This is to certify that the

thesis entitled

WATER TABLE RESPONSE DURING SUBSURFACE IRRIGATION

presented by

KENDALL J. DYKHUIS

has been accepted towards fulfillment
of the requirements for

Master's degree in Agr. Engr. Tech.

George Merva
Major professor

Date February 26, 1988

# WATER TABLE RESPONSE DURING SUBSURFACE IRRIGATION:

by

Kendall J. Dykhuis

A THESIS

Submitted To
Michigan State University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

in

Agricultural Engineering Technology

Department of Agricultural Engineering

1988

ABSTRACT

WATER TABLE RESPONSE DURING SUBSURFACE IRRIGATION

By

Kendall J. Dykhuis

Field experiments were conducted on four sites to determine water table response during subsurface irrigation. Water stage recorders were used to continuously record water table changes. Manual monitoring of water table depths was conducted using a blow tube. Results showed limited horizontal hydraulic conductivity resulted in evapotranspiration removing saturated soil water faster than it could move laterally to a monitored position five meters off the tile lateral on one site. Results of water table response to subsurface irrigation were presented and comparied to predictions from the approximate steady state approach for two sites. Comparison between observed and calulated water table response showed good correlation on two sites with 10 and 20 m tile spacing, respectively. Saturated horizontal hydraulic conductivity was considered a major factor governing performance of subsurface irrigation. All field sites were not recommended for subsurface irrigation. Rainfall resulted in significant rise in the water table. Adequate drainage must be provided in subsurface irrigation design. Yield response to irrigation was shown to result in greater yield increase on granular soil texture than heavier clay soil.

ACKNOWLEDGEMENTS

I wish to thank Dr. Ted Loudon, my major professor, for his advice, encouragement and thoughtful suggestions. I thank Dr. George Merva and Dr. Raymond Kunze for the time and effort they devoted as members of my guidance committee.

A special appreciation is extended to Advanced Drainage Systems Inc. of Columbus, Ohio, for the funding of this project. I want to thank staff menbers of Advanced Drainage Systems Inc., Mr. Bill Miller, Mr. Steve Helmrich, Mr. Jerry Richter, and Mr. Dale Treumner, who have supported the design and concept of subsurface irrigation for farmers using the Irri-Drain™ system.

My deepest thanks is extended to the following farmers who have given of themselves and their resources to make this project successful: Mr. Brad Singer and Mr. Jake Ellenbaum of Pigeon, Michigan and Mr. Roland Iott of Petersburg, Michigan. A special thanks to Mr. John Kemp, of Sebewaing, Michigan, a tiling contractor freely giving of his time and equipment. My appreciation is extended to fellow students who helped with field work, Mr. Phil Brink, Mr. Buell MaCarther and Mr. Lee Wolfe.

Finally, I want to thank my wife, Virginia, for her encouragement, love and patience given me over the course of my studies.

To Joe Boeve

One who has been a friend and
positive influence in my life
by his example in loving and serving
others and wanting their lives to be all
that they can be.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

# I. INTRODUCTION

Many locations in the humid regions of North America experience excessive soil moisture conditions, especially during the time of critical preplanting and/or harvesting operations. It is also common to have a water deficit in the soil profile during some part of the growing season. If the soil water deficit occurs at a critical time in the crop's development, it can limit crop growth and yield. The objective of tile drainage and subsurface irrigation through drain tile is to provide a soil environment that results in optimum conditions for field traffic as well as for plant growth and crop yield.

The state of Michigan generally has the lowest summer rainfall of any state east of the Mississippi River. Drought stress is probable two years out of five for the summer months June through September. Moisture deficiency is likely to occur every year during some portion of the growing season (Lucas and Vitosh, 1978; Linville, 1983).

The state of Michigan has 1.2 million hectares (3 million acres) of soils that would benefit from drainage. The expected post-drainage yield increases on these soils ranges from 15 to 30% (Michigan Data, U.S.D.A., 1982). These increases would primarily be due to the alleviation of early reason wetness. Because of this and because of the midseason potential for drought stress, incorporating a subsurface irrigation-drainage system can be an excellent management tool.

