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TO: WHOM IT MAY CONCERN

FROM: David H. Howells, Director

SUBJECT: Institute Report No. 67--"Water Table Control and Subsurface Irrigation in Mineral and High Organic Coastal Plain Soils"--by Dr. R. Wayne Skaggs and Dr. George J. Kriz, Department of Biological and Agricultural Engineering, North Carolina State University

The attached report presents the results of a field study to determine the feasibility of combined subirrigation-drainage systems on soils with shallow natural water tables. This includes measurements of water table response to subirrigation, drainage, rainfall infiltration, and evapotranspiration and provides data for the design of subirrigation-drainage systems. Recommendations include the steps necessary to apply the procedures developed through the study.

Persons interested in irrigation and drainage in the Coastal Plain will find this report both informative and useful.

DHH:va

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WATER TABLE CONTROL AND SUBSURFACE IRRIGATION IN MINERAL AND HIGH ORGANIC COASTAL PLAIN SOILS

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ABSTRACT

There are approximately 3,000,000 acres of mineral and high organic soils in the Lower Coastal Plain of North Carolina. These soils are common along the southeastern coast from Maryland to Florida and have the following characteristics: flat slopes (less than 2%), shallow water tables, and are usually poorly drained. The soils are generally unsuited for crop production without artificial drainage. Also if the organic soils are adequately drained, there is the danger of subsidence and destruction by fire.

Although this area in North Carolina receives an average of 49 in. of rainfall per year, droughty periods occur and irrigation is necessary, particularly for high valued crops. By practicing good water management excess rainfall can be stored in the subsoil and canals and be reapplied in time of drought. Few criteria, however, are available concerning water management for this area. The purpose of this project was to determine whether water management using subsurface drains is feasible.

Field experiments were conducted at three sites to measure the water table response to subirrigation, drainage, rainfall infiltration, and evapotranspiration. The water table response to drain tube subirrigation and drainage was determined for three drain spacings on a Lumbee sandy loam soil. Results showed that water could be supplied to the root zone at a rate more than sufficient to satisfy plant needs for the 7.5 and 15 m but not the 30 m drain spacings. Theoretical calculations showed that the suggested water table depth range of 60 to 90 cm could be maintained in this soil with a drain spacing of 19.2 m.

An equation derived to determine the upward movement of the water table during subirrigation can be used to accurately predict the water table rise midway between the drain lines except for an initial lag period.

Four theoretical equations were used to calculate drain spacings using water table drawdown rates measured in the field experiments. When the hydraulic conductivity is determined from soil cores or other independent measurements, the order of preference of the four equations is Bouwer and van Schilfgaarde, van Schilfgaarde, Glover, and Hammad. However, if an effective hydraulic conductivity is determined from water table drawdown measurements, the Hammad equation gives the most accurate prediction of the drain spacing. Much greater accuracy can be obtained in all of the above equations by evaluating the drainable porosity based on the initial and final water table depths rather than using a constant value.

Based on continuous water table records it was concluded that a reliable water source is necessary for all subirrigation systems. Also subirrigation systems need to be designed such that adequate drainage is provided because rainfall infiltration results in a significant rise in the water table.

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SUMMARY AND CONCLUSIONS

Field experiments were conducted on three soils to determine the feasibility of combined subirrigation-drainage systems on soils with shallow natural water tables. Measurements of water table response to subirrigation, drainage, rainfall infiltration, and evapotranspiration conditions are presented and discussed. The results of these experiments have provided data and other information which are essential to the objective design of subirrigation-drainage systems for shallow water table soils in eastern North Carolina.

The water table response to drain line subirrigation and drainage was determined for three drain spacings on a Lumbee sandy loam soil. The results showed that water could be supplied to the root zone at a rate more than sufficient to satisfy plant needs for 7.5 and 15 m drain spacings. However, the response was too slow for the 30 m drain lines. Theoretical calculations showed that the suggested water table depth range of 60 to 90 cm could be maintained in this soil with a drain spacing of 19.2 m. An equation was derived for the upward movement of the water table during subirrigation. Except for an initial lag period, the equation can be used to accurately predict the water table rise midway between the drain lines.

For drainage, four theoretical equations were used to calculate drain spacings using water table drawdown rates measured in the three drain spacings. When the hydraulic conductivity is determined from soil cores or other independent measurements, the order of preference of the four equations tested is Bouwer and van Schilfgaarde, van Schilfgaarde, Glover, and Hammad. However, if an effective hydraulic conductivity is

is determined from water table drawdown measurements, the Hammad equation will give a more accurate prediction of the drain spacing than the other three. The accuracy of the other three equations could probably be improved for shallow soils if a procedure for compensating for convergence near the drain tube were available. Much greater accuracy can be obtained in all of the above equations by evaluating the drainable porosity based on the initial and final water table depths rather than using a constant value.

Experiments were conducted on a Pasquotank loam soil to determine the feasibility of using only natural rainfall in conjunction with a high water table to supply irrigation water for crop production. Based on continuous water table records it was concluded that a reliable water source is necessary for all subirrigation systems. The storage of surface runoff in open ditches during periods of excess rainfall did not provide sufficient water for subirrigation during the 1969 and 1970 growing seasons.

Two years of continuous water table records showing the water table response to rainfall, evapotranspiration, and drainage are presented for a Bladen clay loam soil. For subirrigation conditions in which the water table is held at shallow depths, the application of rainfall will result in a significant rise in the water table. Thus, subirrigation systems will have to be designed such that adequate drainage is provided.

RECOMMENDATIONS

The results of the study indicated that combined subirrigation-drainage systems are feasible on certain soils in the North Carolina Lower Coastal Plain. In order to apply the procedures developed during the course of this study to the design of these water management systems, the following steps should be taken:

1. Obtain a soil survey of the potential site. For this system to be practical, it is necessary that either an impermeable layer or a permanent water table exist at a shallow depth not to exceed about 275 cm.
2. Determine the soil-water characteristic and the hydraulic conductivity of the soil. Field techniques such as the auger hole method can be used to measure the hydraulic conductivity. For cases where ditches or drain tubes already exist in the field, a better measurement of the effective hydraulic conductivity can probably be obtained by measuring the draw-down after rainfall and solving for K' in the van Schilfgaarde or Bouwer and van Schilfgaarde equations.
3. Using evapotranspiration rate and optimum water table depth data from the literature, determine the drain tube spacing with equation (5) in the text.
4. Determine the time required to raise the water table to an optimum depth using equation (7) developed herein. If more than 36-48 hours is required, the spacing should probably be reduced.

5. Check the performance of the designed system under drainage conditions. Because the application of rainfall results in large rises in the water table, the system should be designed with sufficient capacity to drain a flooded soil rapidly enough to prevent crop damage.

and 6. As with any irrigation system the design must provide for a reliable source of quality water.

It is further recommended that additional research be undertaken to provide essential data on other soils and to refine the design procedures for subirrigation-drainage systems. Studies are needed to determine crop response to soil water conditions pertaining both to drainage and subirrigation on a field basis on benchmark soils. A basic part of these studies involves the determination of interrelationships between the crop response to a given water table depth and the hydraulic soil properties.

Research is needed to develop shortcut (perhaps approximate) procedures for determining effective field relationships for the hydraulic conductivity function and the soil-water characteristic. The determination of the effect of subirrigation and controlled drainage on the movement and fate of fertilizer nutrients is also worthy of future investigations.

INTRODUCTION

The approximately 3,000,000 acres of mineral and high organic soils in the Lower Coastal Plain of North Carolina are common along the southeastern coast from Maryland to Florida. These soils have flat slopes (less than 2%), shallow water tables, and are usually poorly drained. The mineral soils include the Portsmouth-Hyde series, the Bladen-Elkton series, the Klej-Leon series, and other similar soils. Bayboro, Johnston, Hyde, and other similar soils comprise the intergrade between the mineral and high organic soils. Pamlico, Ponzer, Mattamuskeet, and Belhaven which have 12 to 40 in. of organic material and Dare and Donovan which have greater than 40 in. of organic material and contain buried undecomposed wood are also very common.

Land clearing operations are bringing large areas of these soils into production every year. The area is unsuited for crop production without artificial drainage, and much of it cannot easily be subsurface drained because of location and/or elevation. If, however, the organic soils are adequately drained, there is the danger of subsidence and destruction by fire. In addition, the physical properties of the soils can change quite drastically upon drainage and may become practically unfit for cultivation because of poor physical condition.

Although this area in North Carolina receives an average of 49 in. of rainfall per year, droughty periods occur and irrigation is necessary, particularly for high value crops. However, if the land is surface drained and the water stored in the subsoil and canals by water table control, excess rainfall that causes flooding can be conserved and reapplied to the land in time of drought. Few criteria concerning water management for this area have been available.

The purpose of this project is to determine whether water management using subsurface drains is feasible for soils in the North Carolina Lower Coastal Plain. The end result of such management is conservation of surface water runoff and reduction of deep water depletion that can arise if large numbers of irrigation wells are installed.

REVIEW OF LITERATURE

Van Bavel and Verlinden (1956) state that it is a justifiable conclusion to say that the average soil moisture conditions in North Carolina are not adequate to insure maximum crop production. In dry years this inadequacy becomes very serious and can lead to total crop failure. Drought conditions can start as early as May, reach a peak in June, and occur with lesser probability through September (Sneed, 1971). Therefore irrigation is necessary for maximum crop production.

Many of the physical, chemical, morphological, and mineralogical properties of the mineral and high organic soils of the Lower Coastal Plain have been analyzed and described by the Soil Science Department of North Carolina State University. Some of the data, however, is still in unpublished form. Lee (1955) reported on the formation, identification, and use of the soils of North Carolina. Nelson (1961) and Nelson and McCracken (1962) described the physical, chemical, and mineralogical properties of the Portsmouth soils. Granger (1970) and Smith (1970) studied the mineralogical properties of selected poorly drained soils and well drained soils, respectively, of the Lower Coastal Plain.

Dolman (1967) and Dolman and Buol (1968) investigated the physical, chemical, and mineralogical properties of the organic soils in the Coastal Plain. They found that shrinkage and subsidence caused by water management are considerable in these soils. Compaction and oxidation helped by numerous fires have destroyed much of the organic matter in many areas. However, if these soils have proper water control measures, liming, and fertilization, they can become a very productive medium for plant growth.

Williamson and Kriz (1970) summarized the response of agricultural crops to flooding depths of water table and soil gaseous composition. Much of the work presented was based on work conducted on North Carolina soils by Williamson and co-workers. Experiments on crop response to water table levels in the Everglades have been conducted since 1925 by Tedder and Bryan (1925), Clayton et al. (1942), Weaver and Speir (1960), and Harrison et al. (1963). Many of the results on crop response were inconclusive, and Harrison et al. (1963) stated that the growers in Florida used their personal preference in water control practices because adequate data was not available. Roe (1936) in Minnesota, Ellis and Morris (1954) in Indiana, and Nicholson and Firth (1953) in England also conducted water table - crop response studies on organic soils.

Irwin (1967) emphasized that tile drainage of organic soils is a relatively new practice which involves additional problems in design compared to mineral soils. Harrison and Weaver (1958) and Harrison (1959) discussed the influence of rainfall, irrigation, and pumping on the rise and fall of the water table in organic soils in Florida. Clayton et al. (1942) and Harris et al. (1962) noted that the loss in soil surface elevation was directly proportional to depth to the water table. Cutler et al. (1961) in drainage system endurance studies on organic soils in Michigan indicated that the soil surface subsidence was 0.4 to 1.0 ft. the first year following drainage with little subsidence the following years. Drainage also affects the properties of mineral soils. Lutz (1960) has shown that the physical properties of Bladen silt loam and Portsmouth silt loam can change quite drastically upon drainage, especially during the first several years following installation of tile drains.

Fox et al. (1956) pointed out that certain natural conditions must exist in order for a subsurface irrigation system to be practical. Because the practice involves water table control, it is necessary that either an impermeable layer or a permanent water table exist at a rather shallow depth to prevent excessive seepage losses. Also the land must be nearly flat; otherwise the water table might be an optimum distance from the surface on one side of the field while plants are suffering from too much or too little water on the other side of the field. The soil should have a high hydraulic conductivity so that a reasonable spacing of ditches or drain tubes will provide adequate drainage and irrigation.

Because subsurface drainage is necessary in humid areas, combining subsurface irrigation and drainage systems provides an economical system of water management. Advantages of the combined system include low labor requirements, low maintenance requirements, no delay in cultural practices because of irrigation, and little or no leaching of nutrients from the root zone. The major disadvantage of salt buildup at the soil surface should pose no problem in humid areas because of the high annual rainfall. However, when the water table is maintained at a high elevation for long periods of time, deterioration of soil structure may occur in some soils.

Methods have been presented to solve the governing differential equation for unsaturated steady state flow under subirrigation boundary conditions by Bouwer (1959) and Sewell and van Schilfgaarde (1963). These methods allow the determination of the shape of the water table and the soil and water content distribution for given ditch and drain spacings and known soil hydraulic properties. Fox et al. (1956) presented a simpler, less rigorous procedure for determining ditch spacings required to maintain a given variation in the water table depth. However, very few field data are available on soil-water movement in a subirrigation-drainage system of the type described above.

An exact theoretical characterization of water table drawdown and associated soil water movement above the water table would require the solution of the Richards equation for combined saturated-unsaturated transient flow (Swartzendruber, 1966). Because it has not been possible to obtain a general solution to this nonlinear equation, drain spacing equations have been derived by neglecting flow in the unsaturated zone above the water table and by defining a soil property, "drainable porosity," which represents the total fraction of the soil volume drained as the water table recedes. Although Childs (1960) and others have shown that the assumption of a constant drainable porosity can lead to significant errors, the concept can be used to predict water table drawdown with an accuracy which is probably sufficient for design purposes.

One of the first drain spacing equations based on rate of water table drawdown was derived by Glover (Dumm, 1954) for an initially flat water table. The equation may be written as

$$L^2 = \frac{\pi^2 KDt}{f \ln \frac{4m_o}{\pi m}} , \tag{1}$$

where, as shown in Figure 1, L is the drain spacing; t is time; m_o and m are the distances of the water table above the drain lines at the

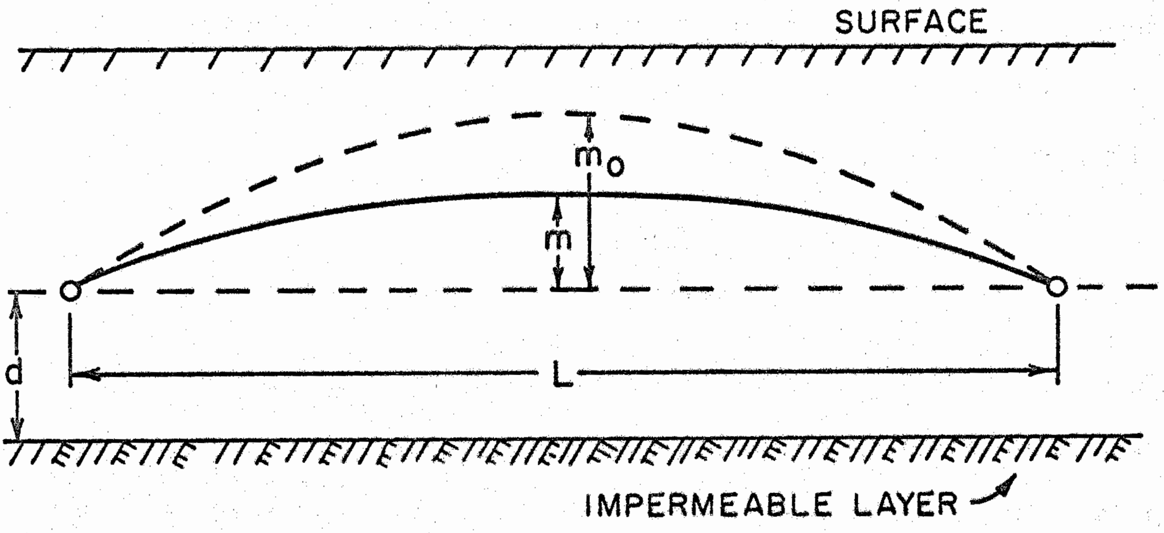

Figure 1. Schematic of the water table during drainage.

midpoint between adjacent drains for t = 0, and t = t, respectively; $D = d + m_o/2$; d is the distance of the drain tube above the impermeable layer; K is the hydraulic conductivity; and f is the drainable porosity. Because equation 1 was derived using the Dupuit-Forchheimer assumptions, a correction factor such as Hooghoudt's equivalent depth (van Schilfgaarde, 1963) should be used to determine D in order to compensate for radial flow near the drain. Tapp and Moody (Dumm, 1964) modified equation 1 to consider a fourth degree parabola as the initial water table shape. However the predicted drain spacings were essentially the same as given by Glover's equation.

