the drains.

By using Equation (3) in DRAINMOD, it is assumed that drainage is limited by the rate of soil water movement to the drains and not by the hydraulic capacity of the drain tubes or of the outlet. This means that when the flux given by Equation (3) exceeds the Drainage Coefficient (D.C.), q is set equal to the D.C. in DRAINMOD (Chieng et al., 1978). The water level in the main outlet may also limit the drainage flux, however,

such outlet limitations are also neglected in DRAINMOD. Skaggs (1982) reported that although Equation (3) was derived mainly for steady state conditions, when applied for short time increments or for small changes in the water table position, the method compared well with transient methods for predicting drainage flux. A modified version of Equation (3) as presented by Ernst (1975) is used in DRAINMOD to calculate sub-irrigation rates:

$$q = \frac{4Km \left(2h_o + \frac{h_o}{D_o} m \right)}{L^2} \quad (4)$$

where $D_o = y_o + d$; y_o is the water table elevation over the drain, d is the distance from the drain to the impermeable layer, and $h_o = y_o + d_e$. Other notations used in Equation (4) are the same as defined previously.

Evapotranspiration

The model uses the empirical method developed by Thornthwaite (1948) to estimate the potential evapotranspiration (PET). The PET is computed in the main program of DRAINMOD from recorded daily maximum and minimum temperature data. The heat index must be determined and inputted, along with the latitude of the site. Based on latitude and date, adjustments for day length and number of days in the month are made in the program. The determination of evapotranspiration is a two-step process in the model. First, using atmospheric data, the daily PET is calculated and is distributed on an hourly basis. The model distributes the PET at a uniform rate for the 12-hour period between 6:00 a.m. and 6:00 p.m. In case of rainfall, hourly PET is set equal to zero for any

hour in which rainfall occurs. After PET is calculated, if soil water conditions are not limiting, evapotranspiration is set equal to PET. When PET is higher than the amount of water that can be supplied from the soil, evapotranspiration is equal to the smaller amount. Several other methods give more accurate estimates of PET than Thornthwaite, but require input data that are not readily available. However, if the input data can be obtained, the evapotranspiration coefficients calculated by other methods can also be read into the program.

Objective Functions

The objectives of agricultural water management systems are to eliminate crop yield reductions due to lack of or excessive soil water conditions. DRAINMOD can be used to simulate the performance of a given system design and evaluate the appropriate objective functions for a long period of weather record (Skaggs, 1978). Objective functions such as number of working days, number of dry days, and a stress factor, such as SEW_{30} are calculated for each year simulated. Then, by making multiple simulations, the system that satisfies the water management objective functions can be identified.

Working Days

This is a parameter used to characterize the ability of a water management system to insure trafficable conditions during planting and harvesting periods. DRAINMOD counts a day as a working day if: (a) the air volume in the profile exceeds a limiting value, AMIN; (b) the rainfall during that day is less than a minimum value, ROUTA; and (c) a minimum number of days, ROUTT, has elapsed since that amount of rainfall occurred. It should be noted that ROUTA and ROUTT are assumed to be independent of AMIN and of the Water Management System (Skaggs, 1978).

AMIN can be estimated from the soil water characteristics curve and the drainage-volume water table depth relationship. ROUTA and ROUTT can be approximated by field observations during the spring period of seedbed preparation. Skaggs (1978) has experimentally obtained these parameters for a wide range of soil types and conditions.

Dry Days

Number of dry days quantifies the length of time during growing season when deficit soil water conditions exist. A dry day is defined as a day in which evapotranspiration (ET) is limited by soil water conditions. The limiting water content depends on the potential evapotranspiration (PET) rate as well as soil and crop properties. Days in which ET is less than PET because of soil water conditions are assumed to be detrimental to optimum crop production and are counted as dry days (Skaggs, 1980).

SEW₃₀

SEW₃₀ concept was originally defined by Sieben (1964) to evaluate the effect of high water table level on crop production. It is the sum of excess water table rises above the 30-cm depth. It is ordinarily measured in cm-days and may be expressed as:

$$SEW_{30} = \sum_{i=1}^n (30 - X_i) \quad (5)$$

where X_i is the water table depth on day i and n is the number of days in the growing season. Negative terms inside the summation are neglected. Sieben (1964) found that crop yields decreased for SEW₃₀ values greater than 100- to 200-cm days. However, his values were the sum of SEW₃₀ for the entire year. Massey et al. (1983) reported that any water management

system that limits SEW_{30} to 100-cm days or less are adequate for corn production. However, depending on the type of the crop and the timing of the excess soil water condition, the optimum value for SEW_{30} may be different.

Therefore, these three objective functions, working days, dry days and SEW_{30} are used in DRAINMOD to quantify the performance of a water management system. Ideally a system should provide a given number of working days during the planting period, a minimum number of dry days to prevent crop damages due to deficient soil water conditions, and SEW_{30} values less than a given maximum to prevent crop stress due to excessive soil moisture conditions.

SIMULATION INPUT DATA AND PROCEDURE

Soil Information and Input Data

Claypan soils in Illinois consist primarily of the Hoyleton-Cisne-Huey soil association which occur on the uplands of south-central and southern Illinois. These soils typically have very dark grayish brown silt loam Ap horizons. The A2 horizons are grayish brown and light gray silty types. Mottled grayish brown heavy silty clay loam makes up the B2t horizon. Mottled light brownish gray silty clay loam B3 horizons and dark grayish brown silt loam C horizons at depth of about 150 cm complete the soil profile of the Cisne series. Typically there is a very tight claypan layer located at a depth of 30 to 75 cm that is slowly permeable and severely limits root development and water penetration.

The saturated hydraulic conductivity data collected by Lembke et al. (1984) on Cisne silt loam soil at a site near Altamont, Illinois, in Effingham County was used in this study. They used a method based on

water table drawdown (Skaggs, 1976) to measure the saturated hydraulic conductivities of four heavy soils in Illinois. The saturated hydraulic conductivity value is listed in Table 1.

The soil water characteristics data were taken from Goetsch (1981) and the University of Illinois Agricultural Experiment Station Bulletin 760 (1979) for Cisne silt loam soil (Figure 2). The main use of this data is to calculate the relationship between drainage volume and water table depth for use in DRAINMOD. This is that volume of the soil profile which becomes air after the gravitational water has moved down to the water table. However, in this study the drainable porosity values collected by Lembke et al. (1984) were used to estimate these relationships. Drainage volume and water table depth relationship calculated from soil water characteristics data is plotted in Figure 3.

Coefficients for the Green-Ampt infiltration equation were determined using the data from the North Central Regional research publication number 259 (1979). A sprinkler infiltrometer was used to collect these data. The infiltration rates were determined by drawing a smooth curve through the observed cumulative infiltration data and taking the slope at various times along the curve. The parameters A and B were estimated from these data by first defining a variable $G = 1/F$ such that Equation (2) could be written as:

$$f = AG + B \quad (6)$$

Then A and B were determined by fitting a straight regression line to a plot F vs. G data. Finally by using the methods suggested by Skaggs (1979), the coefficients of A and B were determined for various water table depths. Values of A and B corresponding to selected initial water table depths are tabulated in Table 2.

Table 1. Summary of input data for soil properties and crop parameters for Cisne silt loam soil.

Input Parameter	Program Variable Name	Value
Depth to restrictive layer	DEPTH	60 cm
Saturated hydraulic conductivity	CONK	1.6 cm/hr
Saturated water content	*	0.355 cm ³ /cm ³
Water content at lower limit available to plants (wilting point)	WP	0.089 cm ³ /cm ³
Initial water table depth	IDTWT	0.0 cm
Maximum corn root depth	ROOTD	35.0 cm
Minimum soil air volume required for tillage operations during spring	AMINI	3.2 cm
Minimum rain to stop field operations during seedbed preparation	ROUTA1	1.2 cm
Minimum time after rain before can till in spring	ROUTT1	2 days
Working period for seedbed preparation	BWKDY	April 15-May 10
Working hours during spring	SWKHR	0800-2000
Depth to which SEW calculations are made	SEWX	30 cm
Year and month simulation starts	START	1952-01
Year and month simulation ends	END	1971-12
Latitude for temperature station	LATT	39°, 30'
Heat index	HET	57.0

*This variable is not a direct input to DRAINMOD, but is used to calculate other parameters.

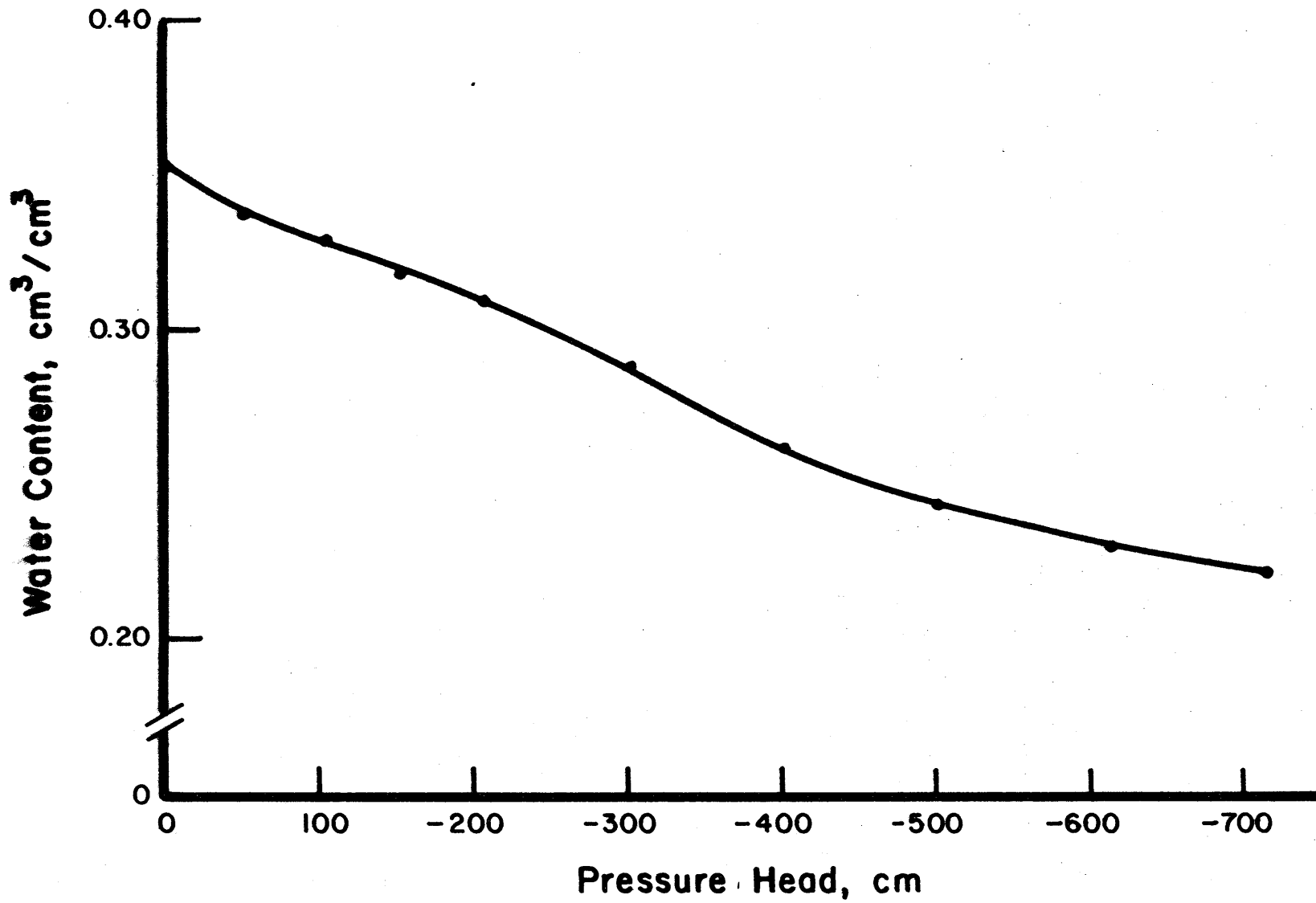


Figure 2. Soil moisture characteristics curve for Cisne silty loam soil.