The primary aim of drainage systems in humid regions like Michigan is twofold: 1) to render the soil workable early in the spring and 2) to remove excess water from the upper layers of the soil so that air can enter the soil voids and become available to the roots of plants. Drainage systems consist of subsurface or surface components, or both. Subsurface drainage systems are usually composed of a network of ditches and/or drain tubes designed to lower the water table by removing excess water from the soil profile and transferring it to a drainage outlet. An adequate drainage system in humid regions is based on a design flow rate. This flow rate is expressed as the drainage coefficient and is defined as the depth of water to be removed from the drained area in a unit of time (cm per day) (Schwab et.al. 1981). Surface drainage should also be provided by land forming or shaping to remove excess surface water in a manner consistent with good erosion control practices. A drainage system, whether subsurface, surface, or a combination of the two, allows for trafficable conditions for seedbed preparation in the spring and harvesting in the fall. It also prohibits excessive soil water conditions, providing a proper soil environment for plant growth during the growing season.

Subsurface irrigation may be defined as the process of regulating the elevation of a shallow ground water table by artificially adding water underground through the subsurface drainage system. Water may be fed to the soil profile by furrows or ditches running parallel to each other or with clay tile or perforated plastic pipe buried 75 to 120 cm under the surface of the field. A barrier against excessive losses through deep percolation must exist in the profile. The barrier may be a relatively impervious layer which impedes downward movement of water in the substratum or it may be a permanently high natural water table which can be manipulated. Theoretically, the water level is maintained above the impervious barrier at a selected depth below the soil surface so that the proper combination of water and air availability to the plant root is assured (Figure 1.1).

Subsurface irrigation has several major advantages: 1) an irrigation system and a drainage system are combined, which allows for substantial savings on initial capital cost when compared to the cost of two separate systems (Worm et.al. 1982); 2) there are lower labor requirements than with sprinkler irrigation; 3) a lower energy cost is realized than with sprinkler irrigation because no system pressure is required and soil matric forces as well as the force of gravity move water throughout the soil profile with minimal energy inputs; and 4) maintenance requirements for subsurface irrigation are low (Massey et.al. 1983).