Hammad (1962) used potential theory and the assumption that the receding water table between drain tubes is nearly flat to derive equations for water table drawdown in both shallow and deep soils. For shallow soils ($d/L < 1/4$), the distance between drains is

$$L = \frac{2\pi K t}{f \ln\left(\frac{m_o}{m}\right) \ln\left(\frac{L^2}{2\pi^2 r d}\right)}, \tag{2}$$

where r is the radius of the drain tube and the other symbols are as previously defined. For computational convenience equation 2 may be rewritten as

$$L \ln L = \frac{\pi K t}{f \ln\left(\frac{m_o}{m}\right)} + \frac{1}{2} \ln(2\pi^2 rd). \tag{2a}$$

Because the field observations in this study were made on a soil with a shallow impermeable layer, Hammad's equation for thick layers will not be presented. The reader is referred to the original paper for further discussion.

Van Schilfgaarde (1963) derived an equation for an initially parabolic water table which may be expressed as

$$L^2 = \frac{9tKd}{f \ln \frac{m_o(2d+m)}{m(2d+m_o)}}. \tag{3}$$

As in Glover's equation, the Dupuit-Forchheimer assumptions were used and thus, Hooghoudt's equivalent depth was substituted for d in equation 3. However, the inherent assumption in Glover's solution of a constant flow depth was avoided in the derivation of equation 3.

The fourth equation considered herein was presented by Bouwer and van Schilfgaarde (1963). They assumed that the instantaneous drainage rate midway between drains may be taken as equal to the steady state drainage rate corresponding to the same water table elevation. Using Hooghoudt's steady state relationship (van Schilfgaarde, 1970) they obtained a transient equation which may be written as

$$L^2 = \frac{8Ktd}{Cf \ln \frac{m_o(m+2d)}{m(m_o+2d)}}, \tag{4}$$

where C is a correction factor that is the ratio of the average flux between drains to the flux midway between drains. Typically C lies between 0.8 and 1.0 with higher values expected for the initial stages of water table recession. Because Dupuit-Forchheimer assumptions were used in the derivation of Hooghoudt's steady state equation, an equivalent depth must be substituted for d in equation 4.

Other proposed drain spacing equations have been reviewed by van Schilfgaarde (1970). However, the four equations discussed above are among the most commonly used and represent a range of assumptions regarding the initial shape of the water table. While it is not feasible to compare the predictions of all the equations that have been proposed in the literature, field data are presented in the results section so that the reader can evaluate the performance of each equation.

OBJECTIVES

The objectives of this investigation are:

1. Determine the water table fluctuations in a given area of land under natural conditions.

2. Determine the vertical and lateral water movement within the soil profile.

3. Control the water level in ditches in an attempt to control the water table in the field by using drain tubes.

4. Compare the field results of water table control with theory.

EXPERIMENTS

Pasquotank Silt Loam

An experiment was conducted on the Durwood Cooper farm at Gum Neck, North Carolina, to determine whether it is feasible to use only natural rainfall in conjunction with a high water table to supply the necessary water for crop production. Subirrigation of this type is commonly referred to as controlled drainage and was discussed by Stephens (1955) for peat and muck soils. A water control structure was installed in an outlet ditch so that surface runoff water could be held in lateral ditches spaced 61 m apart. Three observation wells, 10 cm in diameter and approximately 1.5 m deep, were centrally located between lateral ditches. The water level in the observation wells was continuously recorded during the 1969 and 1970 growing seasons with Stevens type F water level recorders. Potatoes were grown on the Pasquotank silt loam soil in the spring followed by soybeans after the potatoes were harvested in June.

Bladen Clay Loam

The water table depth and its response to rainfall and evapotranspiration conditions were also determined for a Bladen clay loam soil located on the Tidewater Experiment Station at Plymouth, North Carolina. Three observation wells of the type previously described were located midway between adjacent ditches spaced 80 m apart. In one section of the field, two other observation wells were installed 9 m from each ditch in line with the well at midpoint. Rainfall was recorded daily. The water table elevation was recorded continuously during the 1969 and 1970 growing seasons.

Lumbee Sandy Loam

Water Table Movement. Experiments were conducted on the H. C. Austin farm near Aurora, North Carolina, to determine the feasibility of irrigation through subsurface drains and to study the water movement under subirrigation and drainage conditions. A schematic sketch of the field installation is shown in Figure 2. An irrigation application was initiated by closing the gate in the water level control structure (Figure 3) and raising the water level in the main ditch by pumping water into it from a well. The water level in the ditch was then held at a constant elevation and water moved through the drain tubes into the soil. Twelve drain tubes, 12.5 cm in diameter, were installed in sets of four at spacings of 7.5, 15, and 30 m in 1968. The soil is primarily Lumbee sandy loam which consists of a 20-30 cm surface layer and a sandy loam subsoil. The sandy loam subsoil is underlain at about 125-155 cm by a tight clay layer which for practical purposes may be considered impermeable. The drain tubes were placed at a depth of about 1 m on a 0.3 percent grade. Crops grown on the field were potatoes in the spring followed by soybeans planted in late June.

The movement of the water table under subirrigation and drainage conditions was measured using a series of wells and piezometers. Observation wells were centrally located between adjacent drain lines for each of the three drain spacings as shown in Figure 2. The observation wells were 10 cm in diameter and approximately 1.5 m deep. Figure 4 shows one of these wells. The water levels in each observation well and in the outlet ditch were continuously recorded with Stevens type F water level recorders. Two sets of five piezometers were placed on both sides of the observation wells for the 7.5 and 15 m

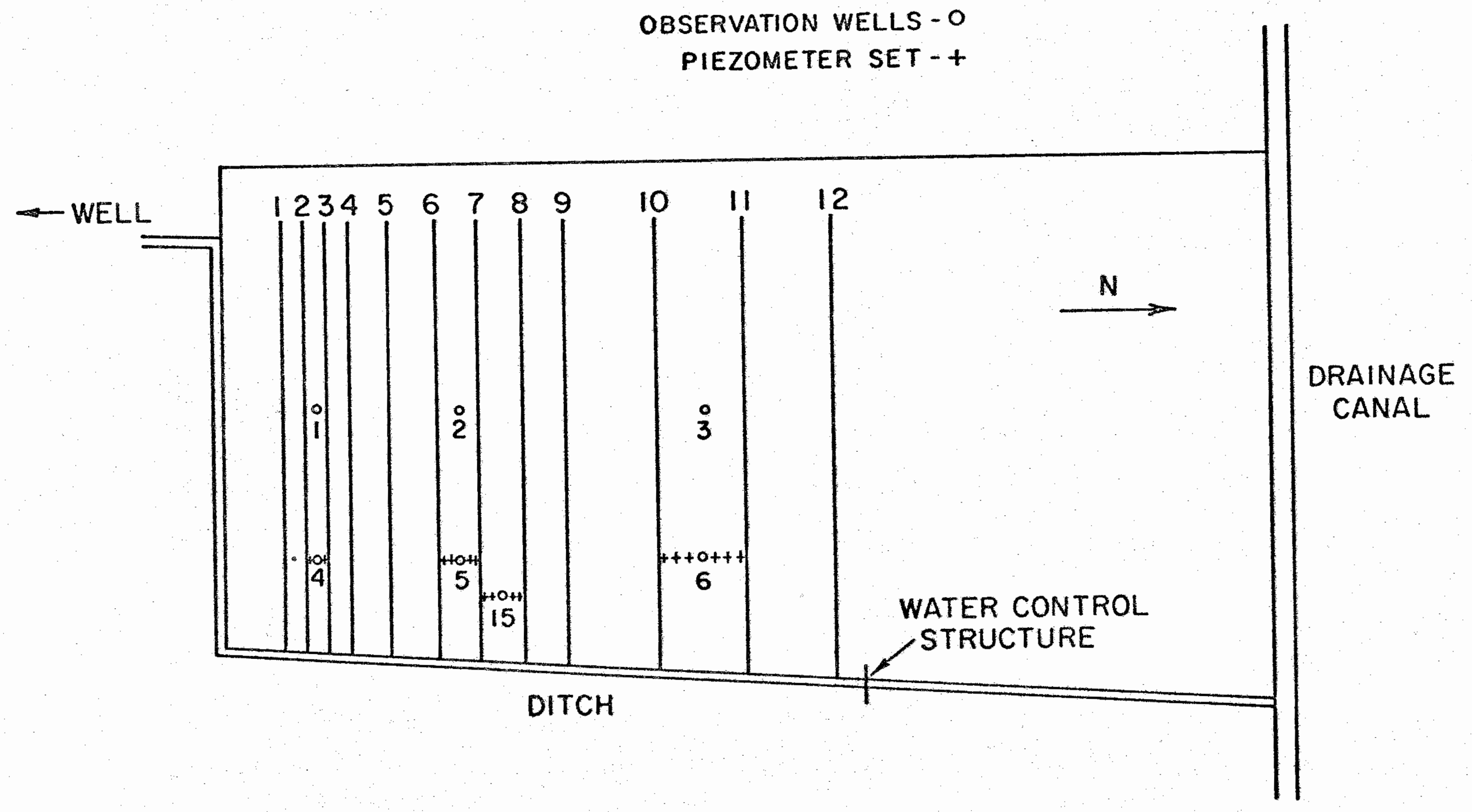

Figure 2. Schematic of experimental setup on the H. Carroll Austin Farm, Aurora, N. C.

Figure 3. Water level control structure on the H. Carroll Austin Farm, Aurora, N. C.

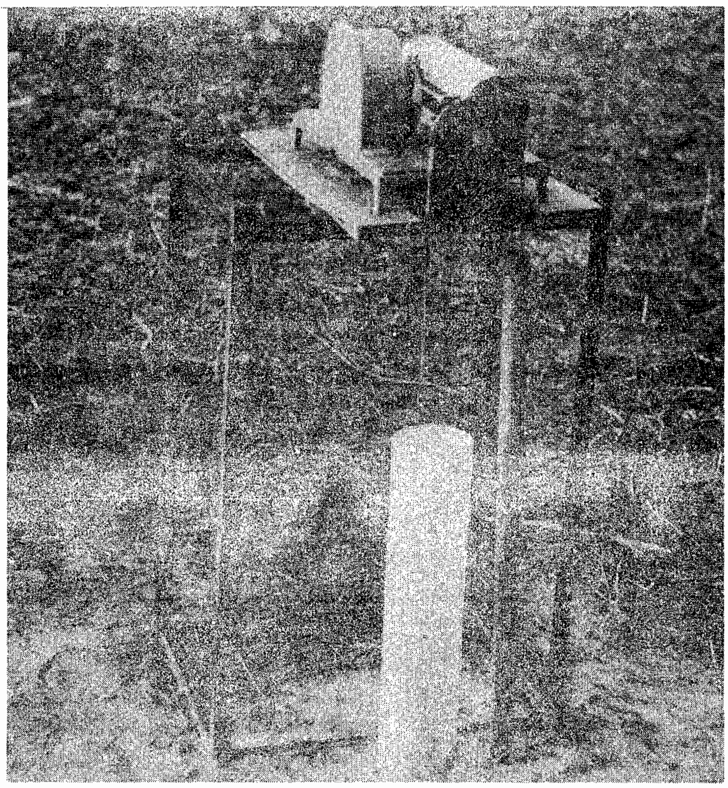

Figure 4. An observation well and water level recorder

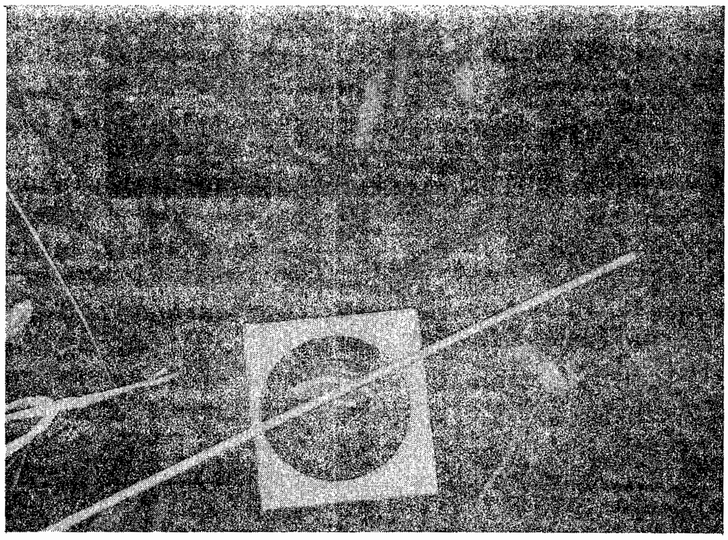

Figure 5. Battery powered electrical conductivity probe.

tile spacings. Three sets of piezometers were used for the 30 m tile spacing (Figure 2). The piezometers were constructed from steel pipe approximately 1.5 cm I.D., and were driven according to the procedure suggested by Reeve (1965) to elevations of 0, 15, 30, 45, and 60 cm above the bottom of the gate in the water level control structure.

Continuous observation well records were obtained for the 1969 and 1970 growing seasons. For potatoes, the water in the outlet ditch was held at a depth of 40 cm above the bottom of the control gate. This gave a depth of about 75 cm at the observation wells. Several short-term tests were conducted in 1970 and 1971 to characterize the hydraulic response of the system to subirrigation and drainage boundary conditions. A test was initiated by raising the water level in the ditch to about 65 cm above the bottom of the gate. This head was maintained for a period of time, 2-5 days, while the water table rose in the field. Then the water was released from the ditch and the field allowed to drain.

Water table elevations as a function of time were recorded in each well and in the ditch during the whole irrigation-drainage period. The level of water in the piezometers was determined with a battery powered electrical conductivity probe (Figure 5) at convenient intervals, nominally three times a day, during the test to define the shape of the water table. Additional drawdown data were obtained following rises in the water table due to rainfall.

Hydraulic Conductivity Measurements. Measurements of the hydraulic conductivity function and its variation with water content and depth were made during the summer of 1971 on a level area with dimensions of 4.6 m x 4.6 m located on the east side of the field shown in Figure 2. The plot was surrounded and defined by a dike made with strips of sheet metal driven into the soil to about a 12 cm depth. Another dike surrounded and defined an area 6.1 m x 6.1 m around the plot so that a guard strip 76 cm wide existed between the sampling site and the field.

The procedure described by Nielsen et al. (1964) was used to measure the hydraulic conductivity function. Tensiometers were used to measure the soil-water tension at depths of 15, 30, 45, 60, and 75 cm during a complete wetting and drainage period. Three sets of tensiometers were distributed in the plot and each set was used to make a separate hydraulic conductivity determination. The tensiometers were connected to mercury manometers and were found to perform satisfactorily. An observation well with a Stevens type F water level recorder was installed in the plot to monitor the water table elevation.

The experiment was initiated by pumping water on the plot and maintaining a ponded surface of about 3.5 cm for a period of 72 hours. Then the soil was allowed to drain. When the plot was nearly free from ponded water, it was covered with a plastic sheet to prevent evaporation. Tensiometer readings were made at intervals of approximately one hour during the first day and two hours during the second day. For the next five days, three readings during each 24-hour period were made. A last reading was made eight days after infiltration had been initiated.

For each set of tensiometers, the values of soil-water suction taken at each depth were plotted versus time. From this curve and the soil-water characteristic, the water content-time relationship was established. The rate at which water passed any particular depth was obtained as a function of time by assuming vertical flow. The hydraulic conductivity values were calculated directly from the Darcy-Buckingham equation using these fluxes and tension gradients.

The saturated hydraulic conductivity was determined in the laboratory on soil cores 8.5 cm in diameter and either 10 or 20 cm in length. A total of 15 cores from the 20-75 cm depth range were tested in 1971.

