RELATIONSHIP OF SOIL MOISTURE DIFFUSIVITY TO DRAINAGE LATERAL SPACING FOR NON - STEADY GROUND WATER FLOW

Thesis for the Degree of M. S.

MICHIGAN STATE UNIVERSITY

ISMAEL OBWOYA UMA

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ABSTRACT

RELATIONSHIP OF SOIL MOISTURE DIFFUSIVITY TO DRAINAGE LATERAL SPACING FOR NON-STEADY GROUND WATER FLOW

By

Ismael Obwoya Uma

The purpose of this investigation was to relate the drainage lateral spacing to soil moisture diffusivity. The assumption made in the study was that ground water flow was a non-steady phenomenon. The investigation was conducted on four plots with different drainage treatments as follows: surface only, tiles only, both tiles and surface, and plastic tiles only. The Toledo Silty Clay soil covered 85 percent of the plots. The Fulton Silty Clay soil covered the remaining 15 percent.

The following measurements were taken from each plot: Tile and surface flow, water table heights above tile drains, soil moisture suctions at 6, 12, 18 and 24 inches soil depths, and the volumetric percentage soil moisture content. The hydraulic conductivity was measured by single auger hole method from plots B and E at 1, 2, 3, 4 and 5 feet soil depths.

From the work of Van De Leur (1958), a model was derived relating drainage lateral spacing to soil moisture

Ismael Obwoya Uma

diffusivity for non-steady ground water flow. The measurements were used to compute the drainage spacing for each plot. The calculated values were within the range recommended for the Toledo Silty Clay Soil. The study also yielded the following information:

1. The hydraulic conductivity of the soil in the plow layer was very high, but it dropped off rapidly after one foot soil depth.
2. The rate of drop of the water table above the tile drains was rapid within the first three days after precipitation. Thereafter, the rate was small and almost constant.
3. The soil moisture suction varied with the position of the water table from the tensiometer cup.

Approved E H Kidder
Major Professor

Approved B A Stout
Department Chairman

Date Nov 19, 1970

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By

Ismael Obwoya Uma

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LIST OF SYMBOLS

a : Center of tile lines above impermeable layer

a_1: Radius of auger hole

b : Duration of steady percolation

b_1: Height of water table above impermeable layer mid-way between tile drains

d : Drain depth above impermeable layer

d_e: Equivalent soil depth to impermeable layer

D : Water table height above impermeable layer

D_e: Soil moisture diffusivity

D_m: Density of mercury

DC_m: Drainage coefficient in mm. per day

g : Acceleration due to gravity

h : Height of water table above impermeable layer

h_o: Water table height in drain above impermeable layer

H_o: Water table height mid-point between drains

h_m: Difference in elevation of mercury in manometer U-tube

H_w: Distance from cup to mercury/water interface

i : Hydraulic gradient

i_o: Index number in Visser's table

j : Reservoir--coefficient

K : Soil hydraulic conductivity

L : Drain spacing

M_e: Average moisture equivalent in percent

n_1: Initial water level in auger hole below water table

n_2: Final water level in auger hole below water table

n_e: Equivalent rate of discharge per unit area

p : Rate of percolation to the saturated zone

q : Rainfall (infiltration) rate under ponded conditions

q_t: Rate of ground water flow from two sides into a unit length of channel at time, t

r_o: Drain radius

R_d: Rate of drop of water table mid-way between tile drains, in feet per day

Q_1: Half total discharge from drain per unit length

t : Time

V : Flux of water

y : Water table height above impermeable layer at any point

y_1: Water table height above center of tile in cm.

$y_{L/2}$: Water table height at mid-point between drains

y_o: Initial water table height from drain axes

y_t: Water table height above a constant water level in outflow channels at time, t

Z : Auger hole depth below water table

γ : Density of water

θ : Volumetric percentage soil moisture content

τ : Soil moisture suction

μ : Drainable porosity

ϕ : Soil water potential

CHAPTER I

INTRODUCTION

Drainage forms an essential part of the farming practice in the humid areas of the world. In the United States, these fall largely within the thirty-one Eastern States. However, the installation of irrigation systems in the drier Western States also calls for the installation of adequate drainage network to handle the water flow and prevent the build-up of salinity.

The Drainage Committee of the American Society of Agricultural Engineers (1946), estimated that over one hundred million acres of crop land were drained, but that about thirty million of these needed additional drainage before they could grow normal crops. Wooten (1953), conducted a census which showed that drainage of agricultural lands was continually increasing in the Unided States.

Growing plants need both air and moisture in the root zones. However, excess water is detrimental to plant growth as it restricts the aeration of the soil in the root zones. In this condition, artificial subsurface drainage is necessary to control the ground moisture to a level which is suitable to maintain crop growth. Surface drainage removes ponded water from the soil surface and reduces the amount of water infiltrating into the soil profile. However, it is not as efficient as subsurface drainage in lowering the water table to create an aerated root zone.

The design of a drainage system for optimum plant growth should therefore take into account the following items:

1. The type of soil, which governs the movement of water through the soil profile.
2. The type of crop, which indicates the rooting behavior, tolerance to excess water and drought, and nutrient and water requirements.
3. Climatic conditions, which indicate the type and frequency of storms to be expected.
4. Soil and crop management practices.

Drainage requirement is generally based on a drainage coefficient. This is usually selected without regard to soil permeability, tile spacing and deep seepage, but is based on field studies and experience. Schilick (1918), measured the discharge from tiles and made the following recommendations for selecting drainage coefficients:

1. 5/16 to 3/8 inch for spacings more than 100 feet.
2. 1/2 inch or more for spacings of 50 feet.
3. Where surface water is to be removed, the drainage coefficient should be increased by 1/8 inch or more.

Lynde (1921), conducted similar studies and made the following recommendations for selecting drainage coefficients:

1. 1/4 inch for spacings of 100 feet or more.
2. 3/8 inch for spacings closer than 100 feet.

The present methods for drainage design are based on approximations. However, the results are sufficiently accurate for practical purposes. The accuracy could be improved if the design capacity of tiles were based on the factors which affect the flow to be removed, such as soil permeabilities, drainable porosities and water table heights.

The benefits of drainage of an agricultural land include the following:

1. Aeration of the soil which encourages extensive plant root development and stimulates microbiological activities.
2. Increase in soil temperature, and hence length of growing season, since it makes earlier planting possible.
3. Improvement in soil tilth due to reduced soil moisture levels and facilitation of harvesting operations due to drier conditions.
4. Removal of toxic substances such as salts which may retard plant growth.

5. Reduction of surface run-off which helps to maintain a low water table following rains.
6. Conservation of water and soil on farm lands.

Through these benefits, drainage enhances farm productivity by:

1. Increasing arable areas without extension of farm boundaries.
2. Improving crop yield and quality.
3. Assuring planting and harvesting at optimum dates.
4. Enhancing good soil management practices on the farm.

For proper soil moisture conditions and plant growth, the plant roots must be maintained in the available moisture range by lowering or raising the water table to an appropriate depth. This necessitates proper control of the rate of rise or drop of the water table in the soil by installing the tile drains at appropriate depth and spacing.

The main emphasis in drainage operation is to maintain the water table at an appropriate depth for easy extraction of moisture by plants. Thus, two limiting depths of the water table may be considered: an upper limit which permits sufficient diffusion of air to the roots, and a lower limit dictated by the water needs of the crops. In practice, however, it is not possible to comply with both demands completely, so that a compromise solution should be chosen when designing a drainage scheme.

For optimum crop production, drain depth and spacing should be based on the Potential Evapotranspiration at a period of critical moisture deficiency so that plants can receive an adequate supply of water throughout the growing season. The possibility that surface run-off reduces the amount of precipitation which may be useful to agriculture may also be taken into account in designing drain depth and spacing. However, no reliable formulae have yet been developed which incorporate the above factors as design parameters.

Luthin and Bianchi (1954), showed that a high water table close to the soil surface depresses root growth, and that roots do not generally penetrate deeper than to approximately 30 cm. above the water table. They also showed that the depression in yield due to too high water table was much greater than that resulting from too low water table. This was particularly true of clay soils which were poorly drained.

It has also been observed that during the growing season, under non-steady ground water flow, crops suffer more on undrained than on drained land during a dry spell. This is because in the spring, the water table is high on undrained land so that plant roots are confined to the surface layer of soil. Later on in the season, these roots will not be able to follow a receding water table. The rate of drop of the water table is very high in the spring and the soil dries out quickly so that the development of new roots is not possible, and stunted plant growth results.

Some additional harmful effects due to a high water table include: weed infestation, disease and difficulty in working the land.

1.1 Objectives

1. To investigate the reservoir--coefficient concept of non-steady ground water flow under an actual, practical drainage situation.
2. To relate the lateral drainage spacing to the reservoir--coefficient and soil moisture diffusivity.

CHAPTER II

REVIEW OF LITERATURE

In installing drainage systems in agricultural lands, the main emphasis is to control the water tables and movement of water through the soil so that an appropriate relationship is maintained between the crops and the water tables.

Land drainage for agricultural purposes has been practised since the Roman Empire and probably earlier. The Romans also used soils information to design their drainage schemes. They knew that deep and covered drains were superior to shallow and uncovered drains under certain conditions, Schwab (1957). Their methods of land drainage remained almost unimproved until the origin of present day tile drainage on the estate of Sir James Graham in England in 1810. Tiles were, however, used as early as 1620 in the Convent Garden at Maubeuge in France, but the practice did not become widespread, Schwab (1957).

Although the practice of land drainage dates from antiquity, its theoretical development started about 100 years ago with the work of Henry Darcy in France. He conducted an experiment in 1856 to investigate the potential gradient and the consequent water movement in saturated beds of sand. He confined his experiment to the case of vertical flow, and enunciated a law which still bears his name.

$$V = -ki \qquad (1)$$

where:

V = flux of water.

k = hydraulic conductivity of the soil.

i = hydraulic gradient.

This work was again not followed up vigorously until the past two decades when information began to appear in various scientific journals on the subject.

Interest in land drainage is keyed to the economic tenor of the times. In periods of low agricultural prices, little drainage work is accomplished. When the prices become high, the interest in drainage is rekindled and farmers install several miles of drains each year. Present day drainage techniques are an outgrowth of the trial and error methods used in the past. The use of approximations simplify the solutions to drainage design. The two assumptions made are that ground water flow occur under steady state and non-steady state conditions.

2.1 Steady State Flow

Two approximate solutions have been developed for designing drainage schemes under steady state conditions, based on the following assumptions:

1. Horizontal Flow.
2. Radial Flow.

The Horizontal Flow solution is based on the two assumptions proposed by Dupuit (1863):

1. That all streamlines in a system of gravity--flow towards a shallow sink are horizontal.

2. That the velocity along these streamlines is proportional to the slope of the free water surface, but independent of the depth.

Colding (1872), developed the ellipse equation which describes the shape of the water table above tile drains. Since then, Rothe (1924) and Kozeny (1932) developed it independently.

Forchheimer (1930), derived a general equation of continuity from the Dupuit assumptions to describe the free water surface:

$$\frac{\partial^2 h^2}{\partial x^2} + \frac{\partial^2 h^2}{\partial y^2} = 0 \qquad (2)$$

where: h = height of water table above impermeable layer.

Russel (1934), reviewed Rothe's work and published it in English. Hooghoudt (1937), used the Dupuit assumptions to develop the ellipse equation which describes the height of the water table between two parallel drains:

$$y^2 - h_o^2 = \frac{2Q_1X}{LK} (L-X) \tag{3}$$

where:

y = height of water table above impermeable layer at any point.

h_o = height of water table in drain above the impermeable layer.

Q_1 = half of total discharge from each drain per unit of length.

L = drain spacing.

K = hydraulic conductivity of the soil.

X = horizontal distance from the drain.

Drain spacing is given by:

$$L = 2K \frac{(H_o^2 - h_o^2)}{Q_1} \tag{4}$$

where:

H_o = water table height midpoint between the drains.

The ellipse equation is used in homogeneous soils to design ditches which penetrate to the impervous layer and those which do not. It is also reasonably accurate for spacing tile drains. It has been proved that the radial flow assumption yields satisfactory results when used to design ditches or tile drains with an impermeable layer at an infinite depth. Hooghoudt (1937), showed that the horizontal and radial flow assumptions yield satisfactory results when combined together. He prepared a set of tables for values of d_e for various values of γ_o, L, and d for use in equation (4), where:

d_e = equivalent soil depth to impermeable layer.

d = drain depth above impermeable layer.

L = drain spacing.

γ_o = drain radius.

d_e replaces h_o in equation (4) and H_o is measured from a fictitious impermeable layer.

Aronovici and Donnan (1946), not aware of the European work, gave the first derivation of the ellipse equation in American literature.

Muskat (1946), showed that the Dupuit--Forchheimer theory yields accurate results when used to determine the flux through a dam or towards a well. But, he argued that the shape of the free water surface and the velocity distribution are wrong when compared with more exact theoretical solutions. He rejected the theory entirely and credited its success to fortuitous coincidence rather than to reasonable approximations.

Van Deemter (1950) and Luthin and Gaskel (1950), developed the relaxation method for drainage design. Luthin and Gaskell's paper applies only to cases where the soil is flooded to the surface. They found the error in using the method was less than 4 percent. Van Deemter (1950), on the other hand, considered the water table as a curved flow boundary in developing the method.

Engelund (1951), verified that the Dupuit--Forchheimer theory was sifficiently accurate if its application was restricted to conditions in which the horizontal flow region was large relative to its depth.

Visser (1954), reported that Ernst and Boumans used the relaxation method to construct a monographic solution of the general problem of the rise of the water table height above tile drains when the rate of rainfall was constant and the impervous layer was found at any depth. The method gave similar results to those obtained by using Hooghoudt's tables. Luthin and Day (1955), showed that the relaxation method could also be used under non-saturated conditions of flow if the soil water tension and unsaturated hydraulic conductivity were known.

Van Schilfgaarde, Kirkham and Frevêrt (1956), showed that the drainage spacing obtained by using Hooghoudt's tables was similar to that given by equation (4), and that the error was less than 10 percent. Hooghoudt's work constituted one of the most comprehensive analysis of drainage problems to be found in the literature. The approximations were reasonably accurate for the conditions where the assumptions were applicable.

Van Schilfgaarde (1957), demonstrated that the Dupuit assumptions implied that there would be no fluid flow. He defined water potential in terms of vector velocity:

$$V = -K\nabla\phi \tag{5}$$

where:

V = velocity of flow.

K = hydraulic conductivity of soil.

ϕ = soil water potential.

Also,

$$\frac{\partial V_x}{\partial z} = \frac{\partial V_z}{\partial x} \text{ and } \frac{\partial V_y}{\partial z} = \frac{\partial V_z}{\partial y}$$

where x, y and z are rectangular cartesian coordinates representing length, breadth and thickness, respectively. If the velocity was independent of the depth, then:

$$\frac{\partial V_x}{\partial z} = \frac{\partial V_y}{\partial z} = \frac{\partial V_z}{\partial x} = \frac{\partial V_z}{\partial y} = 0$$

This showed that the vertical velocity was constant in a horizontal plane. He argued that since the velocity was zero along a vertical surface, it would also be zero everywhere, implying there was no vertical flow, and the slope of the free water surface was zero.

2.2 Non-Steady State Flow

Non-steady ground water flow problems are more difficult to solve than the steady state flow. They are also of greater interest than the steady state flow since most ground water flow is a non-steady phenomenon. However, no acceptable general solution has been found for water flow problems with a changing water table. The ellipse equation has been extended to the solution of the drainage flow problems with a changing water table.

Neal (1934), made a statistical analysis of field data from soils in Minnesota and presented the following empirical formula for spacing drains in flat land:

$$L = \frac{12,000}{M_e^{1.6}\ R_d^{1.43}} \tag{6}$$

where:

L = drain spacing in feet.

M_e = average moisture equivalent in percent.

R_d = rate of drop of water table mid-way between tiles in feet per day.

Roe and Ayres (1954), reported that Neal's formula, when modified, could be applicable to humid areas of the Pacific Northwest. Kano (1940), derived equations for rate of drop of water table from a known height for soils with known drain spacing, porosity and hydraulic conductivity. Kirkham and Gaskell (1951), used the relaxation method for the solution of non-steady ground water flow. They considered the falling water tables as a series of successive steady states so that the relaxation method could be applicable. The results obtained were satisfactory.

Visser (1954), considered storms of shorter duration and higher intensities than the average, constant rate of rainfall, and established that:

$$N_e = \frac{4K}{L^2} (H_o^2 - h_o^2)$$

where:

N_e = equilibrium rate of discharge per unit area.

K, H_o, h_o and L are as defined earlier.

Donnan, Bradshaw and Blaney (1954), developed an equation based on earlier European work for use in the Imperial Valley, California by the Soil Conservation Service for the design of tile drains:

$$L^2 = \frac{4K\ (b_1^2 - a^2)}{q} \tag{7}$$

where:

b_1 = depth of impermeable layer below water table at midpoint between tile drains.

a = distance from impermeable layer to center of tile lines.

q = rainfall rate or infiltration rate under ponded conditions.

Dumm (1954), reported the equation derived by Glover from the heat flow equation which relates tile drain spacing to the rate of drop of the water table at a given height above the drains for a homogeneous soil with equally spaced drains and an impermeable layer underlying the soil. Glover's equation was:

$$L = \Pi \left[\frac{Kt\ (d + y_{o/2})}{\mu \ell_n\ ({}^{4y}{}_{o}/_{\Pi}y_{L/2})} \right]^{1/2} \qquad (8)$$

where:

L = drain spacing.

t = time

K = soil hydraulic conductivity.

d = distance between impermeable layer and tile drains.

y_o = initial height of water table from drain axes.

$y_{L/2}$ = height of water table at mid-point between the drains.

μ = drainable porosity.

Most tile spacing formulae apply only to homogeneous soils where the impermeable layers are at considerable depths below the tile. However, Visser (1954), developed methods of drain spacing for each of the depths to the impermeable layer. Where the impermeable layer is at the same depth as the bottom of the tile, the appropriate formula is:

$$L = 2y_1 \left[\frac{K}{DC_m}\right]^{1/2} \tag{9}$$

where:

L = tile spacing in meters.

y_1 = height of water table above the center of the tile, in cm.

K = soil hydraulic conductivity in meters per day.

DC_m = drainage coefficient in mm. per day.

In the second case, the impermeable layer may be at $100y_1$ or more below the tiles and the spacing formula is:

$$L = \left[\frac{8Ki_oy_1}{DC_m}\right]^{1/2} \tag{10}$$

where:

i_o = an index number based on the spacing and is obtained from tables given by Visser (1954).

The third case applies to soils where the impermeable layer is $100y_1$ or less below the tile. The spacing can be obtained from the nomographs prepared by Visser (1954).

Van De Leur (1958), developed two methods of computing non-steady ground water flow for a deep, homogenous soil, using:

1. A reservoir coefficient.

$$j = \frac{\mu L^2}{\Pi^2 KD} \tag{11}$$

where:

j = reservoir--coefficient

L = distance between outflow channels.

K = soil hydraulic conductivity.

μ = drainable porosity.

D = depth to impermeable layer below water table.

2. A dimensionless diagram showing the increase of ground water outflow during a steady vertical percolation.

CHAPTER III

THEORY

3.1 Model Development

According to Van De Leur (1958), the rate of ground water flow into an outflow channel, and the height of the ground water table above a constant level in the channel, for a non-steady ground water flow, are given by the following equations:

$$q_t = \frac{8}{\Pi^2} PL \, (e^{b/j}-1)e^{-t/j} \quad \text{, (equation 39, appendix)} \qquad (12)$$

$$Y_t = \frac{4}{\Pi} \frac{Pj}{\mu} \, (e^{b/j}-1)e^{-t/j} \quad \text{, (equation 41, appendix)} \qquad (13)$$

where:

b = duration of steady percolation.

j = reservoir--coefficient.

L = spacing between outflow channels.

P = rate of percolation to the saturated zone.

t = time.

q_t = rate of ground water flow from two sides into a unit length of channel at time, t.

μ = drainable porosity.

y_t = ground water table height above a constant water level in the outflow channels at time, t.

$$\frac{y_t}{q_t} = \left[\frac{4}{\Pi}\,\frac{Pj}{\mu}(e^{b/j}-1)e^{-t/j}\right] \div \left[\frac{8}{\Pi^2}\;PL(e^{b/j}-1)e^{-t/j}\right]$$

$$= \frac{4}{\Pi}\,\frac{Pj}{\mu} \quad x \quad \frac{\Pi^2}{8PL}$$

$$= \frac{j\Pi}{2\mu L}$$

$$j = \frac{2\mu L}{\Pi} \quad x \quad \frac{y_t}{q_t} \tag{14}$$

By Van De Leur (1958),

$$j = \frac{1}{\Pi^2}\,\frac{\mu L^2}{KD}\text{, (equation 37, appendix)} \tag{15}$$

where:

D = mean depth of impermeable layer below ground water table.