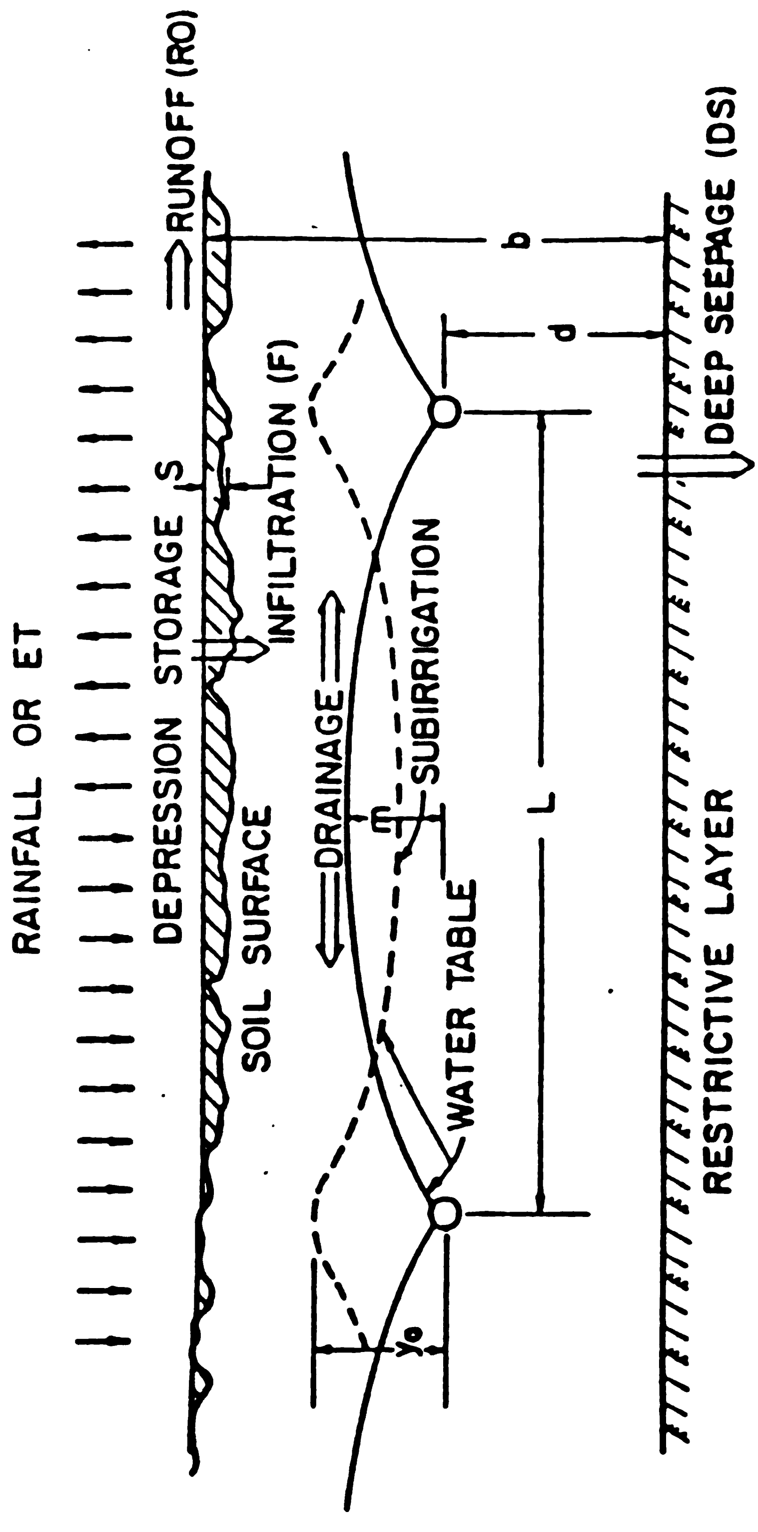


Figure 1.1 Schematic of subsurface irrigation-drainage system.

Dispite these advantages, the practice of subsurface irrigation has not been rapidly accepted. The primary reasons seems to be a lack of knowledge about how water moves during irrigation and drainage phases in specific soil profiles and knowledge about design for effective movement of water (Renfro, 1955). With the understanding of these processes, better subsurface irrigation management practices may be developed.

## II. OBJECTIVES

In order to gain an understanding of the response of the water table during subsurface irrigation and drainage and to apply this understanding to subsurface irrigation and drainage management, the following objectives were formulated for this study:

1. To measure the water table response to water input through subsurface tile in different soil types.

2. To measure the water table response in the transition from irrigation to drainage modes.

3. To develop management principles which may easily be applied to on-farm subsurface irrigation.

## III. LITERATURE REVIEW

To adequately address the issues of water movement in the soil with a subsurface irrigation and drainage system, some knowledge of (a) design parameters and procedures, (b) plant environment and (c) water table management is required. This section provides a review of the more pertinent literature and theory associated with these topics.

### A. Design Parameters and Procedures

Design of a subsurface irrigation system begins with a site inspection. A site inspection involves the assessment of the need for drainage, slope of the field, location of the tile outlet and water input, hydraulic conductivity, and depth to the impermeable barrier. Luthin (1959) concluded that it is difficult to transfer subsurface irrigation-drainage requirements and optimum water table depths from one location to another. Each location should be treated as an individual field having its own set of parameters. Fox et.al. (1956) indicated that an appropriate site for subsurface irrigation should have the following characteristics:

1. The site needs subsurface drainage for the removal of excess water as it exists in its present state.

2. The site should be relatively flat, with a surface slope of less than one percent.

3. There exists on the site a slowly permeable layer which is relatively shallow, from 1 to 3 meters below the surface, or the site has a naturally high water table.

4. The site has an adequate water supply available which will provide enough water to meet crop needs during the driest months.