Soil-Water Characteristic. The drainage branch of the soil-water characteristic was determined on soil cores taken from the plot at depths of 15, 30, 45, 60, and 75 cm. Pressure plate apparatuses of the Tempe type and the volumetric type discussed by Tanner and Elrick (1958) were used. The soil-water characteristic determinations were repeated in 1971 on four replications from the 30-75 cm depth range. Details concerning the laboratory measurements of the soil-water characteristic and the saturated hydraulic conductivity were presented by Bernal (1971).

RESULTS AND DISCUSSION

Pasquotank Silt Loam

The water table elevation during the growing season is plotted versus time in Figure 6 for the Pasquotank silt loam on the Cooper Farm. The elevations are referenced to the bottom of the observation well which is 1.7 m below the soil surface. Although the closed ditches caused a reduced drawdown following rainfall, there were substantial periods during the growing season, e.g. May 20 - June 10, when the water table dropped below the bottom of the observation wells. During these periods the water table was approximately 45-90 cm deeper than the optimum depth for potato production. Although the effect on crop yield of these periods of water stress was not measured and may have been negligible, the fact that this method of subirrigation will not maintain a controlled water table during extended droughty periods severely limits its usefulness. Thus a water supply in addition to runoff will be necessary for subirrigation systems in eastern North Carolina.

Bladen Clay Loam

Water table elevations for the Bladen silt loam during 1969 and 1970 are plotted in Figure 7 with the elevations being referenced to a point 1.7 m below the soil surface. Thus, the water table ranged from 60 to 160 cm below the surface during the given period. An indication of the variation of the water table measurements for three different blocks is given in Figure 8 for the period August 30 - October 4, 1969. The expanded scale of Figure 8 gives a clear indication of the water table response to rainfall.

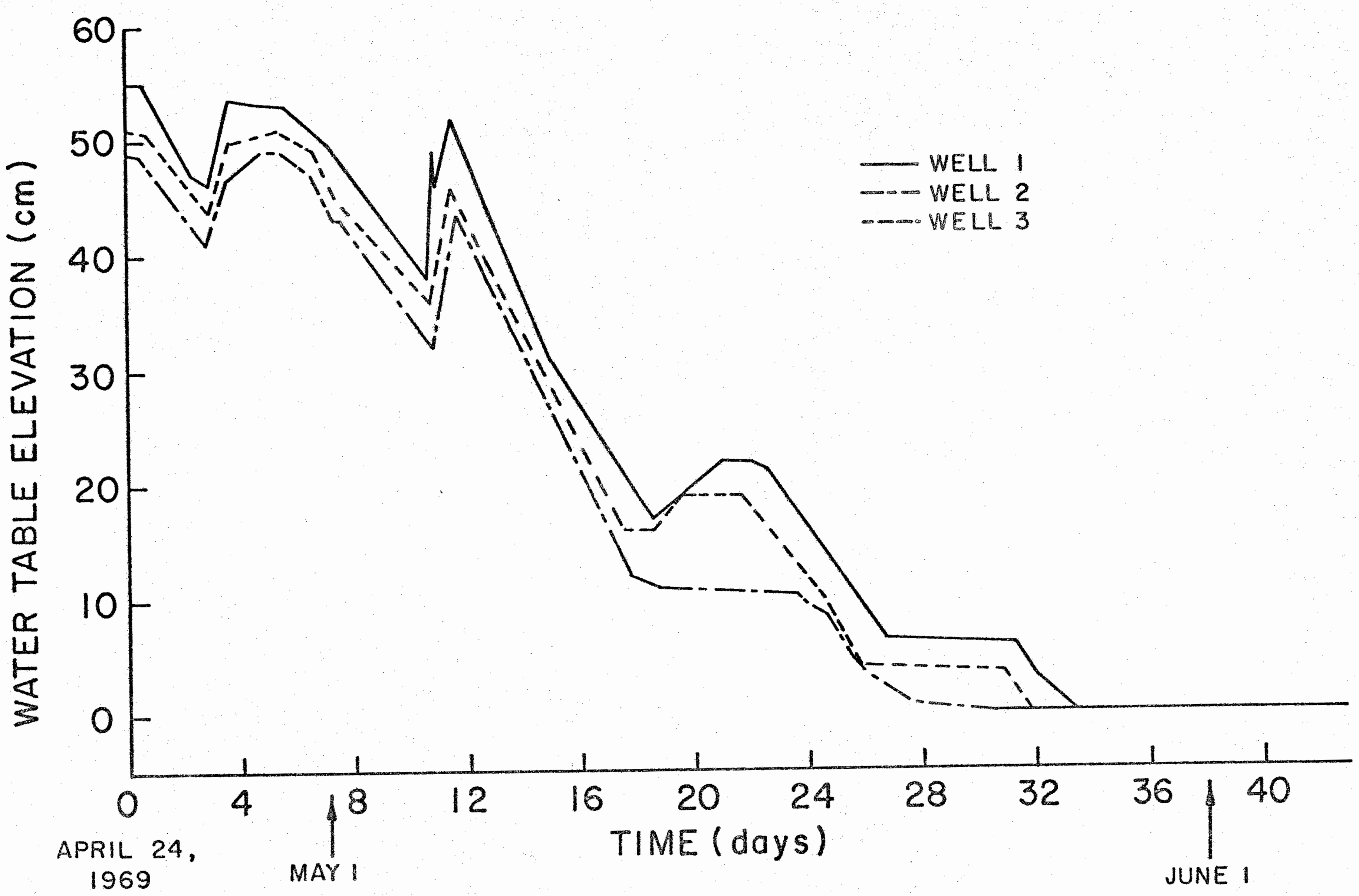

Figure 6. Water table elevations on Pasquotank silt loam on Durwood Cooper Farm, Gum Neck, N. C.

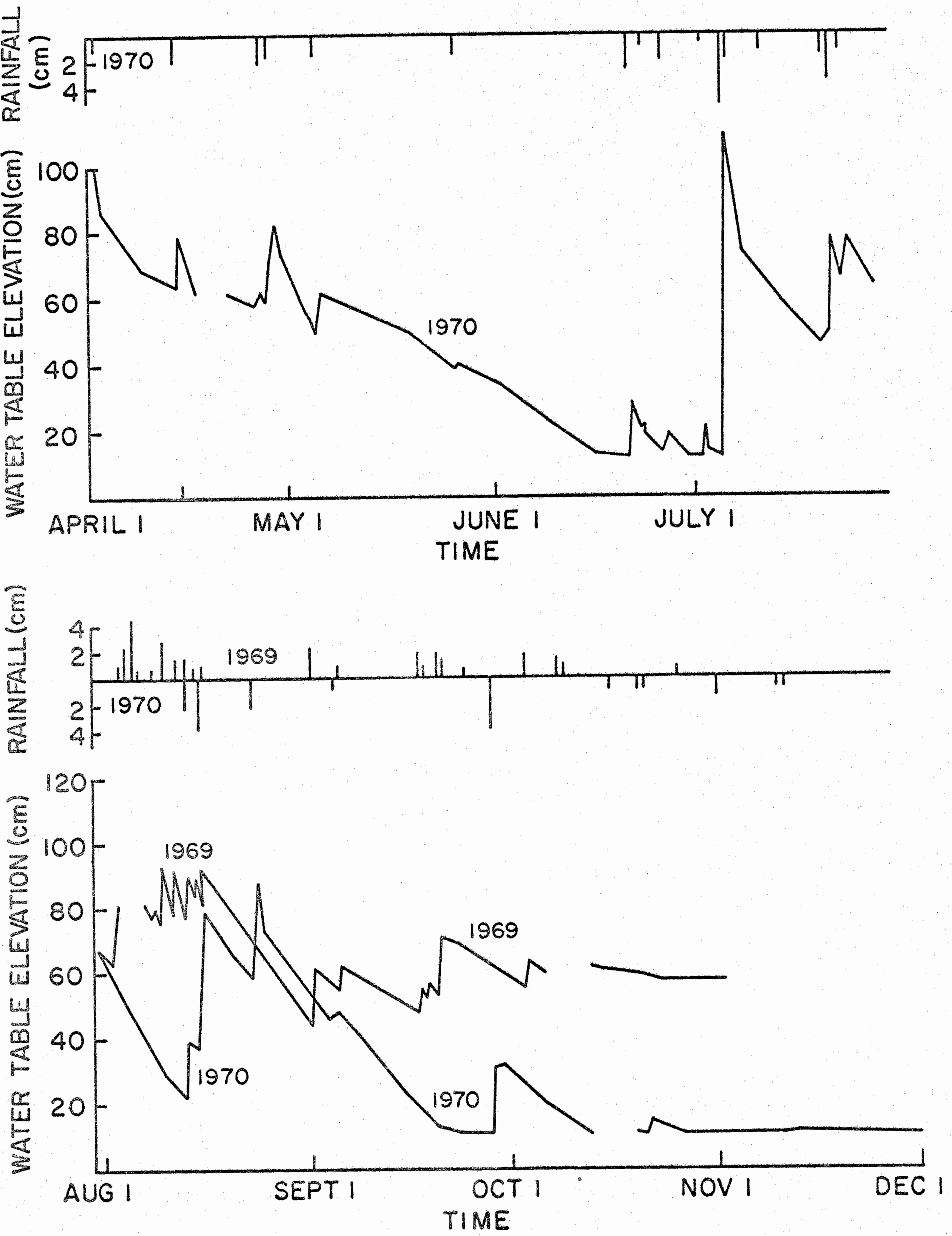

Figure 7. Water table elevations on Bladen clay loam during 1969 and 1970 at the Tidewater Research Station, Plymouth, N. C.

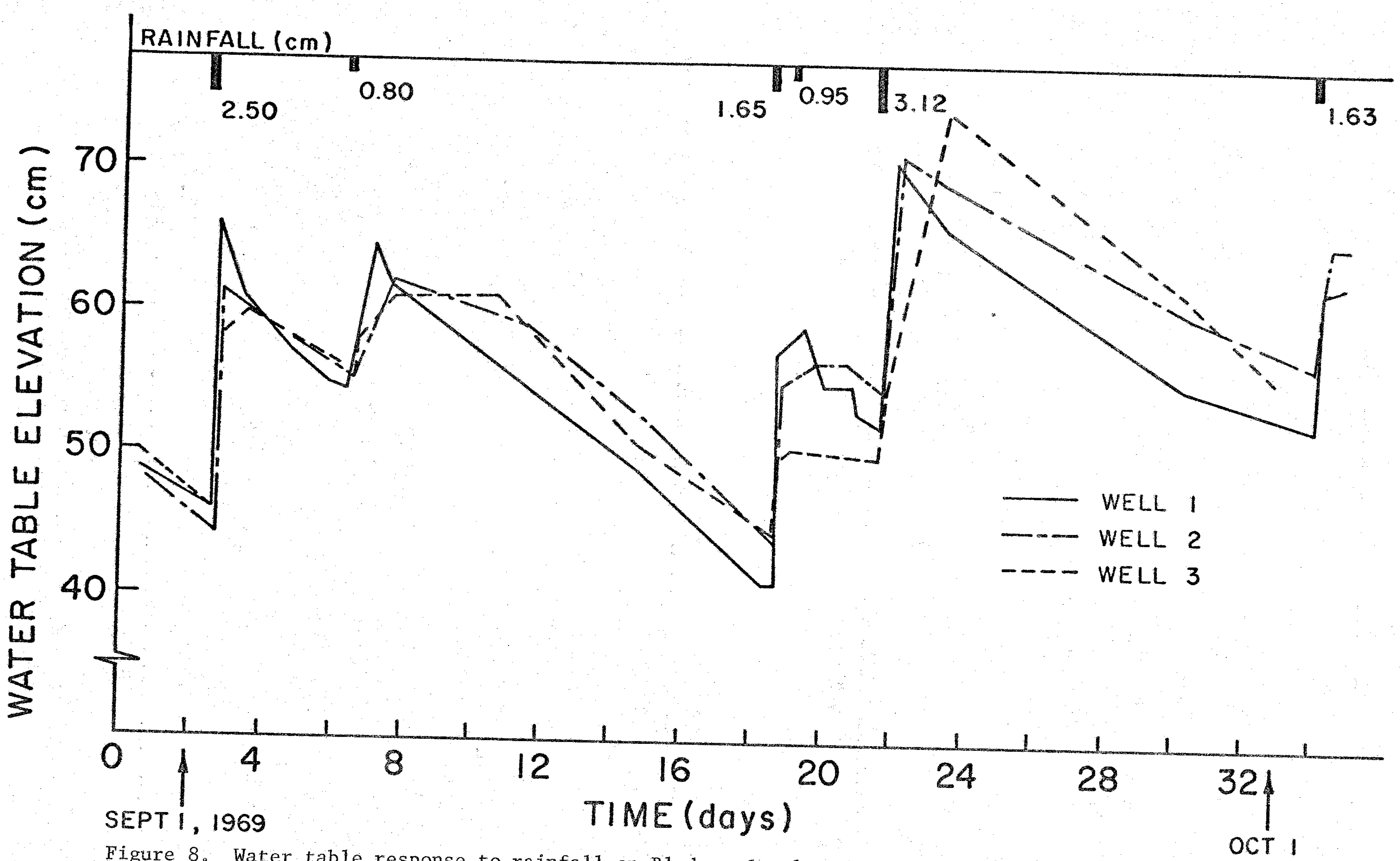

Figure 8. Water table response to rainfall on Bladen clay loam at the Tidewater Research Station, Plymouth, N. C.

The sharp rise in the water table due to rainfall is of particular interest in the design of subirrigation systems. For example, a rain of 2.5 cm on September 1, 1969, resulted in a rise in the water table of between 15 and 20 cm. Similar responses in the water table after rainfall were also observed on the Pasquotank and Lumbee soils. The rise of the water table is dependent on the amount and rate of rainfall, initial water table elevation, unsaturated water content distribution, hydraulic soil properties, and the rate water drains from the profile. This relationship will be discussed in more detail for the Lumbee soil. It can be noted here, however, that the design of a subirrigation system must provide for drainage of excess water from the soil profile at a rate sufficient to prevent crop damage due to poor aeration. This requires better drainage when subirrigation is used because high water tables result in a larger water table rise from a given rainfall event.

Lumbee Sandy Loam

Extensive tests were conducted on the Lumbee sandy loam to determine the soil-water movement under subirrigation, drainage, and rainfall infiltration conditions, and to measure the hydraulic properties. The measured relationships were then used to determine the suitability of theoretical design equations. The results of the experiments will be discussed in the following order: (1) hydraulic conductivity, (2) soil-water characteristic, (3) subirrigation, and (4) drainage.