K = hydraulic conductivity of the soil.

From (14) and (15),

$$\frac{2\mu L}{\Pi} \quad x \quad \frac{y_t}{q_t} = \frac{\mu L^2}{\Pi^2 KD}$$

$$L = 2\Pi KD \; x \; \frac{y_t}{q_t} \tag{16}$$

KD is in square units per unit time. This defines soil moisture diffusivity.

$$\text{Hence} \quad D_e = KD \tag{17}$$

where:

D_e = soil moisture diffusivity.

From (16) and (17),

$$L = 2\Pi D_e \times \frac{y_t}{q_t} \tag{18}$$

By Rose (1966), soil moisture diffusivity is given by:

$$D_e = \frac{K}{\gamma g C_{vol}} \quad \text{(equation 36 appendix)} \tag{19}$$

where:

D_e = soil moisture diffusivity.

K = soil hydraulic conductivity.

g = acceleration due to gravity

γ = density of water

$$C_{vol} = \frac{\Delta\theta}{\Delta\tau}, \text{ Rose (1966), (equation 35 appendix)} \tag{20}$$

where:

θ = percentage soil moisture content (dimensionless).

τ = soil moisture suction.

From (19) and (20),

$$D_e = \frac{K.\Delta\tau}{\gamma g.\Delta\theta} \tag{21}$$

$$= \frac{K}{I/L} \quad \text{(equation 31 appendix)} \tag{22}$$

$$= \frac{K}{\theta/\tau} \qquad \text{(equation 32 appendix)} \tag{23}$$

From (18),

$$L = 2\Pi \left(\frac{K}{\theta/\tau}\right) \frac{y_t}{q_t} \tag{24}$$

or

$$L = \frac{2\Pi K\tau y_t}{\theta . q_t} \tag{25}$$

CHAPTER IV

EXPERIMENTAL SET-UP

4.1 Field Layout

The experiment area was laid out in four rectangular plots, each 120 by 200 feet as shown in Figure 1. Each plot represented a drainage area of 0.55 acre, and was surrounded with about 6 inch earth-dike borders to prevent surface flow of water into, or from the plot. Lateral movement of soil moisture between the plots and grass roadways was prevented by installing a vertical 8-mil polyethylene plastic barrier four feet deep in trenches dug along the perimeters of the plots.

The plots were subjected to four different drainage treatments as follows:

1. Plot 3B contained surface drainage only with a 0.2 percent slope. The entire surface of the plot also falls uniformly towards this drainage outlet at a slope of 0.2 percent as shown in Figure 22(b) (appendix B).

2. Plot 3C contains tile drainage only with a level surface as shown in Figure 20(a) (appendix B).

3. Plot 3D contains both tile and surface drainage. It has a surface drainage outlet with a slope of 0.2

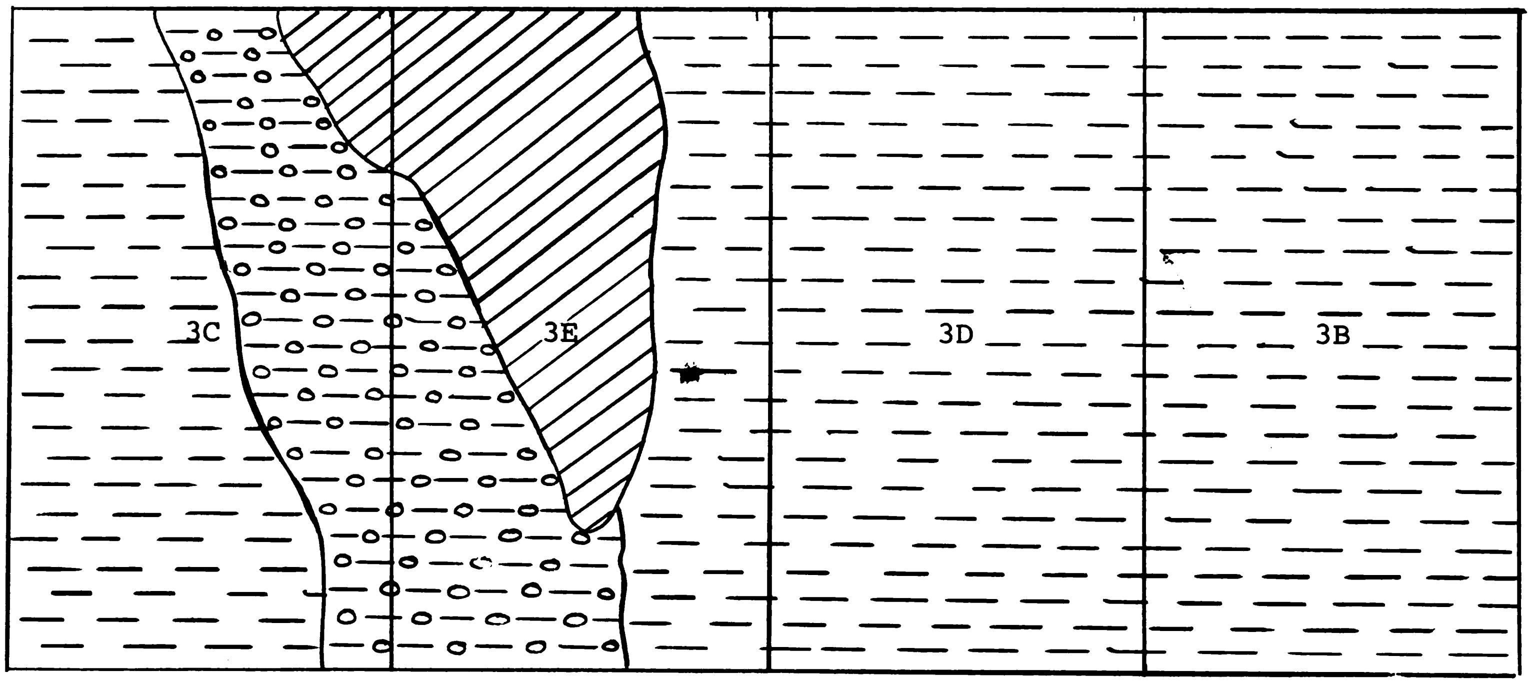

Figure 1. Soil Map of Experimental Plots.

Key: ________ Plot boundaries

Soil boundaries

Toledo Silty clay

Toledo Silty clay (transional)

Fulton Silty clay

Scale: 1" = 60'

Toledo. The B horizon contains about 62 percent clay and the soil is generally less permeable than the Toledo Silty clay. Both soil types are found extensively in the lake bed region of North Central United States.

Plots 3B, 3D and parts of 3C and 3E contain Toledo Silty clay soil. Parts of 3C and 3E contain Fulton Silty clay soil as shown in Figure 1.

4.3 Equipment

1. Description

(a) 30^{o}V-Weir

The Weir consists of a V-entrance with sides inclined at 30^{o} to the vertical. The entrance leads into a cast iron container where the water level is recorded by an FW-1 recorder.

The FW-1 recorder consists of a clock-work mechanism mounted at the bottom of a cylindrical drum of diameter and length 3.75 and 6 inches, respectively. The drum is driven continuously by the clock-work. A 192-hour chart is wound around the drum and water levels are recorded on it automatically by an inked pen. The whole ensemblage is as shown in Figure 2 (a) for measuring tile flow.

(b) 1.25 Feet H-Flume

The H-Flume is a concrete structure 1.25 feet high and 2.50 feet wide at the entrance as shown in Figure 2 (b).

Figure 2(a). The 30° V-weir and FW-1 Recorder.

Figure 2(b). The H-Flume.

A screen is installed at the entrance of the flume to keep out grass clippings which might plug the drainage pump. The entrance of the flume leads to a manhole with a cast iron container where the surface flow collects and is automatically recorded by an FW-1 recorder.

(c) Water Table Pipes

Each of the twenty 1/2 inch water table cast iron pipes were 3-1/2 feet long. They were perforated with 1/4 inch holes spaced at 6 inch intervals along 3 feet lengths, starting from the bottom. These lengths of pipes were then wrapped with muslin cloth to prevent the pipes from being blocked by soil particles when installed into the soil.

(d) Mercury Tensiometers

Sixteen tensiometers were used in units of four, corresponding to four different soil depths of installation, as shown in Figure 3(a). Each tensiometer had a porous filter cylinder of diameter 0.95 inch and was connected to a mercury manometer.

Each mercury manometer was a glass tube of fine capillary bore. The glass tube was bent to lengths of 33 inches to form a manometer which was then mounted on a wooden board 4 inches wide and 3 feet long. The manometer was filled with 13 inches length of mercury in each limb and connected to the tensiometer with tygon tubing, which ensured vacuum connection. The tensiometer, tygon tubing

Figure 3(a). The Tensiometers with Mercury Manometers and Water Table Pipe (Red Cap).

Figure 3(b). Arrangement of Tensiometers in the Plots.

and the portion of the manometer tube not filled with mercury had previously been filled with distilled water. The filling was conducted to eliminate all air bubbles from the apparatus.

(e) Blow Tubing

The blow tubing was of flexible tygon tubing of diameter 0.375 inch and length 5 feet. The tubing was calibrated at one inch intervals and readings could be taken to the nearest 0.02 inch.

(f) Other Equipment

Other equipment used consisted of: Two 3-inch core samplers, two 3-inch augers, one hand pump, three meter sticks, 4-inch concrete tiles installed in plots 3C and 3D and 3-inch plastic tiles installed in plot 3E.

2. Installation

(a) Tile Drains

Tile drains were installed in plots 3C, 3D and 3E. In plots 3C and 3D, 4-inch concrete tiles were installed at a depth and spacing of 3 and 40 feet, respectively, with spacers at one end so as to give a uniform crack width of about 1/8 inch. The arrangement of the tiles in the two plots and the earth dikes at the ends of the plots are shown in Figures 20 (a) and 20 (b) (appendix B).

In plot 3E, which was formerly plot 3A and undrained, 3-inch plastic tiles were installed at a depth and spacing of 2 and 20 feet, respectively. The installation was done 4 months prior to this experiment. The arrangement of the drains and earth dikes in the plot are as shown in Figure 21 (a) (appendix B).

(b) Surface Drains

Surface drains were installed in plots 3B and 3D. The soil in the plots were ploughed to a depth of about 10 inches prior to earth moving and land smoothing operations. The plots were graded with a small tractor scraper. The maximum cut or fill in the plots was about 0.5 foot. Most of the soil fill was obtained from or near the surface drain.

The surface channels were built to shallow depths with a motor grader to side slope of 0.2 percent. The arrangement of the surface drains and earth dikes in the plots are as shown in Figures 20 (b) and 21 (b) (appendix B).

A drainage pump installed near plot 3B provided an adequate outlet for the surface and tile drains by pumping the water collected in the sump (Figure 22) to an irrigation canal about 400 yards away. The plot runoff were collected and fed into the sump by concrete tile mains consisting of concrete bell and spigot tiles sealed with rubber gaskets. The mains were installed at a depth of

4 feet, one foot deeper than the concrete tiles in plots 3C and 3D and two feet deeper than the plastic tiles in plot 3E.

(c) Water Table Pipes

The water table pipes were installed in 3/4 inch holes drilled to depths of 3 feet and 6 inches. The first 6 inches of the holes were filled with sand and the pipes centrally inserted. The remaining spaces between the pipes and the holes were also filled with sand so that the pipe walls and the holes were in contact with sand, but not with the silty clay soil which might coat the pipes and interrupt free entry of water into the pipes.

The pipes were installed with 6 inches above the ground and 3 feet below the ground. The top 3 inches of pipes above the ground were painted red for easy identification. Figure 3 (a) illustrates one of such pipes midway between the tensiometers. The pipes were installed at 20 feet intervals, as in Figure 22 (appendix B). For plots 3C, 3D and 3E the third pipe in each plot was installed over the tile drain. Five water table pipes were installed in each plot three weeks before the first irrigation to enable the water levels in the pipes to come into equilibrium with those in the soil.

(d) Tensiometers

Four tensiometers of lengths 6, 12, 18 and 24 inches were installed in each plot at depths corresponding to their lengths. Figure 3 (a) shows a typical arrangement of the tensiometers in one plot and Figure 3 (b) shows the arrangement of the tensiometers in the four plots.

The tensiometers were installed in holes formed by driving a steel shaft of diameter 1-1/4 inches into the soil. They were placed centrally into the holes and the cups pushed firmly into the soil to ensure good contact so that approach to equilibrium was not hindered by contact impedance. The empty spaces between the tensiometers and the walls of the holes were also carefully filled with soil to promote good contact between tensiometer and soil.

The mercury manometer boards were supported vertically by wooden rods driven 6 inches into the soil and standing 3 feet above the ground. The whole ensemblage for each plot is as shown in Figure 3 (a).

The tensiometers and readings were examined carefully to detect any leakages in the apparatus. The locations of the tensiometers in the four plots are as shown in Figure 22 (appendix B).

(e) Auger Holes

Single auger holes each of diameter 3 inches were formed by drilling 3-inch augers at depths of 1, 2, 3, 4 and 5 feet into the soil. Hydraulic conductivity measurements were done in plots 3B and 3E. The locations of the holes are as shown in Figure 22 (appendix B).

(f) Sprinkler Irrigation Layout

The irrigation sprinklers were placed at a spacing of 40' x 40' as shown in Figure 23. The irrigation water was obtained from a canal fed by artesian wells and tile drains. The water was pumped through an underground 8-inch asbestos cement pipe to the experimental area. The sprinkler irrigation system consisted of 70 sprinklers which applied water to the four plots.

CHAPTER 5

EXPERIMENTAL PROCEDURE

5.1 Irrigation

Water was applied to the plots by sprinkling as shown in Figure 4(a). The application rate was approximately 0.23 inches per hour. The irrigation period was 13 hours so that the net rainfall was about 3 inches, after allowing for the losses within the irrigation system and evaporation. This precipitation was equivalent to a 10 to 15 year frequency storm. Water was applied so that overlap between sprinklers was nearly 100 percent. The plots were irrigated during the night and early morning so that most of the measurements could be taken during the daylight hours.

At the end of the irrigation period, water was ponding on the surface of the plots. However, plots 3B and 3D with surface drainage had ponding only in small depressions across the field. Field 3C with tiles at 3 feet depth had more ponding than field 3E with tiles at a depth of 2 feet.

Figure 4(a). Irrigation of the Plots.

Figure 4(b). Measuring the Water Table with a Blow-Tubing.

The plots were irrigated twice; the first when the corn plants were 6 inches high, and the second when the plants were 18 inches high.

5.2 Water Table Measurement

1. Principle

The principle involved in the measurement of the water table is that water moves into, or out of the perforated pipe until the water levels in the pipe and the soil reach equilibrium. The water level in the pipe defines a surface of zero hydrostatic pressure. This is also the definition of the water table--"The surface of zero hydrostatic pressure." Hence, the water level in the pipe gives an approximate soil depth at which a water table exists.

2. Measurement

Water tables were measured in the 1/2 inch perforated pipes by blowing into the calibrated tygon tubing as it was lowered into the pipes, as shown in Figure 4(b). When bubblings were first heard, the tube had just reached the water level. The length of tubing from the top of the pipe which entered into the pipe was noted (x_1). The length of the pipe projecting above the ground surface was also noted (x_2).

Hence, the depth to the water table from the soil surface = $(x_1 - x_2)$. If the depth of tile below ground level is x_3, then the height of the water table above the tile drain = $[x_3 - (x_1 - x_2)]$.

Measurements were taken immediately following the first and second irrigations, and also every two hours for the first day after irrigations; every six hours for the next two days and every twenty-four hours for the following six days. Five water table pipes were installed in each plot and the average of these values for a particular time was taken as the water table in the plot at that moment. The water table was measured to the nearest 0.01 foot.

The water table heights above tile drains at different times after irrigation are shown in Tables 3 and 4 (Appendix A) for the plots investigated. Figures 5 and 6 show curves of water table heights above the tile drains against time after irrigation.

5.3 Flow Measurement

1. Tile

Tile flow was recorded automatically and continuously throughout the experimental stage with a 30° V-weir and an FW-1 water level recorder as shown in Figure 2(a). The flow was recorded by an inked pen on a 192-hour chart wound around a cylindrical drum. The chart was changed

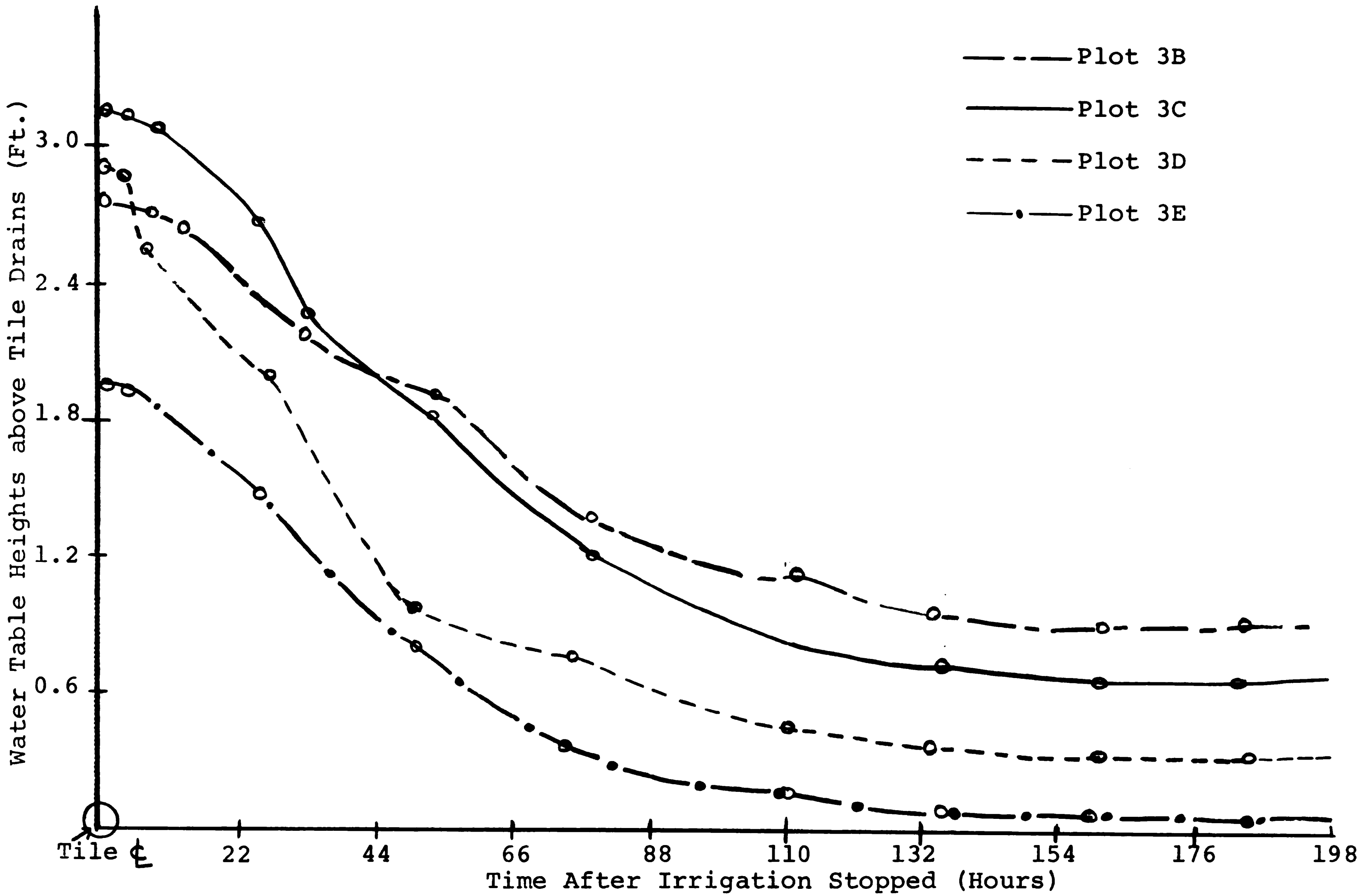

Figure 5. Water Table Heights above Tile Drains vs. Time After First Irrigation Starting Time June 5, 1970.