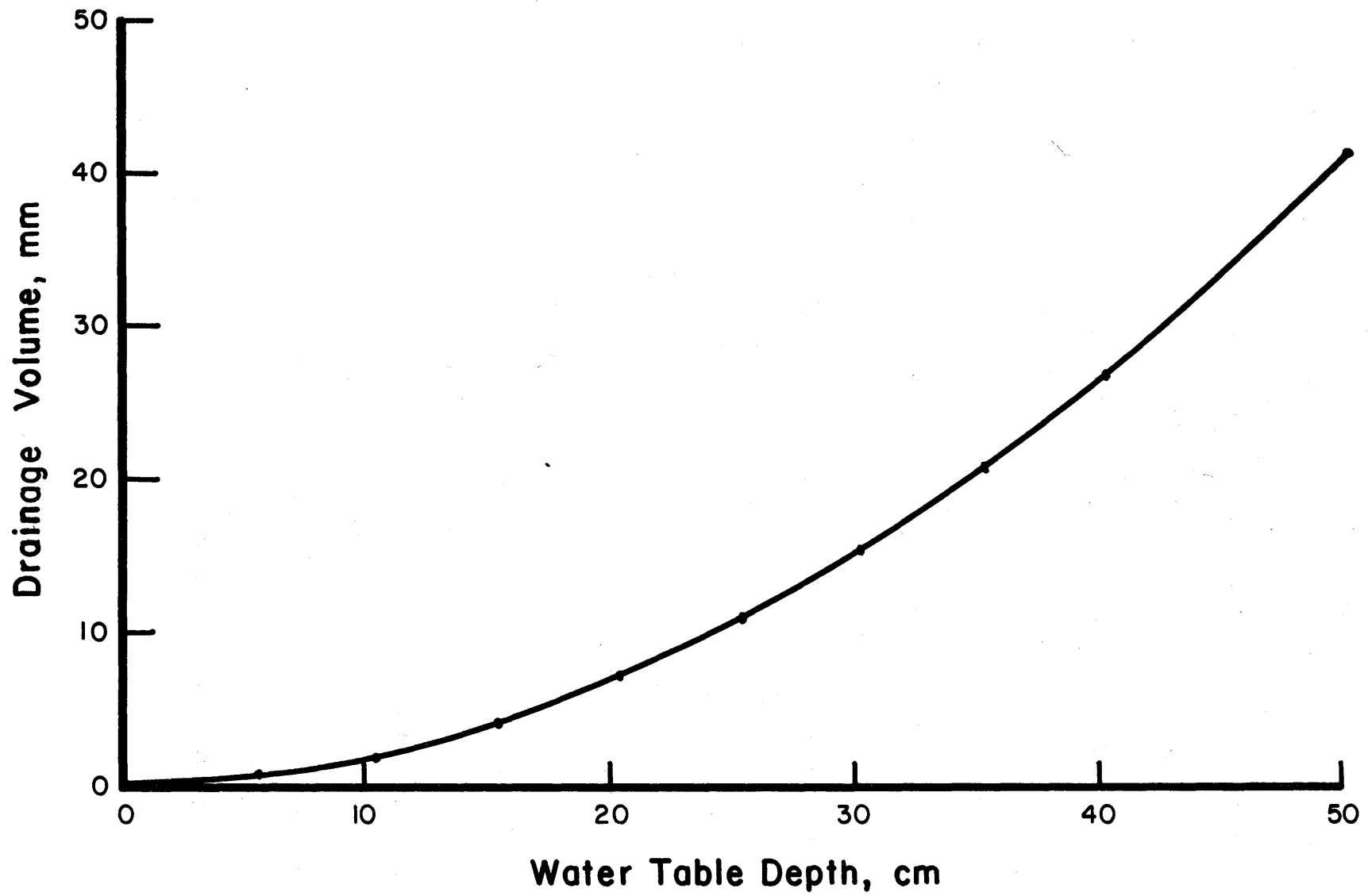


Figure 3. Drainage volume or air volume (mm^3/mm^2) as a function of water table depth for Cisne silt loam soil.

Table 2. Coefficients for the Green-Ampt infiltration equation as a function of initial water table depth.

Water table depth, cm	A, cm ² /hr	B, cm/hr
0	0.00	0.00
20	0.63	1.60
30	0.78	1.60
50	1.25	1.60
100	4.79	1.60
200	8.62	1.60
400	18.22	1.60
500	20.13	1.60

The trafficability parameters for the soil of this study are listed in Table 1. These parameters were estimated from the texture of the plow layer by comparing the physical characteristics of Cisne silt loam with those of soils for which the parameters values have been previously measured and reported by Skaggs (1978).

Several methods are available for estimating the relationship between maximum rate of upward water movement and water table depth. As Skaggs (1978) reported, the entire concept is approximate because the relationship in DRAINMOD is defined for steady state conditions while the actual upward water movement process is transient. These relationships, plotted in Figure 3, were estimated using a computer program developed by Skaggs (1978). The computer program defines these relationships by numerically solving Richards equation for vertical unsaturated water movement due to evapotranspiration at the surface. A summary of some of other soil input data as used in DRAINMOD for the Cisne silt loam soil is presented in Table 1.

Crop Input Data

Crop input data to DRAINMOD include the relationship between effective rooting depth and time and the days to initiate and stop SEW and Dry Day computation. The effective root zone depth was assumed to be dependent on time after planting and was taken as that given by the 60 percent curve from the data of Mengel and Barber (1974) as suggested by Skaggs (1982). Since soil moisture will be removed from a shallow surface layer by evaporation even when the land is fallow, therefore an effective root zone depth of 3 cm was assumed for the periods before and after the growing season. The maximum effective root depth for corn in this study was assumed to be 35 cm. The period between April 15 and May 10 was assumed for beginning and ending Julian dates for spring planting, respectively, and was used for SEW and Dry Date computation.

Drainage System and Climatological Input Data

The system input data are the drain spacing, drain depth, effective depth to the impermeable layer and the depth of surface depressional storage. A parallel drain tube for subsurface drainage or subirrigation was assumed. Drains were assumed to be 10.2 cm (4.0 inches) inside-diameter corrugated plastic tubing. Drain spacings varied between 200 and 1500 cm, and the drain depth was assumed to be 60 cm. The effective drain depth to the impermeable layer, a parameter used to account for convergence near the drains was obtained using a computer program developed by Skaggs (1978). The effective depth (d_e), depends on drain depth, spacing and radius.

The depressional storage parameter used to quantify surface drainage is somewhat more difficult to define. Gayle and Skaggs (1978)

quantified surface drainage by means of surface drainage depression storage measurements on several soils of North Carolina. They published a subjective guideline for estimating the surface storage. For this study two levels of surface storage were selected for simulation purposes. These were 3 mm for good surface drainage and 30 mm for poor surface drainage. A summary of these input data for Cisne silt loam soil is presented in Table 3. Hourly precipitation and daily maximum and minimum temperature records are the required input by DRAINMOD. The temperature data is used by the model to calculate the evapotranspiration by Thornthwaite method which derives the element for the equation from the temperature data, latitude, and heat index for the location. Twenty years (1952-1971) of climatological data from Springfield, Illinois, were employed in this study.

Table 3. Summary of drainage input parameters used in simulation for Cisne silt loam soil.

Input Parameter	Program Variable Name	Value
Drain depth	DDRAIN	55.0 cm
Drain spacing	SDRAIN	200,300,400,500,600,700,800,900,1000,1200,1500 cm
Actual depth to impermeable layer	*	60.0 cm
Drain diameter	*	10.0 cm
Effective drain radius, r_e	*	0.51 cm
Surface depression storage	STMAX	3.0 mm, 30.0 mm
Effective depth from drain to impermeable layer	*	depends on drain depth, spacing and radius (Skaggs, 1978)

*These variables are not direct inputs to DRAINMOD, but are used to calculate other input parameters.

RESULTS AND DISCUSSION

Model Performance:

The performance of DRAINMOD was tested by comparing measured and simulated SEW_{30} values for a combination of surface and subsurface drainage treatment. The data collected on a Cisne claypan soil at the Brownstown Agronomy Research Center in Southern Illinois during the 1982 growing season was used to test the model. The research study area consisted of 40 plots, 0.064 ha each. Each plot had one of ten different combinations of irrigation and drainage treatments. The irrigation treatments were sprinkler, furrow, and no irrigation, while the drainage treatments were surface, subsurface, both surface and subsurface, and no drainage. Three lines of corrugated plastic tubing 75 mm in diameter and spaced 6.0 m apart provided the subsurface drainage. Surface drained plots had a slope of 0.5 percent parallel with the long dimension of the plot. Precipitation, temperature and evaporation data for a period of 7 years are available from the research site. During 1982, two observation wells were installed at the center line between the subsurface drains for each of the plots after planting operations. Water table elevation readings were taken in each well on a daily basis during periods of high water table, and SEW_{30} for each drainage treatment was calculated using Equation (4).

The data collected from the Brownstown Research Center were used as input to DRAINMOD to simulate the SEW_{30} values for a combination of surface plus subsurface drainage treatment with no irrigation. A 75-mm tubing diameter with 6.0-m spacing were used for simulation. The impermeable layer was assumed to be at 45-cm (18-in.) depth, as is the case in Brownstown. The saturated hydraulic conductivity and infiltration data used in the simulation were those reported by Lembke et al.

(1984) and the North Central Regional research publication No. 259 (1979) for Cisne Soil Association, respectively. Precipitation and temperature data employed in this simulation were collected from the research site. Surface drainage was simulated by using a depression storage of $S = 3$ mm.

Predicted and measured weekly cumulative SEW_{30} values for 1982 growing season were in excellent agreement (Figure 4) with a coefficient of determination of 0.91. The total measured SEW_{30} values for the 1982 growing season was 24.56-cm day as compared to 27.33-cm day for the simulated ones. Although the comparison shown in Figure 4 is just for one growing season, the close agreement with the experimental results indicate that DRAINMOD is a reliable and useful tool for simulating the effect of drainage system design on water table elevations for claypan soils of the Midwest.

Simulations:

Simulations were conducted for 20 years of climatological data from 1952 to 1971. The performance of conventional drainage, and sub-irrigation systems were evaluated. In subirrigation mode, a weir is placed in the drainage outlet and water is pumped into the drainage system as required to maintain a constant water level.

Various drain spacings and depths combinations for both good and poor surface drainage were simulated. Good surface drainage was simulated by a surface depressional storage of $S = 3$ mm, which can be provided by land-forming or shaping the surface (Skaggs and Nassehzadeh-Tabrizi, 1983). Poor surface drainage represents no improvement from the natural conditions and was simulated by using a surface depressional storage of $S = 30$ mm.