Hydraulic Conductivity. Values of the soil-water suction at each depth were plotted versus time for all three sets of tensiometers. Data from one tensiometer set are plotted in Figure 9. In general, the curves are smooth and have relationships that are consistent with the theory

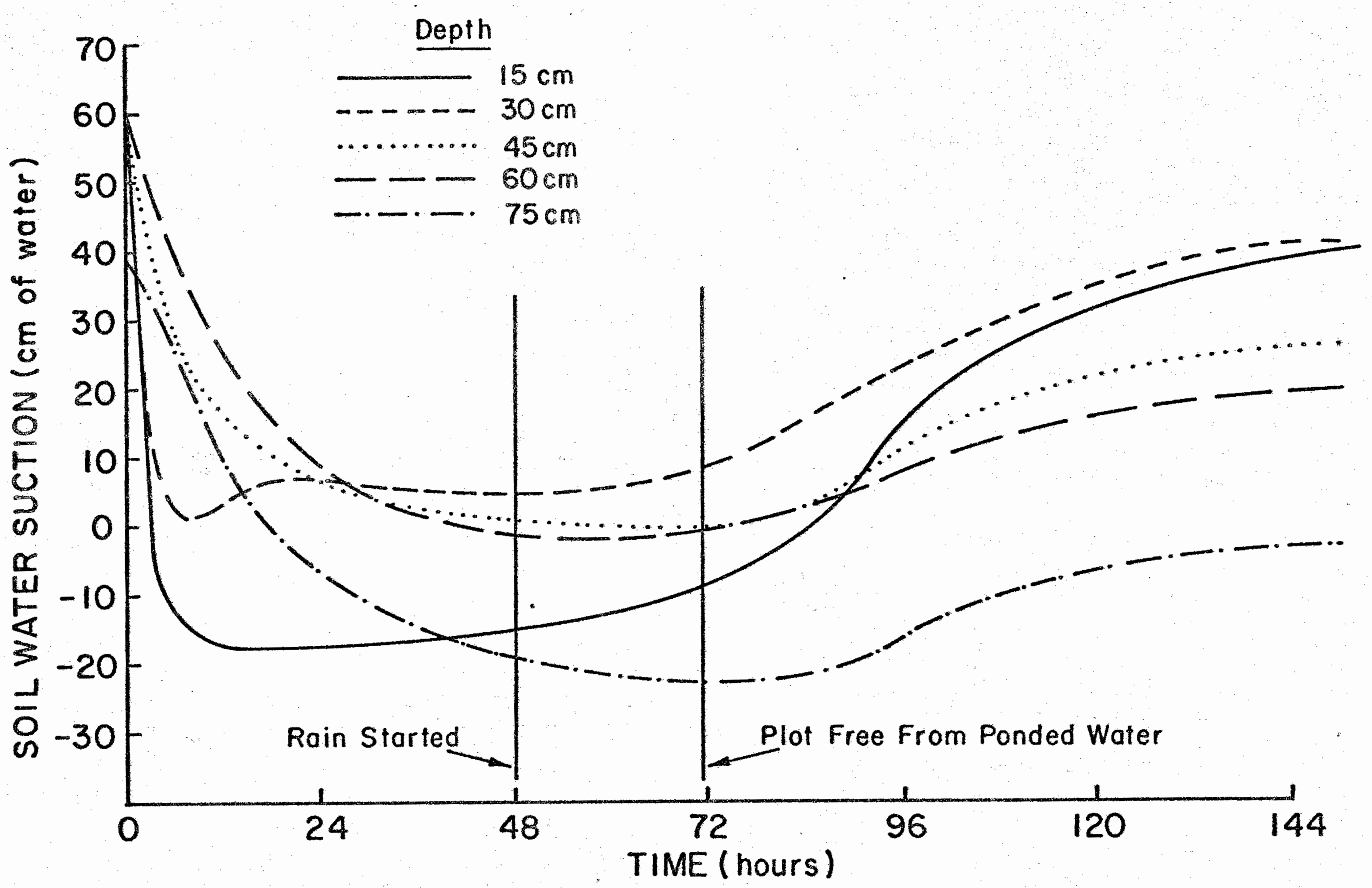

Figure 9. Soil-water tension versus time of infiltration for depths of 15, 30, 45, 60, and 75 cm as measured by tensiometers on a Lumbee sandy loam.

of soil water movement. However, the suction values at the 30 cm depth are higher than expected as they are always greater than zero, indicating that the soil at that depth is never saturated.

Figure 10 shows plots of soil-water suction versus depth for five different times during the experiment. After 21 hours of infiltration, variation of soil-water suction with depth is rather small and, in general, larger for the greater depths. After 71 hours the application of water to the soil surface was ceased and the soil began to drain. As expected, suctions near the soil surface increased, while those of greater depths decreased during the first part of the drainage period. After 118 hours a noticeable increase in the soil-water suction at all but the 75 cm depth had occurred. From 118 to 196 hours a rather uniform increase of suction at all depths was observed. The soil-water suction distribution after 196 hours indicated that the soil was almost drained to equilibrium. The suctions at the 15 and 30 cm depths were 53 and 47 cm of water, respectively, as compared to values of 60 and 45 cm, which would be obtained for those depths when the soil is drained to equilibrium.

Soil-water characteristics were determined in the laboratory on soil cores taken from each tensiometer depth. Using these curves, the soil-water contents with depth were determined directly from the tensiometer readings. Soil-water content distributions for selected times during the drainage period are shown in Figure 11. Although the soil profile was essentially saturated after 47 hours, the volumetric water content, as shown in Figure 11, was not constant due to the variation of porosity with soil depth. Early in the drainage phase the water contents in the top 45 cm substantially decreased while those

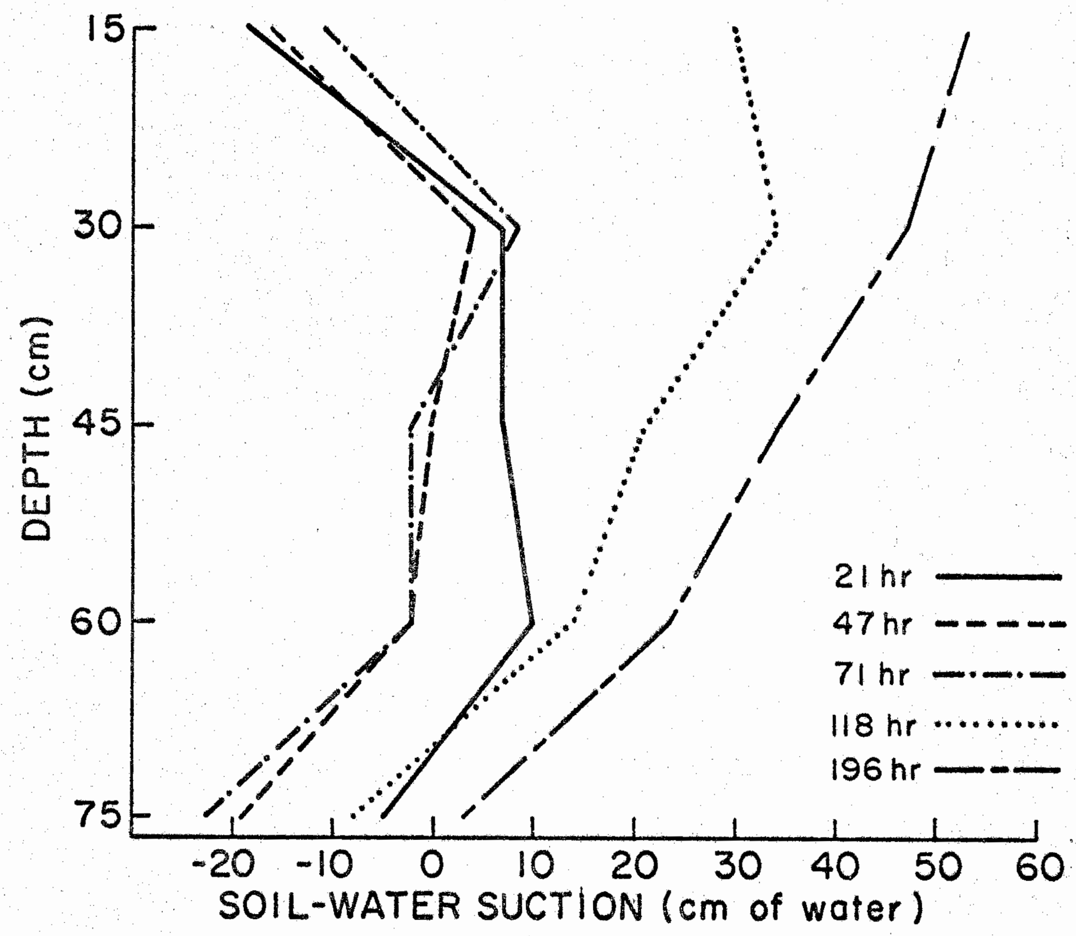

Figure 10. Soil-water suction versus soil depth measured by tensiometers during infiltration and drainage at 21, 47, 71, 118, and 196 hr after initiation of infiltration on a Lumbee sandy loam.

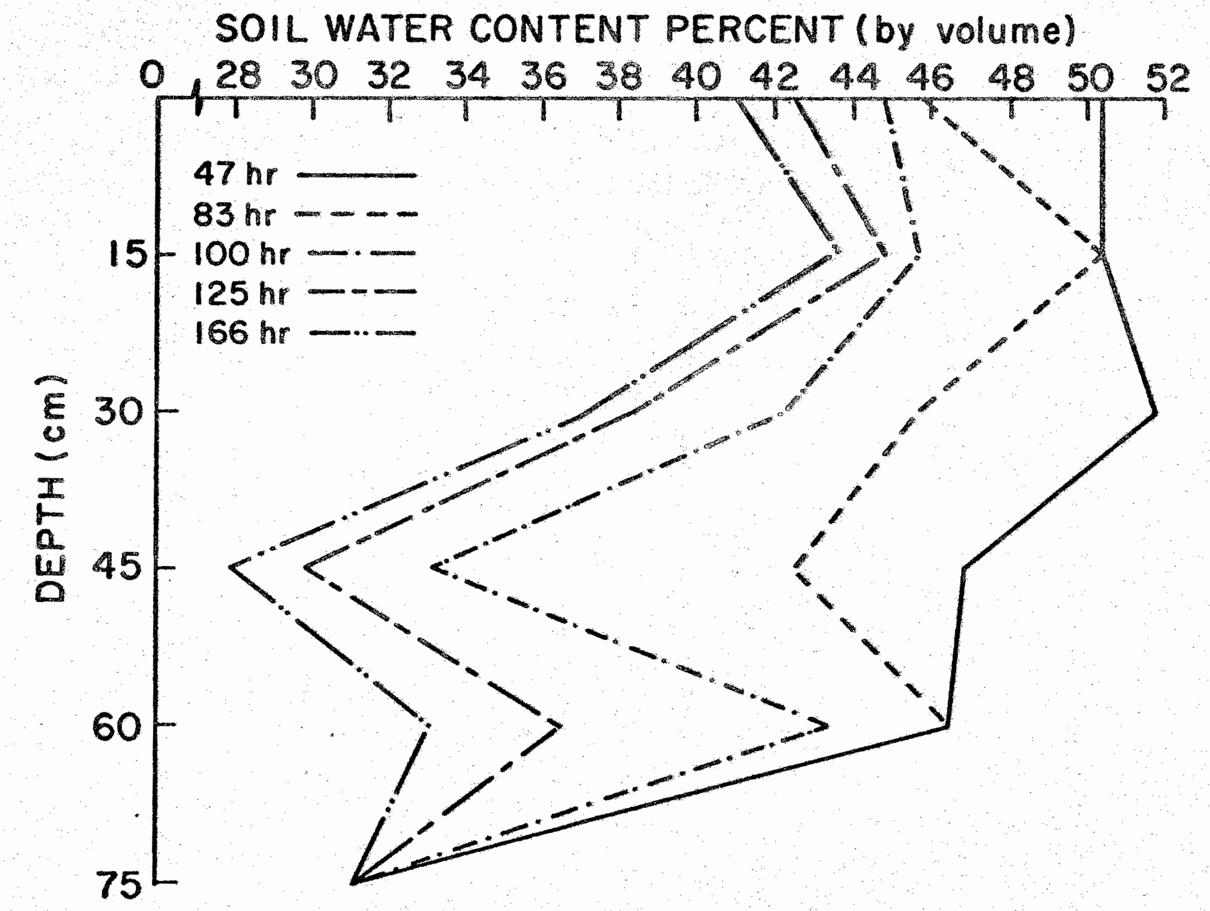

Figure 11. Soil-water contents during drainage for a period of 47 to 166 hr after initiation of infiltration on a Lumbee sandy loam.

at greater depths remained nearly constant. At the 75 cm depth, the soil-water content remained saturated and hence constant during the whole drainage period considered.

The decrease in the average water content for each time interval was calculated and the water flux (q) across the 15, 30, 45, and 60 cm depths determined from the graphs of soil-water content versus depth during drainage by the technique used by Nielsen et al. (1964). Average values of the gradient at each depth during the corresponding time intervals were calculated from the soil-water suction data, and the conductivity determined from the Darcy-Buckingham equation.

Figure 12 shows hydraulic conductivity versus soil-water content for the 15, 30, 45, and 60 cm depths. Data points represent values for the water contents that existed during the experiment. In general, the hydraulic conductivity function increased with depth. For most values of water content, conductivity for the 15 cm depth is comparable to that for the 30 cm depth, both of them being much smaller than those at 45 and 60 cm. Because the surface soil was loose and seemingly more porous than that at the 45-60 cm depth, these data seem entirely inconsistent with expected conductivity values. However, close inspection of the soil profile revealed a tight hardpan at about the 18-21 cm depth. The presence of this restricting layer could have accounted for the relatively low conductivity functions obtained for the 15 and 30 cm depths.

The results of the hydraulic conductivity determinations have been discussed in detail by Bernal (1971). The values obtained were

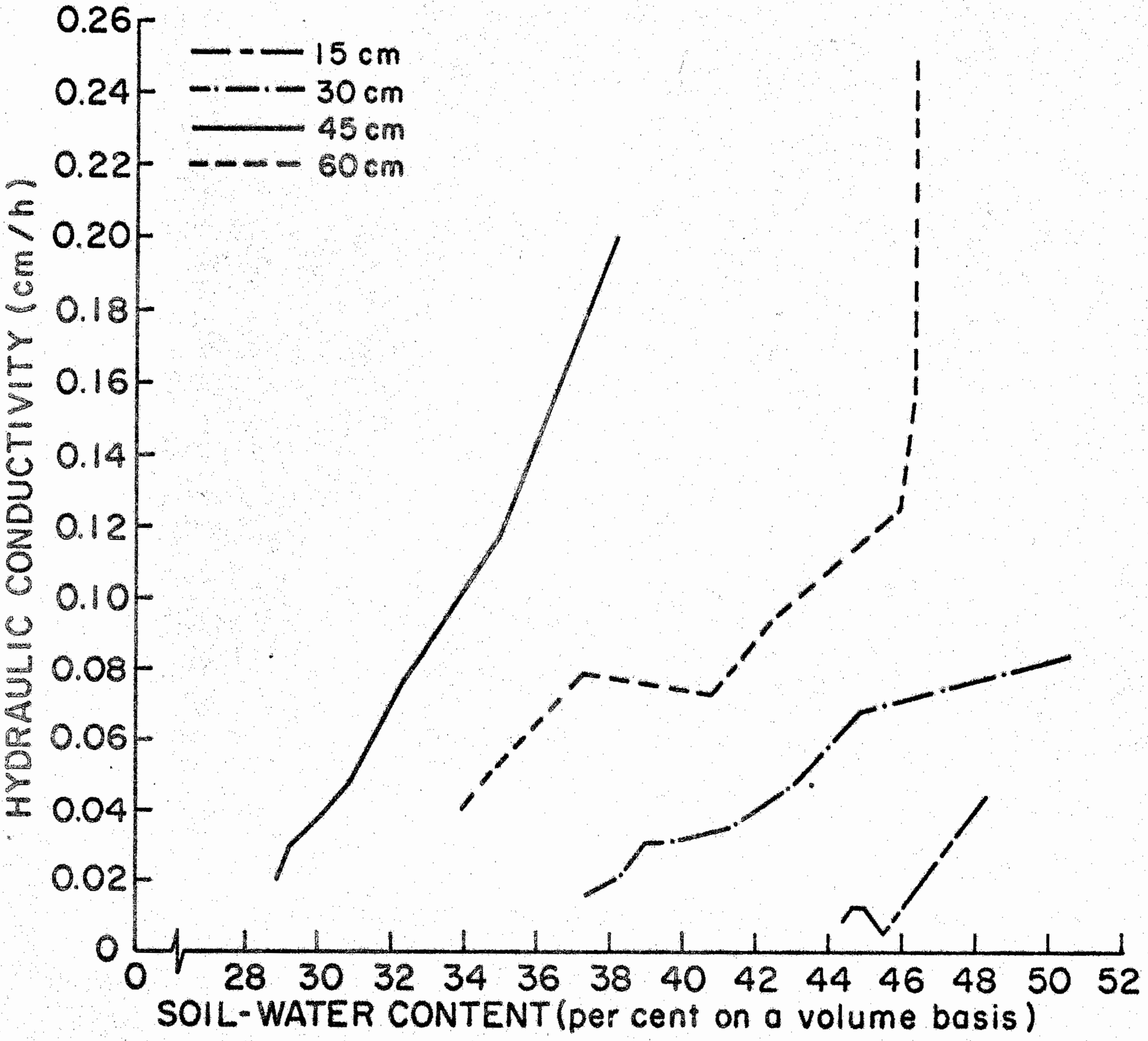

Figure 12. Hydraulic conductivity versus soil-water content on a Lumbee sandy loam.

quite inconsistent and unexpectedly low with the maximum saturated hydraulic conductivity being 0.24 cm/hr. This may be compared with a mean value of 4.2 cm/hr obtained for the saturated hydraulic conductivity of the core samples. The inconsistency in the determinations was probably due to the assumption of vertical drainage from the profile. Further analysis has shown that appreciable horizontal water movement probably occurred under the test conditions. The hardpan at the bottom of the plow layer was another confounding factor that caused difficulty in evaluating the drainage flux from the top 20 cm of the profile.