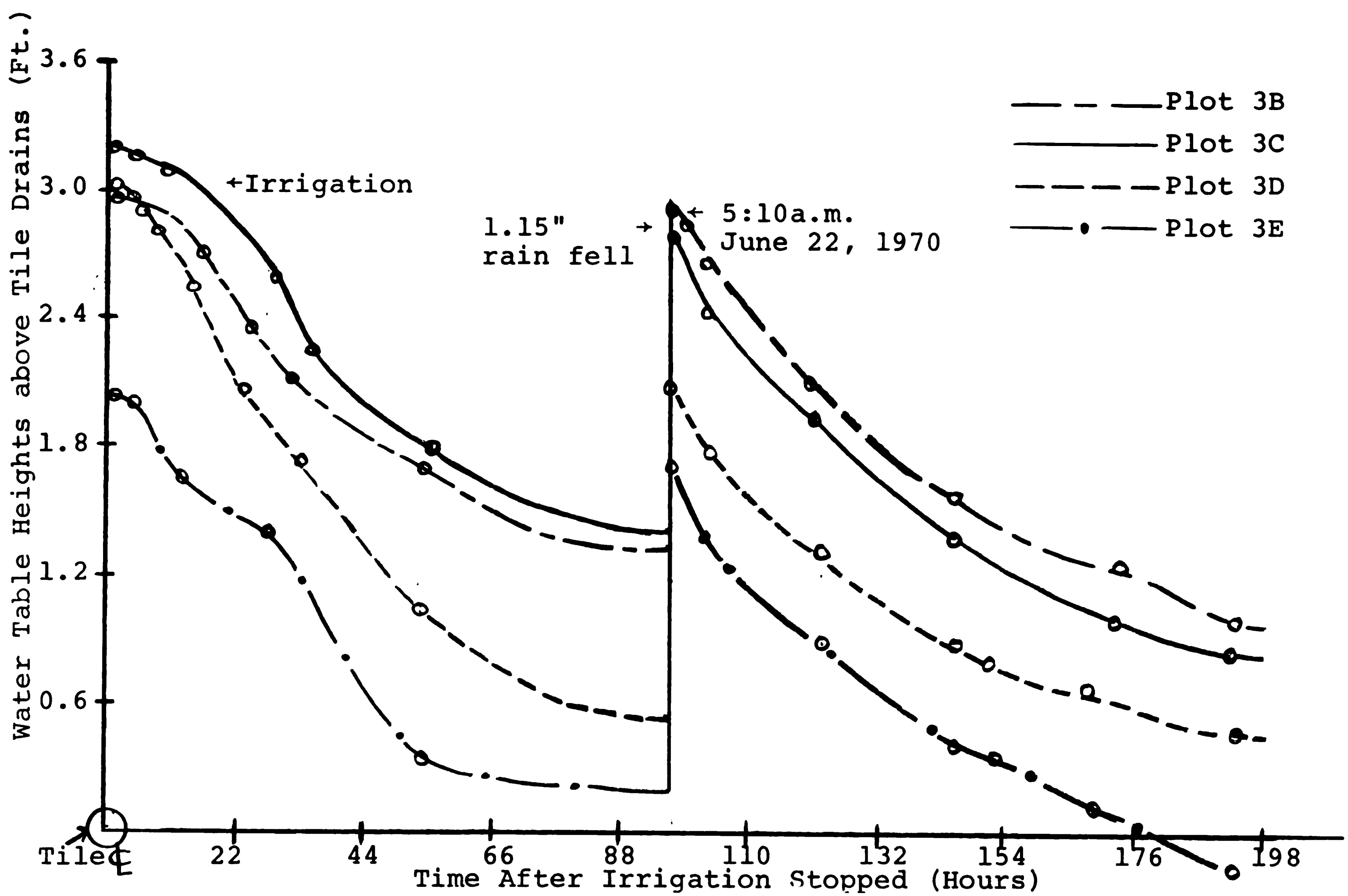

Figure 6. Water Table Heights above Tile Drains vs. Time after Second Irrigation. Starting time June 18, 1970.

every 192 hours. The recorded flow on the chart was converted to depth of tile flow in inches per day using a calibrated chart at the Research Station.

Rainfall was recorded on a 9-inch-24-hour chart with a Universal Rain Gauge throughout the experimental period.

2. Surface

Surface flow was recorded automatically and continuously throughout the experimental period with a 1.25 feet H-Flume and an FW-1 water level recorder as shown in Figure 2(b). The flow was also recorded on a 192-hour chart. A screen installed at the entrance to the flume prevented grass clippings from plugging the drainage pump.

The chart was changed every 192 hours and the recorded flow converted to depth of run-off in inches per day using a calibration table at the Research Station.

Table 5 (Appendix A) gives the tile and surface flows at various times for the two irrigations. Table 6 gives the average values of the corresponding flows for a particular time for the two irrigations.

Figure 7 shows the graph of Tile or Surface flow against time after irrigation for the readings in Table 6. Figures 8(a) and 8(b) and Figure 9 show graphs of Tile flow against water table heights above tile drains for the readings in Table 6.

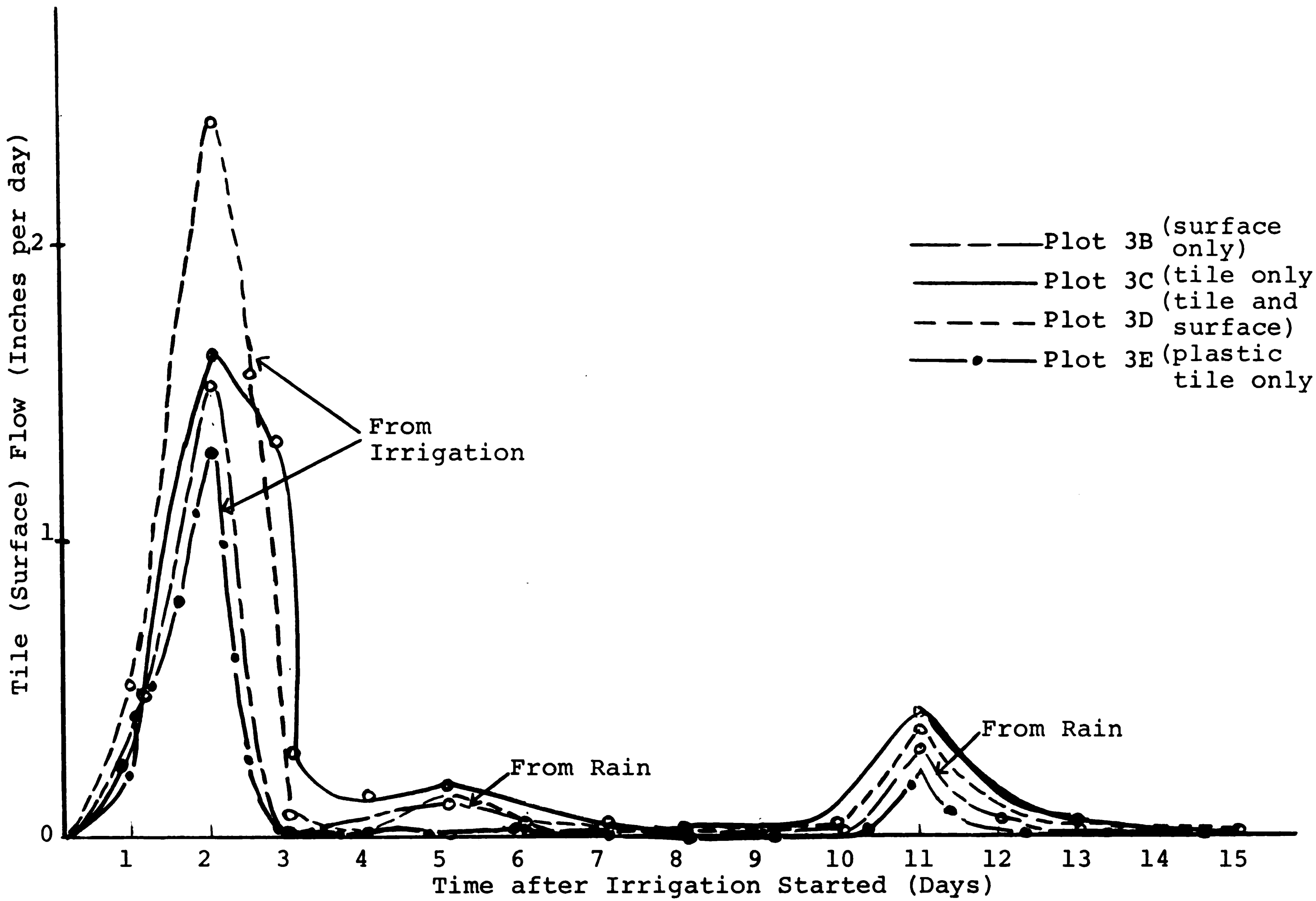

Figure 7. Tile (Surface) Flow vs. Time after Irrigation. Average of First and Second Irrigation Readings. First Irrigation: June 4, 1970. Second Irrigation: June 17, 1970.

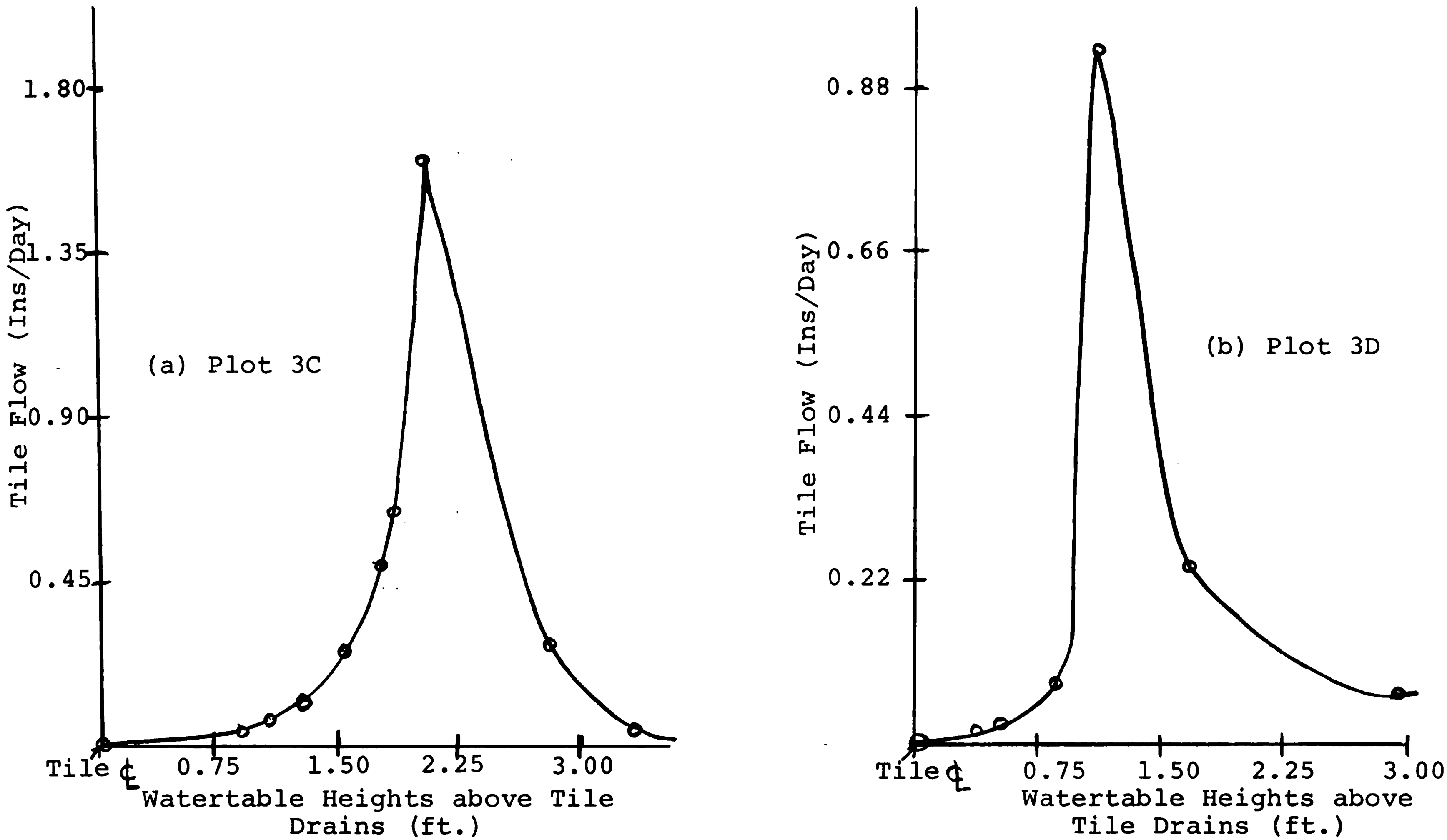

Figure 8. Tile Flow vs. Watertable Heights above Tile Drains I.

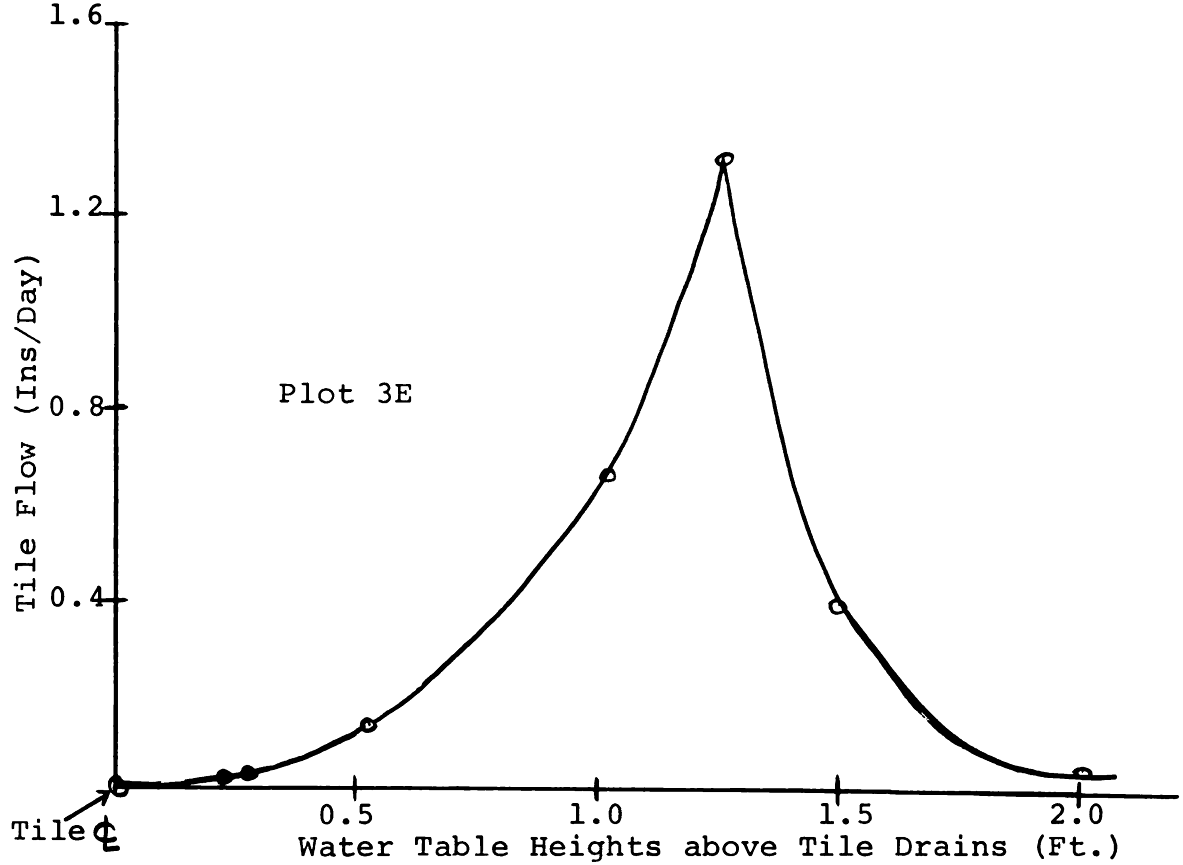

Figure 9. Tile Flow vs. Water Table Heights above Tile Drains II.

5.4 Soil Moisture Content Measurement

1. Sampling

The percentage moisture contents were determined gravimetrically on volumetric basis. Soil samples were taken at field capacity from each of the plots after each irrigation. The samples were taken with a cylindrical core sampler of diameter and length 3 inches, weighed, dried in an oven at 107°F and weighed again to determine the loss in weight and volume of moisture in the original samples. The volume of the soil samples equals the volume of the sampler.

Two soil samples were taken from each plot at a depth of 6 inches.

2. Volume of Sampler

Sampler dimension: 3" diameter, 3" height

$\therefore$ Volume of sampler $= \frac{\pi d^2 h}{4}$

where d = diameter of sampler,

h = height of sampler.

$\therefore$ Volume of sampler $= \frac{\pi (3)^2 (3)}{4} = \frac{27\pi}{4}$ cu. ins.

1 inch = 2.5 cm.

$\therefore$ Volume of Sampler $= \frac{27\pi}{4}(2.5)^3$ c.c. = 338 c.c.

$\therefore$ Volume of Soil Sample = 338 c.c.

The percentage moisture contents obtained for the plots are as shown in Table 7 (Appendix A).

5.5 Hydraulic Conductivity

1. Measurement

The hydraulic conductivity of the soil was measured by the single auger hole method. The auger holes were three inches in diameter, formed by driving a 3-inch auger into the soil at depths of 1, 2, 3, 4 and 5 feet. The holes were dug immediately after irrigation stopped, and allowed to fill overnight to allow the water tables in the holes and the soil to reach equilibrium. Hydraulic conductivity measurements were taken the following day, from plots 3B and 3E. Figure 22 (Appendix B) shows the locations of the auger holes in the plots.

The depth to water table from the soil surface was taken for each hole for equilibrium condition. The water was then pumped out of the hole to a new level with a hand-pump and the depth to this level from the soil surface measured with a meter stick. Time was noted and the rate of rise of water in the hole was taken with a meter stick and a stop watch.

2. Calculation

The hydraulic conductivity was calculated by using Hooghoudt's method for homogeneous soil (Figure 24, Appendix C).

By Hooghoudt (1937),

$$K = \frac{a_1 s \; l_n \frac{n_1}{n_2}}{(2Z + a)t} \tag{26}$$

$$S = \frac{a_1 Z}{0.19} \tag{27}$$

where a_1 = radius of auger hole

K = hydraulic conductivity

n_1 = initial water level in hole below water table

n_2 = final water level in hole below water table

t = time for water to rise from n_1 to n_2.

Z = auger hole depth below water table

Tables 1 and 8 show the values of the hydraulic conductivity at various soil depths for the two plots.

Figure 10 shows the graph of hydraulic conductivity against soil depths for the two plots.

5.6 Soil Moisture Suction

1. Tensiometer Principle

The tensiometer consists of a porous filter cup. It is filled with distilled water before installation into the soil. The water in the soil and tensiometer cup eventually come into equilibrium. But, as the soil dries up, more water from the tensiometer cup enters into the soil and the tensiometer reading increases. This indicates the soil moisture suction or soil moisture stress.

Table 1. Values of Soil Hydraulic Conductivity I.