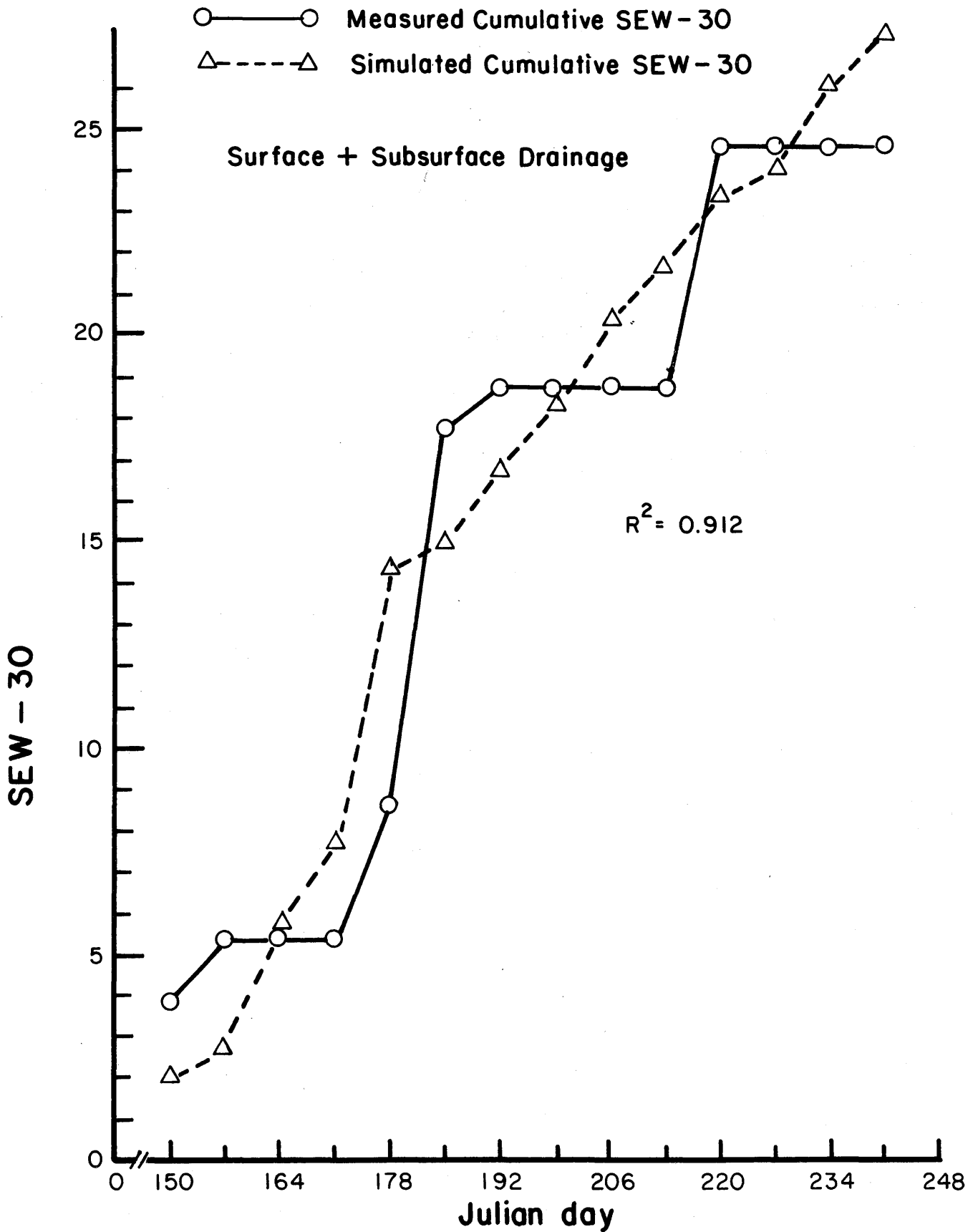


Fig. 4. Simulated and measured weekly cumulative SEW_{30} values for a combination of surface and subsurface drainage treatments during the 1982 growing season.

A design for each system was selected to meet the trafficability and crop protection requirements for continuous corn. It was assumed that 10 working days during the 1 month prior to planting time were required to plant the corn based on a 5-year recurrence interval. The actual length of time required for seedbed preparation depends on several factors such as the size of operation and availability of equipment and labor. A design that gives a 5-year recurrence interval of 100-cm days or less SEW_{30} value was chosen to protect the crop from excess soil water conditions during the growing season.

Effects of Subirrigation on SEW_{30} , Working Days and Dry Days:

The effect of drain spacing and weir depth on the number of working days during the one-month period prior to planting is shown in Figure 5 for a 5-year recurrence interval. Surface drainage had little effect on the number of working days and similar relationships were obtained for both good and poor surface drainage. Any drain spacing up to 8 m would provide the required number of working days (10 or more days) for seedbed preparation, however, other objective functions such as dry day and SEW_{30} will be the dominant factors in determining the optimum weir setting depth.

The results of 20 years simulations conducted to study the effects of weir setting depth during subirrigation of Cisne soil on SEW_{30} values are shown in Figures 6 and 7. Relationships are plotted on a 5-year recurrence interval (5 YRI) for poor ($S = 30$ mm) and good ($S = 3$ mm) surface drainage, respectively. The results show that SEW_{30} is strongly dependent on drain spacing and weir setting depth. These results also indicate the importance of good surface drainage if subirrigation is to

5 YEAR RECURRENCE INTERVAL

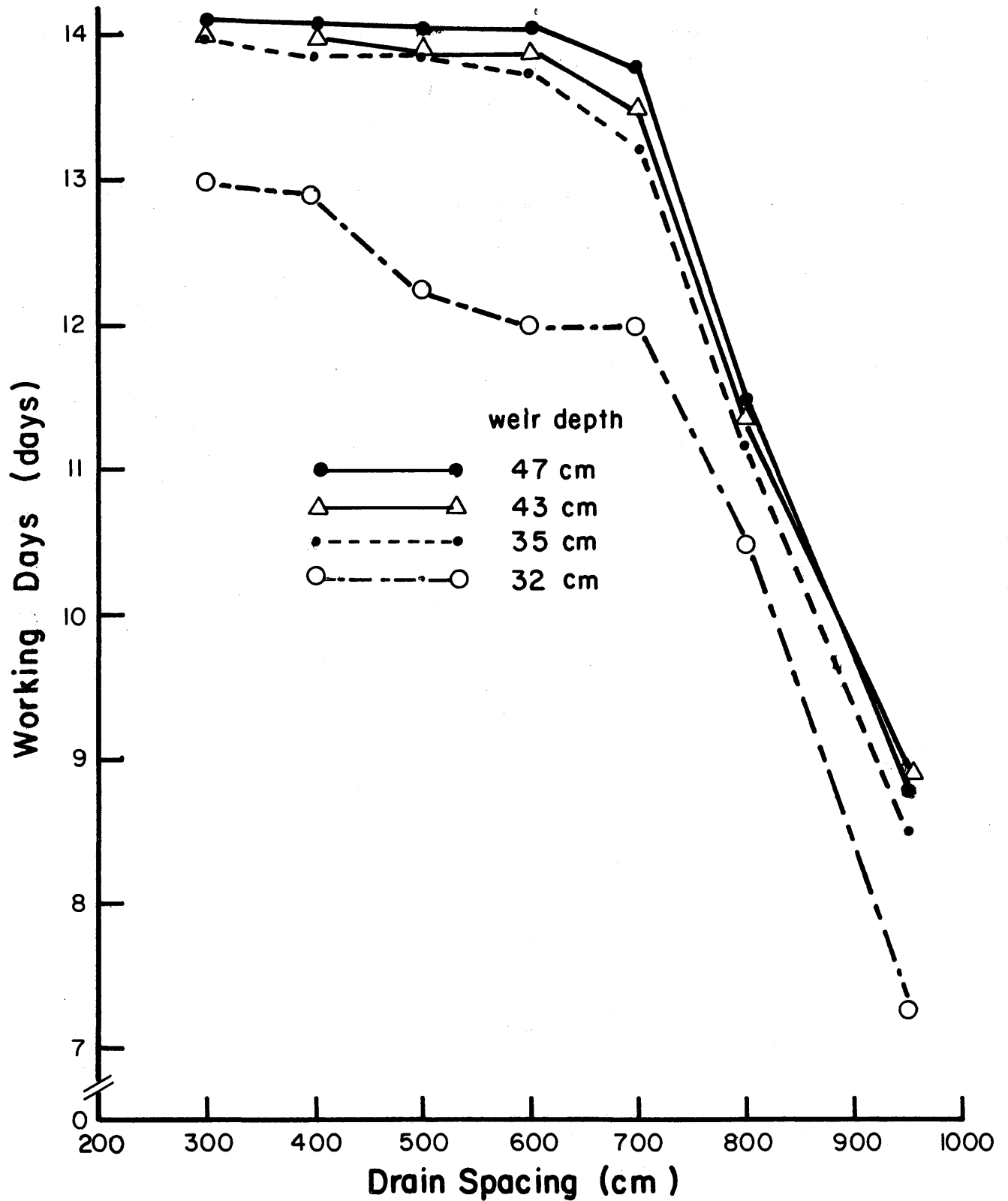


Fig. 5. Working days versus drain spacing for four weir depths on Cisne silt loam soil under subirrigation