Soil-Water Characteristic. Soil-water characteristic data obtained for soil samples from the 30-75 cm depth range are plotted in Figure 13. According to these data, the soil water content between the depths of 30-75 cm would be between 30 and 40 percent when the soil is drained to equilibrium above a water table at a one meter depth. This is consistent with soil-water content data collected at various times throughout the study.

Subirrigation. Plots of the water table elevations referenced to the bottom of the control gate for the 7.5, 15, and 30 m tile spacings on the Aurora site are given in Figure 14 for a 6-day period prior to the initiation of subirrigation. Elevations are referenced to the bottom of the gate in the water level control structure which is approximately 115 cm below the soil surface. The water receded for all three drain spacings at a rate of approximately 2-3 cm per day. The plots in Figure 14 were recorded at wells 1, 2, and 3 at which location the drain tubes are about 35 cm above the bottom of the gate. Therefore,

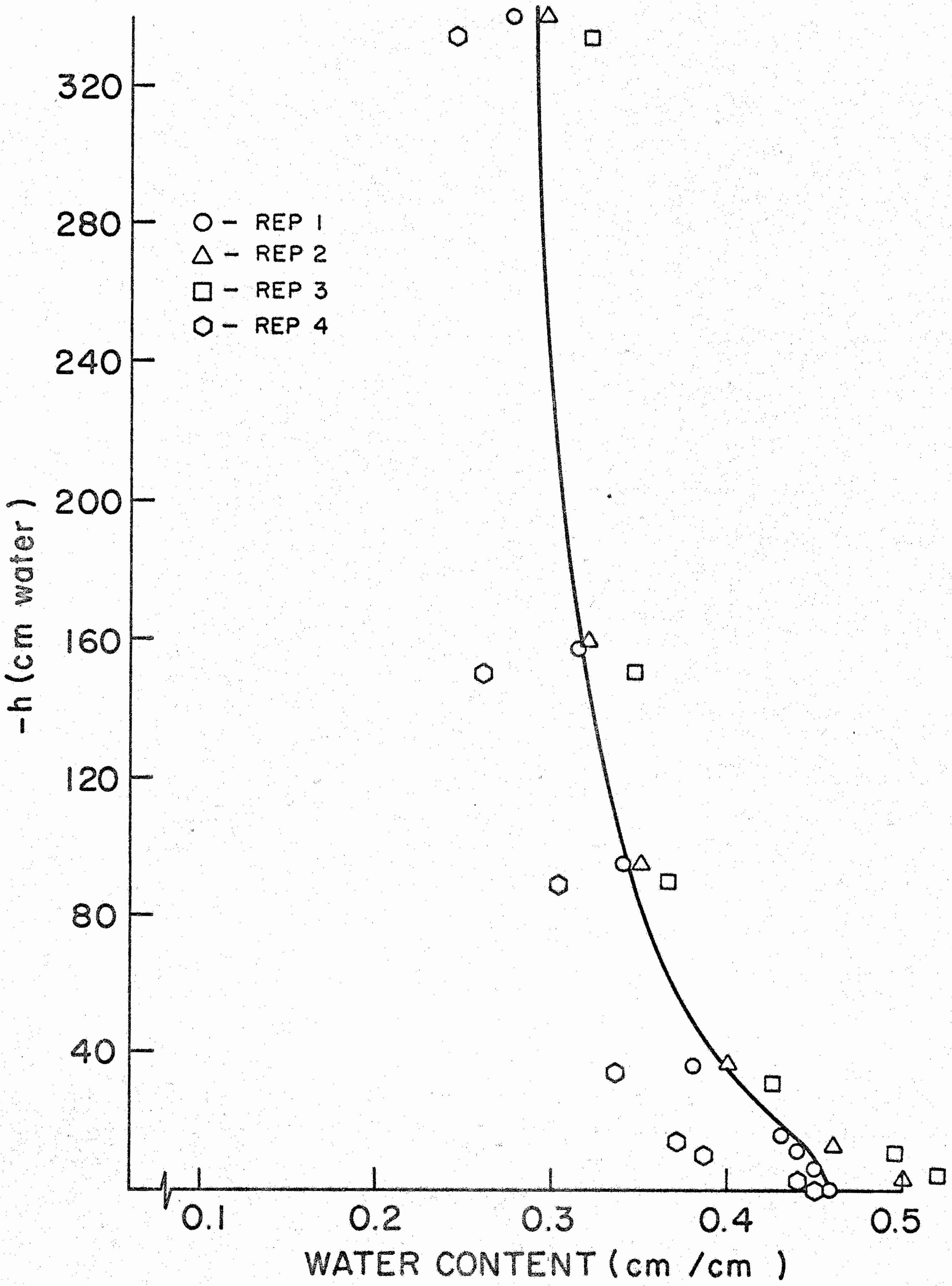

Figure 13. Soil-water characteristic for a Lumbee sandy loam.

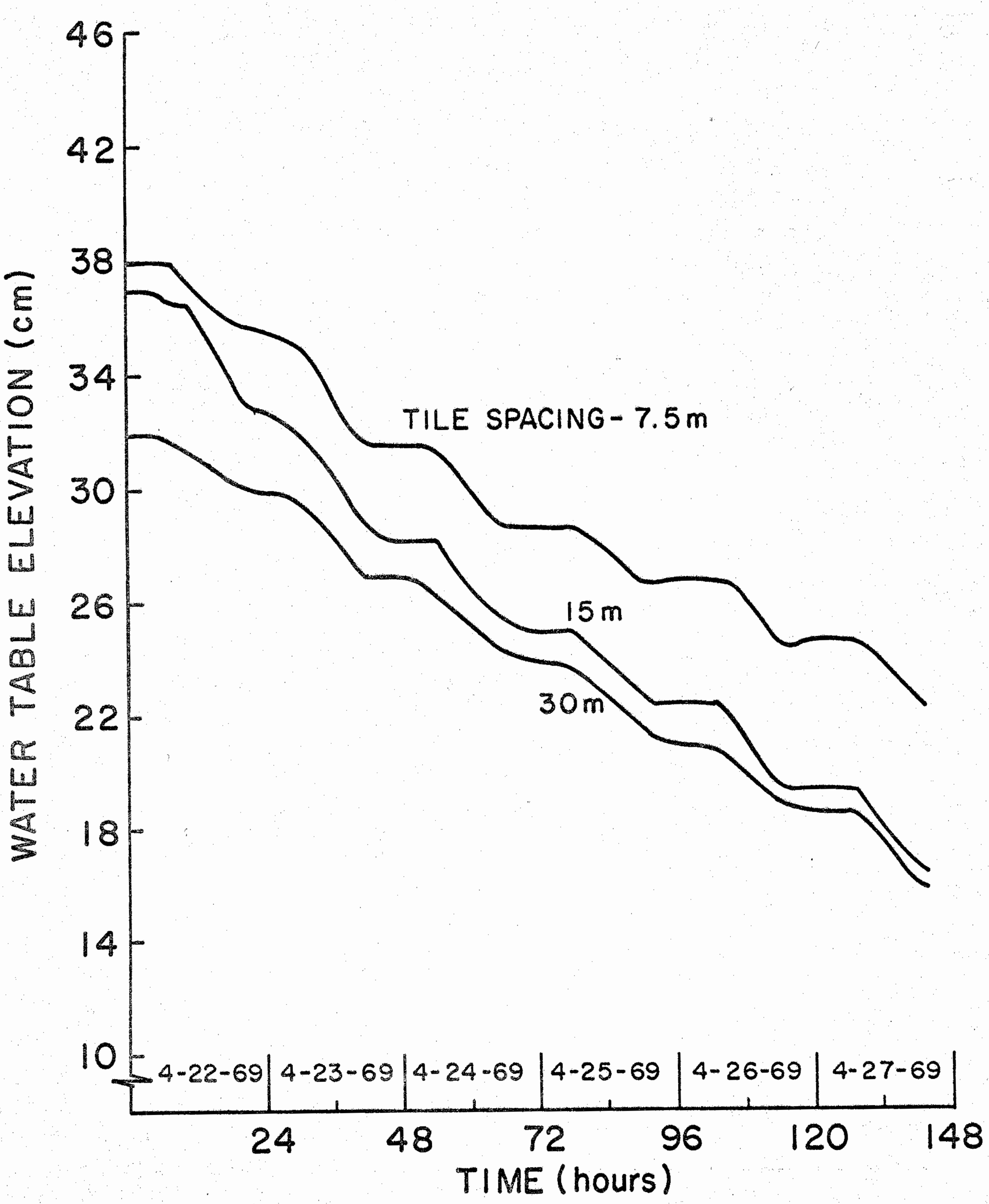

Figure 14. Water table drawdown due to evapotranspiration on a Lumbee sandy loam.

the drawdown may be attributed solely to upward movement due to evapotranspiration. The drawdown curves consist of steeply declining segments that occur during the period of evapotranspiration from approximately 0900 to 1800 hours followed by relatively flat segments occurring between 1800 and 0900 hours the next day. The daily amount of drawdown depends on the water table elevation and the stage of crop growth. Rates in the order of 4-5 cm per day were recorded for similar water table elevation ranges during the latter stages of crop growth in early June.

The results of subirrigation on the water table elevations for the three drain spacings are plotted in Figure 15. The water level in the outlet ditch was raised from 25 to 40 cm on 5-5-69 and maintained at that elevation for the duration of the period. For the 7.5 m spacing, the water table midway between the drain lines rose to an average elevation of 33 cm by 5-6-69. Subsequently, the water table receded by 1-2 cm during the day due to evapotranspiration, but rose back to its original level during the night. The water table midway between drain lines spaced 15 m apart was held at an average elevation of 18 cm with a rising and falling pattern similar to that observed for the 7.5 m spacing. The elevation of the water table midway between the drain lines spaced at 30 m dropped at a rate of about 1.5 cm per day. This represents a reduction from the 3-4 cm/day observed fall when subirrigation was not being applied. However, the 30 m spacing is not sufficient to hold the water table at a constant elevation during peak use periods for this soil.

For subirrigation with a constant evapotranspiration rate at the surface, the steady state water table takes the general shape given in

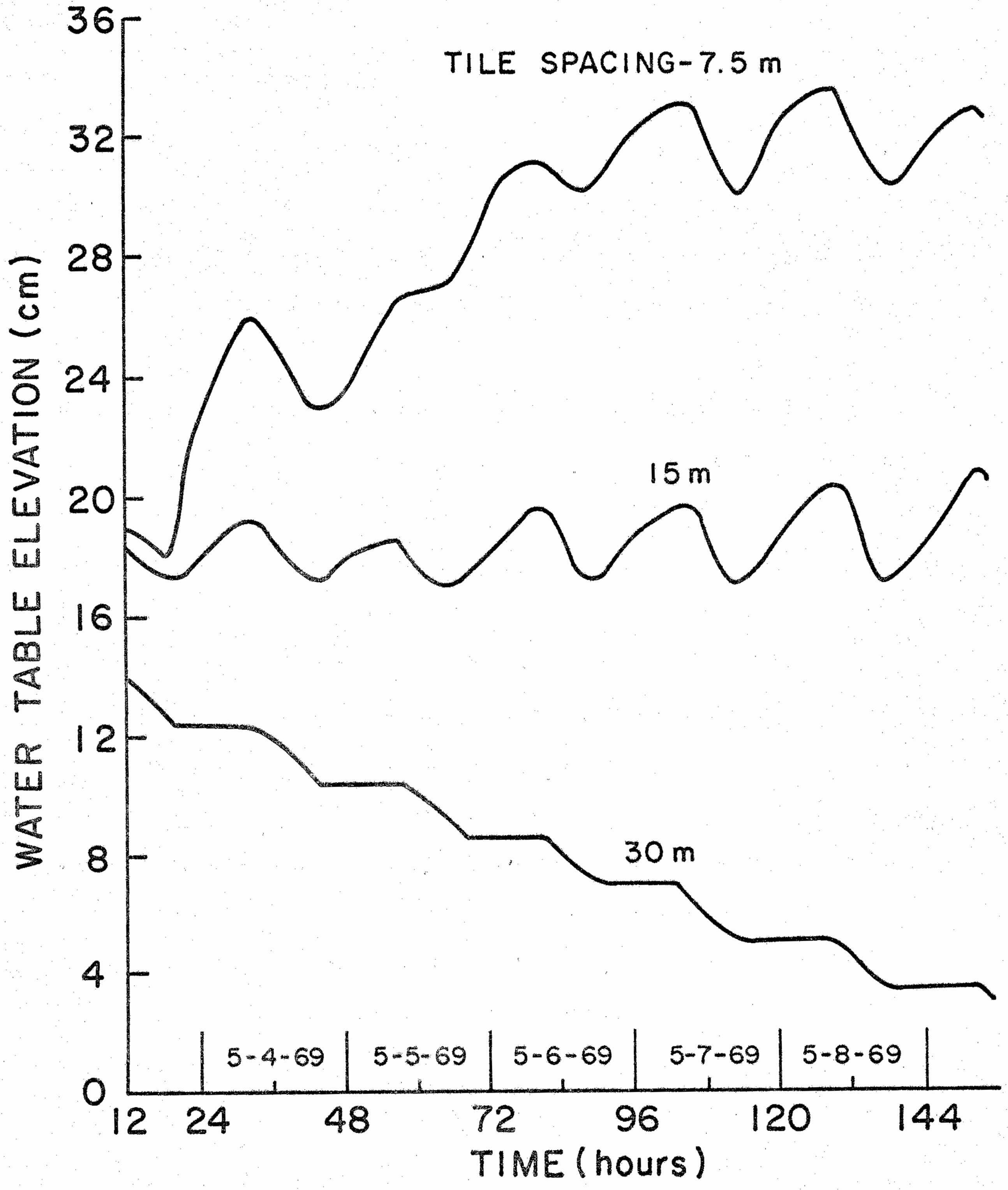

Figure 15. Water table response to subirrigation on a Lumbee sandy loam.

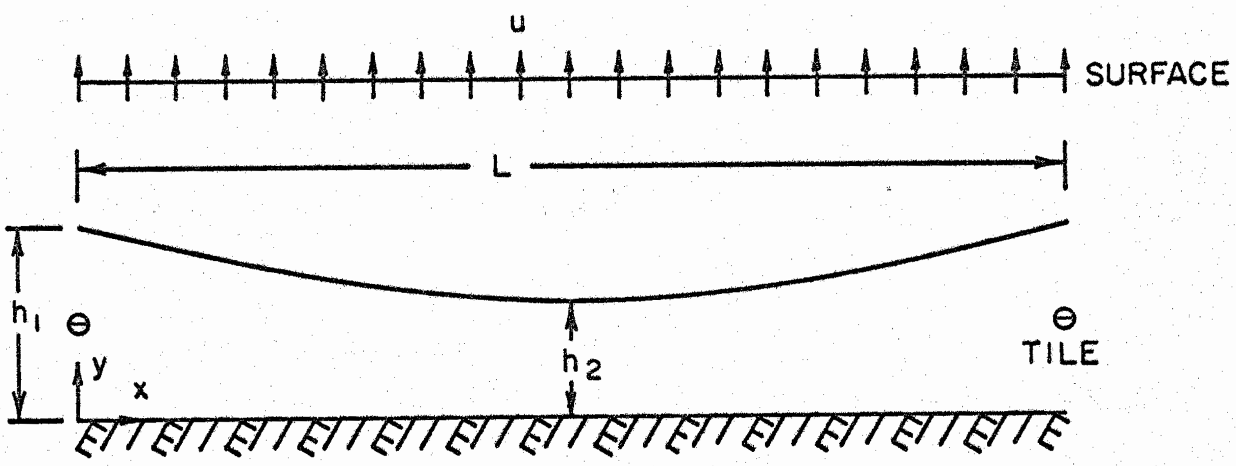

Figure 16. Schematic of the water table during subirrigation.