Plot	Depth of holes (ft.)	K Meter/Day	K Ins./Day	Plot treatment
3B	0.5	0.741	29.000	First Irrigation
	1	0.114	4.450	
	2	0.038	1.480	
	3	0.015	1.170	
	4	0.026	1.010	
	5	0.016	0.650	
3E	0.5	0.700	27.200	Second Irrigation
	1	0.096	3.725	
	2	0.034	1.370	
	3	0.026	1.110	
	4	0.021	0.831	
	5	0.011	0.413	

As the soil gets wet due to irrigation or rainfall, less water enters the soil from the tensiometer cup. The tensiometer reading correspondingly decreases, showing a smaller soil moisture stress. This indicates that the soil moisture suction goes through a series of

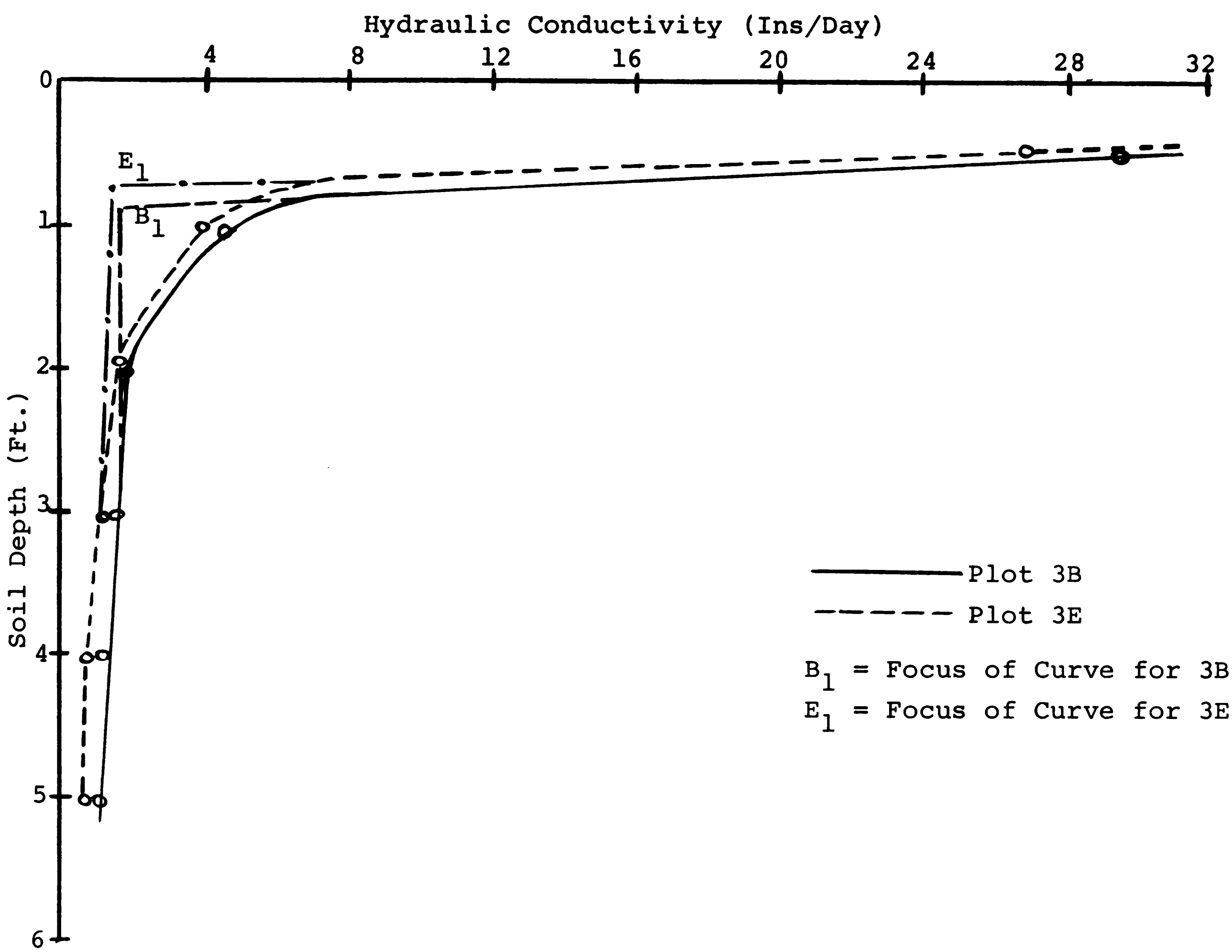

Figure 10. Hydraulic Conductivity vs. Soil Depth.

hysteresis loop as the soil moisture varies with time. This has made the tensiometer a useful instrument for scheduling irrigations without actual reference to the soil moisture content. But, it has the following limitations in its range of applications:

1. It has a small working range. The highest reading is about 0.8 of an atmosphere.

2. Approach to equilibrium may be hindered by contact impedance if good contact is not established between the soil and tensiometer cup.

3. The diffusional equilibrium depends on the permeability of the cup and the surrounding soil. The tensiometer cup-pores should be small enough to eliminate air from penetrating the cup walls during the experiment.

4. It is difficult to ensure airtight and leakproof connections.

5. Tensiometers are temperature sensitive. The caps should be securely closed to eliminate the thermometer effect.

6. The Mercury manometer should have fine capillary bore.

2. Measurement

The soil moisture suctions were measured with porous cup tensiometers at soil depths of 6, 12, 18 and 24 inches as shown in Figure 3(a). Four tensiometers with mercury manometers were installed in each plot at the four different soil depths shown above. The difference in elevation of mercury in the manometer U-tube and the distance from the porous cup of tensiometer to the Mercury/Water interface were recorded. Measurements were taken immediately after each irrigation, and every 24 hours for the following eleven days.

3. Calculation

By Marshall (1959),

$$\tau = (h_w D_w - h_m D_m), \text{ eq. 42, Appendix C}$$

where:

τ = hydrostatic pressure within porous cup

h_w = distance from cup to Mercury/Water interface (Figure 25, Appendix C).

D_w = density of water

h_m = difference in elevation of mercury in the U-tube (Figure 25, Appendix C).

D_m = density of mercury

The results of the soil moisture suctions for plots 3C, 3D and 3E are shown in Tables 9, 10 and 11, respectively in Appendix A. The curves for soil moisture suctions vs. time after irrigation, and for water table heights above tile drains vs. soil moisture suctions for plot 3C are shown in Figures 11, 12 and 13. The curves for plot 3D are contained in Figures 14, 15 and 16; and for plot 3E in Figures 17, 18 and 19.

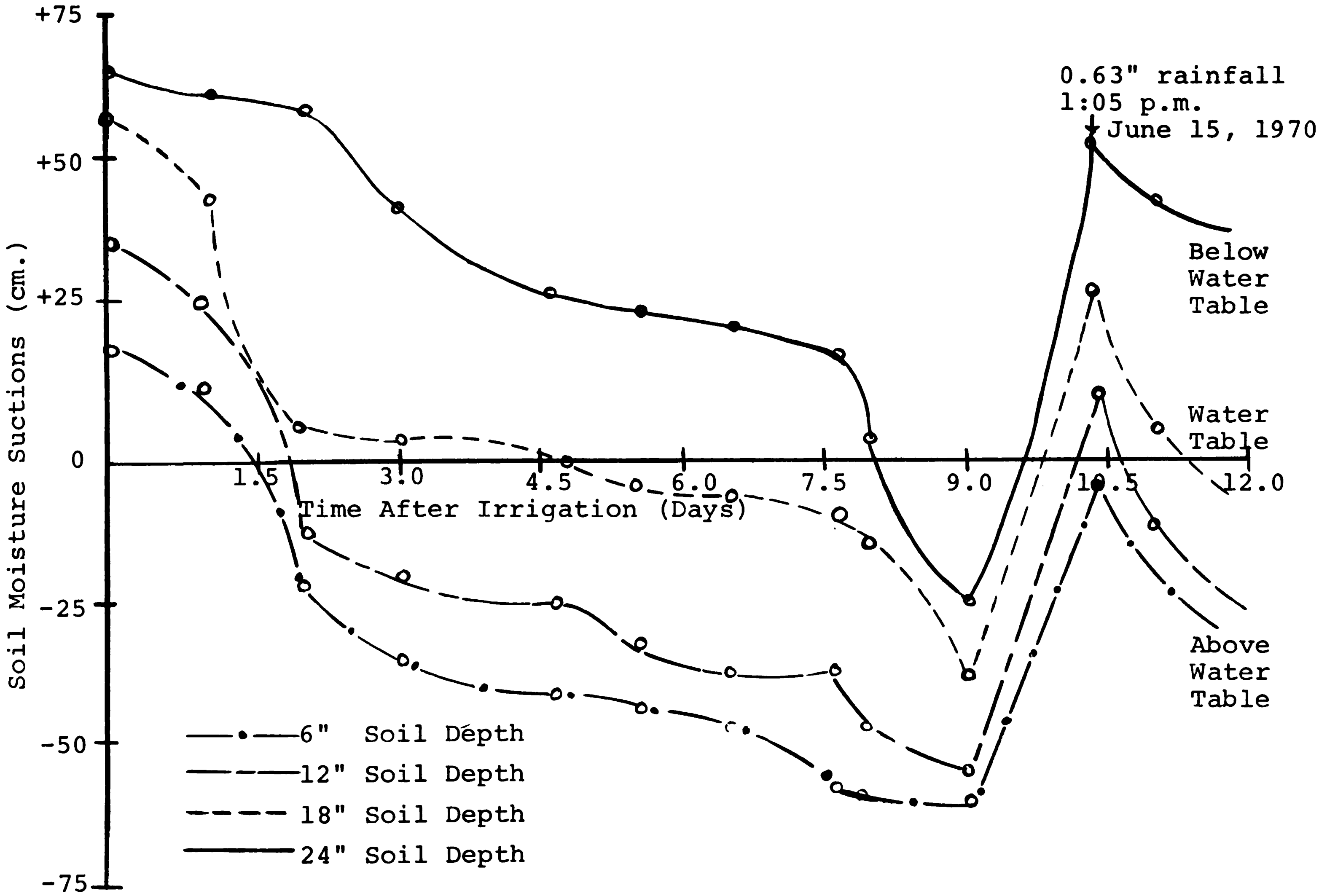

Figure 11. Soil Moisture Suctions vs. Time After First Irrigation. Corn Crops 6" high on plot. Plot 3C. Starting Time: June 5, 1970.

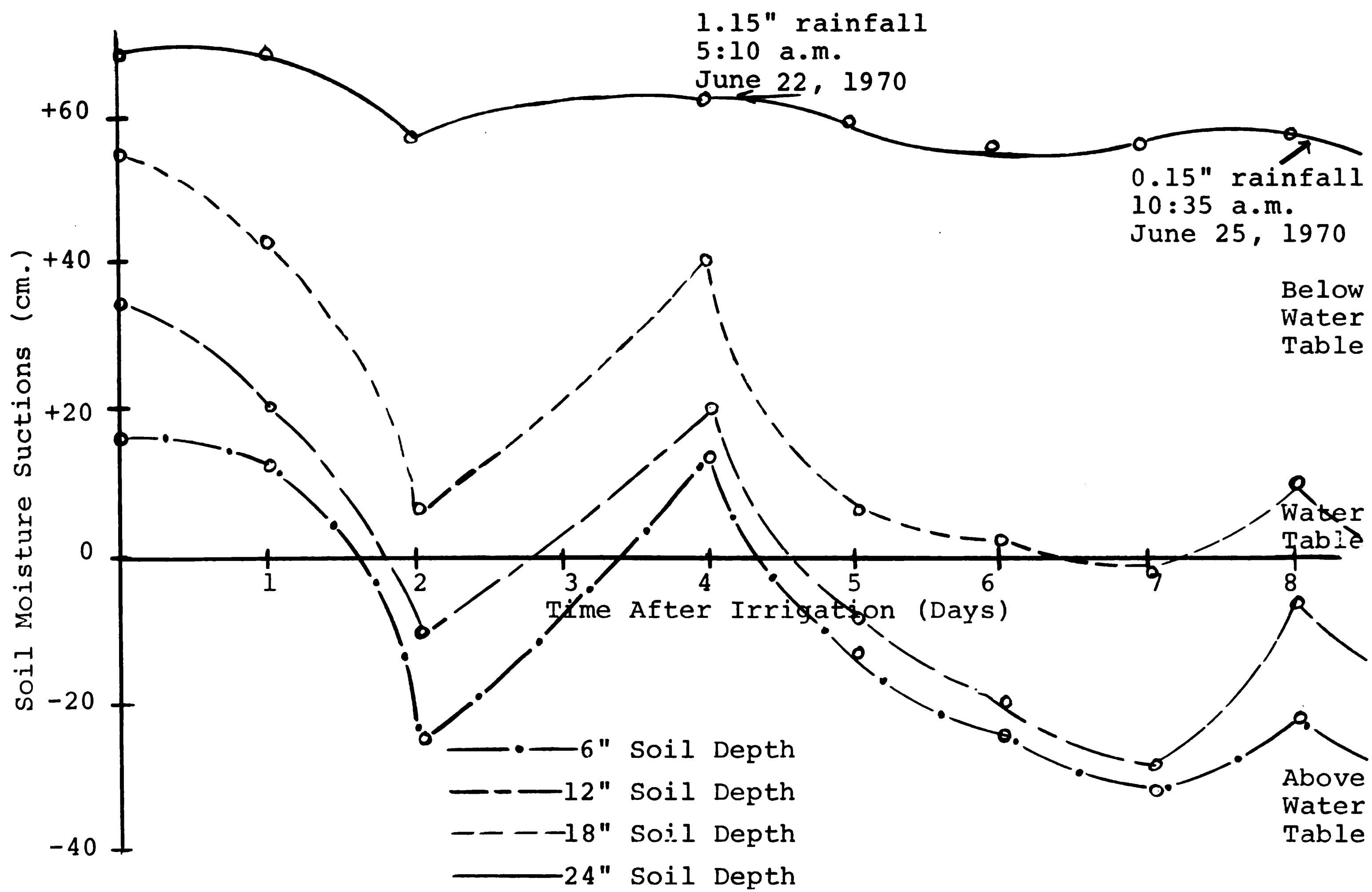

Figure 12. Soil Moisture Suctions vs. Time After Second Irrigation. Corn Crop 18" High on Plots. Plot 3C. Starting Time: June 18, 1970.

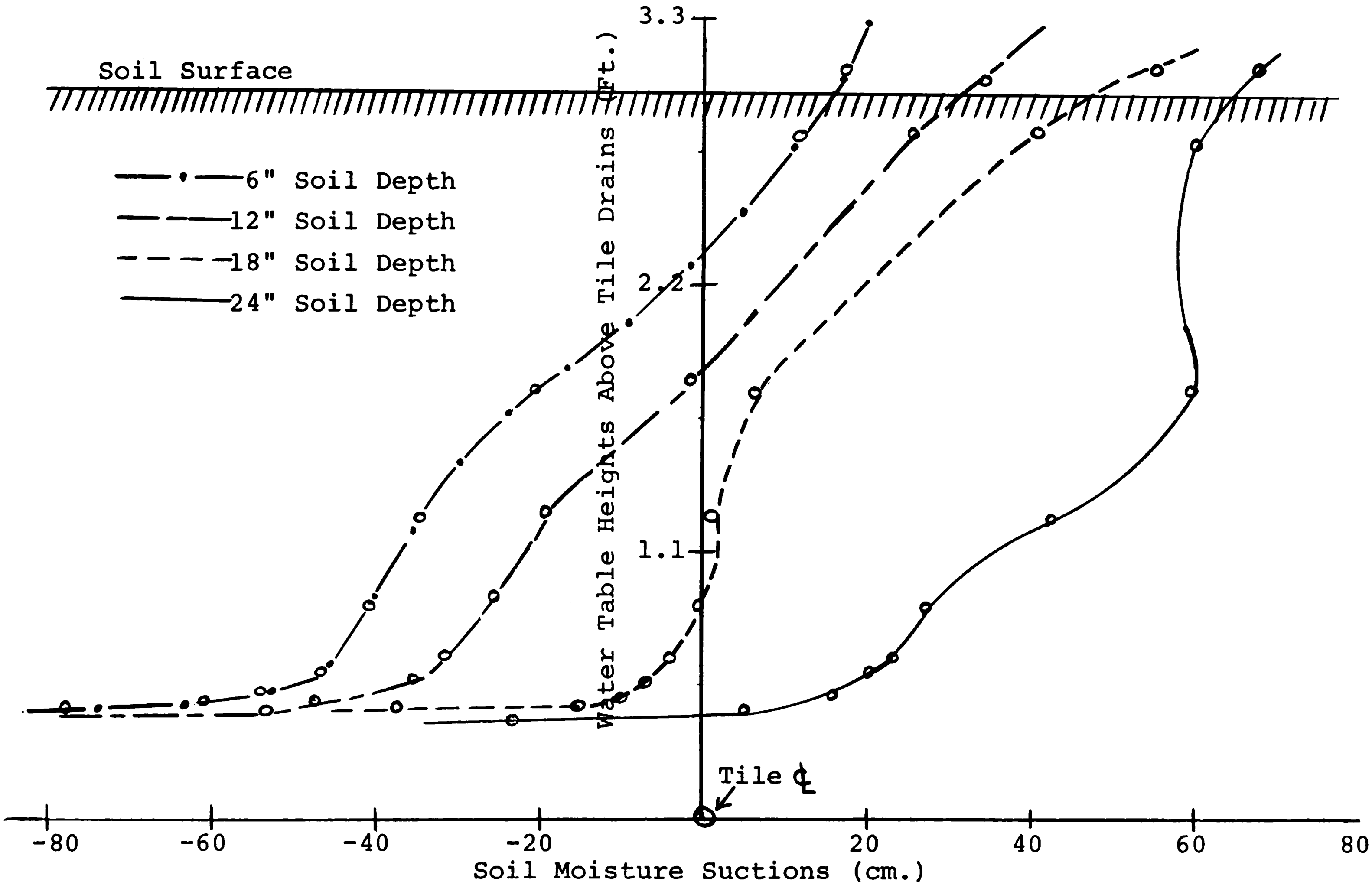

Figure 13. Water Table Heights Above Tile Drains vs. Soil Moisture Suctions. First Irrigation. Starting Time: June 5, 1970. Plot 3C.

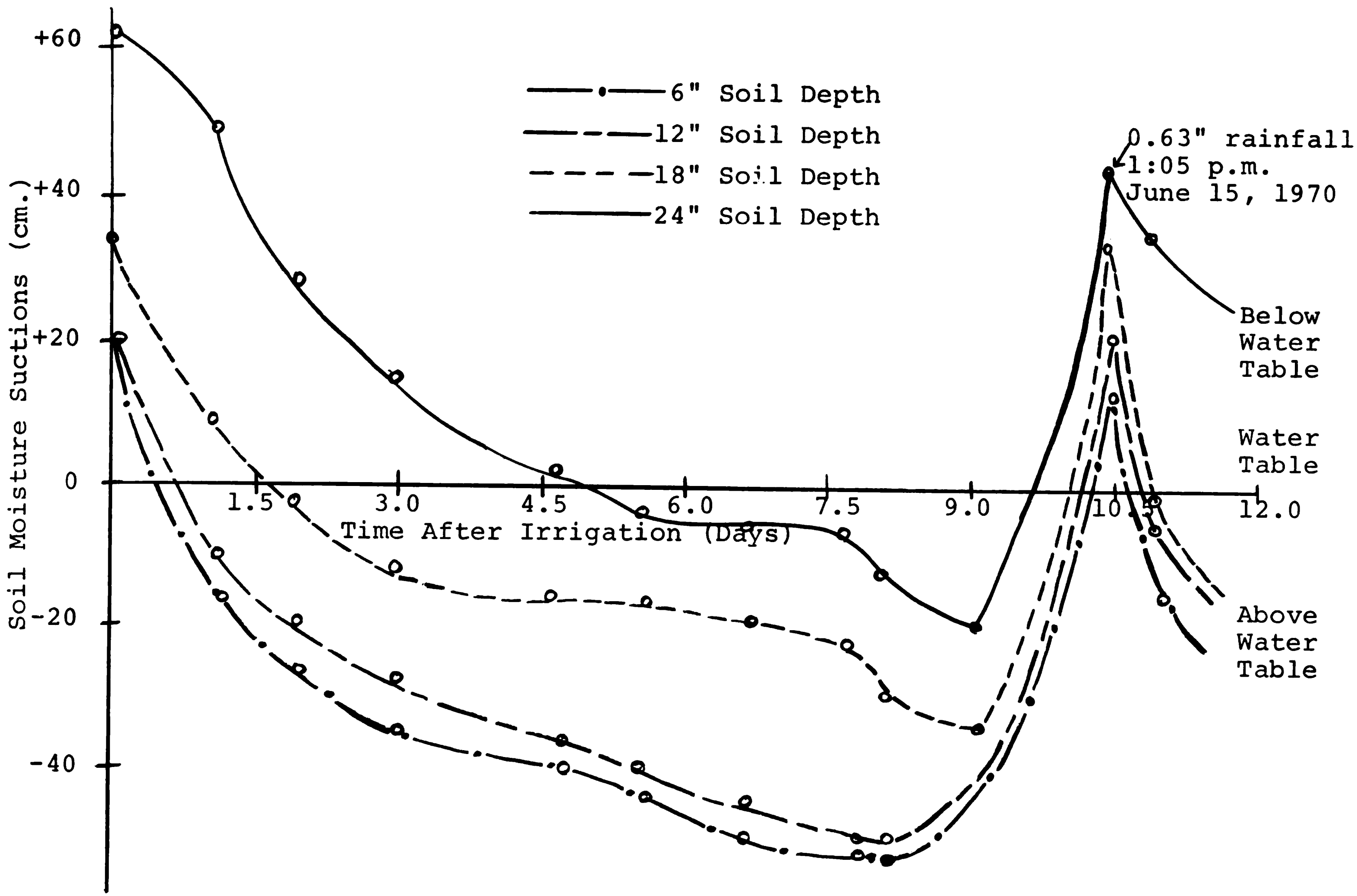

Figure 14. Soil Moisture Suctions vs. Time After First Irrigation. Corn Crops 6" High on Plot. Plot 3D. Starting Time: June 5, 1970.