5 YEAR RECURRENCE INTERVAL

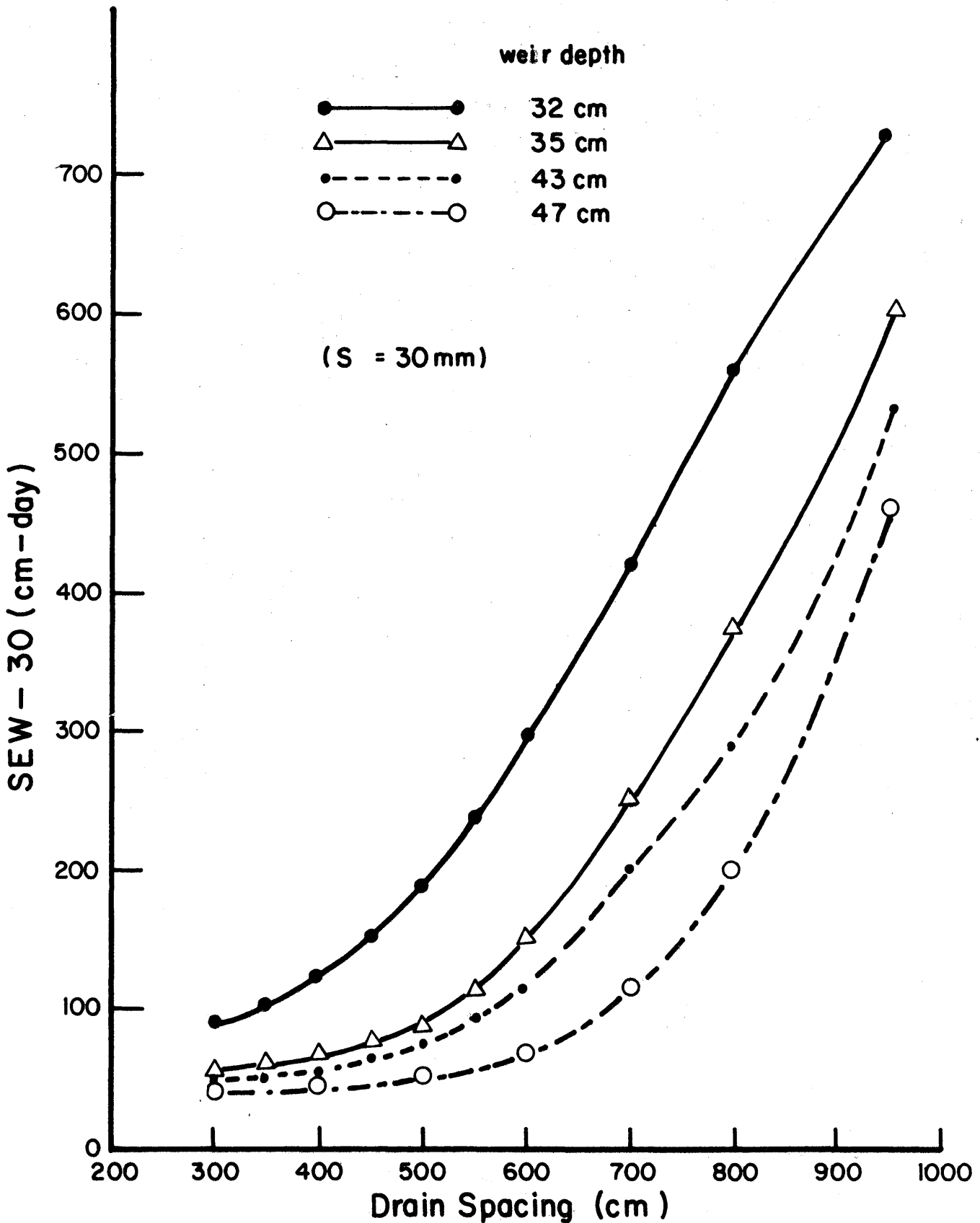


Fig. 6. SEW_{30} versus drain spacing for four weir depths on Cisne silt loam soil with poor surface drainage ($S = 30$ mm) and subirrigation.

5 YEAR RECURRENCE INTERVAL

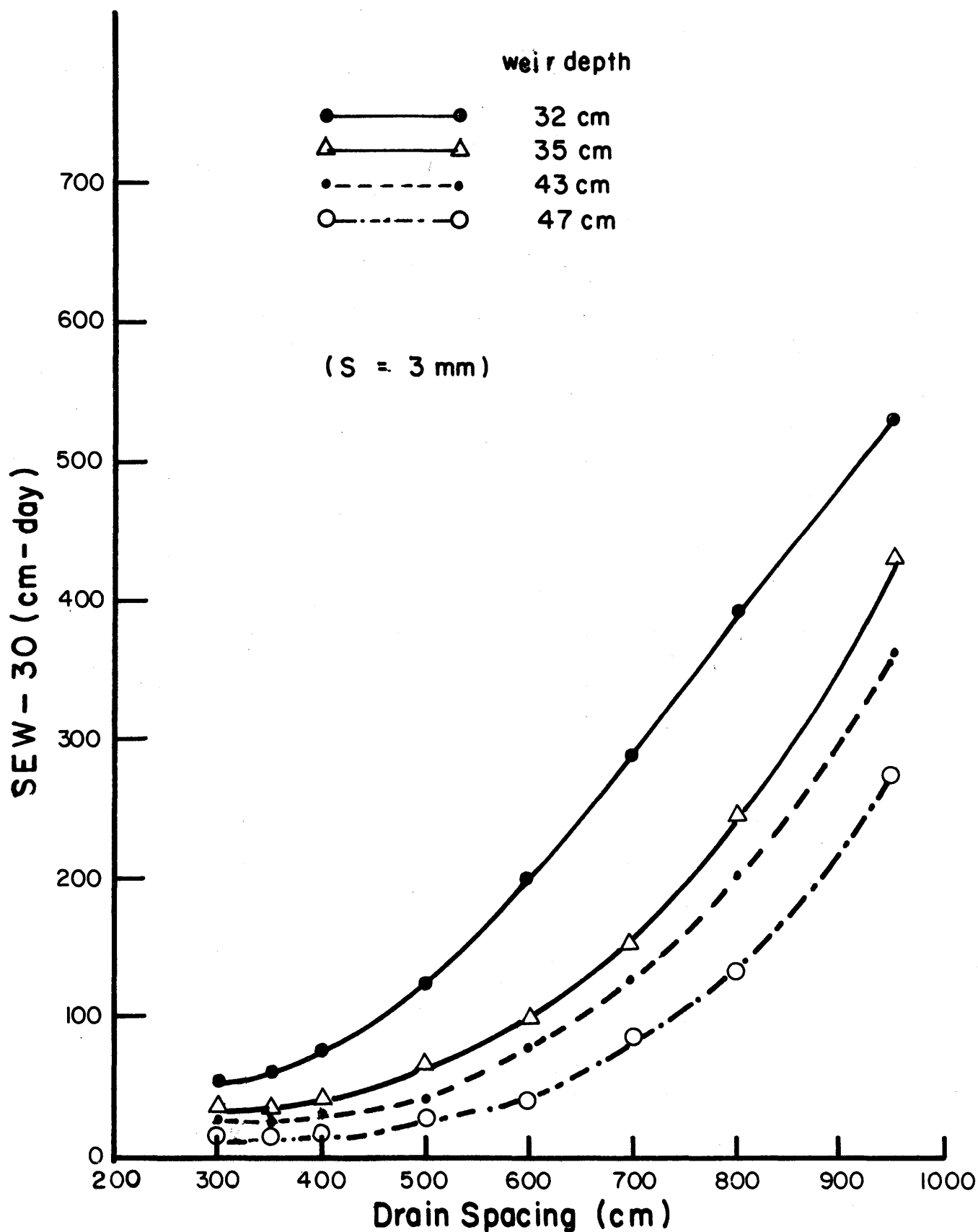


Fig. 7. SEW₃₀ versus drain spacing for four weir depths on Cisne silt loam soil with good surface drainage (S = 3 mm) and subirrigation.

be used. An SEW_{30} value of less than 100-cm days can be obtained with a drain spacing of 6 and 5 m for weir setting depths of 35, 43, and 47 cm with good and poor surface drainage, respectively (Figures 6 and 7). However, the effect of weir setting depth and drain spacing on the number of dry days plotted for a 5-year recurrence interval (Figure 8), indicate that a 6-m spacing would result in about 2 dry days at weir setting depth of 32 and 35 cm and 7 dry days for weir settings at 43- and 47-cm depths. Closer inspection of the simulation results showed that for 6 m spacing, 5 out of 7 dry days under 43- and 47-cm weir depths occurred during the second half of July. This is the period that corn is pollinating and moisture stress has a severe negative effect on crop yield. On the other hand, the detailed analysis of simulation results indicated that the 2 dry days under weir setting depths of 32 and 35 cm occurred immediately after planting when rooting depths were negligible and subirrigation had just been started. Under these circumstances, the 2 dry days appear to be acceptable and, therefore, the optimum drain spacing sufficient for subirrigation on the Cisne soil would be 6 m under good surface drainage, and a weir setting depth of 35 cm on a 5-year recurrence interval basis. This means that 4 years out of 5 or 80 percent of the years suitable conditions would be available for proper subirrigation of corn on a Cisne soil if the drain spacing is 6 m and weir setting depth is 35 cm. This 35-cm weir setting depth at the drainage outlet indicate that the water table depth directly over the drain tubes during subirrigation will be approximately 35 cm, but it will increase with distance away from the drain during the dry periods because of evapotranspiration (Skaggs, 1980). The 35-cm depth was

5 YEAR RECURRENCE INTERVAL

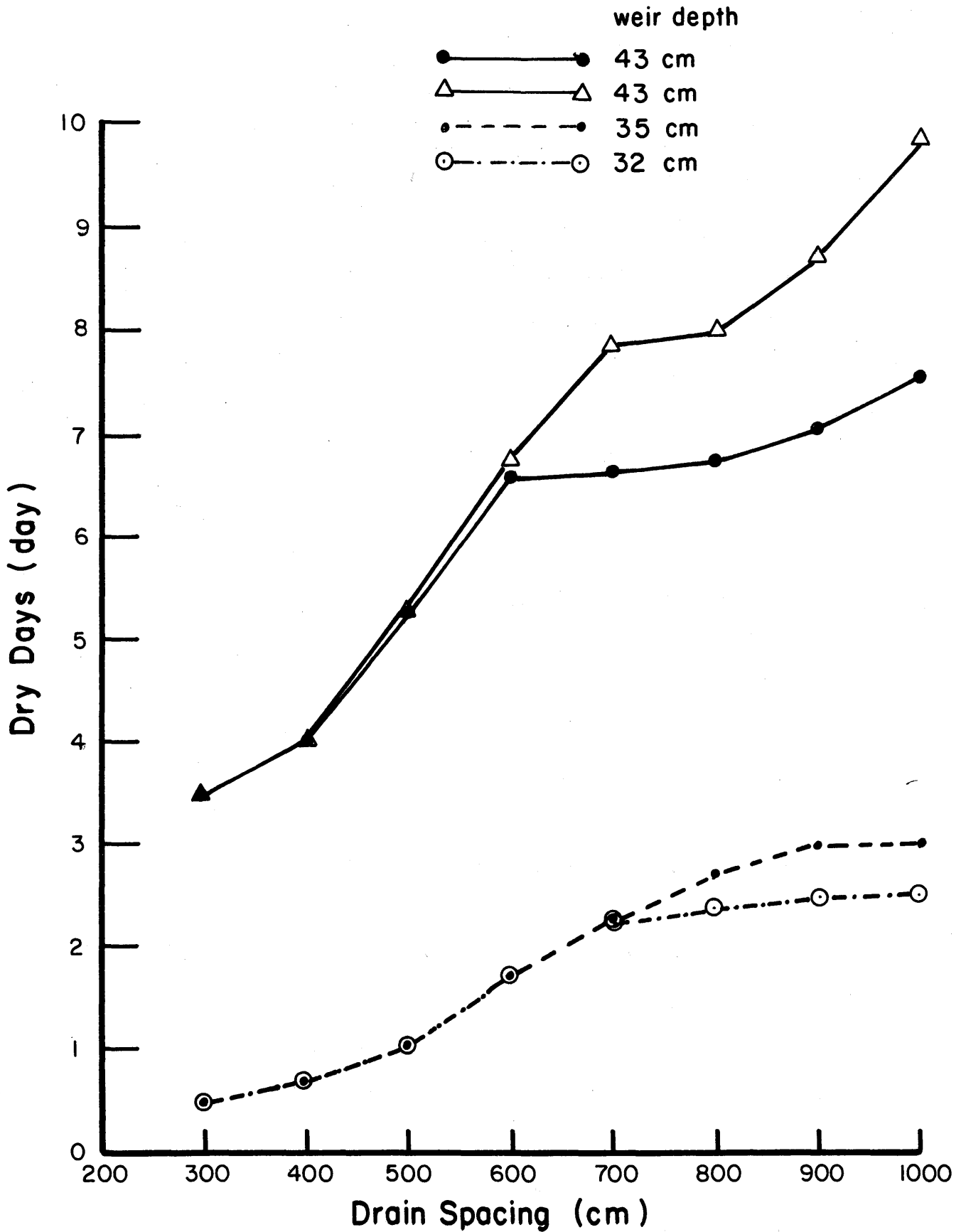


Fig. 8. Dry days versus drain spacing for four weir depths on Cisne silt loam soil under subirrigation.

chosen so that the water table would not be too close to the surface directly over the drain tubes.