Figure 16. An exact description of the water table would require solving the Laplace equation for combined saturated and unsaturated flow by analog or numerical methods (e.g. Bouwer, 1959; Sewell and van Schilfgaarde, 1963). However, Fox et al. (1956) used the Dupuit-Forchheimer assumption to derive an approximate algebraic expression describing the water table. The equation may be written in the following form to determine the drain or ditch spacing required to give a maximum difference, h_1-h_2 in the water table elevation directly over and midway between the tile lines,

$$L = \left[\frac{4K}{u} \left(h_1^2 - h_2^2\right) \right]^{\frac{1}{2}} , \qquad (5)$$

where L is the distance between drain lines, K is the hydraulic conductivity, u is the evapotranspiration rate, h_1 and h_2 are the distances of the water table above the impermeable layer at the drain line and midway between the drain lines, respectively.

The suitability of equation 5 for design purposes was checked using the data given in Figure 15. An evapotranspiration rate of

$u = .60$ cm/day was assumed (Schwab et al., 1966). An average value of $K = 4.2$ cm/hr was determined from soil cores. Because the bottom of the control gate was approximately 25 cm above the impermeable layer, this value was added to the elevations given in Figure 15 to determine h_2. The water table at the drain lines was assumed to be at the same elevation as that in the outlet ditch, $h_1 = 65$ cm above the impermeable layer. When these values were substituted into equation 5, theoretical drain spacings of 8.5 and 12.6 m were calculated for actual spacings of 7.5 and 15 m, respectively.

Because the evapotranspiration rate was not measured and because the hydraulic conductivity determined from cores is often different from the effective field value, equation 5 was used to obtain a ratio K/u which would predict the correct drain spacing for the 15 m spacing. This K/u value of 237 gave a predicted spacing of 10.1 m for the 7.5 m spacing. A theoretical spacing was not calculated for the 30 m case because equilibrium conditions were not established at the midpoint. When equation 5 was solved for an h_2 that would result in an equilibrium condition for the 30 m spacing, it was found that the water level at the midpoint would be below the impermeable layer. Further, equation 5 with $K/u = 237$ shows that it would be necessary to hold the water level in the ditch 88 cm above the bottom of the gate to maintain an elevation of 18 cm midway between the 30 m lines. Then the water table depth would vary from 27 cm directly over the drain lines to 97 cm at the midpoint.

The design spacing for this soil can be computed by choosing an optimum water table depth and a maximum allowable variation. Van Hoorn's data (Williamson and Kriz, 1970) shows an optimum water table depth of between 60 and 90 cm for potatoes. Using these limits for the water table depth with values of $h_1 = 80$ and $h_2 = 50$ cm and solving equation 5 for L, the calculated design spacing is L = 19.2 m.

The results of a test to determine the response of the water table to an increased water level in the ditch are given in Figures 17 and 18 for drain spacings of 15 and 30 m. Prior to the beginning of the test which was conducted while the soil was fallow, the profile was draining with a water table elevation of 12-20 cm above the tile for both the 15 and 30 m spacings. At time zero, the water level in the ditch was raised to 65 cm and held within 5 cm of that elevation for 5 days.

Observed profiles for both the 15 and 30 m spacings showed a slow transition from a concave downward to a concave upward shape and then a rather uniform upward movement of the water table with a relatively small slope inward from the drain lines. During the transition period for the 30 m spacing, the profile midway between adjacent drain lines continued to drain with a total drop in the water table at the midpoint of 2 cm. The water table also dropped at the piezometer banks located 5 m from the observation well before beginning to move slowly upward after 21 hours. It was 74 hours before the water table at the midpoint between drain lines responded to subirrigation. Between times of 74 and 105 hours, the water table at this point rose by 6 cm.

Water table response to subirrigation was more rapid for the 15 m spacing (Figure 17). Initially, the draining profile was nearly level after 10 hours and began to move upward at the midpoint after 21 hours. Between 21 and 95 hours, the water table at the midpoint rose a total

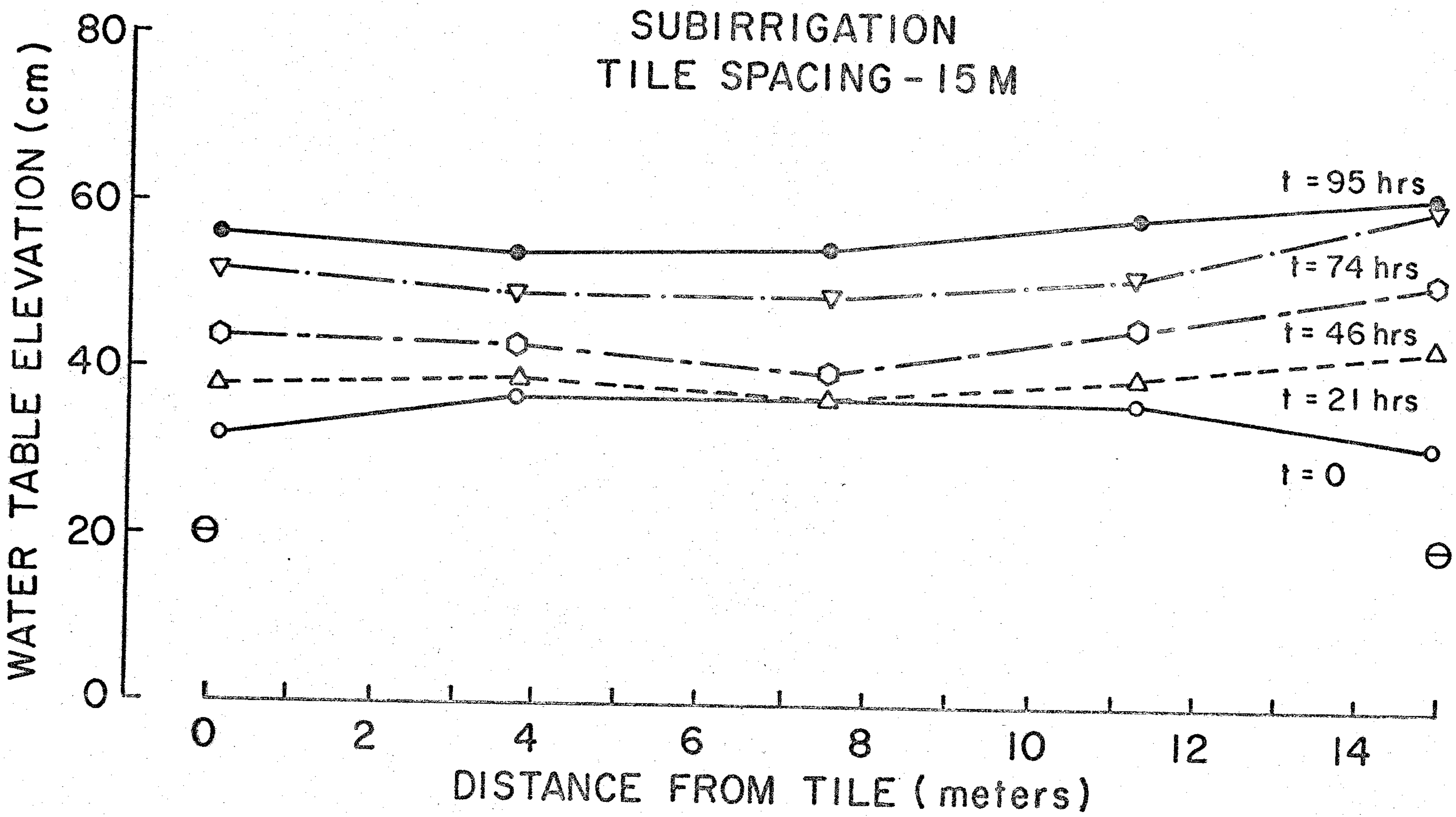

Figure 17. Water table profiles for subirrigation through drain lines spaced at 15 m on a Lumbee sandy loam.

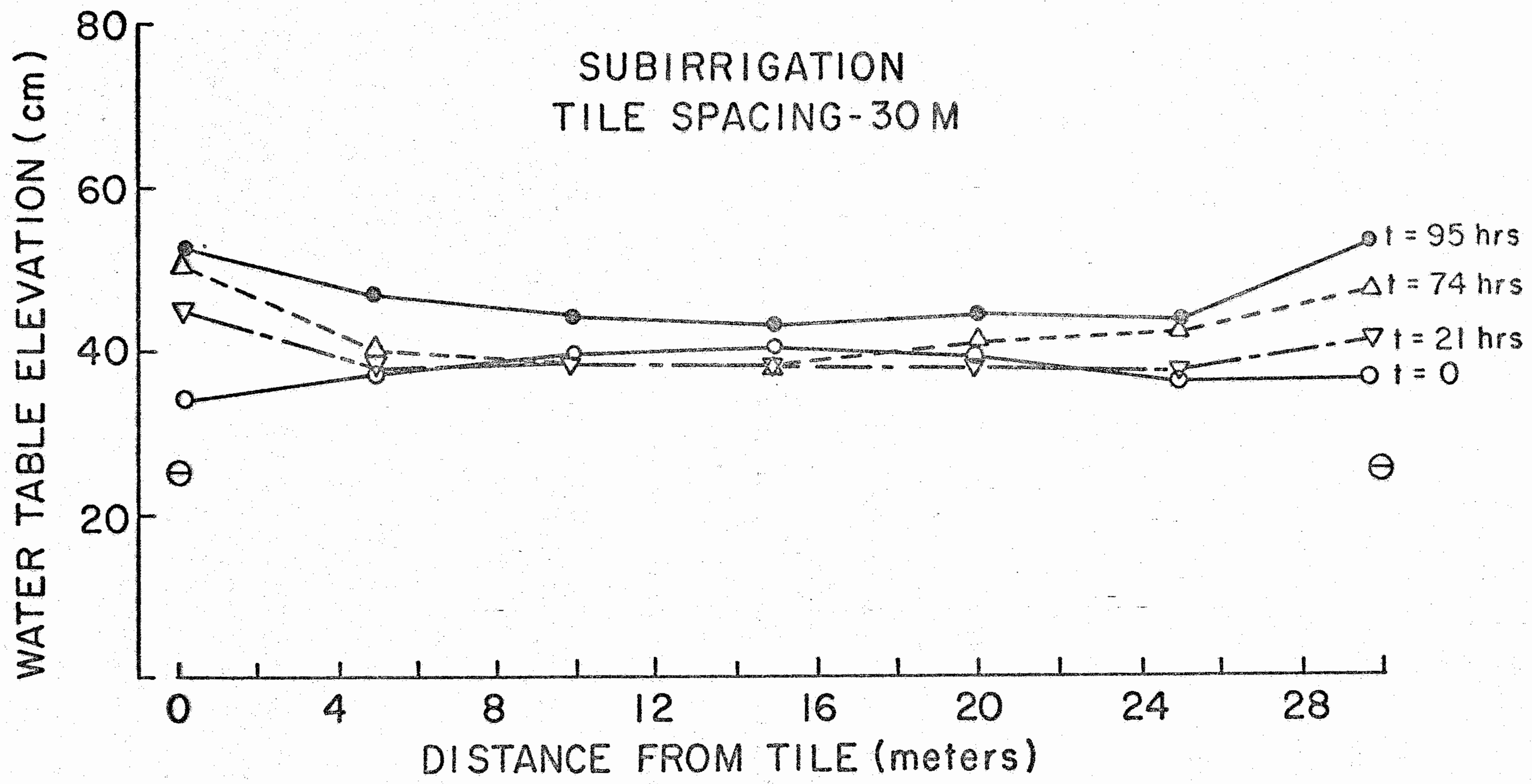

Figure 18. Water table profiles for subirrigation through drain lines spaced at 30 m on a Lumbee sandy loam.

of 22 cm.

An equation to characterize the upward movement of the water table under subirrigation conditions was derived using the methods of Bouwer and van Schilfgaarde (1963). If the water table rises without change of shape, the flux per unit area is uniform and can be expressed by

$$\frac{dm}{dt} = \frac{u}{f} , \qquad (6)$$

where m is the height of the water table above the center of the drain at the midpoint between drains, t is time, u is the instantaneous subirrigation rate or upward flux (units of length/time), and f is the fillable porosity. Then a steady state relationship such as equation 5, which also assumes a uniform flux, can be used in equation 6 to describe the rate of rise. Solving equation 5 for u, substituting into equation 6, and integrating between t_o, m_o and t, m yields

$$t - t_o = \frac{fL^2}{8K(d + y_1)} \ln \left(\frac{2d + y_1 + m}{y_1 - m} \Big/ \frac{2d + y_1 + m_o}{y_1 - m_o} \right) , \qquad (7)$$

where m_o is the water table elevation at $t = t_o$, y_1 is the elevation of the water in the outlet ditch, and d is distance from the center of the tile to the impermeable layer.

It is obvious from Figures 17 and 18 that the upward flux was not uniform during the initial period of subirrigation when the water table at the midpoint was stationary or still moving downward. Neither will it be uniform for large times when the water table directly over the drain has reached the controlled water level in the outlet ditch, but is still rising at the midpoint. Bouwer and van Schilfgaarde (1963) treated similar situations for the drainage case by introducing a correction factor, C, and writing equation 6 as

$$u = fC \frac{dm}{dt} , \qquad (8)$$

where C is considered as the ratio of the average upward flux to the flux midway between the drains. C would also be introduced in the numerator of the right side of equation 7. Because the upward flux at the midpoint is zero, the factor C is undefined for the initial period of subirrigation. Thus, equation 7 is only valid after the water table assumes a level or concave upward shape and begins to rise.

A plot of the observed and calculated rise of the water table at the midpoint between adjacent drain lines is given in Figure 19. The calculated curves were obtained from equation 7 by choosing t_o as the time the water table assumed an approximately level shape in the transition period from drainage to subirrigation. The t_o values chosen were 0, 10, and 21 hours with corresponding m_o values of 0, 16, and 16 cm for the 7.5, 15, and 30 m spacings, respectively. The values of the other parameters in equation 7 were $K = 4.2$ cm/hr, $f = .095$, $d = 51$ cm, and $y_1 = 44$ cm. The water table elevations are plotted with reference to the center of the drain lines which is 21 cm above the bottom of the water level control gate.