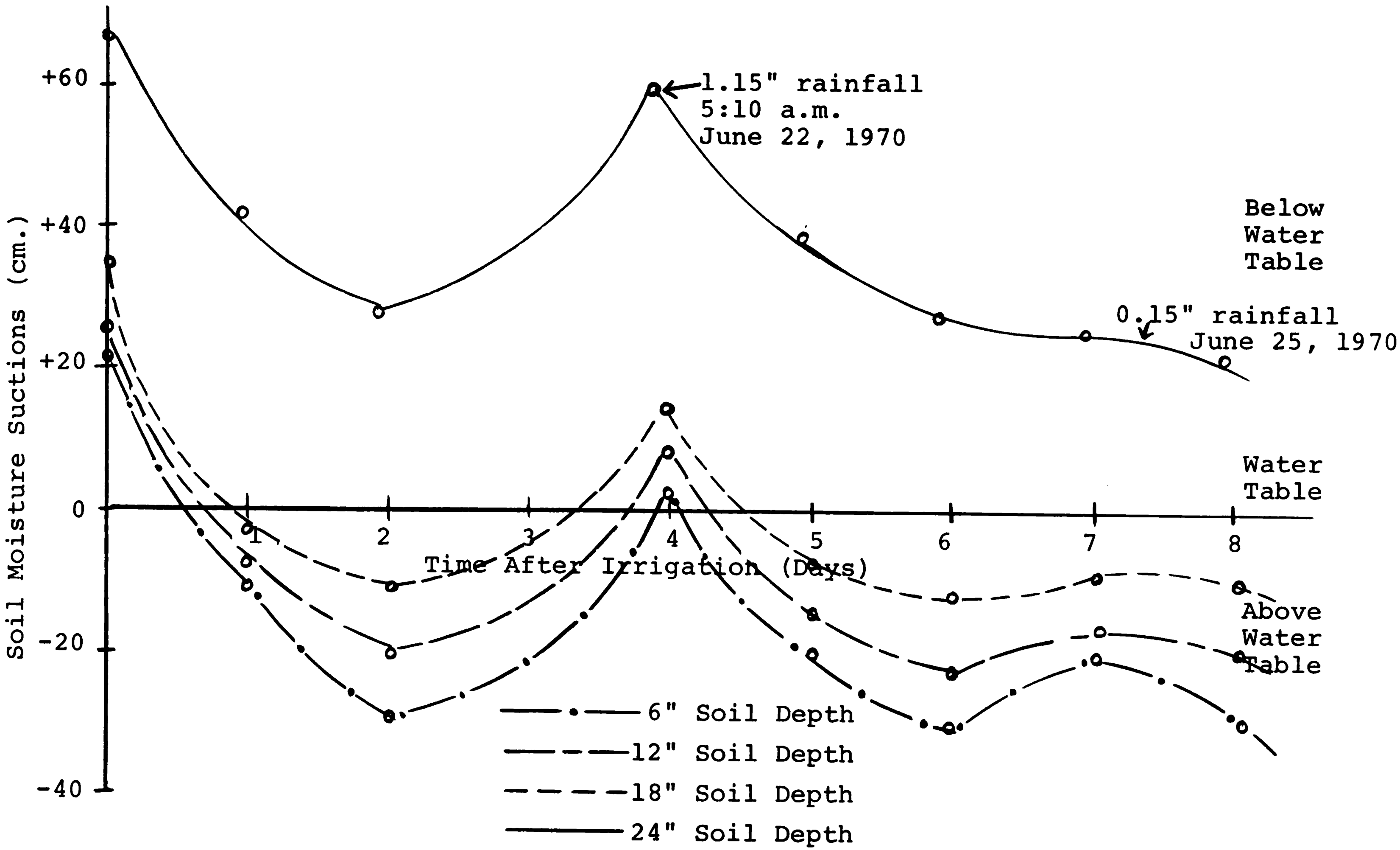

Figure 15. Soil Moisture Suctions vs. Time After Second Irrigation. Corp Crops 18" High on Plot. Plot 3D. Starting Time: June 18, 1970.

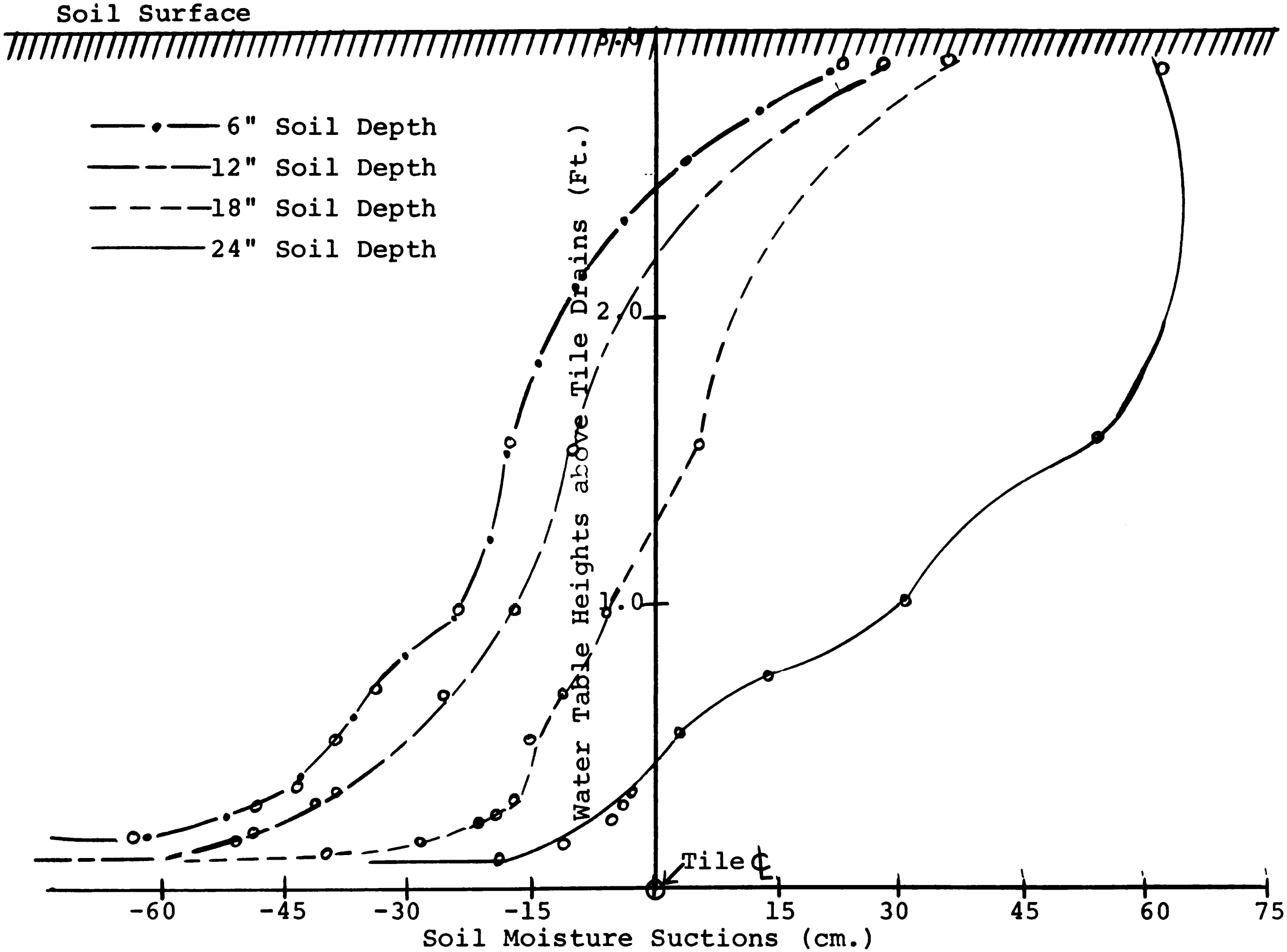

Figure 16. Water Table Heights above Tile Drains vs. Soil Moisture Suctions. First Irrigation. Starting Time: June 5, 1970. Plot 3D.

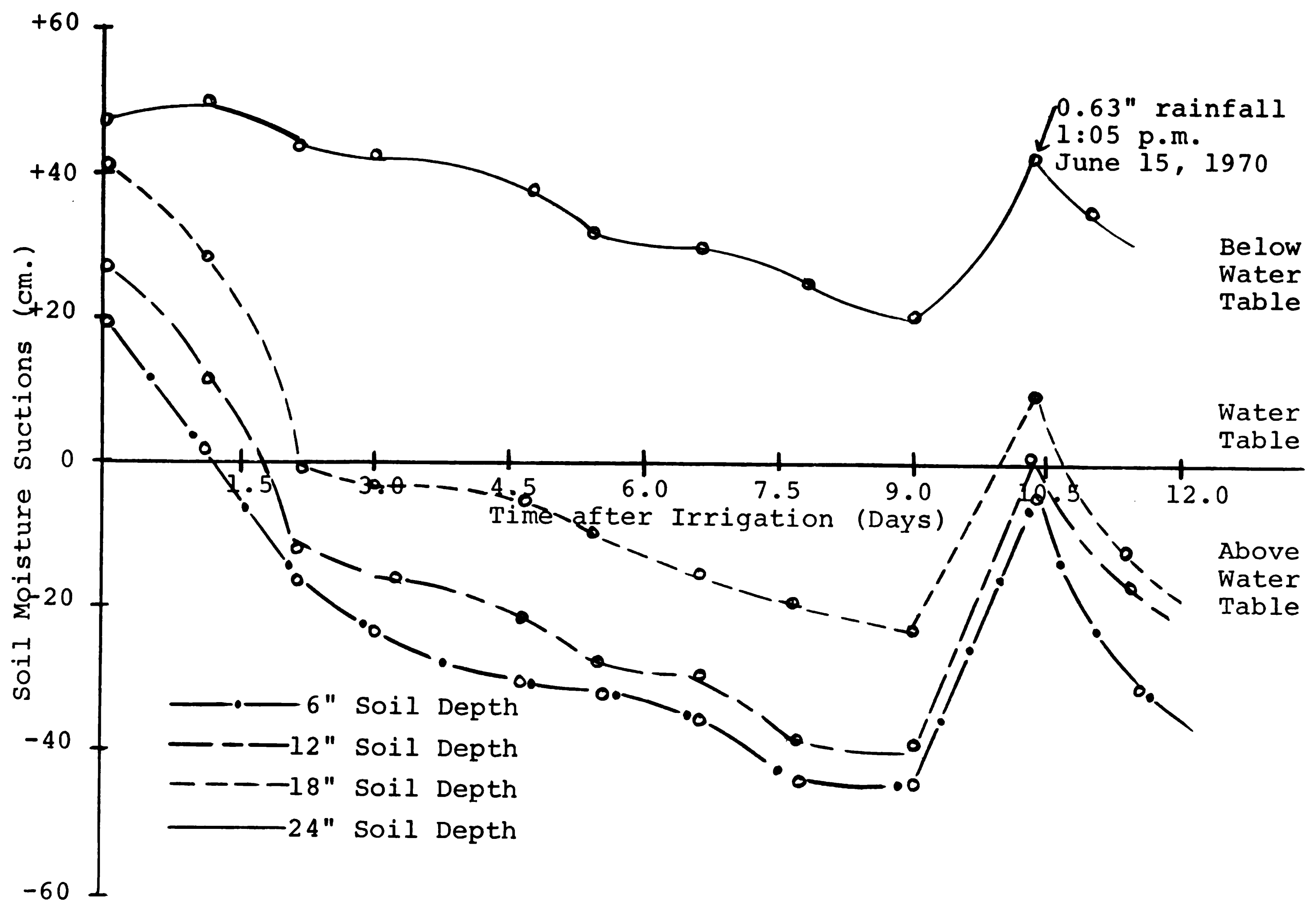

Figure 17. Soil Moisture Suctions vs. Time after First Irrigation. Corn Crops 6" High on Plot. Plot 3E. Starting Time: June 5, 1970.

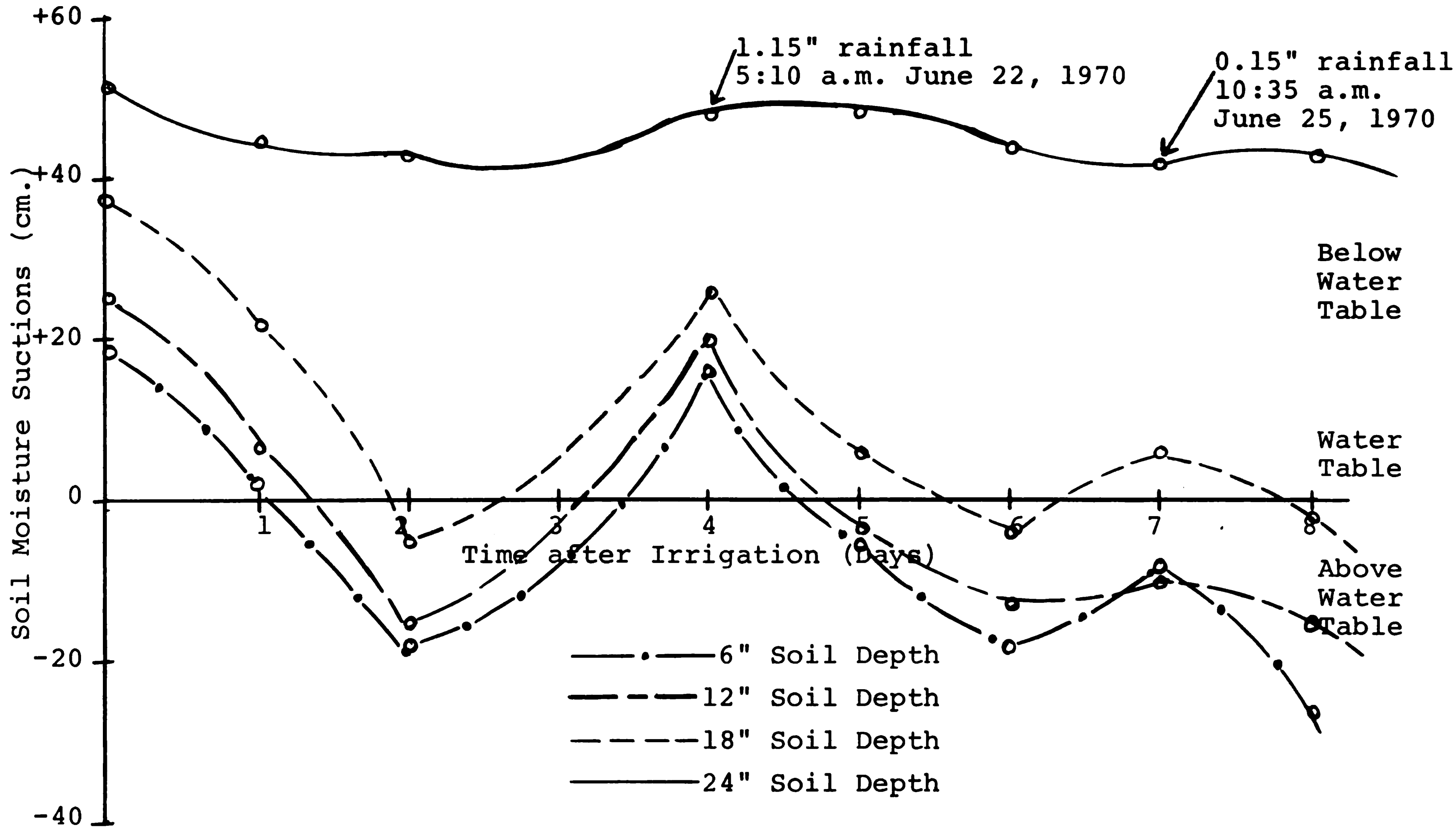

Figure 18. Soil Moisture Suctions vs. Time after Second Irrigation. Corn Crops 18" High on Plot. Plot 3E. Starting Time: June 18, 1970.

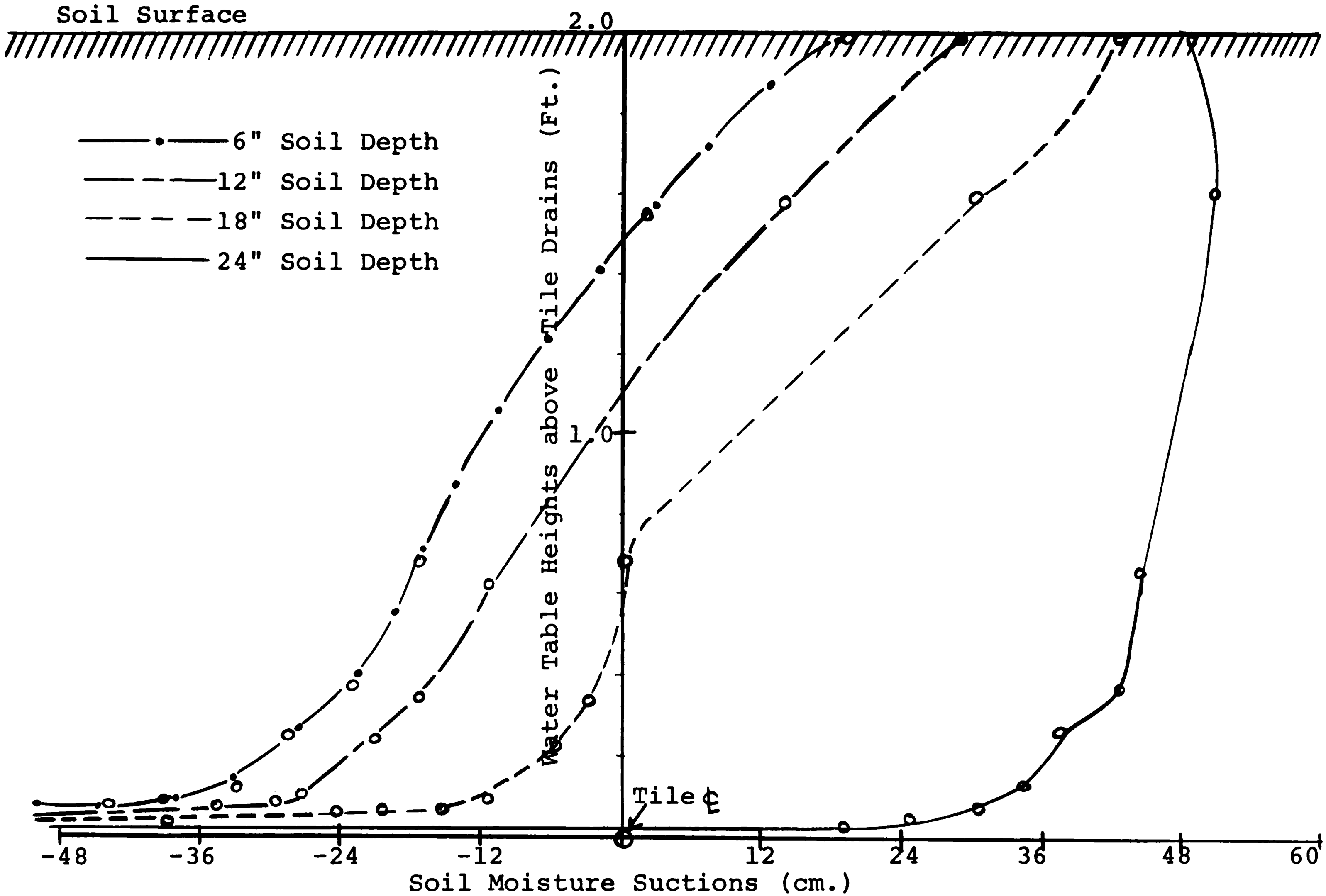

Figure 19. Water Table Heights above Tile Drains vs. Soil Moisture Suctions. First Irrigation. Starting Time: June 5, 1970. Plot 3E.

CHAPTER VI

DRAIN SPACING FORMULA

6.1 Drainage Equation Parameters

From (25),

$$L = \frac{2\Pi K\tau y_t}{\theta . q_t}$$

where:

L = drain spacing.

K = soil hydraulic conductivity.

τ = soil moisture suction at which the water table height above tile drains approach the same constant value for the different suction depths.

y_t = water table height (at peak flow) above tile drains.

θ = volumetric percentage soil moisture content.

q_t = peak tile flow.

1. Hydraulic Conductivity

Figure 10 shows the curves for the hydraulic conductivity against soil depths for plots 3B and 3E. The figure shows that the hydraulic conductivity decreases rapidly from high values in the A_p horizon to infinitely low values below this layer. For this type of soil, the hydraulic conductivity of major importance in drainage design occurs in the plow layer. The transition from high to low values occurs at about one foot soil depth. The curves are nearly rectangular hyperbolas with foci at 0.75 and 0.95 feet soil depths for plots 3B and 3E, respectively.

From Figure 10, B_1 is the focal point for the curve of plot 3B and E_1 is the focal point for plot 3E. The hydraulic conductivities at B_1 and E_1 are 1.6 and 1.4 inches per day, respectively. These values represent the hydraulic conductivities in transition from very high values in the plow layer to very low values in the lower horizons. The hydraulic conductivity at the transitional point seems more appropriate to use in drainage design formula for this soil because of the following reasons:

1. It incorporates both the hydraulic conductivity of the plow layer and the lower horizons.

2. The hydraulic conductivity of the plow layer is too high because the porosity of the soil has been modified markedly by cultivations and microbilogical activities. Its use in a drainage design formula would result in too wide drain spacing which would be insufficient to lower the water table to promote active plant growth.

3. The hydraulic conductivity of the horizons below the plow layer is too low because the soil porosity must have been affected by deposition of clay particles

from the upper horizons. Its use in a drainage formula would result in too narrow drain spacing which would lower the water table too rapidly and cause drought conditions for plant growth.