To further examine the effects of surface drainage quality on the drainage protection for crop growth, the drain spacing versus SEW_{30} relationships for both poor and good surface drainage under subirrigation with weir setting at 35-cm depth are replotted in Figure 9. One can see that the effect of surface drainage is greater for poor (wider drain spacings) than good subsurface drainage. For example, with a subsurface drain spacing of 6 m, the SEW_{30} value is reduced only by 50-cm days when good surface drainage is practiced, while at 9.5-m spacing the reduction in SEW_{30} value due to good surface drainage is 175-cm days. In other words, having good surface drainage reduces the subsurface drainage requirements. However, this reduction in drain spacing is not of much significance for heavy soils such as Cisne silt loam (Figure 9). As was mentioned earlier, an SEW_{30} value of 100-cm days can be obtained with drain spacing of 5 m for poor surface drainage and 6 m for good surface drainage. This means a reduction of about 15 percent in tubing and installation costs when good surface drainage is practiced. However, the total cost of the alternatives should be compared and other factors such as compatibility with the farming operation be considered before a final decision is made. When surface drainage is poor during high rainfall, water may be stored on the surfaces and cause flooding conditions and it can only be removed either by evaporation or subsurface drainage. Because of the very slow permeability of Cisne silt loam soil, it might take quite some time to remove the surface water by subsurface drainage. Therefore, it is very important that a reasonable combination of good surface and subsurface drainage be used on these types of soil.

5 YEAR RECURRENCE INTERVAL

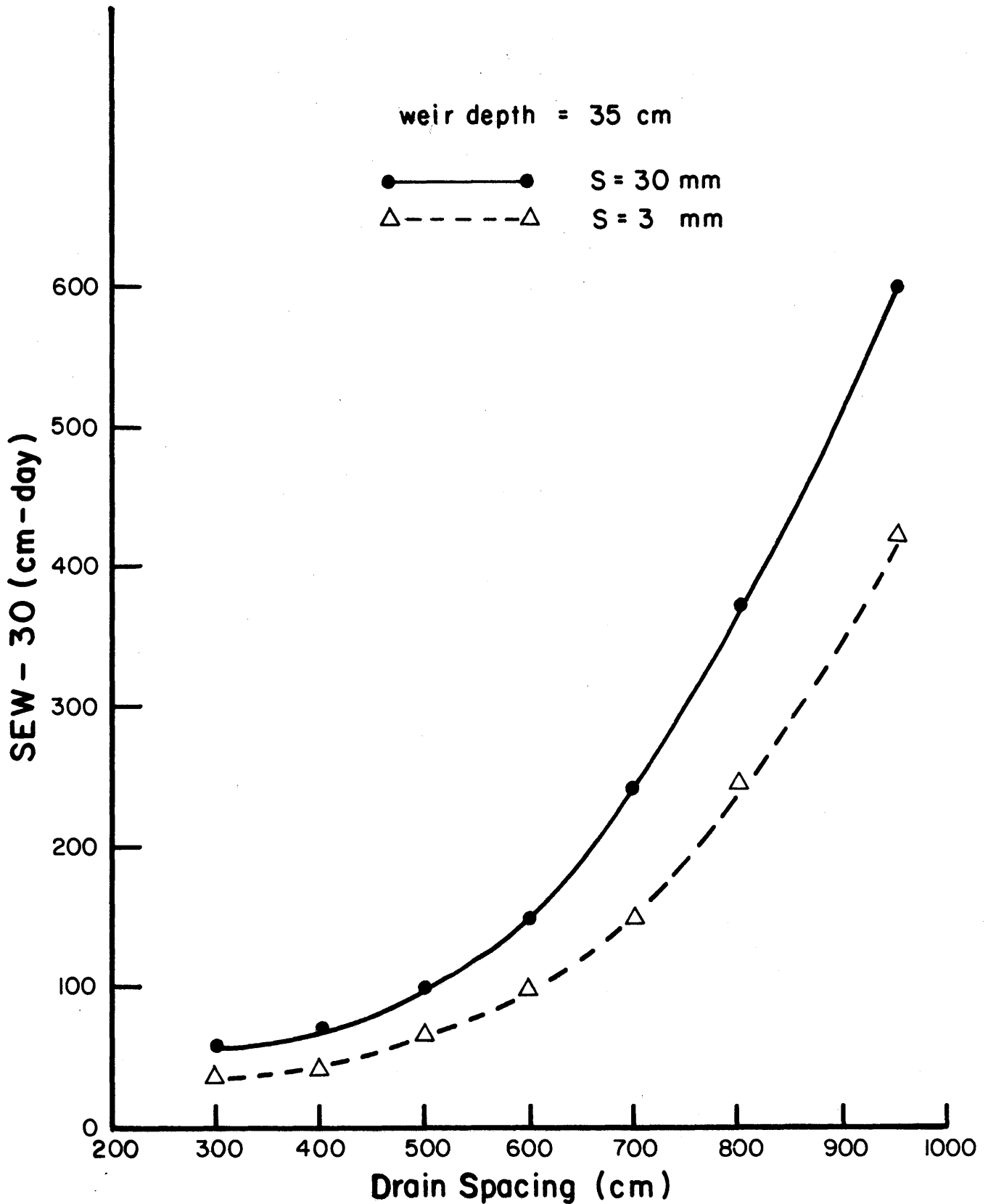


Fig. 9. SEW₃₀ versus drain spacing for both good (S = 3 mm) and poor (S = 30 mm) surface drainage with subirrigation control weir located at 35-cm depth.

5 YEAR RECURRENCE INTERVAL

Depth to Impermeable Layer

- 50 cm
- 60 cm
- △— 75 cm

weir depth = 35 cm
($S = 3 \text{ mm}$)

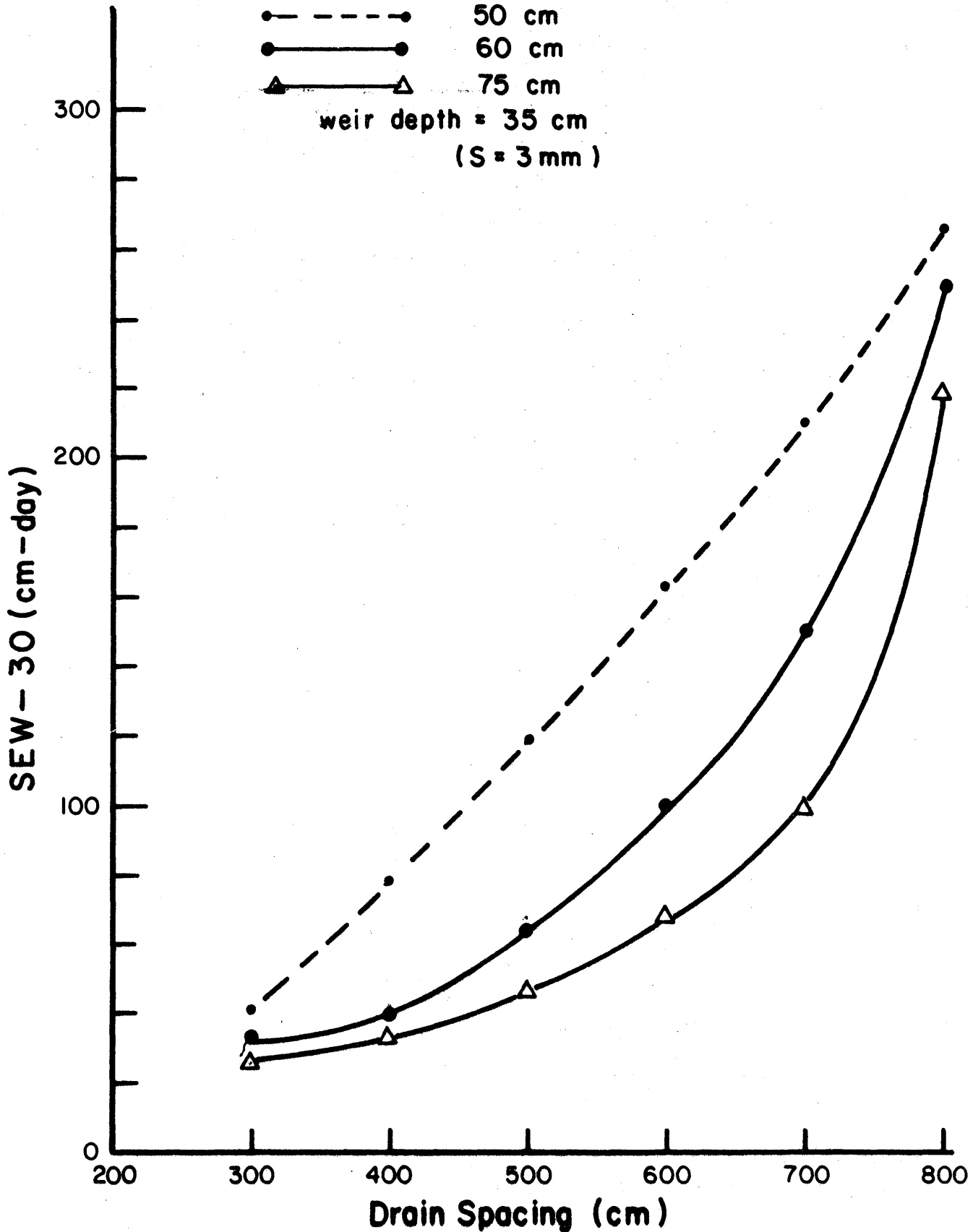


Fig. 10. The effect of depth to the impermeable layer on SEW_{30} for good surface drainage ($S = 3 \text{ mm}$) and subirrigation with an assumed drain depth of 35 cm.

Our results indicate that the limiting factor on drain spacing for a combined drainage-subirrigation system on Cisne claypan soil is the drainage rather than irrigation requirement. For instance, a drain spacing of 9.5 m and a weir depth of 35 cm would result in less than 3 dry days which would satisfy the irrigation requirement (Figure 8). However, this drain spacing of 9.5 m would give an SEW_{30} value of 425-cm days which would be unacceptable from the crop protection aspect (Figure 9). These results are compatible with those reported by Skaggs (1981) for subirrigation of a sandy loam soil in North Carolina conditions.