Relatively good agreement between the observed and calculated results was obtained for all three drain spacings. The largest deviations occurred for small times when there was a lag before the water table at the midpoint began to move upward. Because equation 7 was derived under the assumption of uniform upward flow, the lag is not reflected in the calculated curves. While further development is needed to characterize the lag at the midpoint and to evaluate the

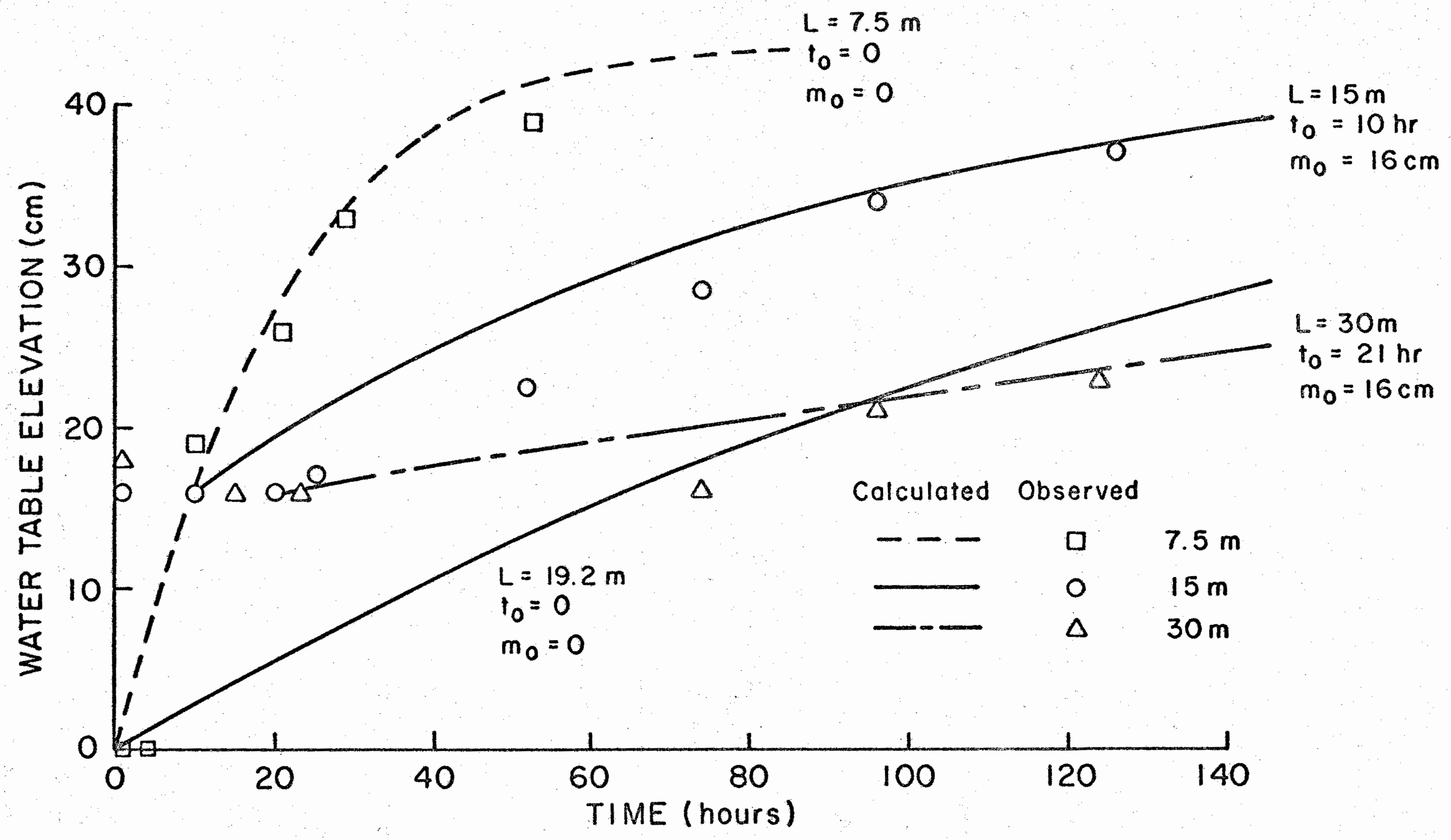

Figure 19. Water table elevation versus time at the midpoint between adjacent drain lines for a Lumbee sandy loam.

equation under other boundary conditions, it appears adequate at present for design use providing reliable estimates of the soil properties can be obtained.

A curve for the water table rise for the calculated design spacing of 19.2 meters is also plotted in Figure 19. Assuming a maximum water table depth of 90 cm, which is approximately 4 cm above the center of the drain line, equation 3 gives a required rise time from an initially level water table of 14 hours. Then, assuming the lag time not accounted for by equation 3 is 15 hours, approximately 29 hours would be required to establish optimum subirrigation conditions. Therefore subirrigation with tile spacings of 19.2 m appears to be feasible for this soil. By raising the water in the outlet ditch to 65 cm above the bottom of the control gate, the water table could be raised at a point midway between drain lines to within 90 cm of the surface in about 29 hours. Then the water in the outlet ditch could be lowered to an elevation of 55 cm and a steady state water table with a depth varying from 60 cm directly above drain lines to 90 cm midway between drain lines would be established.

Drainage. It has already been noted that the drainage requirement is critical when rain occurs during subirrigation because a high water table elevation reduces the storage available for infiltrating water and results in a pronounced rise due to the rainfall. The response of the water table to rainfall as measured at the midpoints of the three drain spacings is shown in Figure 20a. These observations were made one day after a subirrigation test in which the water table had been held in the 60 cm range for 2 days. Immediately prior to the beginning

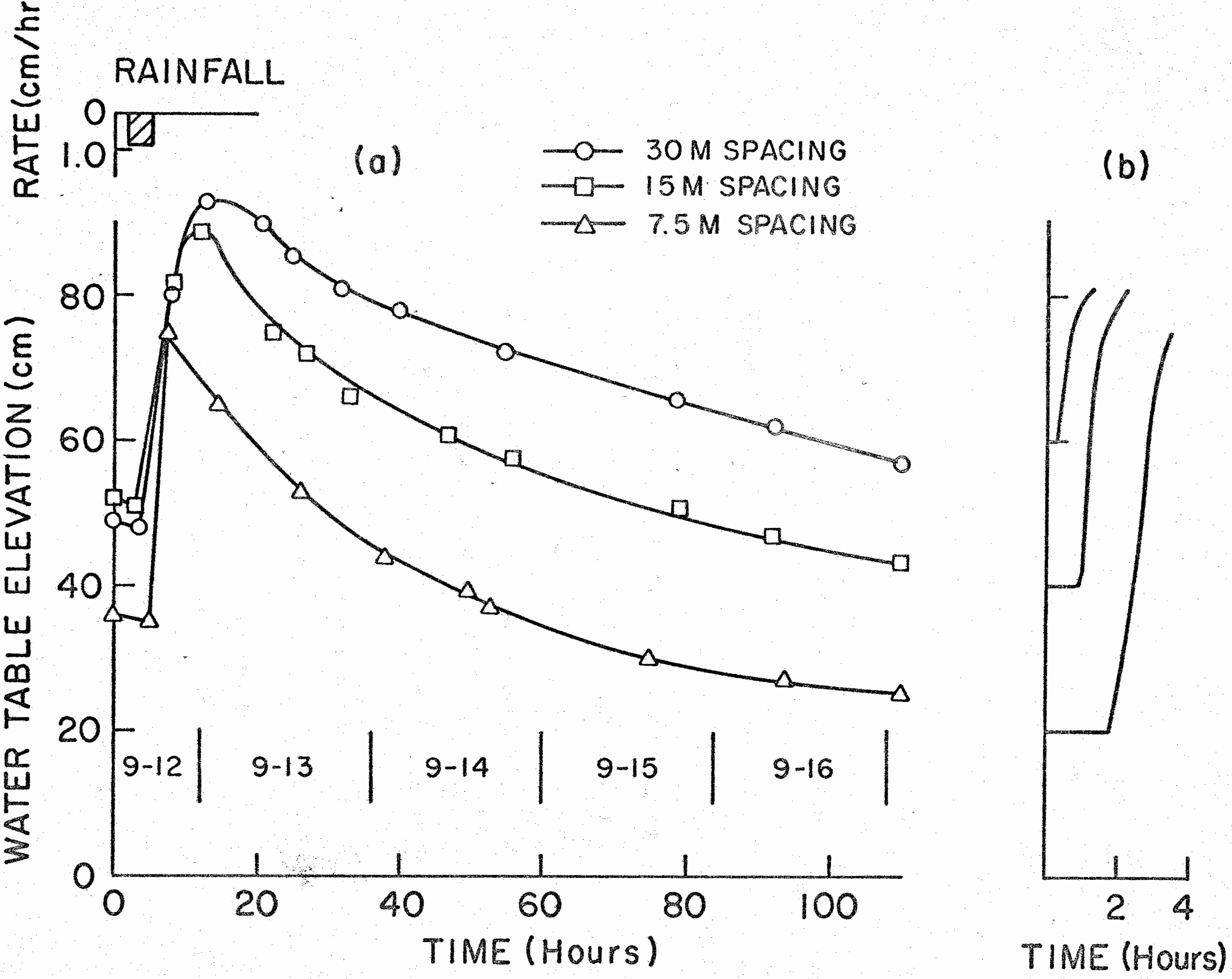

Figure 20. (a) Observed water table response to rainfall infiltration and subsequent drainage in a Lumbee sandy loam.
(b) Predicted water table response to infiltration for a Lumbee sandy loam.

of rainfall the soil was draining and the water table elevations were 35, 51, and 49 cm for the 7.5, 15, and 30 m spacings, respectively. Rainfall occurred at a nearly constant rate over a 3.25 hour period with the total volume being 2.82 cm. The water table for the 15 and 30 m spacings began to rise after about 1.5 hours of rainfall and had total increases in elevation of 37 and 41 cm, respectively, after 7 hours. Due to the lower initial water table elevation for the 7.5 m spacing, the water table did not respond until about 2.6 hours after initiation of rainfall. However, the rise in elevation of 38 cm in 3.2 hours is larger and more rapid than would be expected based on the results for the 15 and 30 m spacings. The observation well data shown in Figure 20a were in agreement with piezometer readings taken both before and after the rainfall event.

In order to determine if the observed rise in the water table was consistent with the theory of soil-water movement, the Richards equation (Swartzendruber, 1966) for one-dimensional vertical flow was solved for initial water table elevations of 20, 40, and 60 cm. A constant flux was assumed at the top boundary and the soil was assumed to be drained to equilibrium above the water table at time zero. The other input data were the soil-water characteristic and the hydraulic conductivity function which was calculated by the procedure of Millington and Quirk (1960) with a matching factor at saturation as suggested by Kunze, et al. (1968). The Richards equation was solved numerically by the INFIL3 computer program described by Skaggs, Monke, and Huggins (1970). The solutions are given in Figure 20b. The predicted infiltration volumes were 1.4, 3.2, and 5.3 cm for initial water table elevations of 60, 40, and 20 cm respectively. As expected the predicted lag time before the water table begins to rise decreases and the rate of rise increases with initial water table elevation. Because profile layering was not considered in the numerical solutions, the results cannot be compared directly with measured values. However, the solutions are similar in form to the observed results. Furthermore, for an initial water table elevation of 40 cm, an infiltration volume of 3.2 cm gave a predicted rise of nearly 40 cm which is consistent with the field observations.

Water table profiles determined from piezometer and observation well measurements during drainage are plotted in Figure 21 for the 30 m drain spacing. These results are from the same test represented in Figure 20a with a shift in the time axis such that the profile denoted by t = 0 in Figure 21 occurred at t = 23 hrs in Figure 20a. The water table profile was relatively flat and had essentially a constant shape during the entire period of observation. Similar profiles were observed for the 15 and 7.5 m spacings.

The relative drawdown rates for 7.5, 15, and 30 m spacings as recorded in wells 4, 5, and 6 are given in Figure 20a. Drawdown data were also recorded in wells 1, 2, and 3 for the same time period. Additional drawdown data were obtained for several other drainage periods during 1970 and 1971. Drain spacings were predicted from water table elevation records of the type given in Figure 20a by using the drawdown observed for a given time increment in equations 1-4 given in the INTRODUCTION. The impermeable layer was assumed to be 140 cm below the soil surface and the value of d was calculated from the slope of

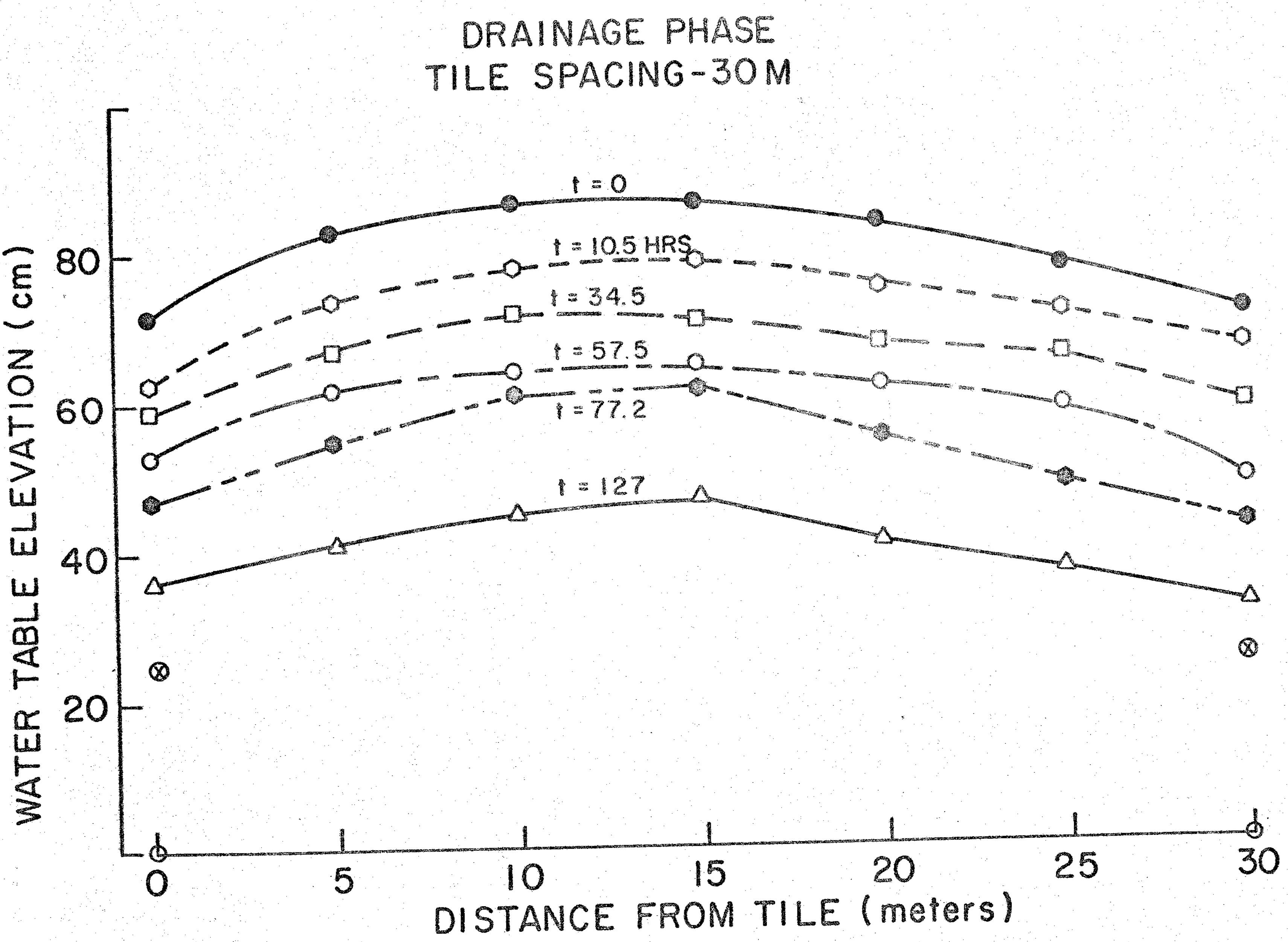

Figure 21. Water table profiles during drainage for 30 m drain spacing in a Lumbee sandy loam.

the drain line and the distance between the ditch and the observation well. Then, m_o and m were determined from water table elevation records. Eight cases were considered for the 7.5 m spacing and six cases each for the 15 and 30 m spacings.

The drainable porosity was calculated from the soil-water characteristic by assuming that the soil above the water table was always drained to equilibrium. It was determined as a function of initial and final water table depths and is plotted in Figure 22. The drainable porosity ranged from 0.045 to 0.10 for the tests analyzed in this study. Because drain spacing calculations are usually made with a constant drainable porosity, an average value of f = 0.079 was also used to determine the predicted drain spacing for each test.

The initial and final water table elevations at the midpoint, soil properties, and calculated drain spacings for all tests are presented in Table 1. Three calculations of the theoretical drain spacing were made with each equation for each test. One calculation was made with the measured conductivity of K = 4.2 cm/hr and the drainable porosity as determined from Figure 22. However, because the hydraulic conductivity measured on cores is often considerably different from the effective field values, hydraulic conductivities were determined by forcing the respective equations to predict the 15 meter spacing. Hydraulic conductivities (K') of 2.5, 2.8, 3.3, and 0.92 cm/hr were determined by this procedure for the van Schilfgaarde (1963), Bouwer and van Schilfgaarde (1963), Glover (Dumm, 1954), and Hammad (1962) equations, respectively. These K' values were used to determine two theoretical drain spacings; one with the drainable porosity obtained from Figure 22 and one with an average drainable porosity, f = 0.079.