From Figure 10, the average hydraulic conductivity for soil depths B_1 and E_1 is 1.5 inches per day. This value will be used for K in the Drain Spacing Formula (equation 25).

2. Soil Moisture Suction

Figures 13, 16 and 19, show curves of Water Table Heights Above Tile Drains vs. Soil Moisture Suctions at four different soil depths for the plots 3C, 3D and 3E, respectively. They show that at a certain suction, for each plot, the water table heights above the tile drains approach the same constant value, irrespective of the tensiometer soil depths. The values of the soil moisture suctions at which the water table heights approach the same constant value above the tile drains are as tabulated below:

τ = 60 cm = 1.96 feet for plot 3C, Figure 13

τ = 60 cm = 1.96 feet for plot 3D, Figure 16

τ = 45 cm = 1.64 feet for plot 3E, Figure 19

These values are appropriate for use in the drain spacing formula.

3. Peak Tile Flow

Ponding of water at the soil surface is injurous to plant growth. Drains should be spaced in the fields to eliminate ponding by removing water from the fields rapidly after a heavy rainfall or irrigation. In the drainage formula, q_t corresponds to the peak tile flow, and y_t to the water table height above the tile drains at peak tile flow. Figures 8 (a), 8 (b) and 9 show curves of Tile Flow vs. Water Table Heights Above Tile Drains for plots 3C, 3D and 3E, respectively.

From Figure 8 (a), q_t = 1.6 inches per day, y_t = 1.90 ft. for plot 3C

From Figure 8 (b), q_t = 0.95 inch per day, y_t = 1.02 ft. for plot 3D

From Figure 9, q_t = 1.3 inches per day, y_t = 1.25 ft. for plot 3E

4. Volumetric Percentage Soil Moisture Content

From Table 7, the average value of θ = 49 percent.

6.2 Calculated Drain Spacing

$$L = \frac{2\Pi K\tau y_t}{\theta . q_t}$$

Table 2. Calculated vs. Actual Drain Spacing

Plot	K (ins/day)	τ (cm)	q_t (ins/day)	y_t (ft.)	θ (%)	Tile Depth (ft.)	Tile Spacing Actual (ft.)	Tile Spacing Calculated (ft.)
3C	1.5	60	1.6	1.9	49	3	40	47
3D	1.5	60	0.95	1.02	49	3	40	42
3E	1.5	45	1.3	1.25	49	2	20	27

CHAPTER VII

RESULTS AND DISCUSSIONS

7.1 Water Table Time Curves

Tables 3 and 4 (appendix A) show the variations of the water table heights above the tile drains with time for the four plots under different drainage treatments, following the first and second irrigations. The first and second measurements extended over 10 and 8 days, respectively.

The water table height-time relationships are shown graphically in Figures 5 and 6, for the first and second irrigations, respectively. There was a striking similarity in the water table variations with time for the plots and the two irrigation replications. The rate of drop of the water table was rapid over the first three days following irrigations. Thereafter, the rate dropped to a low, nearly constant value.

The high rate of drop of the water table within the first three days after irrigation could be attributed to the high hydraulic head over the tile drains, which resulted in large tile flow. As the head decreased, the tile flow tapered off because the hydraulic head was not large enough to overcome the entrance resistance to the tile drains rapidly to produce large flow. The water table heights were maintained at nearly constant heights of 0.7, 0.4 and 0.1 foot above tile drains for plots 3C, 3D and 3E, respectively. This was because the tiles in plot 3E were installed at a shallower depth than those in plots 3C and 3D. Plot 3D, with both tile and surface drains, was better drained than plots 3C and 3E with tiles only.

7.2 Flow--Time Curve

Tile and surface flow from the plots were measured over a 14 day period following each irrigation. The results are shown in Table 5 and the average flow for the two irrigations is shown in Table 6, appendix A. The Flow--Time curve is shown in Figure 7. It shows that, for each plot, the flow reached a peak value on the second day after irrigation. This was probably due to the slow infiltration and percolation rates of the silty clay loam soil below the plow layer.

The relationships of Tile Flow to Water Table Heights Above Tile Drains are shown in Figures 8 (a), 8 (b) and 9 for plots 3C, 3D and 3E, respectively. Plot 3C, with drains at 3 feet soil depth and no surface drains, had more ponding than plots 3D and 3E. The water table was also higher than in 3D or 3E.

Plot 3D had both tile and surface drains. It had no ponding and had the highest rate of drop of the water table. Similarly, plot 3E, with plastic tiles installed at 2 feet depth, had no ponding. Its rate of drop of the water table was similar to plot 3C. Maximum tile discharge occurred at a water table height of 1.90 feet above the tile drains in plot 3C. In plots 3D and 3E, maximum flows occurred at water table heights of 1.02 and 1.25 feet, respectively, above tile drains.

7.3 Soil Depth--Hydraulic Conductivity Curve

The hydraulic conductivities of the soil, measured at five different soil depths, are shown in Table 1. The detailed results are shown in Table 8, appendix A. The Hydraulic Conductivity--Soil Depth relationship is shown in Figure 10. The figure shows that the hydraulic conductivity of the silty clay loam soil decreases from a high value in the plow layer to an infinitestimal value at a soil depth of five feet. This shows that the hydraulic conductivity of interest for this particular soil type lies in the plow layer.

Many formulae for drainage spacing incorporates the soil hydraulic conductivity as one of the design parameters. However, in practice, drainage spacing is done on the basis of the drainage coefficient. The formula presently derived utilizes the hydraulic conductivity of the soil as one of the design parameters. The hydraulic conductivity at a soil depth when the value was changing from high to low values was used in the design formula, Figure 10. This value represented both the conductivity of the plow layer and the lower horizon. The computed spacing was within the recommended values for the Toledo Silty Clay Soil.

7.4 Soil Moisture Suction--Time Curve

The soil moisture suctions measured at four different soil depths in plot 3C are shown in Table 9, appendix A. The Soil Moisture Suction--Time curves for the first and second irrigations are shown in Figures 11 and 12, respectively. The Water Table--Soil Moisture Suction curve is illustrated in Figure 13.

The corresponding results for plots 3D and 3E are shown in Tables 10 and 11, appendix A. The curves for plot 3D are shown in Figures 14, 15 and 16; for plot 3E are shown in Figures 17, 18 and 19. The Soil Moisture Suction--Time curves illustrate that soil moisture suction is a non-steady process and varies with the position of the water table in the soil. The Water Table Height--Soil Moisture Suction relationships show that at a certain suction, the water table heights above the tile drains approach the same, nearly constant value, irrespective of the suction soil depth, for each plot (Figures 13, 16 and 19), cf. 6.1, 2.

CHAPTER VIII

CONCLUSIONS

The following conclusions are based on the investigations conducted on drained plots containing Toledo Silty Clay Soil, in North Central Ohio.

1. A formula was derived for spacing tile drains which utilizes the hydraulic conductivity of the soil, soil moisture suctions, peak tile flow, water table height at peak tile flow and volumetric percentage soil moisture content.
2. The computed tile drain spacing shows close agreement with the actual spacing and falls within the range of recommended spacing for the Toledo Silty Clay Soil.
3. The data are insufficient to warrant far-reaching conclusions covering other soil types.

CHAPTER IX

RECOMMENDATIONS FOR FURTHER STUDIES

In an undrained land, the main difficulty is in the accurate estimation of the quantity of water to be removed from the field, when the flow cannot be measured directly. The results of this research suggest the need for additional studies in the following areas:

1. An investigation to determine the expected tile flow in an undrained field. Two tile lines may be installed in the field at a known spacing, and flow measured from each of them over a four year period.
2. Water table pipes and tensiometers should be installed between the tile lines to record the fluctuations of the ground water tables and soil moisture suctions.
3. The hydraulic conductivities of many soils vary with the soil depth. Measurements should be conducted, for each soil type, to determine the accurate value of the soil hydraulic conductivity for use in the drain spacing formula.
4. From the data collected, determine:
   a. The desired tile flow rate.
   b. The maximum permissible water table.
   c. The correct drain spacing and depth.

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APPENDIX A

TABLES OF RESULTS

Table 3. Water Table Heights above Tile Drains after First Irrigation. Starting Time: June 4, 1970.

Field	Water Table Pipe No.	Water Table Heights at Different Times above Tile Drains after Irrigation (Ft.) 0 hours	2 hrs.	4 hrs.	7.5 hrs.	12 hrs.	24 hrs.	31 hrs.	48.75 hrs.	55.75 hrs.	79.75 hrs.	86.25 hrs.	110.25 hrs.	134.25 hrs.	158.25 hrs.	182.25 hrs.	249.25 hrs.	Remarks
	1	3.16	3.14	3.17	3.09	2.86	2.76	2.96	2.83	2.29	1.59	1.29	1.42	1.29	1.33	1.27	2.21	0.63" rain fell
	2	3.26	3.21	3.17	3.09	2.86	2.76	2.96	2.83	2.80	2.42	2.13	2.04	1.42	1.25	1.29	2.25	just before the
3C	3	2.92	2.92	2.84	2.84	2.65	2.43	1.09	0.75	0.61	0.13	0.00	0.00	0.00	0.00	0.00	1.46	249.25 hour
	4	3.16	3.17	3.17	3.13	2.93	2.59	2.33	1.83	1.76	1.00	0.92	0.81	0.50	0.42	0.40	2.13	measurement
	5	3.16	3.17	3.17	3.13	2.93	2.59	2.46	1.43	1.37	1.00	0.79	0.81	0.50	0.42	0.40	2.13	
Average		3.13	3.12	3.10	3.06	2.85	2.63	2.36	1.93	1.77	1.23	1.03	1.01	0.74	0.68	0.68	2.03	
	6	3.00	2.86	2.75	2.97	2.66	2.17	1.82	1.25	1.17	0.92	0.88	0.75	0.53	0.46	0.58	1.71	
	7	2.92	2.86	2.84	2.88	2.58	2.17	1.99	1.33	1.25	0.92	0.79	0.59	0.50	0.37	0.28	1.33	
3D	8	2.92	2.86	2.63	1.75	1.51	1.14	0.98	0.33	0.33	0.21	0.08	0.25	0.28	0.20	0.20	1.46	
	9	2.83	2.86	2.84	2.88	2.49	2.02	1.78	0.92	0.83	0.67	0.46	0.42	0.42	0.37	0.28	1.54	
	10	2.92	2.86	2.84	2.85	2.52	2.27	1.73	1.13	1.04	0.88	0.75	0.59	0.50	0.46	0.58	1.42	
Average		2.92	2.87	2.78	2.67	2.41	2.05	1.66	0.99	0.93	0.72	0.59	0.52	0.45	0.39	0.38	1.49	
	11	2.00	2.06	1.98	1.89	1.71	1.50	0.94	1.07	0.92	0.33	0.13	0.07	-0.03	-0.08	-0.25	0.83	The negative
	12	2.00	2.06	1.91	1.94	1.79	1.50	1.10	0.83	0.77	0.71	0.63	0.22	0.54	0.42	0.25	0.75	sign shows
3E	13	2.00	1.91	1.91	1.79	1.75	1.42	0.56	0.54	0.37	0.33	0.08	0.03	0.25	0.17	0.08	0.92	water table
	14	2.00	2.01	1.98	1.94	1.79	1.71	1.10	0.88	0.75	0.29	0.28	0.00	-0.25	-0.17	-0.25	0.83	was below
	15	2.00	1.91	1.92	2.04	1.84	1.75	1.18	1.01	0.99	0.33	0.18	0.01	-0.03	0.00	0.25	1.08	tile drain
Average		2.00	1.99	1.94	1.92	1.78	1.58	0.98	0.87	0.72	0.40	0.26	0.07	0.10	0.07	-0.08	0.88	
	16	3.00	3.00	2.84	2.79	2.75	2.75	2.53	1.89	1.85	1.09	1.25	0.92	0.83	0.92	0.91	2.08	
	17	2.79	3.00	2.84	2.79	2.75	2.62	2.30	1.86	1.85	1.09	1.25	1.00	0.79	0.93	0.73	1.85	
3B	18	2.83	3.00	2.88	2.84	2.84	2.71	2.39	1.89	1.85	1.46	1.17	1.13	1.15	1.13	1.04	2.04	
	19	2.67	2.96	2.84	2.84	2.75	2.71	2.34	2.15	1.90	1.80	1.42	1.42	1.38	1.33	1.37	2.25	
	20	2.76	2.91	2.84	2.79	2.79	2.67	2.37	2.00	1.93	1.80	1.29	1.33	1.13	1.08	1.08	2.00	
Average		2.81	2.97	2.85	2.81	2.78	2.67	2.39	1.95	1.88	1.44	1.28	1.16	1.05	1.06	1.08	2.04	

Table 4. Water Table Heights above Tile Drains after Second Irrigation. Starting Time: June 17, 1970.

Field	Water Table Pipe No.	Water Table Heights above Tile Drains at Different Times after Irrigation (Ft.)																	Remarks
		0 hr.	2 hrs.	4 hrs.	7.5 hrs.	12 hrs.	24 hrs.	31.5 hrs.	54.5 hrs.	96 hrs.	102.5 hrs.	120.5 hrs.	126.5 hrs.	144.5 hrs.	150.5 hrs.	168.5 hrs.	174.5 hrs.	192.5 hrs.	
3C	1	3.21	3.17	3.17	3.17	2.99	2.70	2.92	2.79	3.00	3.00	2.92	2.79	2.63	1.75	2.46	1.96	1.38	1.15" rain fell before 96-hour measurement. 0.15" rain again fell before 168.5-hour measurement.
	2	3.21	3.17	3.17	3.17	2.99	2.70	3.04	2.87	3.00	3.00	2.92	2.88	2.79	2.63	2.71	2.38	1.71	
	3	3.08	3.17	3.00	2.91	2.74	2.42	1.50	0.79	2.50	1.84	1.17	1.00	0.58	0.50	2.71	2.38	1.71	
	4	3.21	3.12	3.12	3.12	2.82	2.55	1.92	1.17	2.79	2.17	1.58	1.38	0.83	0.83	0.75	0.83	0.58	
	5	3.21	3.12	3.17	3.12	2.82	2.59	2.04	1.33	2.83	2.21	1.67	1.38	1.04	1.04	0.96	0.88	0.71	
Average		3.18	3.15	3.13	3.10	2.87	2.59	2.29	1.79	2.83	2.44	2.05	1.88	1.58	1.35	1.46	1.26	0.91	
3D	6	3.00	2.99	2.93	2.80	2.82	2.44	1.99	1.25	2.50	2.08	1.58	1.50	1.08	1.08	0.83	0.71	0.57	
	7	3.00	2.99	2.93	2.80	2.73	2.56	1.82	1.17	2.50	1.88	1.58	1.50	1.13	1.04	0.92	0.66	0.65	
	8	3.00	2.79	2.43	2.00	1.75	1.50	1.28	0.63	1.29	1.13	0.75	0.71	0.58	0.54	0.46	0.25	0.19	
	9	3.00	2.99	2.96	2.78	2.62	2.44	1.86	1.04	2.13	1.84	1.46	1.17	0.92	0.88	0.79	0.54	0.40	
	10	3.00	2.99	2.98	2.75	2.64	2.48	1.90	1.17	2.17	1.96	1.58	1.46	1.13	1.08	0.75	0.62	0.65	
Average		3.00	2.97	2.85	2.63	2.53	2.28	1.77	1.05	2.12	1.78	1.39	1.27	0.97	0.93	0.75	0.56	0.49	
3E	11	2.00	2.06	2.02	1.83	1.71	1.29	1.14	0.29	1.75	1.37	0.79	0.63	0.25	0.29	0.38	0.33	-0.22	The negative sign shows water table was below tile drain.
	12	2.08	2.00	2.02	1.88	1.67	1.29	1.14	0.67	1.83	1.42	1.00	0.92	0.67	0.63	0.63	0.59	0.03	
	13	2.00	2.06	1.99	1.79	1.37	0.84	0.54	0.25	1.71	1.00	0.67	0.42	0.29	0.25	0.38	0.29	-0.22	
	14	2.00	2.01	1.98	1.88	1.83	1.71	1.48	0.29	1.83	1.71	1.21	0.88	0.38	0.29	0.63	0.50	-0.22	
	15	1.96	2.08	2.02	1.92	1.88	1.75	1.22	0.33	1.83	1.75	1.00	0.75	0.46	0.33	0.59	0.46	-0.10	
Average		2.01	2.04	2.01	1.86	1.69	1.38	1.10	0.37	1.79	1.45	0.93	0.72	0.41	0.36	0.52	0.43	-0.15	
3B	16	3.00	2.96	2.96	2.91	2.87	2.55	2.20	1.60	2.92	2.79	2.25	1.83	1.46	1.42	1.59	1.58	1.07	
	17	3.00	2.92	2.86	2.84	2.75	2.44	2.38	1.82	2.79	2.62	1.96	1.79	1.38	1.33	1.25	1.21	1.03	
	18	3.00	2.92	2.88	2.84	2.67	2.21	2.29	1.93	2.83	2.56	1.79	1.58	1.42	1.33	1.75	1.59	1.02	
	19	3.00	2.92	2.92	2.79	2.71	2.44	2.14	1.63	2.83	2.62	2.08	1.88	1.59	1.50	1.96	1.79	1.16	
	20	3.00	2.88	2.88	2.79	2.71	2.36	2.30	1.78	2.83	2.42	2.04	1.63	1.50	1.33	1.42	1.25	1.03	
Average		3.00	2.92	2.90	2.83	2.74	2.40	2.26	1.76	2.84	2.60	2.02	1.74	1.47	1.38	1.59	1.48	1.06	

Table 5. Tile and Surface Flow. First Irrigation. Starting Time: June 4, 1970. Second Irrigation. Starting Time: June 17, 1970.

Time after Irrigation Started (Days)	Tile Flow (Ins/Day)			Surface Flow (Ins/Day)		Plot Treatment
	Plot 3C	Plot 3D	Plot 3E	Plot 3B	Plot 3D	
1	0.111	0.138	0.056	0.010	0.094	First irrigation. Corn crops 6" high on plots
2	1.470	0.781	1.224	1.821	1.202	
3	0.351	0.046	0.002	0.000	0.000	
4	0.044	0.010	0.000	0.000	0.000	
5	0.000	0.000	0.000	0.000	0.000	
6	0.000	0.000	0.000	0.000	0.000	
7	0.000	0.000	0.000	0.000	0.000	
8	0.000	0.000	0.000	0.000	0.000	
9	0.000	0.000	0.000	0.000	0.000	
10	0.000	0.000	0.000	0.000	0.000	
11	0.000	0.000	0.000	0.000	0.000	
12	0.044	0.038	0.001	0.000	0.000	0.092" rain fell
13	0.000	0.000	0.000	0.000	0.000	
14	0.000	0.000	0.000	0.000	0.000	
15	0.000	0.000	0.000	0.000	0.000	
1	0.491	0.372	0.731	0.830	0.360	Second Irrigation. Corn crops 18" high on plots 1.031" rain fell
2	1.768	1.126	1.426	1.275	1.330	
3	0.314	0.041	0.002	0.000	0.000	
4	0.080	0.005	0.000	0.000	0.000	
5	0.266	0.153	0.214	0.251	0.090	
6	0.156	0.047	0.021	0.000	0.000	
7	0.041	0.018	0.000	0.000	0.000	
8	0.006	0.001	0.000	0.000	0.000	
9	0.000	0.000	0.000	0.000	0.000	
10	0.000	0.000	0.000	0.000	0.000	
11	0.433	0.268	0.431	0.679	0.462	1.37" rain fell
12	0.114	0.043	0.025	0.060	0.000	
13	0.065	0.013	0.000	0.030	0.000	
14	0.028	0.000	0.000	0.000	0.000	

Table 6. Average of Tile and Surface Flow for First and Second Irrigations.

Time after irri-gation started (Days)	Plot 3C Tile Flow (Ins/Day)	Plot 3C Water-Table Height above tile drains (ft.)	Plot 3D Tile Flow (Ins/Day)	Plot 3D Surface Flow (Ins/Day)	Plot 3D Water-Table Height above tile drains (ft.)	Plot 3E Tile Flow (Ins/Day)	Plot 3E Water-Table Height above tile drains (ft.)	Plot 3B Surface Flow (Ins/Day)	Plot 3B Water-Table Height above tile drains (ft.)
0	0.051	3.157	0.061	--	2.959	0.025	2.000	--	2.905
1	0.301	2.907	0.254	0.227	1.568	0.394	1.476	0.420	2.586
2	1.619	1.912	0.954	1.266	1.019	1.325	1.217	1.548	1.580
3	0.330	--	0.044	0.000	--	0.002	--	0.000	--
4	0.662	1.880	0.008	0.000	1.317	0.680	1.029	0.000	2.000
5	0.133	1.396	0.077	0.045	0.854	0.107	0.514	0.126	1.539
6	0.078	1.130	0.024	0.000	0.624	0.011	0.238	0.000	1.238
7	0.021	1.023	0.009	0.000	0.467	0.001	0.217	0.000	1.238
8	0.003		0.005	0.000				0.000	
9	0.000		0.000	0.000				0.000	
10	0.000		0.000	0.231				0.000	
11	0.217		0.134	0.000				0.340	
12	0.079		0.041	0.000				0.030	
13	0.033		0.007	0.000				0.015	
14	0.014		0.000	0.000				0.000	
15	0.000		0.000	0.000				0.000	

Table 7. Volumetric Percentage Soil Moisture Content.