5. There exists a good drainage outlet to let water out of the system or an outlet where water may be pumped out.

6. The site has moderate to high lateral hydraulic conductivity.

Two essential properties to consider for crops being grown are the range of rooting depths to be accommodated and different evapotranspiration rates at each growth stage. These characteristics affect the amount of water needed and the water table depth to be maintained in relation to the soil surface. Analysis of climatological data will show the historical growing season rainfall, weather patterns, and evaporative conditions which the design must be prepared to meet.

The most important parameter that influences the design of a subsurface irrigation-drainage system is a property called hydraulic conductivity (K). K is the ability of the conducting medium to transmit a liquid in response to a head gradient.

Hydraulic conductivity was first defined by the French engineer Henri Darcy during an investigation of seepage rates through sand filters (Hillel, 1980). Darcy's law says that

$$q = K\Delta H/L \qquad (3.1)$$

or for one dimensional flow in differential form:

$$q = -K\, dH/dx \qquad (3.2)$$

where q equals the specific discharge rate or volume of water flowing through a unit cross-sectional area per unit time (called flux); $\Delta H/L$ equals the hydraulic gradient or the head drop per unit distance in the direction of flow; and K is the proportionality factor known as the hydraulic conductivity with units of length (L) over time (t).

The hydraulic conductivity (K) is affected by physical properties of the soil profile and by the properties of the fluid. The soil characteristics which affect K are the total porosity, the distribution of pore sizes, and the pore geometry of the soil. The properties of the fluid which affect K are fluid density and viscosity. The electrolytic concentration also affects K due to swelling and dispersion within the soil matrix. Doering (1965) found from laboratory experiments that the detachment of clay particles and the entrapment of air bubbles resulted in the clogging of pores, and that a three fold change in the K value can result from either of these causes. Criddle and Kalisvaart (1967) pointed out that a soil profile with layers of silt or clay, even with good permeability, presents two problems for subsurface irrigation: 1) such soils generally have a slow capillary rise, 2) they often lose their permeability under subsurface irrigation practices. Subsurface irrigation on such soils may be satisfactory in the beginning, but under saturated conditions, they often become less permeable or even impermeable.

Many agricultural soils are not a homogeneous mix, but can have horizons with varying properties of texture and thickness, and the hydraulic conductivity may vary with depth and location.

Once it has been determined from a field evaluation that a subsurface irrigation system is feasible, the next step in the design is to choose the spacings of the tile drainage lines, or the spacing of the lateral ditches. The objectives of tile and/or ditch spacing are to satisfy both drainage and subsurface irrigation requirements. The design must place the drains close enough together to maintain some minimum water table during peak water use. The water level in the field must be lowered after a rainfall or prior to expected rainfall to facilitate rapid drainage and prevent crop damage due to poor aeration.

Therefore, the drain spacing used must:

1. Provide trafficable conditions for timely tillage and field operations during field preparation and harvesting;

2. Protect the crop from excessive soil water conditions by the removal of excessive soil water during the drainage process;

3. Provide rapid and uniform water input so that yields are not reduced because of drought stress (Skaggs et.al. 1973; Skaggs, 1981).

Because tile spacing contributes greatly to the cost of the subsurface irrigation-drainage system, a knowledge of the optimum spacing will allow the farmer to do a cost analysis to determine if the expenses of construction, when compared with the benefits, justifies the investment. A site which allows the water to move laterally through the soil rapidly (sandy loam and loamy sand) may offer the most significant cost return for two reasons. First, the tile or open ditch laterals can be spaced farther apart than laterals in more finely textured soils. Second, the yield increase due to irrigation is somewhat greater because the coarser soils do not have the water holding capacity found in clay and clay loams and therefore have lower yields without irrigation.

At least four methods have been used for determining tile spacing for subsurface irrigation:

1. The exact approach, which utilizes the numerical solution of the two-dimensional Richards' equation for exact boundary conditions;

2. The assumption of the steady state condition for saturated flow in the soil profile;

3. A (rule of thumb) percent of the spacing required for drainage alone;

4. Drainmod, a computer simulation program that considers soil properties, climatological data, and crop and site properties to predict the performance of subsurface irrigation and/or drainage at different tile or open ditch lateral spacings based on several years of weather data (Skaggs, 1981).