All of our results presented were based on an assumed depth to the impermeable layer of 60 cm and depth to the center of drain of 55 cm. One possibility for increasing the drain spacing for subirrigation is to increase the drain depth. However, the drain depth may be limited by the depth of impermeable layer as is the case for claypan soils. The depth to the impermeable layer of claypan soils of Midwest varies between 30 to 75 cm, depending on their location. Simulations were run to study the effects of depth to the impermeable layer of a Cisne soil on the drain spacing for subirrigation. The effect of drain spacing on SEW_{30} at various depths to the impermeable layer is shown in Figure 10. It is assumed that drains are located on the impermeable layer and that good surface drainage exists. Thus, the depth to the center of a 4-inch tile would be 45, 55, and 70 cm for depths to the impermeable layer of 50, 60, and 75 cm, respectively. By placing the drains at a depth of 70 cm, rather than 45 cm, the drain spacing could be increased from 4.5 to 7 m for good surface drainage, an increase of about 55 percent in spacing. This alternative would also be satisfactory from the trafficability aspect (Figure 11), since it would provide 13 or more working

5 YEAR RECURRENCE INTERVAL

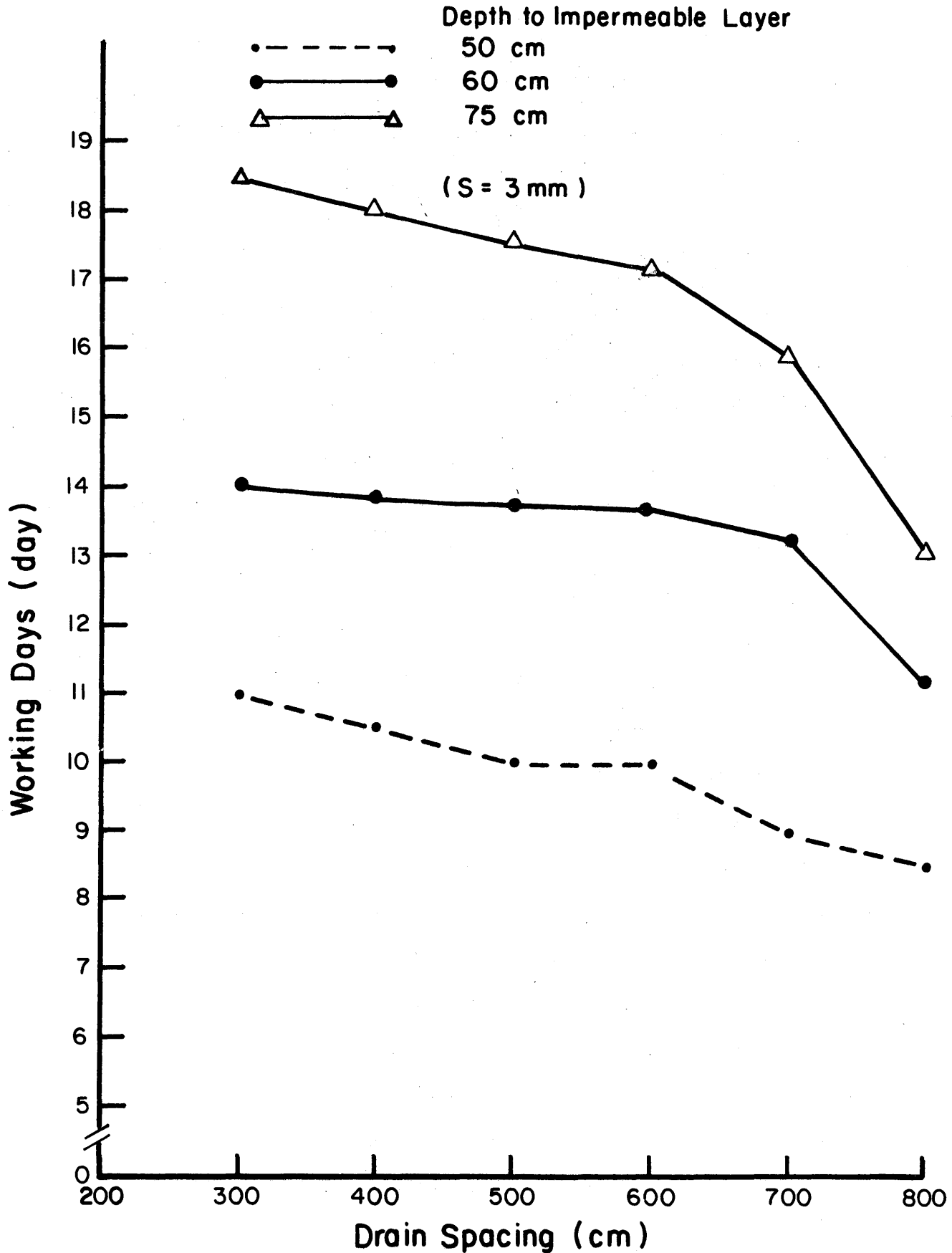


Fig. 11. The effect of depth to the impermeable layer on working days for good surface drainage and subirrigation with an assumed weir depth of 35 cm.

days on a 5-year recurrence interval basis. The results presented in Figure 11 also indicate that trafficability during seedbed preparation is heavily dependent on drain spacing and drain depth. As drain spacing and depth increases, more working days would be available for seedbed preparation and planting. Increasing the drain depth from 45 cm to 70 cm has little effect on the number of dry days during the growing season (Figure 12) and less than 4 dry days would result during the growing seasons of 4 out of every 5 years. It should be emphasized that the depth to the impermeable layer of claypan soils is a limiting factor on drain depth and it is not always practical to install the drain at the desired depth.

The results of a 5-year study on irrigation and drainage of corn by Walker et al. (1982) on Cisne claypan soil indicated average corn yield increase of 0.8 and 2.4 t/ha due to drainage and irrigation, respectively. The interactive effect of irrigation and drainage produced an average yield increase of 4.8 t/ha. Their results support the necessity of both drainage and irrigation practice on these soils. If feasible, subirrigation which provides both drainage and irrigation could be an appropriate water management system for claypan soils. However, a 6-m spacing between the drains is probably not an economical practice for grain crops and our results indicate that wider drain spacings would not be practical for subirrigation mainly because of the restricted lateral water distribution in claypan soils. These findings are in agreement with those reported by Rausch and Nelson (1984) on subirrigation of claypan soils in Missouri. After one year of field experimenting with subirrigation of alfalfa on a claypan soil, they concluded that water distribution was a serious problem and that more

5 YEAR RECURRENCE INTERVAL

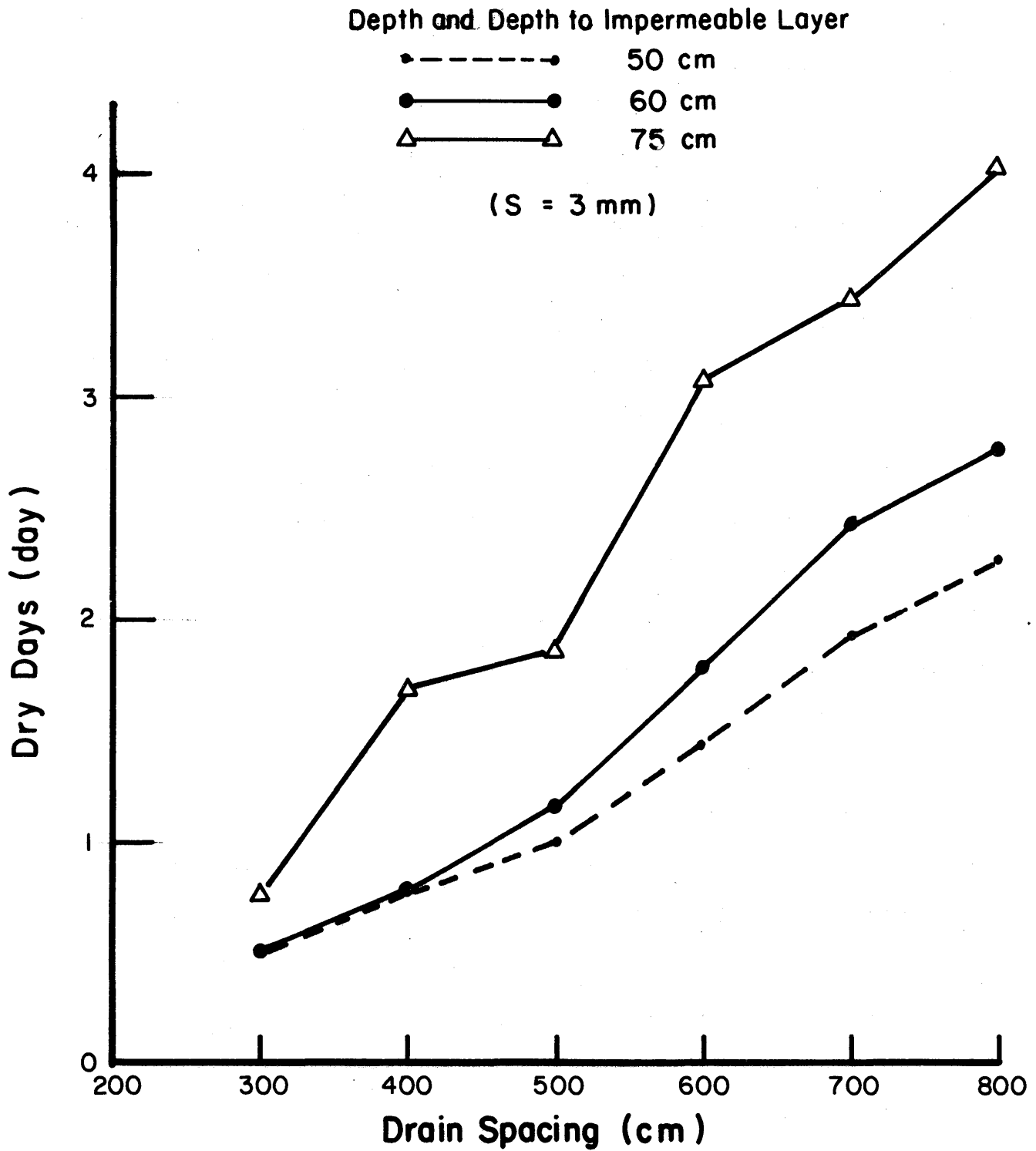


Fig. 12. The effect of depth to the impermeable layer on dry days, for good surface drainage and subirrigation with an assumed weir depth of 35 cm.

research is needed to improve the horizontal movement of subirrigation water in claypan soils.

Effect of Combined Surface and Subsurface Drainage on SEW₃₀ Working Days and Dry Days:

The current recommendation for drainage practice on Cisne claypan soils is surface drainage, but surface drainage systems have not been very satisfactory because land grading removes the topsoil from some areas of the field and reduces its productivity (Walker et al., 1982). Simulations were run to identify alternatives of surface and subsurface drainage system that would satisfy trafficability and crop protection requirements. In these simulations, it was assumed that the depth to the center of the subsurface drain was 55 cm and the drain was rested on the impermeable layer.