Plots	Can No.	Wt. of can + lid (gm)	Wt. of can + lid + wet soil (gm)	Wt. of can + lid + dry soil (gm)	Wt. of moisture in soil sample (gm)	Volume of moisture in soil sample (c.c.)	Volume of soil sample (c.c.)	Volumetric Percentage moisture content in soil %	Plot treatment
3B	114	78.50	735.50	572.00	163.50	163.50	338	48.37	First Irrigation
3C	184	79.05	747.00	586.00	161.00	161.00	338	47.63	June 4, 1970. Measurement
3D	149	79.05	792.00	615.00	177.00	177.00	338	52.66	June 5, 1970.
3E	174	79.05	772.00	608.00	164.00	164.00	338	48.37	
3B	121	79.80	742.00	582.00	160.00	160.00	338	47.50	Second Irrigation
3C	185	79.00	771.00	605.00	166.00	166.00	338	49.20	June 17, 1970.
3D	162	79.80	775.00	604.00	171.00	171.00	338	50.60	Measurement June 18,
3E	180	79.80	776.00	611.00	165.00	165.00	338	48.80	1970.

Table 8. Values of Soil Hydraulic Conductivity II.

Plots	Depth of Holes (ft.)	a meter	s meter	n_1 meter	n_2 meter	d meter	t minutes	K meter/day	K Ins/day	Plot treatment
3B	0.5	0.0375	0.0248	0.1138	0.1129	0.1254	5	0.7410	29.0000	First Irrigation June 4, 1970. Measurement June 6, 1970.
	1	0.0375	0.0365	0.1730	0.1380	0.1850	12	0.1140	4.4500	
	2	0.0375	0.0885	0.4740	0.4310	0.5000	12	0.0378	1.4800	
	3	0.0375	0.1420	0.5220	0.4480	0.7710	28	0.0153	1.1700	
	4	0.0375	0.2200	0.7560	0.4890	1.1160	35	0.0259	1.0100	
	5	0.0375	0.2730	0.7600	0.3800	1.3850	20	0.0164	0.6500	
3E	0.5	0.0375	0.0251	0.1144	0.0890	0.1271	5	0.7000	27.2000	Second Irrigation June 17, 1970. Measurement June 19, 1970.
	1	0.0375	0.0249	0.1200	0.0930	0.1260	12	0.0955	3.7250	
	2	0.0375	0.0950	0.4250	0.3890	0.4820	12	0.0344	1.3700	
	3	0.0375	0.1480	0.7100	0.5600	0.7480	48	0.0259	1.1100	
	4	0.0375	0.2120	0.9920	0.7840	1.0770	58	0.0213	0.8310	
	5	0.0375	0.2640	0.8760	0.5930	1.3410	47	0.0106	0.4130	

Table 9. Soil Moisture Suctions at Different Soil Depths and Time after Irrigations. Plot 3C. First Irrigation: Starting Time, June 4, 1970. Second Irrigation: Starting Time, June 17, 1970.

Time after Irrigation (Days)	Water Table Heights above Tile Drains (ft.)	6" Soil Depth h_w	6" h_m	6" τ	12" Soil Depth h_w	12" h_m	12" τ	18" Soil Depth h_w	18" h_m	18" τ	24" Soil Depth h_w	24" h_m	24" τ	Plot Treatment
0.0	3.13	69.6	3.8	+17.9	83.4	3.6	+34.4	99.6	3.2	+56.1	119.8	3.9	+66.8	First
1.0	2.83	70.4	4.3	+11.9	83.7	4.2	+26.5	99.8	4.2	+42.6	118.8	4.2	+61.7	Irrigation
2.0	1.83	70.7	6.8	-21.8	84.1	7.4	-16.5	100.2	7.0	+ 5.2	119.1	4.3	+60.6	Corn Crops
3.0	1.23	71.2	7.8	-34.9	83.8	7.6	-20.6	100.3	7.2	+ 2.4	120.4	5.8	+41.5	6" High on
4.6	0.93	71.5	8.4	-42.7	84.4	8.1	-25.8	100.6	7.4	+ 0.0	120.6	6.9	+26.6	Plot
5.6	0.74	71.6	8.5	-44.1	84.6	8.5	-31.1	100.7	7.7	- 4.3	120.7	7.1	+24.2	
6.6	0.68	71.7	8.7	-46.4	84.8	8.8	-35.1	100.8	7.9	- 6.4	120.9	7.4	+20.1	
7.6	0.59	72.0	9.3	-54.3	84.9	8.9	-36.1	100.9	8.1	- 9.1	121.0	7.7	+16.1	
8.0	0.50	72.8	9.8	-60.1	85.7	9.8	-48.6	101.5	8.5	-15.0	121.7	8.7	+ 3.6	
9.0	0.38	74.1	11.1	-77.4	86.9	10.4	-54.5	102.4	10.2	-37.2	122.3	10.8	-24.6	
10.4	2.03	69.9	5.4	- 3.6	83.0	5.4	+ 9.5	99.4	5.3	+27.4	119.6	4.9	+53.0	0.63" rain
11.0		70.7	6.9	-23.3	83.9	6.9	-10.1	100.2	6.8	+ 7.7	119.8	5.5	+44.8	fell
0.0	3.18	68.6	4.0	+14.2	84.9	3.6	+35.9	98.7	3.2	+55.2	118.7	3.6	+69.7	Second
1.0	2.79	69.4	4.1	+13.6	83.5	4.6	+20.9	98.1	4.0	+43.7	118.9	3.6	+69.9	Irrigation
2.3	1.79	71.0	7.1	-25.5	83.8	6.9	- 9.8	100.3	7.0	+ 5.3	119.4	4.5	+58.2	Corn Crops
4.0	2.83	70.5	4.0	+14.1	83.7	4.7	+19.8	98.9	4.3	+40.3	119.4	4.1	+63.6	18" High
5.0	2.05	70.3	6.2	-14.0	83.9	6.8	- 8.6	101.1	7.0	+ 5.9	119.5	4.4	+59.6	on Plot
6.0	1.58	70.7	7.0	-24.4	84.3	7.7	-20.4	101.2	7.3	+ 1.9	120.1	4.7	+56.2	1.15" rain fell
7.0	1.46	71.1	7.7	-33.6	84.7	8.4	-29.5	101.9	7.5	- 0.1	119.4	4.7	+55.5	0.15" rain
8.0	1.26	71.3	6.9	-22.5	83.8	6.6	- 6.0	100.3	6.6	+10.5	122.2	4.8	+56.9	fell

Table 10. Soil Moisture Suctions at Different Soil Depths and Time after Irrigations. Plot 3D. First Irrigation: Starting Time, June 4, 1970. Second Irrigation: Starting Time, June 17, 1970.

Time after Irri-ga-tion (Days	Water Table Heights above Tile Drains (ft.)	Soil Moisture Suctions (cm.)												Plot Treatment
		6" Soil Depth			12" Soil Depth			18" Soil Depth			24" Soil Depth			
		h_w	h_m	τ	h_w	h_m	τ	h_w	h_m	τ	h_w	h_m	τ	
0.0	2.92	72.9	3.8	+21.9	75.5	3.6	+26.6	95.0	4.4	+34.4	112.8	3.8	+61.9	First
1.0	1.55	74.8	6.8	-17.7	76.4	6.4	-10.6	96.1	6.7	+ 4.5	113.1	4.6	+50.6	Irrigation
2.0	0.99	74.8	7.4	-25.8	76.6	7.0	-18.6	96.4	7.6	- 6.4	113.7	6.1	+30.7	
3.0	0.72	75.1	8.0	-33.8	76.6	7.6	-26.6	96.5	8.0	-12.4	114.4	7.4	+13.8	
4.6	0.52	75.3	8.5	-40.2	76.7	8.3	-36.3	96.5	8.2	-15.1	115.5	8.2	+ 2.5	
5.6	0.32	75.5	8.8	-44.5	76.9	8.6	-40.1	96.6	8.3	-16.4	115.7	8.8	- 4.3	
6.6	0.29	75.6	9.1	-48.3	77.1	8.8	-42.7	96.6	8.5	-18.9	115.8	8.9	- 5.2	
7.6	0.23	75.7	9.3	-50.6	77.3	9.4	-50.7	96.7	8.7	-21.5	115.9	9.0	- 6.3	
8.0	0.20	89.6	11.1	-61.8	89.1	10.3	-50.9	101.2	9.6	-29.4	126.4	10.2	-12.3	
9.0	0.12	--	--	--	--	--	--	103.3	10.7	-42.2	127.7	10.8	-19.2	
10.4	1.49	74.0	4.4	+14.1	75.8	3.9	+22.7	96.0	4.4	+36.2	112.5	4.9	+45.8	0.63" rain
11.0	--	74.4	6.7	-16.6	76.5	6.0	- 5.1	96.0	7.1	- 0.5	114.2	5.8	+35.2	fell
0.0	3.00	73.6	3.8	+21.9	78.3	3.8	+26.6	95.2	4.5	+34.0	112.7	3.3	+67.8	Second
1.0	1.58	74.0	6.2	-10.3	78.0	6.3	- 7.7	95.9	7.3	- 3.4	114.7	5.3	+42.6	Irrigation
2.3	1.05	74.8	7.6	-28.4	76.9	7.1	-20.1	96.4	7.9	-11.0	114.5	6.4	+27.5	
4.0	2.12	73.7	5.3	+ 1.6	78.9	5.2	+ 8.1	81.6	6.0	+14.8	113.8	3.9	+60.8	1.15" rain
5.0	1.39	75.2	7.0	-20.0	77.0	6.7	-14.1	96.7	7.6	- 6.7	114.1	5.5	+39.3	fell
6.0	0.97	75.4	7.7	-29.3	87.0	8.0	-21.8	95.3	8.0	-12.5	114.4	6.4	+27.4	
7.0	0.75	74.9	6.9	-18.9	71.7	6.5	-16.7	96.9	7.8	- 9.2	115.2	6.7	+24.2	0.15" rain
8.0	0.59	74.8	7.5	-27.2	76.7	7.0	-18.5	96.3	7.8	- 9.7	114.7	6.7	+20.7	fell

Table 11. Soil Moisture Suctions at Different Soil Depts and Time after Irrigations. Plot 3E. First Irrigation: Starting Time, June 4, 1970. Second Irrigation: Starting Time, June 17, 1970.

Time after Irri-ga-tion (Days)	Water Table Heights above Tile Drains (ft.)	Soil Moisture Suctions (cm.)												Plot Treatment
		6" Soil Depth			12" Soil Depth			18" Soil Depth			24" Soil Depth			
		h_w	h_m	τ	h_w	h_m	τ	h_w	h_m	τ	h_w	h_m	τ	
0.0	2.00	67.2	3.5	+19.6	74.7	3.5	+27.1	90.5	3.6	+41.5	111.5	4.7	+47.5	First
1.0	1.58	67.7	4.8	+ 2.5	74.7	4.5	+13.8	88.9	4.4	+28.9	110.8	4.4	+50.8	Irrigation
2.3	0.67	68.5	6.3	-17.1	75.0	6.4	-12.0	89.4	6.6	- 0.2	111.1	4.9	+43.5	Corn Crops
3.0	0.36	68.7	6.7	-22.3	75.1	6.8	-17.4	89.6	6.8	- 2.9	111.2	5.0	+43.2	6" High on
4.6	0.27	68.9	7.2	-29.1	75.2	7.1	-21.3	89.7	7.0	- 5.6	111.4	5.4	+37.9	Plot
5.6	0.10	69.1	7.5	-32.9	75.4	7.5	-26.6	89.8	7.4	-10.8	111.5	5.7	+34.0	
6.6	0.07	69.2	7.6	-34.0	75.6	7.7	-29.3	90.0	7.7	-14.9	111.7	6.0	+30.2	
7.6	0.08	71.3	8.4	-43.1	77.5	8.5	-38.3	91.1	8.2	-19.9	112.6	6.8	+25.0	
8.0														
9.0	--	72.1	8.6	-45.0	72.1	8.7	-39.1	92.3	8.5	-23.4	113.6	6.9	+20.0	
10.4	0.88	68.0	5.3	- 4.0	74.4	5.4	+ 0.9	89.0	5.8	+10.0	110.9	5.0	+42.9	0.63" rain
11.0		69.0	7.4	-31.6	75.1	6.7	-15.9	89.6	7.0	-14.4	111.5	5.6	+35.3	fell
0.0	2.00	68.0	3.6	+19.0	74.2	3.5	+26.6	89.8	3.5	+38.1	111.1	4.3	+52.6	Second Ir-
1.0	1.38	68.8	4.9	+ 2.2	75.3	5.0	+ 7.3	89.6	4.9	+23.0	111.7	4.8	+46.4	rigation
2.3	0.37	68.5	6.4	-18.5	75.1	6.8	-17.4	89.6	7.0	- 5.4	110.8	4.8	+45.6	Cron Crops 18" High on Plot
4.0	1.79	67.1	3.7	+16.8	73.9	4.0	+19.5	86.8	4.4	+27.0	111.0	4.6	+48.4	1.15" rain
5.0	0.93	68.0	5.2	- 2.7	75.6	5.7	- 1.9	88.5	6.0	+ 6.9	111.0	4.6	+48.4	fell
6.0	0.41	70.4	6.0	-18.0	74.7	6.4	-12.3	90.1	6.9	- 3.7	109.9	4.8	+44.6	
7.0	0.52	70.7	5.6	- 5.5	74.8	6.0	- 6.8	90.4	6.2	+ 6.1	111.1	5.0	+43.1	0.15" rain
8.0	0.20	68.7	6.9	-25.3	74.9	6.5	-13.6	89.4	6.7	- 1.6	111.1	5.0	+43.1	fell
9.0														

APPENDIX B

DETAILS OF EXPERIMENTAL SET-UP

Figure 20(a). Details of plot 3C. Tile Drains Only.

Figure 20(b). Details of Plot 3D. Tile and Surface Drains.

Scale: 1" = 40'

Key:

6" Earth dike and plot boundary

4" Tile at 3' depth and 40' spacing

Surface drain 0.2% slope

30° V-weir

1.25' H-flume

Sealed tile main and 4' depth plastic barrier

Note: Weir and flume not to scale.

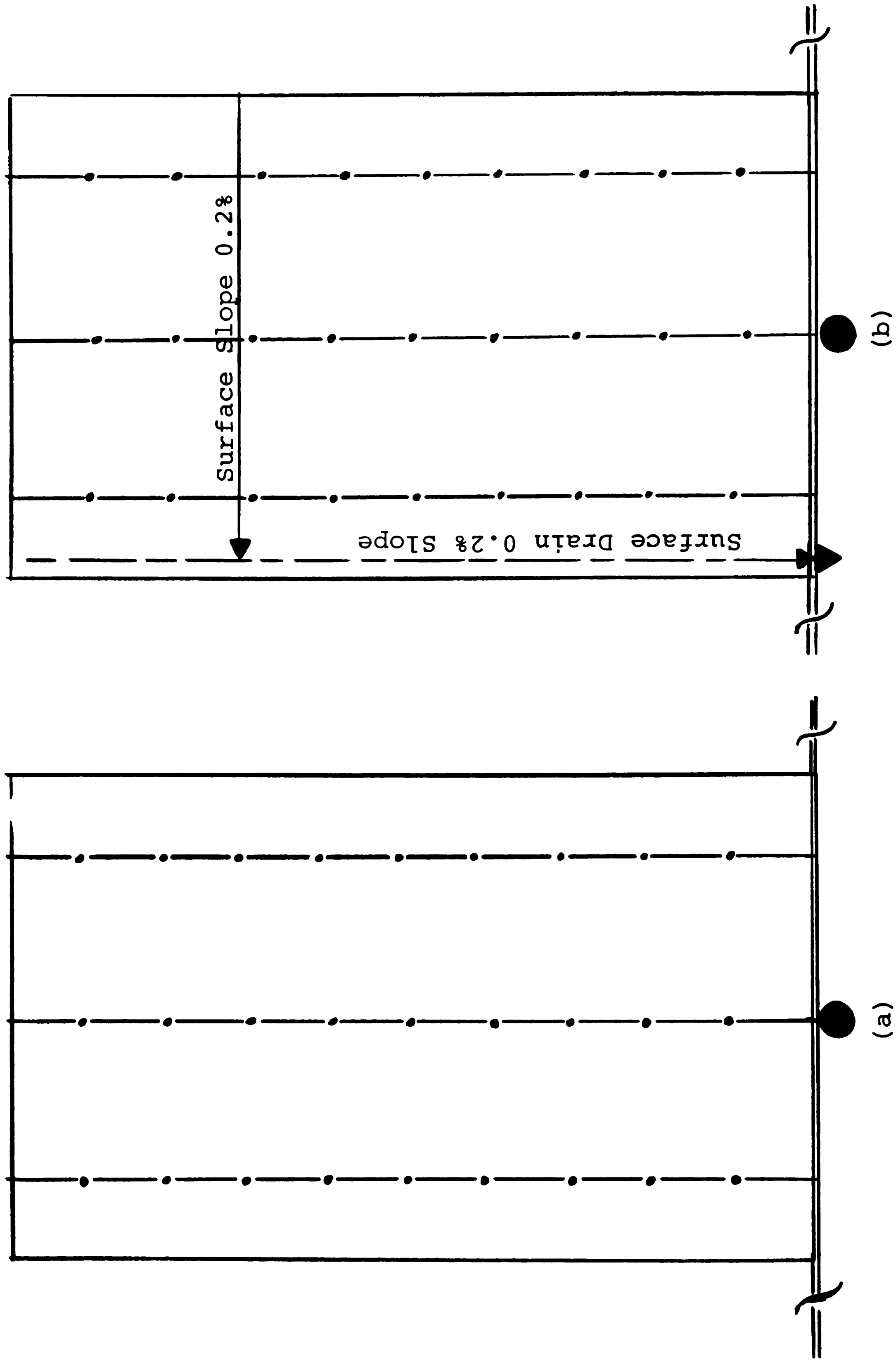

Surface Slope 0.2%
Surface Drain 0.2% Slope
(b)
(a)

Figure 21(a). Details of Plot 3E. Plastic Tile Drains Only.

Figure 21(b). Details of Plot 3B. Surface Drain Only.

Scale: 1" = 40'

Key:

6" Earth dike and plot boundary

3" plastic tile at 2' depth and 20' spacing

Surface drain 0.2% slope

30° V-weir

1.25' H-flume

Sealed tile main and 4' depth plastic barrier

Note: Weir and flume not to scale.