Exact Approach. Two dimensional water movement in the soil can be characterized by an equation proposed by Richards (1931) and is an exact approach that uses appropriate boundary conditions. While this approach has the advantage of not requiring simplifying assumptions and of being adaptable to most boundary conditions, numerical solutions are often difficult to obtain. Tang and Skaggs (1977) state that it is both difficult and expensive to characterize effective field values of the soil properties required in the exact approach.

Approximate Steady-State Approach. The approximate approach is considered less accurate than solutions to the Richards equation. However, the approximate methods for predicting water table movement during drainage and subsurface irrigation is acceptable for most field situations. The solutions have the advantage of being easy to apply and require fewer soil property inputs than more sophisticated approaches (Tang and Skaggs, 1977).

The steady-state condition for determining spacing uses the approximate method based on the Dupuit-Forcheimer (D-F) assumptions (Hillel, 1982). These assumptions ignore the zone in which water moves by unsaturated flow (Bouwer and van Schilfgaarde, 1963; Kirkham, 1958). The assumptions of D-F are that:

1. Water moves to the drain in a horizontal direction.

2. The velocity at each point in the soil profile is proportional to the slope of the water table and independent of the depth while under the influence of gravity (Hillel, 1982).

Mathematical models using the D-F assumptions assume a homogeneous soil with a constant hydraulic conductivity and a constant steady state condition. Hooghoudt (1937), using the assumptions of D-F, obtained an equation for the elliptical shape of the water table between the drains for steady state condition (Figure 3.1).

$$L = ((4Km/q) * (2d+m))^{0.5} \quad \ldots\ldots\ldots\ldots\ldots\ldots (3.3)$$

where L equals the distance between the drains, K equals the saturated hydraulic conductivity, d equals the height of the drain above the impervious layer, q equals the quantity of water passing through a unit plane per unit time, m equals the height of the water table above the center of the tile lateral, measured at the midpoint between adjacent tile lines. This equation has been used frequently in the past (Hillel, 1982).

There have been a number of modifications made to the steady-state models to account for new understanding of saturated flow. Bouwer and van Schilfgaarde (1963) modified Hooghoudt's equation which assumed that the water table falls without change of shape, and the flux per unit area of water table is uniform between tile laterals. However, their assumption that the water table falls without change of shape is of limited validity. In a ponded condition, the water table falls faster near the drains than midway between the drains. Having receded faster near the drains than midway between the drains, the water table reaches a position where it falls for some time without appreciable change in shape (uniform water table movement). As recession progresses, the water table eventually falls faster midway between the drains than in the vicinity of the drains. Thus, the flux in general