The effect of drain spacing on the number of working days available for seed preparation and planting is shown in Figure 13. Results for both good and poor surface drainage are plotted on a 5-year recurrence interval basis. The effect of surface drainage on the number of working days depends on the quality of subsurface drainage. At very close drain spacings (less than 4 m), there are no significant differences in the number of available working days. However, as the drain spacing increases the effect of surface drainage becomes more pronounced (Figure 13), and more working days are available with good surface drainage. However, trafficability has a stronger dependency on subsurface drainage than surface drainage on these soils. For instance,

5 YEAR RECURRENCE INTERVAL

●—● S = 3 mm
△- - -△ S = 30 mm

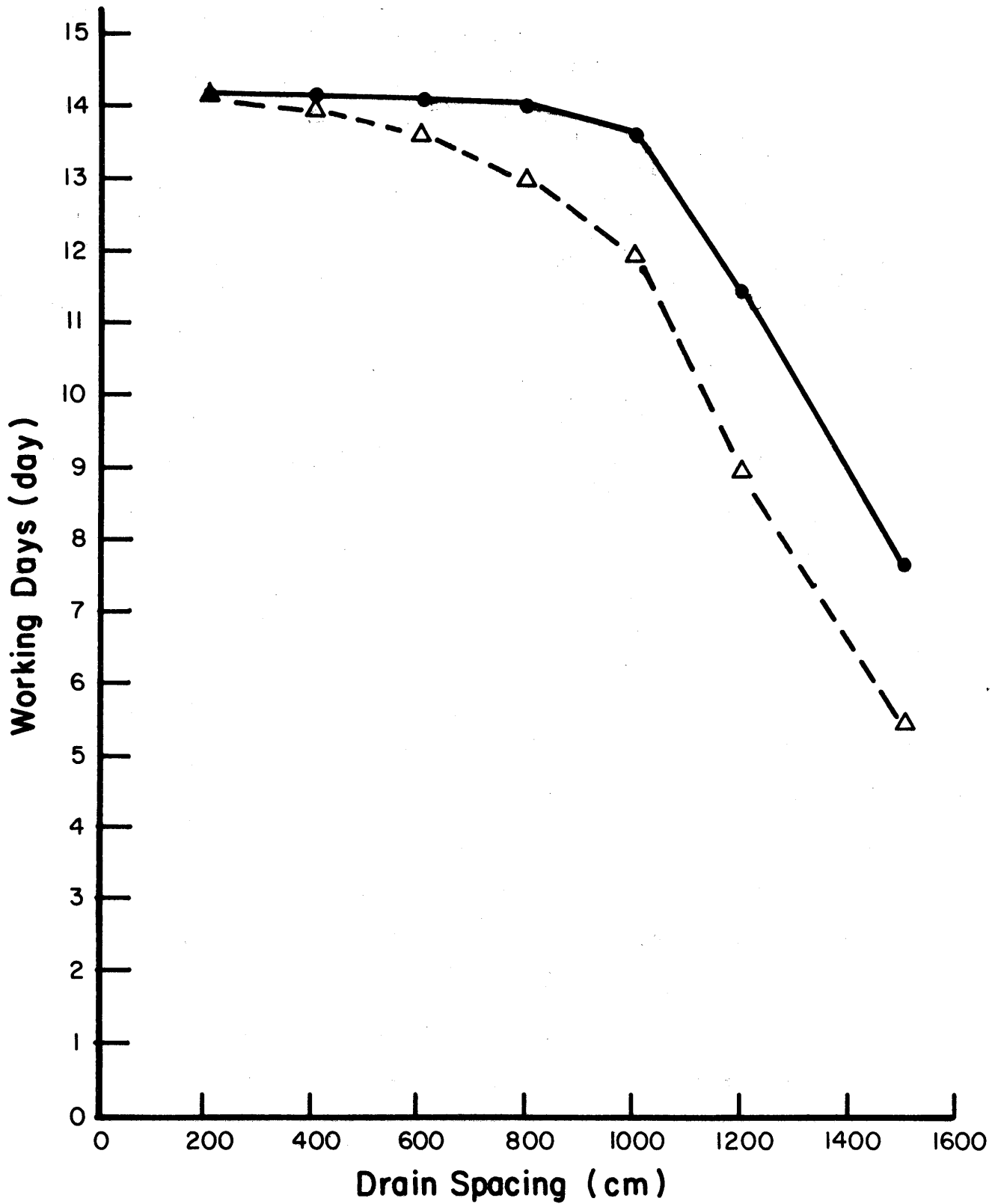


Fig. 13. Working days versus drain spacing for both good ($S = 3$ mm) and poor ($S = 30$ mm) surface drainage and conventional sub-surface drainage.

the difference in the number of working days between good and poor surface drainage is 2.5 days at best, whereas, increasing the subsurface drain spacing from 2 to 15 m would result in a decrease of about 8.5 and 6.5 days in the number of available working days for poor and good surface drainage, respectively. The results presented in Figure 13 also indicate that surface drainage has a relatively small effect on the subsurface drain spacing required to insure a given number of working days on a 5-year recurrence interval basis.

The relationships between SEW_{30} and drain spacing for both good and poor surface drainage are plotted in Figure 14. Drain spacings of 10 m and 12 m would result in the required crop protection ($SEW_{30} < 100$ -cm days) for poor and good surface drainage, respectively. Both of these combinations would provide 10 or more working days for seedbed preparation and planting (Figure 13). Again subsurface drainage has a much greater effect than surface drainage on the value of SEW_{30} . The effect of surface drainage quality on SEW_{30} is more pronounced at wider drain spacings (Figure 14).

The effect of drain spacing on the number of dry days is shown in Figure 15. The quality of surface drainage had no apparent effect on the number of dry days. In DRAINMOD, a dry day is defined as a day in which the crop is under stress. That is evapotranspiration is limited by soil water conditions. These results indicate that on the average, 4 out of every 5 years we should expect to have 8 or fewer dry days during the growing season for any drain spacing of 15 m or less. Further examination of the simulation results showed that 6 of these 8 dry days occur during the second half of July and first week of August, a period during which the corn crop is most susceptible to moisture stress in Midwest.

5 YEAR RECURRENCE INTERVAL

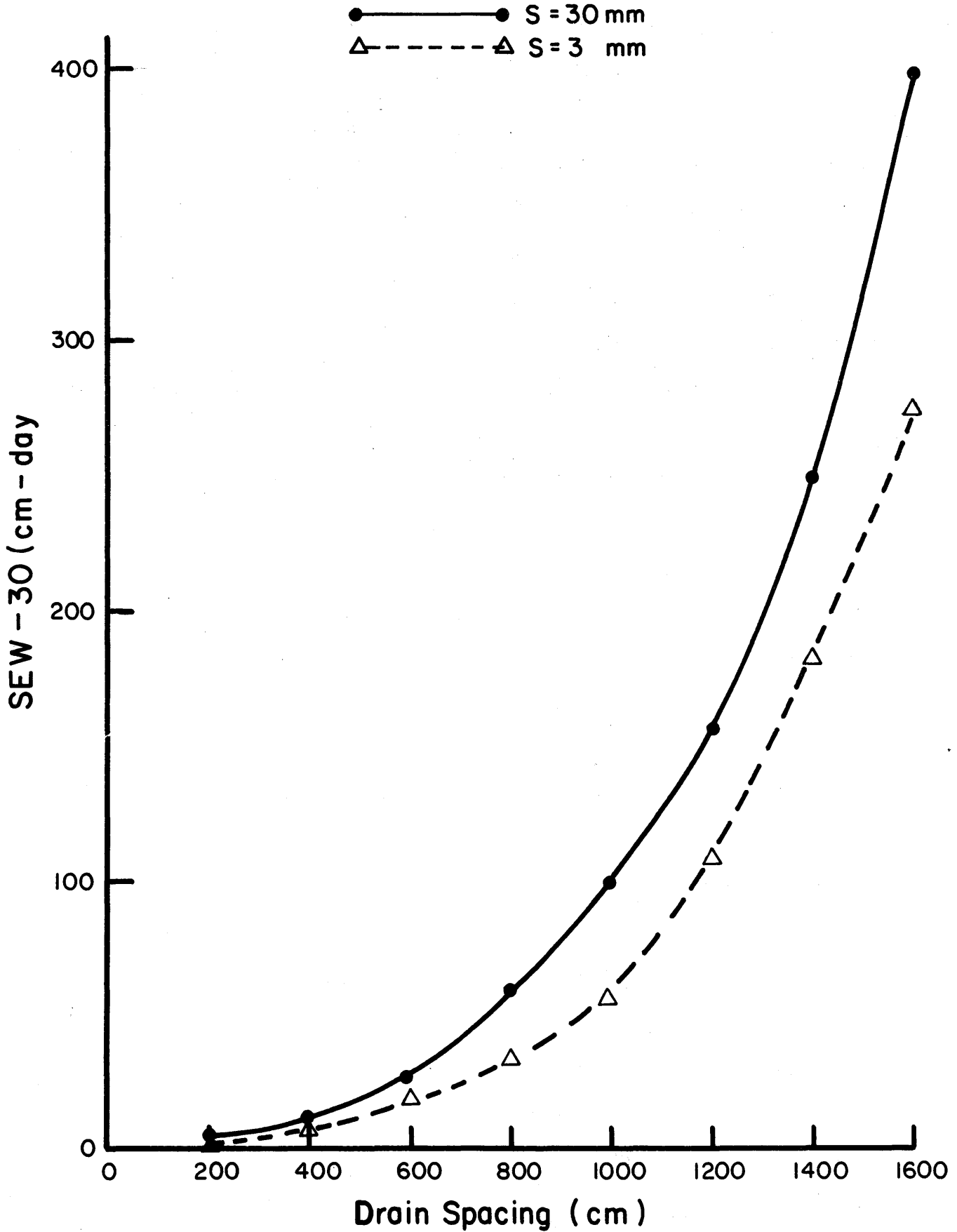


Fig. 14. SEW_{30} versus drain spacing for both good ($S = 3$ mm) and poor ($S = 30$ mm) surface drainage and conventional subsurface drainage.

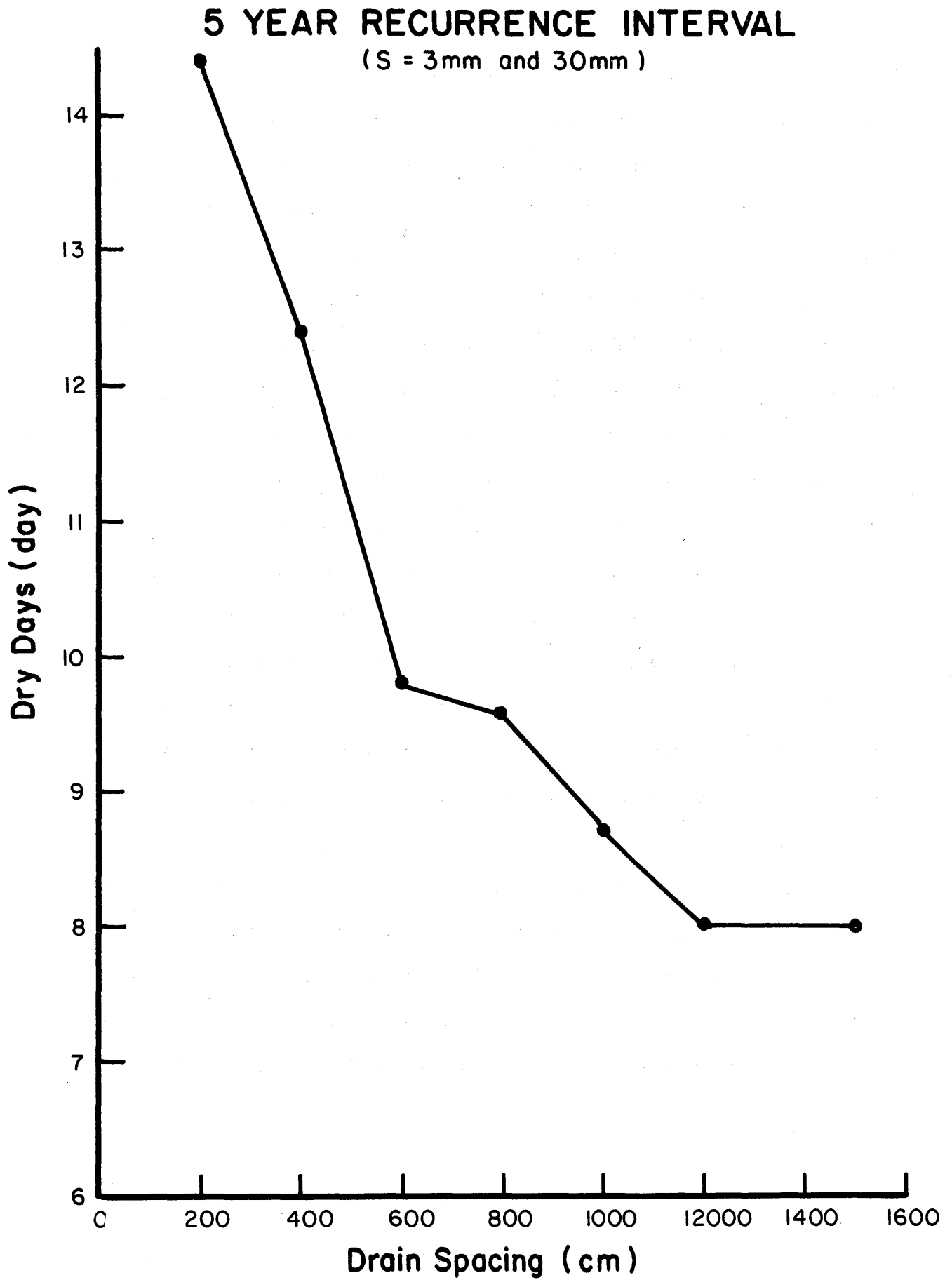


Fig. 15. Dry days versus drain spacing for both good (S = 3 mm) and poor (S = 30 mm) surface drainage and conventional sub-surface drainage.