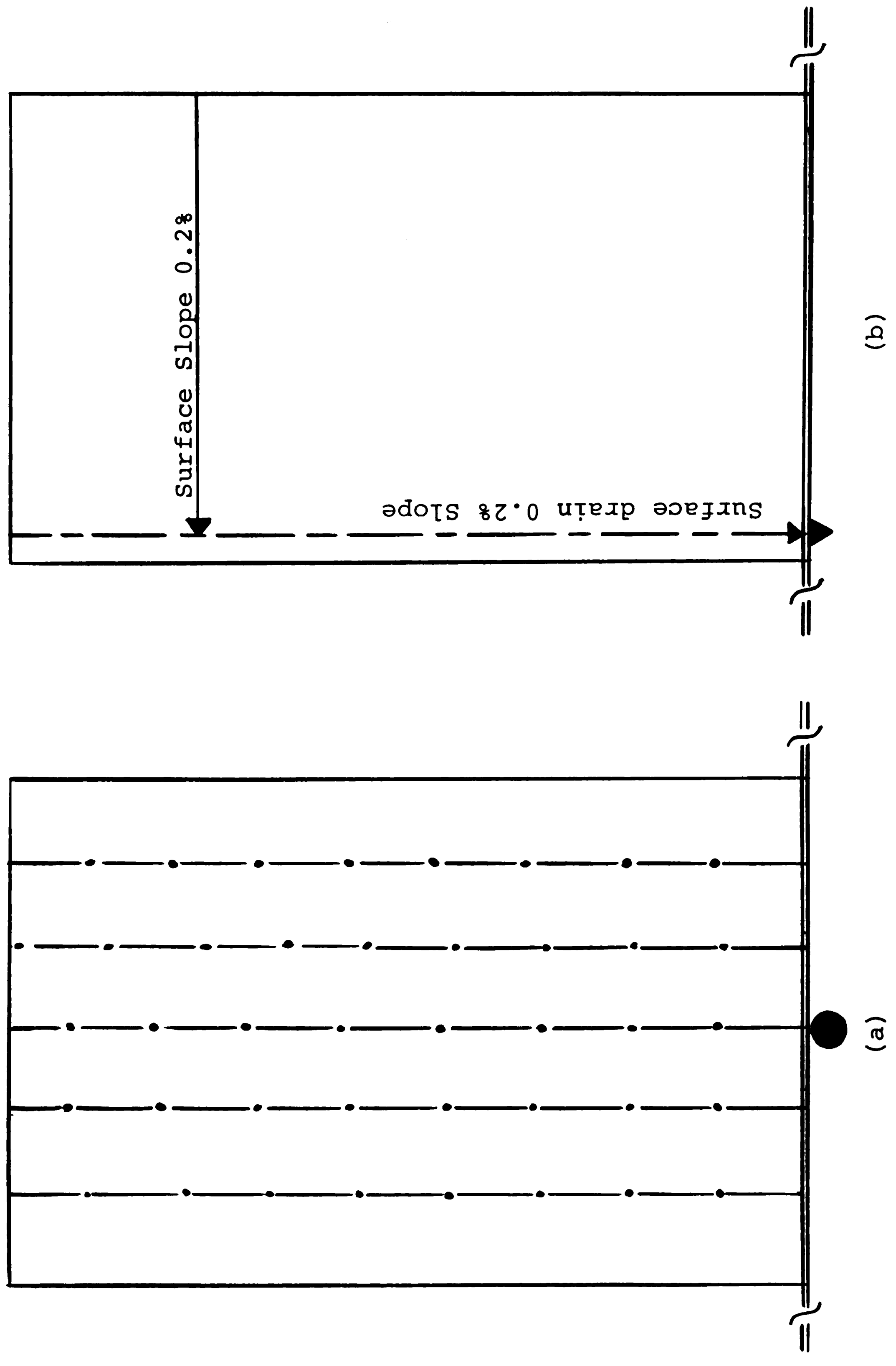

Surface Slope 0.2%
Surface drain 0.2% Slope
(b)
(a)

Figure 22. Details of Experimental Plots.

Scale: 1" = 60'.

Key:

Plot boundary

Tile drains

(a) 4" clay tiles in 3C and 3D

(b) 3" plastic tiles in 3E

1/2" water table pipes

Tensiometers

3" Auger holes for hydraulic conductivity measurement

30° V-weir

1.25' H-flume

Surface drain (0.2% slope)

Note: Water table pipes, tensiometers, auger holes, weir and flume are not to scale.

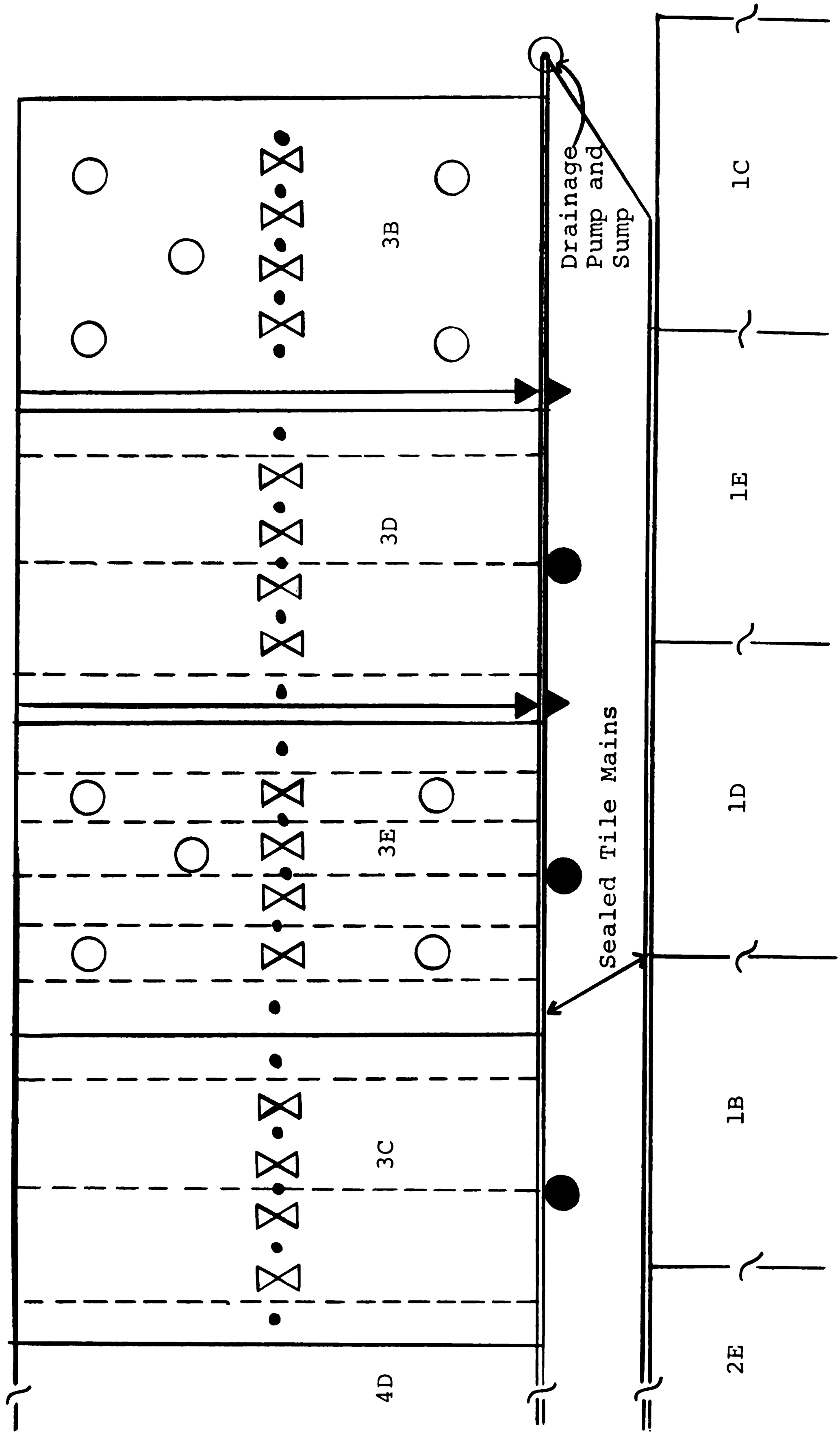
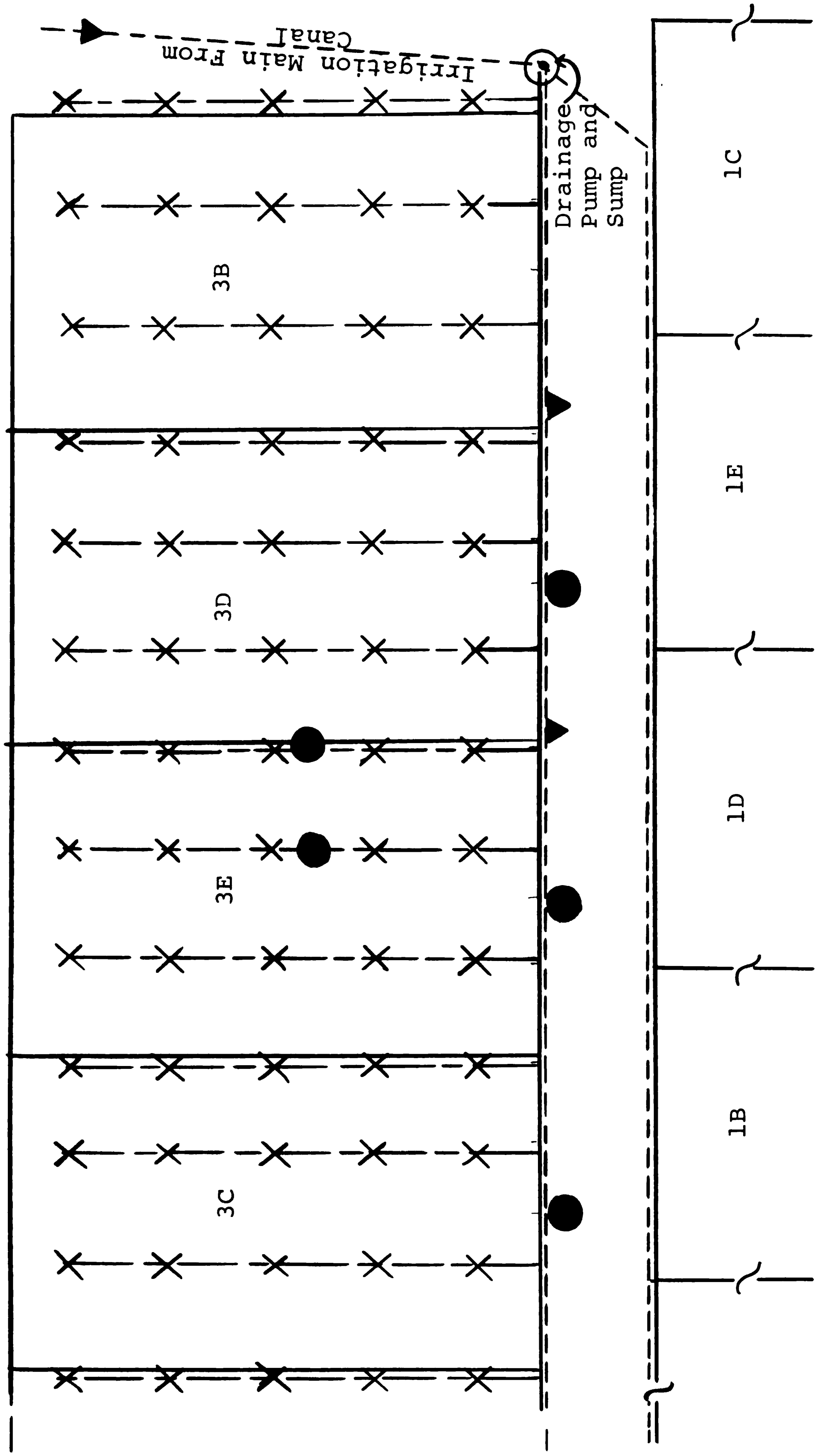

Drainage Pump and Sump
Sealed Tile Mains
3B
3D
3E
3C
4D
1C
1E
1D
1B
2E

Figure 23. Details of Plots Showing Sprinkler Irrigation Layout.

Scale 1" = 60'

Key:
- Plot boundary
- Sprinkler lateral
- × Sprinkler nozzle (40' x 40')
- Sprinkler Main
- ● V-Weir
- ▼ 1.25' H-Flume

Note: Drainage pump, flume and weir not drawn to scale.


Irrigation Main From Canal
Drainage Pump and Sump
3B
3D
3E
3C
1C
1E
1D
1B

APPENDIX C

FORMULAE

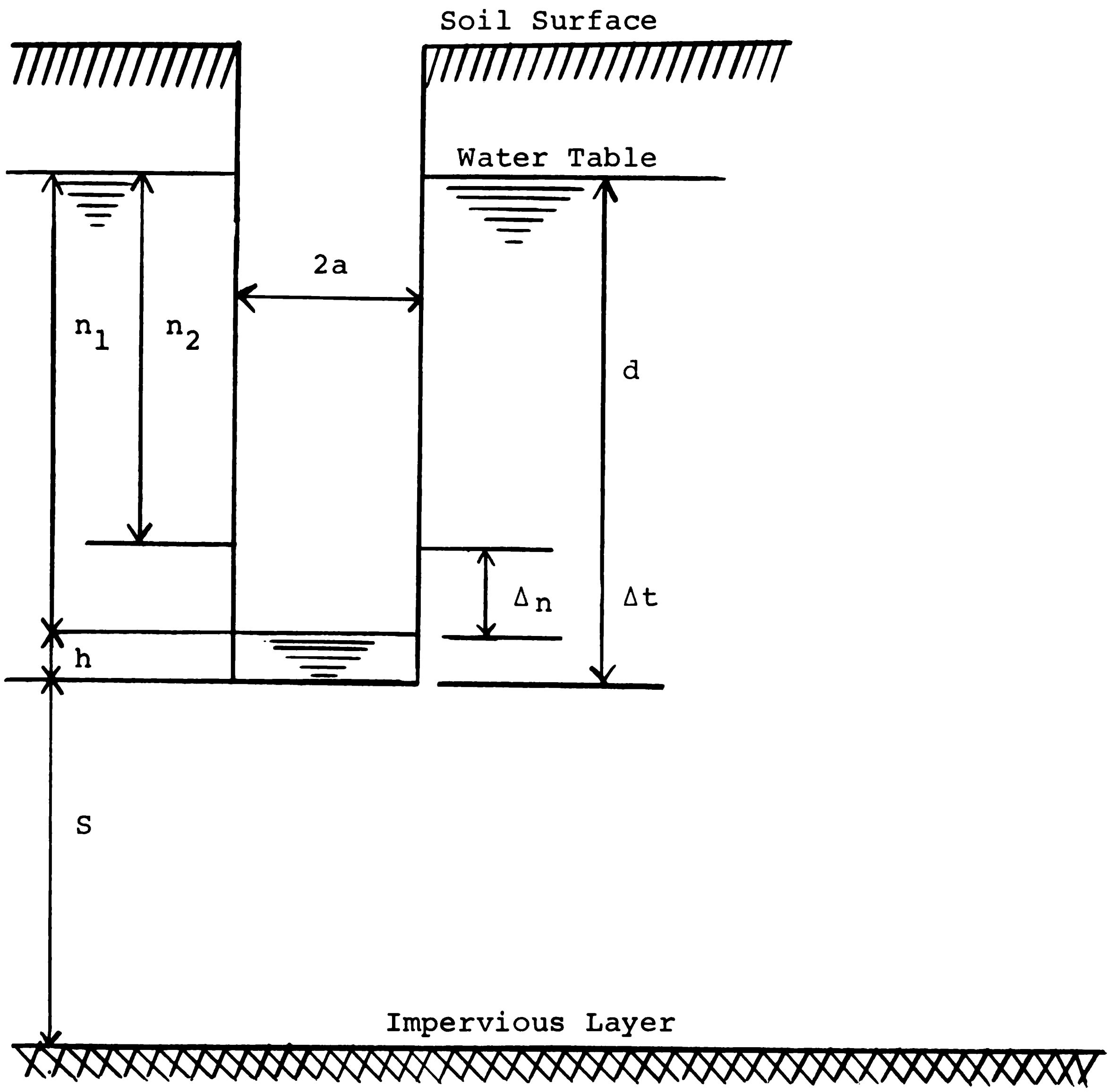


Figure 24. Calculation of Hydraulic Conductivity by Hooghoudt's Method of Single Auger Hole.

From: "Drainage of Agricultural Lands." Agronomy, Vol. 7. American Soc. of Agronomy, page 420-424, by James N. Luthin (ed.).

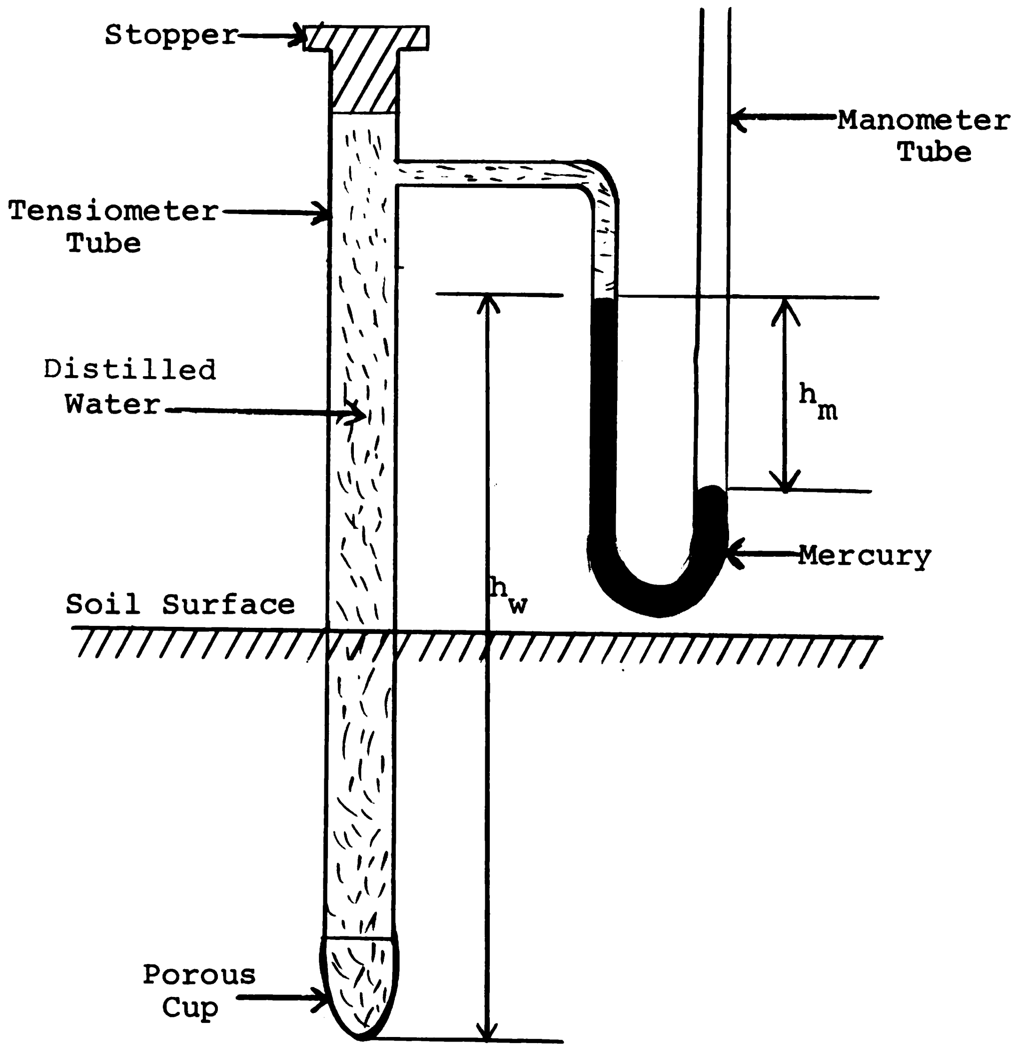


Figure 25. Longitudinal Section of Mercury Tensiometer. Marshall (1959).

Note: $\tau = (h_w D_w - h_m D_m)$ units of length. (42)

EQUATIONS

DIMENSIONAL VERIFICATION OF DIFFUSIVITY

From (20), $$C_{vol} = \frac{\Delta\theta}{\Delta\tau} = \frac{1}{\frac{ML}{L^2T^2}} = \frac{LT^2}{M} \qquad (28)$$

where

L = Lenght
M = Mass
T = Time

From (21), $$D_e = \frac{K.\Delta t}{\gamma g.\Delta\theta} = \frac{\frac{L}{T} \cdot \frac{M}{LT^2}}{\frac{M}{L^3} \cdot \frac{L}{T^2}} = \frac{L^2}{T} \qquad (29)$$

From (19), $$D_e = \frac{K}{\gamma g C_{vol}}$$

Multiply and divide the denominator of the above equation by yg.

$$\frac{\gamma g C_{vol}}{\gamma g} \times g = \frac{\frac{M}{L^3} \cdot \frac{L}{T^2} \cdot \frac{LT^2}{M} \cdot \frac{M}{L^3} \cdot \frac{L}{T^2}}{\frac{M}{L^3} \cdot \frac{L}{T^2}} = 1/L \qquad (30)$$

= fraction or percentage per unit length.

From (19) and (30), $$D_e = \frac{K}{1/L} \qquad (31)$$

$$= \frac{K}{\text{Percentage moisture per unit length}}$$

$$= \frac{k}{\theta/t} \qquad (32)$$

From (18), $L = 2\pi(\frac{K}{\theta/\tau}) \frac{y_t}{q_t}$ (33)

$$= \frac{2\pi K\tau y_t}{\theta \cdot q_t} \quad (34)$$

$C_{vol} = \frac{\Delta\theta}{\Delta\tau}$, Rose (1966) (35)

$D_e = \frac{K}{\gamma g C_{vol}}$, Rose (1966) (36)

$j = \frac{1}{\pi 2} \frac{\mu L^2}{K}$, Van De Leur (1958) (37)

$k = \frac{as\ln \frac{n_1}{n_2}}{(2Z + a)t}$, Luthin (1957) (38)

$q_t = \frac{8}{\pi 2} PL \, (e^{b/j}-1)e^{-t/j}$, Van De Leur (1958) (39)

$s = \frac{aZ}{0.19}$, Luthin (1957) (40)

$y_t = \frac{4}{\pi} \frac{P_j}{\mu} (e^{b/j}-1)e^{-t/j}$, Van De Leur (1958) (41)

$\tau = (h_w D_w - h_m D_m)$, Marshall (1959) (42)

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