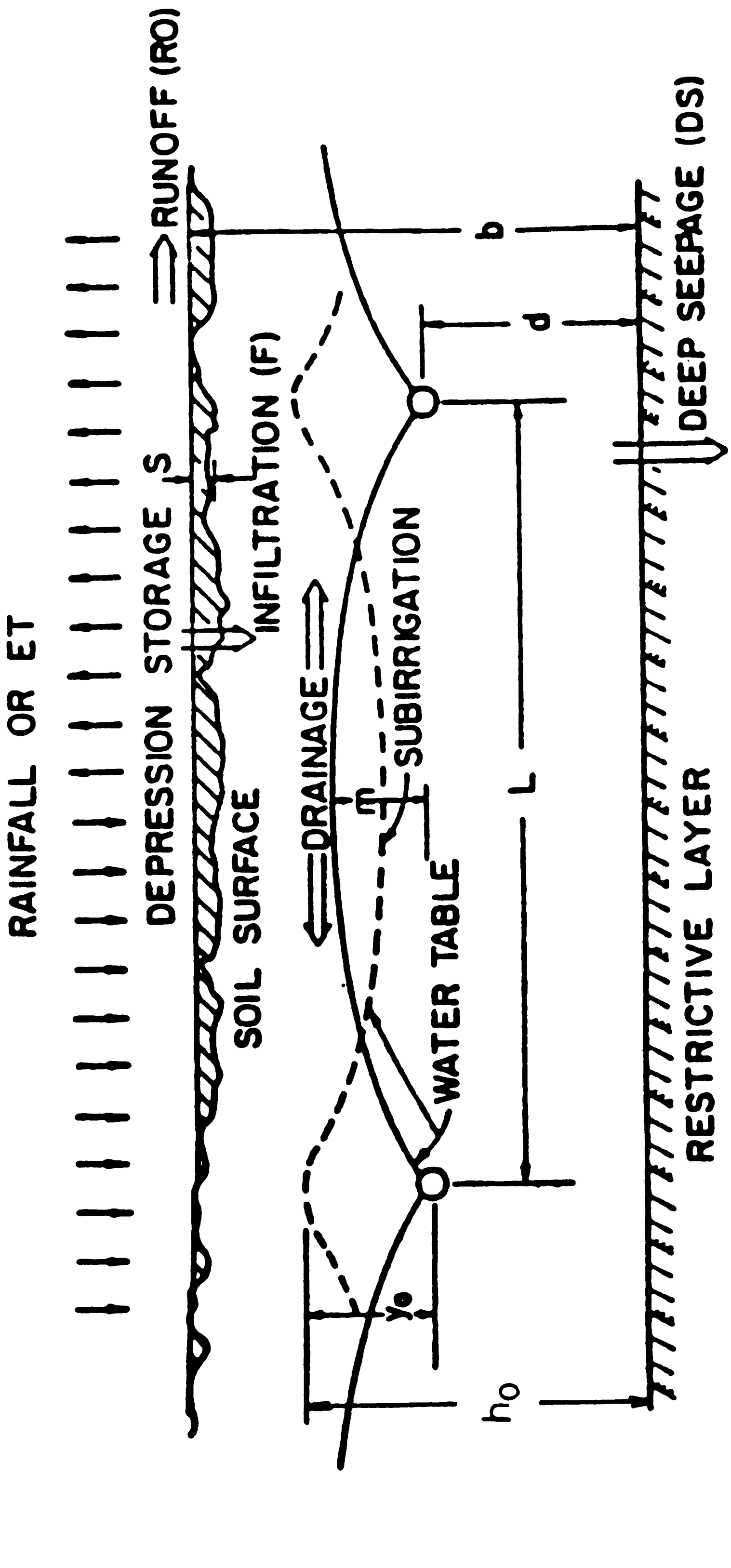


Figure 3.1 Schmatic of subsurface irrigation drainage system:

varies with distance from the drain. In order to use steady-state solutions for prediction of the rate of fall of the water table, which assumes a flux that is independent of time and distance from the drains, a correction factor C has been proposed (Bower and van Schilfgraade, 1963). C accounts for the non-uniformity of flux per unit area of water table if the water table changes in shape during recession (or rise).

$$L = ((4Km/qC) * (2d+m))^{0.5} \qquad \text{...............(3.4)}$$

C can be determined by calculating the ratio of the average distance of fall of the entire water table to the fall midway between the drains for a certain time increment. Bouwer (1959) has shown that this ratio is about 0.8 for m/L values from 0.02 to 0.08 and low d values (Figure 3.1). A C value of approximately 1.0 is indicated by Childs' (1947) work for higher water tables with m/L exceeding 0.15. C values of 1.0 are applicable for water tables that recede uniformly with time. C values greater than 1.0 can be expected for the initial stages of water table recession following a ponded case.

Two other D-F assumptions, continuous steady-state flow into the drain tile without restriction and homogeneous soil profiles, do not hold true in actual field situations. Hooghoudt (1937) characterized flow to the drains by considering radial flow in the region near the drains and applied the D-F assumptions to the region away from the drains. This analysis has been widely used to determine an equivalent depth, $d_e$, which tends to correct for convergence near the drains. Moody (1966) when considering the decrease in the inflow of water near the tile line as a result of convergence assumed an equivalent depth, $d_e$, at some point above the impervious layer rather than the actual depth between the impervious layer and the tile lateral.

Skaggs (1978) used equations developed by Moody (1966) who examined Hooghoudt's solutions and presented the following equations from which $d_e$ can be obtained.