It should be pointed out that all of these results are based on an assumed maximum rooting depth of 35 cm. One method for decreasing the number of dry days under conventional drainage would be to increase the crop root depth (Skaggs, 1981). In claypan soils, root depths are mostly limited by the hard claypan and it has been reported that high fertility level will encourage deeper root growth on claypan soils (Fehrenbacher et al., 1969). In some cases, root depths are limited by high water table which prunes back deeper roots. Thus, improving the rooting depth in this case, is a matter of providing good drainage and selecting a crop variety which has deeper rooting characteristics (Skaggs, 1978). For example for the conditions of Cisne claypan soils, increasing the rooting depth from 35 cm to 50 cm reduced the number of dry days from 8 to 2 (results not shown). However, it should be emphasized that the removal of a physical barrier like the claypan by deep chisel plowing might not be possible and/or feasible. It appears that supplemental irrigation is required for proper soil and water management of crop production on these soils. As indicated earlier, our results indicate that a 6-m drain spacing is required for a subirrigation system to function properly on claypan soils. Such a close drain spacing could not be economically feasible. Therefore other alternatives such as surface irrigation or improved fertility management practices along with a proper drainage system should be considered and the least cost alternative that would provide proper water management for claypan soils be selected.

SUMMARY AND CONCLUSIONS

There are about 4 million hectares of claypan soils in the Midwest. These soils have a 30- to 75-cm layer of silt loam topsoil with a heavy clay subsoil that is very slowly permeable and severely limits root development and water penetration. The crop yields on these soils are usually low because of limited water management. Subirrigation systems are designed to provide total water management for crop production. Climate, topography, subsoil characteristics, and high water table associated with the claypan soils are particularly adaptable to subirrigation. This was a study to evaluate the suitability of subirrigation along with alternative soil and water management practices on claypan soils.

A water table management simulation model, DRAINMOD, was used for this study. Simulations were run on 20 years of climatological data and several years of crop, soil, and weather data collected on a claypan soil in Illinois. The performance of subirrigation and conventional drainage systems were evaluated. Various weir setting depths and drain spacings, and depths combinations for both good and poor quality surface drainage were simulated. A design for each system was selected to meet the trafficability and crop protection requirements for continuous corn production.

The following conclusions were drawn from this study:

1. Surface drainage had a nonsignificant effect on the number of trafficable days in the field and similar results were obtained for both good and poor quality surface drainage with subirrigation practice.
2. SEW₃₀ value, the sum of excess water table rises above 30-cm depth was strongly dependent on drain spacing and weir setting depth. The

results also emphasize the importance of good surface drainage if subirrigation is to be practiced.

3. The optimum drain spacing sufficient for subirrigation on the Cisne claypan soil would be 6 m under good surface drainage and a weir setting depth of 35 cm on a 5-year recurrence interval basis. This means that 4 out of 5 years or 80 percent of the years suitable conditions would be available for proper subirrigation of corn crops.
4. Under subirrigation, the effect of surface drainage is greater for poor (wider drain spacing) than good subsurface drainage. In other words, having good surface drainage reduces the subsurface drainage requirements.
5. The limiting factor on drain spacing for a combined drainage-subirrigation system on Cisne claypan soil is the drainage rather than irrigation requirement.
6. One possibility for increasing the drain spacing, thereby reducing the cost for subirrigation is to increase the drain depth. By placing the drains at a depth of 70 cm, rather than 45 cm, an increase of about 55 percent in spacing can be resulted. As drain spacing and depth increases, more trafficable days would be available for seedbed preparation and planting. However, it should be emphasized that the depth to the impermeable layer of claypan soils is a limiting factor on drain depth and it is not always practical to install the drain at the desired depth.
7. Detailed analyses of the occurrence of the number of dry days during a growing season using 20 years of climatological data suggests that supplemental irrigation is required for proper water management and

crop production on claypan soils in the Midwest. Our results indicate that a 6-m drain spacing is needed for a subirrigation system to function properly on claypan soils. Such a close drain spacing may not be an economical practice for grain crops and wider drain spacings would not be practical for subirrigation mainly because of the restricted lateral water distribution in claypan soils. Therefore, other alternatives such as surface irrigation and improved fertility management practices along with a proper drainage system should be considered and the least cost alternative be selected.

REFERENCES

- Bouwer, H. 1969. Infiltration of water into nonuniform soil. J. Irrigation and Drainage Division, ASCE, 95(IR4):452-462.
- Bouwer, H., and J. Van Schilfgaarde. 1983. Simplified method of predicting fall of water table in drained land. Transactions of the ASAE 6(4):288-291.
- Bryan, B. B., and Baker, J. 1964. Small diameter plastic pipe for use in subirrigation. Arkansas Farm Research XIII:(6), Nov.-Dec. 1964.
- Chieng, S. T., R. S. Broughton, and N. Foroud. 1978. Drainage rates and water table depth. Journal of Irrigation and Drainage Division of the ASCE, 104(IR4):413-433.
- Childs, E. C., and M. Bybordi. 1969. The vertical movement of water in stratified porous material-1. Infiltration. Water Resources Res. 5(2):446-459.
- Cole, T. E. 1971. Subsurface and trickle irrigation. A survey of potentials and problems. ORNL-NDIG g; US-80-Reactor Technology, Oak Ridge National Laboratory, Oak Ridge, TN, 68p.
- Criddle, W. D., and C. Kalisvaart. 1967. Subirrigation systems. In Irrigation of Agricultural Lands. Agronomy Monograph 11:905-921. American Society of Agronomy, Madison, Wisconsin.
- Doty, C. W., T. S. Currin, and R. E. McLin. 1975. Controlled subsurface drainage for Coastal Plain soil. J. Soil & Water Conserv., Soil Conserv. Soc. Am. 30(2):82-84.
- Eldin, F. E. 1970. Progress report on mechanical subsoil irrigation. Arizona State University, 197p.
- Ernst, L. F. 1975. Formulae for groundwater flow in areas with subirrigation by means of open conduits with a raised water level. Mixc. Reprint 178, Institute for Land and Water Management Research, Wageningen, The Netherlands. 32p.
- Fehrenbacher, J. B., G. W. Ray, and J. D. Alexander. 1969. How soils affect root growth. Crops and Soils. January:14-18.
- Follett, R. F., E. J. Doering, G. A. Reichman and L. C. Benz. 1974. Effect of irrigation and water table depth on corn yields. Agron. J. 66:304-308.
- Gayle, G. A., and R. W. Skaggs. 1978. Surface storage on bedded cultivated lands. Transactions of the ASAE 21(1):102-104, 109.
- Goetsch, W. D. 1981. Field study and simulation model of moisture and corn yield on an Illinois claypan soil. M.S. Thesis, Department of Agricultural Engineering, University of Illinois, Urbana.

- Green, W. H., and G. A. Ampt. 1911. Studies on soil physics. In Van Schilfgaarde, J. (Ed.) Drainage for Agriculture, Agronomy Monograph 17:67-69. American Society of Agronomy, Madison, Wisconsin.
- Hoskyn, J. P. and B. B. Bryan. 1969. Subsurface irrigation research in Arkansas. Water Resources Research Center. Publication No. 3, University of Arkansas, Fayetteville, 28p.
- Lambert, J. R., C. W. Doty, and V. L. Quisenberry. 1981. Irrigation scheduling in humid areas. In Irrigation Scheduling for Water and Energy Conservation in the 80's. ASAE Publication 23-81. Proceedings of the ASAE Irrigation Scheduling Conference. American Society of Agricultural Engineers, St. Joseph, Michigan, p. 132-143.
- Lembke, W. D., J. G. Arnold, and J. G. Cherry. 1984. Field evaluation of subsurface drainage. Final report to USDA-SCS, under the Contract No. 53-6526-1-667. 31p.
- Massey, F. C., R. W. Skaggs, and R. E. Sneed. 1983. Energy and water requirements for subirrigation vs. sprinkler irrigation. Transactions of the ASAE 26(1):126-133.
- Mengel, D. B., and S. A. Barber. 1974. Development and distribution of the corn root system under field conditions. Agronomy J. 66:341-344.
- North Central Regional Research Publication 259. 1979. Water infiltration into representative soils of the North Central Region. Illinois Agricultural Experiment Station. 26 p.
- Rausch, D. L. and C. J. Nelson. 1984. Drainage and subirrigation of a claypan soil. USDA-ARS Watershed Research Unit, Columbia, Missouri. Unpublished report. 17 p.
- Sepaskhah, A. R., S. A. Sichani, and B. Bahrani. 1976. Subsurface and furrow irrigation evaluation for bean production. Transactions of the ASAE 19(6):1089-1092, 1097.
- Sieben, W. H. 1964. Literature translated in Drainage for Agriculture, Edited by J. Van Schilfgaarde and published by American Soc. of Agron., 1974, 70p.
- Skaggs, R. W. 1976. Determination of the hydraulic conductivity-drainable porosity ratio from water table measurements. Transactions of the ASAE 19(1):73-80, 84.
- Skaggs, R. W. 1977. Evaluation of drainage-water table control systems using a water management model. Proc. Third Nat. Drain. Symp., ASAE 1(77):61-68.
- Skaggs, R. W. 1978. A water management model for shallow water table soils. Report No. 134, Water Resources Research Institute of the University of North Carolina, North Carolina State Univ., Raleigh, 178p.

- Skaggs, R. W. 1980. A water management model for artificially drained soils. Tech. Bull. No. 267. North Carolina Agricultural Research Service, North Carolina State Univ., Raleigh, 54 p.
- Skaggs, R. W. 1982. Field evaluation of a water management simulation model. Transactions of the ASAE 25(3):666-674.
- Skaggs, R. W., and A. Nassehzadeh-Tabrizi. 1983. Optimum drainage for corn production. Tech. Bull. No. 274. North Carolina Agricultural Research Service, North Carolina State Univ., Raleigh, 41p.
- Thorntwaite, C. W. 1948. An approach toward a rational classification of climate. Geog. Rev. 38:55-94.
- Walker, P. N., M. D. Thorne, E. C. Benham, and S. K. Sipp. 1982. Yield response of corn and soybeans to irrigation and drainage on a claypan soil. Transactions of the ASAE 25(6):1617-1621.
- Zetzsche, J. B. 1964. Evaluation of subirrigation with plastic pipe. ASAE Paper No. 64-731. ASAE, St. Joseph, Michigan.