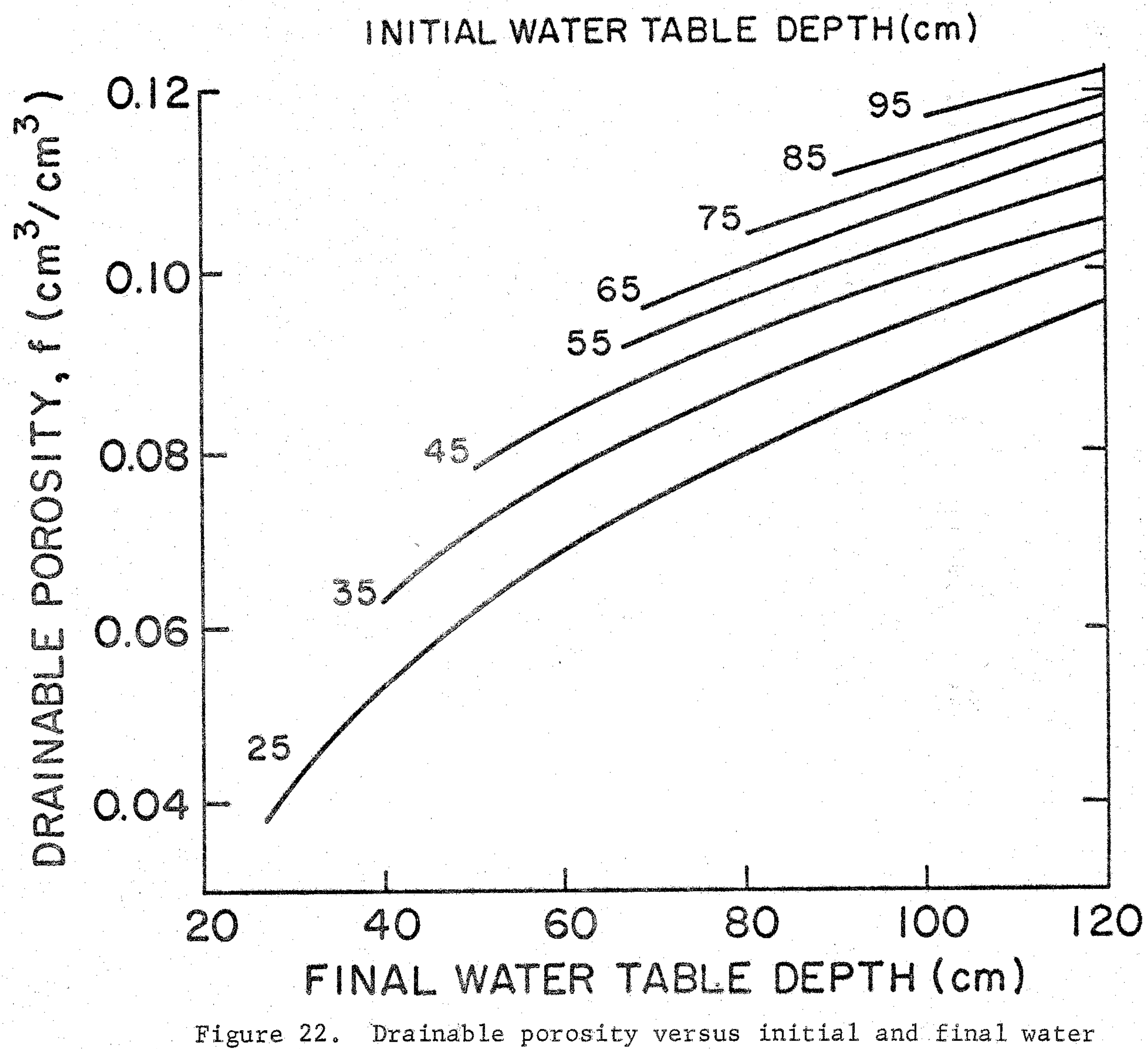

Figure 22. Drainable porosity versus initial and final water table depths for a Lumbee sandy loam.

Table 1. Drawdown data and computed drain spacings.

										Calculated spacings (meters)		
TEST	WELL	d (cm)	m_o (cm)	m (cm)	Δt (Hrs)	Actual spacing (meters)	K (cm/hr)	f (cm^3/cm^3)	van Schilfgaarde *	Bouwer and van Schilfgaarde	Glover	Hammad
1	1	62	56	24	48	7.5	4.2	.089	13.9(85)	13.1(75)	13.6(81)	25.8(244)
							K'	.089	10.8(44)	10.7(43)	12.0(60)	8.6(15)
							K'	.079	11.4(52)	11.3(51)	12.5(67)	9.3(24)
2	1	62	30	14	48	7.5	4.2	.103	12.9(72)	12.2(63)	12.2(63)	25.0(233)
							K'	.103	10.1(35)	9.9(32)	10.7(43)	8.3(11)
							K'	.079	11.4(52)	11.2(49)	12.1(61)	10.0(33)
4	1	62	48	16	48	7.5	4.2	.095	11.5(53)	10.8(44)	11.6(55)	20.1(168)
							K'	.095	8.9(19)	8.8(17)	10.2(36)	6.8(-9)
							K'	.079	9.7(29)	9.6(28)	11.1(48)	7.8(4)
5	1	62	44	25	48	7.5	4.2	.093	16.5(120)	14.5(93)	14.9(99)	34.1(350)
							K'	.093	12.8(71)	12.5(67)	13.2(73)	11.1(48)
							K'	.079	13.8(84)	13.6(81)	14.1(88)	12.4(65)
1	4	51	48	12	48	7.5	4.2	.079	10.2(36)	9.7(29)	10.8(44)	19.4(159)
							K'	.079	8.0(7)	7.7(3)	9.5(27)	6.6(-12)
							K'	.079	7.9(5)	7.7(3)	9.4(25)	6.6(-12)
2	4	51	31	10	48	7.5	4.2	.090	10.3(36)	9.8(30)	10.4(39)	20.5(173)
							K'	.090	8.0(7)	7.8(4)	9.1(21)	7.0(-7)
							K'	.079	8.5(13)	8.3(11)	9.6(28)	7.6(1)
5	4	51	34	13	48	7.5	4.2	.084	11.8(57)	11.1(48)	11.6(55)	24.5(226)
							K'	.084	9.2(23)	9.0(20)	10.2(36)	8.1(8)
							K'	.079	9.3(24)	9.2(23)	10.4(39)	8.5(13)

Table 1. cont.

TEST	WELL	d (cm)	m_o (cm)	m (cm)	Δt (Hrs)	Actual spacing (meters)	K (cm/hr)	f (cm^3/cm^3)	van Schilfgaarde	Bouwer and van Schilfgaarde	Glover	Hammad
6	4	51	27	6	48	7.5	4.2	.092	6.9(-8)	6.5(-13)	7.1(-5)	11.6(55)
							K'	.092	5.3(-29)	5.2(-30)	6.2(-17)	4.3(-43)
							K'	.079	5.7(-24)	5.6(-25)	6.7(-11)	4.7(-37)
1	2	62	49	32	48	15	4.2	.089	19.8(32)	18.7(25)	17.0(13)	44.0(190)
							K'	.089	15.4(3)	15.1(1)	15.1(1)	13.9(-7)
							K'	.079	16.2(8)	16.0(7)	15.9(6)	11.2(-25)
2	2	62	36	19	48	15	4.2	.089	14.7(-2)	13.8(-8)	13.5(-10)	29.5(97)
							K'	.099	11.4(-24)	11.1(-26)	11.9(-20)	9.7(-35)
							K'	.079	12.7(-15)	12.5(-17)	13.4(-11)	12.6(-16)
4	2	62	52	37	48	15	4.2	.086	22.8(52)	21.5(43)	18.7(25)	54.2(260)
							K'	.086	17.7(18)	17.4(16)	16.5(10)	16.8(12)
							K'	.079	18.4(23)	18.2(21)	17.2(15)	17.9(19)
1	5	51	54	29	48	15	4.2	.063	19.2(28)	18.1(21)	17.9(19)	47.1(214)
							K'	.063	15.0(0)	14.7(-2)	15.8(5)	14.8(-1)
							K'	.079	13.2(-12)	13.1(-13)	14.2(-5)	15.2(+1)
2	5	51	45	31	48	15	4.2	.060	23.7(58)	22.4(49)	19.9(33)	67.2(350)
							K'	.060	18.5(23)	18.2(21)	17.6(17)	20.5(37)
							K'	.079	16.0(7)	15.8(5)	15.3(2)	16.7(11)
3	15	47	40	26	46	15	4.2	.082	17.6(17)	16.6(11)	15.2(1)	45.0(200)
							K'	.082	13.7(-9)	13.4(-11)	13.5(-10)	14.2(-5)
							K'	.079	13.9(-7)	13.7(-9)	13.7(-9)	14.6(-3)
1	3	62	61	44	48	30	4.2	.055	29.8(-1)	28.1(-6)	24.3(-19)	80.3(168)
							K'	.055	23.2(-23)	23.0(-23)	21.5(-28)	24.1(-20)
							K'	.079	19.2(-36)	19.0(-37)	17.8(-41)	18.4(-39)

Table 1. cont.

TEST	WELL	d (cm)	m_o (cm)	m (cm)	Δt (Hrs)	Actual spacing (meters)	K (cm/hr)	f (cm^3/cm^3)	van Schilfgaarde	Bouwer and van Schilfgaarde	Glover	Hammad
4	3	62	62	44	48	30	4.2	.075	24.9(-17)	23.5(-22)	20.6(-31)	60.1(100)
							K'	.075	19.4(-35)	19.1(-36)	18.2(-39)	18.5(-38)
							K'	.079	18.7(-38)	18.6(-38)	17.7(-41)	17.8(-41)
5	3	62	61	48	48	30	4.2	.073	30.4(1)	28.7(-4)	22.9(-24)	82.1(174)
							K'	.073	23.6(-21)	23.3(-22)	20.3(-32)	24.1(-20)
							K'	.079	22.5(-25)	22.3(-26)	19.4(-35)	23.3(-22)
1	6	51	56	42	48	30	4.2	.048	31.5(5)	29.6(-1)	24.9(-17)	99.6(230)
							K'	.048	24.5(-18)	24.1(-20)	22.0(-27)	29.6(-1)
							K'	.079	18.9(-37)	18.7(-38)	17.1(-43)	20.3(-32)
2	6	51	54	33	48	30	4.2	.053	22.4(-25)	21.1(-30)	20.0(-33)	59.3(100)
							K'	.053	17.4(-42)	17.1(-43)	17.7(-41)	18.2(-40)
							K'	.079	14.1(-53)	14.0(-53)	14.4(-52)	13.6(-58)
5	6	51	71	50	48	30	4.2	.051	28.6(-5)	27.0(-10)	23.9(-20)	80.6(+170)
							K'	.051	22.3(-26)	22.0(-27)	23.0(-23)	24.3(-19)
							K'	.079	17.7(-41)	17.6(-41)	16.9(-44)	17.5(-42)

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*Numbers in parentheses represent the percentage differences between calculated and actual spacings.

The averages of the calculated drain spacings are given in Table 2. When the measured K = 4.2 cm/hr was used, the predictions given by the Hammad equation were two to three times higher than the actual spacings. The other three equations gave better agreement but still gave high predictions for the 7.5 and 15 m spacings and low predictions for the 30 m spacing. When K' values were used, the spacings calculated from all equations were reduced. This resulted in improved predictions for the Hammad equation at all spacings and for the other three equations at spacings of 7.5 and 15 m. There were larger differences between the calculated and actual values for the 30 m spacing when K' rather than when K = 4.2 cm/hr was used. The use of a constant drainable porosity, f = 0.079, increased the difference between the calculated and actual spacings for all equations.

In order to determine the equation giving the best results, variations of 10, 20, and 30 percent from the actual drain spacings were computed. The number of times results given by each equation fell within the variations is shown in Table 3. A variation of 20 percent seems reasonable as a basis for comparing the equations because of the difficulties encountered in measuring the hydraulic conductivity. When K' is used, the order of preference of the equations is: (1) Hammad, (2) Bouwer and van Schilfgaarde, (3) van Schilfgaarde, and (4) Glover. The order is the same for both the measured and average drainable porosities. When the measured K = 4.2 cm/hr is used, the Hammad equation ranks last while the order of the other equations remains the same as above.

The errors in the drain spacings calculated with the Bouwer and

Table 2. Averages of calculated drain spacings.

Actual Spacing (meters)	K (cm/hr)	f (cm^3/cm^3)	Average Calculated Spacing (meters) van Schilfgaarde	Bouwer and van Schilfgaarde	Glover	Hammad
7.5	4.2	Fig. 6	11.7	11.0	11.5	22.6
	K' *	Fig. 6	9.1	9.1	10.2	6.8
	K' *	.079	9.7	9.8	10.9	8.4
15	4.2	Fig. 6	19.6	18.5	17.0	47.8
	K' *	Fig. 6	15.0	15.0	15.0	15.0
	K' *	.079	15.1	15.1	15.1	15.3
30	4.2	Fig. 6	27.9	26.3	22.8	72.9
	K' *	Fig. 6	21.7	21.8	20.5	23.3
	K' *	.079	18.5	18.6	17.4	18.5

* K' values were determined for each equation such that the average predicted spacing would be correct for the 15 m case. The k' values used were 2.5, 2.8, 3.3, and 0.93 cm/hr for the van Schilfgaarde, Bouwer and van Schilfgaarde, Glover, and Hammad equations, respectively.

Table 3. Variation of calculated drain spacing.

	K	f	No. within given percentage error		
	(cm/hr)	(cm^3/cm^3)	10%	20%	30%
van Schilfgaarde	4.2	Fig. 6	6	8	11
	K'	Fig. 6	5	8	15
	K'	.079	4	7	11
Bouwer and van Schilfgaarde	4.2	Fig. 6	5	9	13
	K'	Fig. 6	4	9	14
	K'	.079	4	7	12
Glover	4.2	Fig. 6	3	8	10
	K'	Fig. 6	4	7	12
	K'	.079	4	7	9
Hammad	4.2	Fig. 6	0	0	0
	K'	Fig. 6	7	14	14
	K'	.079	4	9	12

van Schilfgaarde, van Schilfgaarde, and Glover equations appear to be due to convergence near the drain tubes. As was already noted, Hooghoudt's equivalent depth (van Schilfgaarde, 1963) is normally used in equations derived using the Dupuit-Forchheimer assumptions in order to compensate for radial flow near the drains. However, for the range of d in this study, Hooghoudt's equivalent depth as determined from Bouwer and van Schilfgaarde (1963) is approximately equal to the actual depth to the impermeable layer, and presumably no correction for radial flow is necessary. Nevertheless, there is evidence that the difference between the actual spacings and those calculated using the Bouwer and van Schilfgaarde, van Schilfgaarde, and Glover equations could be due to convergence near the drains.

Piezometric measurements such as those plotted in Figure 21 indicated that even though the drain was flowing with no back pressure, it was not always intersected by the water table. Furthermore, these measurements showed that a large portion of the total drop in hydraulic head occurred close to the drain. Because a larger percentage of the flow is radial for the closer drain spacings, failure to compensate for convergence in the determination of K' and subsequent calculations for the spacings given in Table 1 resulted in predicted values that were too high for the 7.5 m spacing and too low for the 30 m spacing. Therefore, if convergence at the drain were properly accounted for, there would probably be closer agreement between actual and predicted drain spacings. The convergence of flow at the drain is caused in part by the restriction between tile joints (Kirkham, 1950). This effect was also noted by Hoffman and Schwab (1964) in their procedure for using drain outflow to determine values for the hydraulic conductivity. Because Hooghoudt's equivalent depths are based on a completely open drain, the effect of the crack restriction is not considered. This effect may not be as critical for the plastic tubing now used for agricultural drainage because the drain openings are of uniform width and are more closely spaced along the tube.

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GLOSSARY OF SYMBOLS

Symbols	
C	correction factor - ratio of the average flux between drains to the flux midway between drains
D	$d + m_o/2$ (L)
d	distance of the drain tube above the impermeable layer (L)
f	drainable or fillable porosity
h_1	distance of the water table above the impermeable layer at the drain line (L)
h_2	distance of the water table above the impermeable layer midway between drain lines (L)
K	hydraulic conductivity (L/T)
L	drain spacing (L)
m	distance of the water table above the drain lines at the midpoint between adjacent drains for $t = t$ (L)
m_o	distance of the water table above the drain lines at the midpoint between adjacent drains for $t = 0$ (L)
r	radius of the drain tube (L)
t	time (T)
u	evapotranspiration rate (L/T)