For $0 < d/L < 0.3$

$$d_e = \frac{d}{1 + d/L*( 8/\pi \ *\ln(d/r) - \alpha )} \qquad \ldots\ldots\ldots (3.5)$$

in which $\alpha = 3.55 - 1.6*(d/L) + 2*(d/L)^2$

and for $d/L > 0.3$

$$d_e = \frac{L\pi}{8*(\ln (L/r) - 1.15)} \qquad \ldots\ldots\ldots\ldots\ldots\ldots (3.6)$$

in which r is the drain radius. Usually $\alpha$ can be expressed as $\alpha = 3.4$ with negligible error for design purposes.

The tile's circumferential area is not all porous, porosity is actually a small fraction of the total area. The converging water is forced to enter the drainage tile through a limited inlet area. This results in a restriction of the water volume entering the drainage tile laterals. To account for this additional convergence loss as the water approaches the finite number of openings in a real rather than completely open drain tube, an effective drain tube radius, $r_e$, is defined. Skaggs and Tang (1979) define an effective drain tube radius, $r_e$, such that a completely open drain tile with radius $r_e$ will offer the same resistance to inflow as a real tile line with radius r. Skaggs and Tang used the work done by Bravo and Schwab (1975) to define $r_e$ for a 114 mm (4 inch) corrugated pipe with slots 1.6 mm wide and 27 mm long as, $r_e = 5.1$ mm.

The Dupuit-Forcheimer (D-F) assumptions used in horizontal saturated lateral steady-state equations assume a homogeneous profile. Most soils do not have homogeneous soil profiles but rather have layered profiles with different properties of texture and porosity. This results in a non-constant saturated hydraulic conductivity throughout the soil profile and the Hooghoudt assumptions not holding true. Compensation for the different soil profile layers with changing lateral conductivities must be made (Skaggs, 1979).

The compensation for the lack of homogeneous lateral hydraulic conductivity through a layered soil profile was accomplished by measuring the depth and conductive properties of each layer and taking a weighted average. The weighted average includes only those layers occupied by the water table and is called the equivalent hydraulic conductivity ($K_e$).

$$K_e = \frac{K_1 d_1 + K_2 D_2 + K_3 D_3}{d_1 + D_2 + D_3} \quad \text{.................(3.7)}$$

where $K_e$ equals the equivalent hydraulic conductivity; $K_1$ equals the lateral conductivity in the first layer and $d_1$ equals the depth of the first layer, $K_2$ equals the lateral conductivity of the second layer and so on. If the water table is not positioned in the first layer of soil, then $K_1$ and $d_1$ equal zero.

Bouwer and van Schilfgaarde (1963) found a good correlation when comparing the approximate method proposed by Hooghoudt to the more exact numerical solution proposed by Richards for two-dimensional flow. However, because the inputs and computations required to use the Richards equation are difficult, the steady state method using the D-F assumptions appears preferable for predicting spacing of drains provided convergence near the drain can be accounted for (Skaggs, 1978).

Percent of the Spacing. Commonly, the tile spacing used for tile drainage in a given area is the spacing that seems optimal, based on contractor and farmer experience with a particular soil type. The spacing chosen for subsurface irrigation is usually less than the spacing for drainage. A typical rule of thumb has been to space laterals for subsurface irrigation at 65% of the spacing commonly used for drainage.

Drainmod. The fourth method which can be used to calculate subsurface irrigation and drainage spacing is a computer program called Drainmod (Skaggs, 1979). Drainmod utilizes the soil properties, climatological data, crop parameters and site parameters to predict the position of the water table and the total number of trafficable days in a given period for tillage and harvesting operations. The model is used to simulate the performance of a chosen tile or open ditch lateral spacing for subsurface irrigation and/or drainage over several years of weather data. It utilizes a quasi-steady state equation to predict drainage lateral spacings. The $K_e$ concept (equivalent hydraulic conductivity) is incorporated to account for changes in hydraulic conductivity for a layered soil profile. The convergence losses at the drain are treated in the same manner for subsurface irrigation as for drainage by equating $h_o$ to the sum of $d_e$ plus the water table elevation above the center of the drains ($y_o$).

The result from Drainmod is that the spacing for a subsurface irrigation and drainage system will be predicted for a determined crop yield performance and trafficable condition for a particular field, crop characteristics and geographic location (Skaggs, 1979).

## B. Plant Environment

### 1. Soil Aeration

Plant respiration and soil aeration are important factors that affect crop response when saturated soil conditions or lack of soil moisture exist (Harris and van Bavel, 1957a; Grable, 1966). Drainage plays a key role in the removal of excess water during periods of high soil moisture content to enhance soil aeration. Subsurface irrigation plays a role in the addition of water during conditions of moisture deficit.

The process of respiration by plant roots and organisms involves the exchange of gases with the soil air. Harris and van Bavel, (1957b) concluded that root respiration was the most sensitive aspect of plant activity in regard to soil aeration. They found that reduction in respiration activity is the first step in growth-limiting effects caused by insufficient aeration.

The gaseous exchange of air between the soil and the atmosphere can occur by two different mechanisms: convection and diffusion (Hillel, 1982). Convection is the process of air moving as a mass from a zone of higher pressure to one of lower pressure. Diffusion is the movement of each molecular species from a higher concentration to a lower concentration as a result of thermal agitation.. An example would be the diffusion of high $CO_2$ concentrations in the soil, produced by the respiration of plant roots and soil organisms, to the atmosphere where the $CO_2$ concentration is less.

The diffusion of gas can take two different forms. It can occur within the soil profile partly in the gaseous phase and partly in the liquid phase. Diffusion through the air-filled pores maintains the exchange of gases between the atmosphere and the soil, whereas diffusion through water films of various thicknesses maintains the supply of oxygen to, and the disposal of $CO_2$ from, live tissue such as root hairs. The rate of diffusion, however, is greater in the gaseous phase than in the dissolved water phase.

There has been some discussion about the process and exact amount of $O_2$ diffusion which takes place in the root zone. Hillel (1980) describes the diffusion process by Fick's law, where diffusion is a flux (mass diffusing across a unit area per unit time). Lemon and Erickson (1952) proposed a means of measuring the potential $O_2$ diffusion rate supplied to the root zone with a platinum electrode. Oxygen must diffuse through a film of water surrounding the platinum electrode wire much as oxygen diffuses to a root; thus the measurement approximates the rate at which oxygen can continually be supplied to a root.

The amount of $O_2$ diffusing to the root zone tends to vary from one researcher's findings to another. Erickson (1965) concluded that there is a certain threshhold oxygen diffusion rate below which plants cannot survive.

There is then a response curve where increasing the oxygen diffusion rate results in an increase in plant growth. The critical $O_2$ diffusion rate for most plants was approximately 35-40x$10^{-8}$ gms/$cm^2$-min, and partial suffocation may result below this critical level. Erickson did not correlate the diffusion rate with any stage of growth in the plant. Williamson (1964) set up an experiment using lysimeters in field installations to measure the rate of $O_2$ diffusion in the soil. Water tables were maintained throughout the growing season at intervals ranging from 150 to 762 mm below the soil surface. The soil type was a fine sandy loam. His conclusions were that the highest yields were obtained at $O_2$ diffusion rates of approximately 15x$10^{-8}$ gms/$cm^2$-min for sweet corn and dwarf field corn when soil moisture was not limiting in a growing crop.

The review given by Grable (1966) made clear that the effect of temporary $O_2$ deficiency caused by flooding depends not only on plant species but also on the physiological stage of growth, time and duration of water logging, light intensity, fertility of the soil, and temperature. A growing plant needs a critical amount of $O_2$ to maintain metabolic function. Williamson and Kris (1970) and Unger and Danielson (1965) found that a reduced $O_2$ supply rather than a buildup of $CO_2$ may be responsible for reduced growth of young corn plants under poorly aerated soil conditions.

The location of a static water table affects the rate of $O_2$ diffusion into the root zone. Hiler et.al. (1971) found that with a static water table at 300 mm, the $O_2$ diffusion rates never exceeded $20x10^{-8}$ gms/$cm^2$-min in the root zone during the growing season. Williamson (1964) concluded that $O_2$ diffusion rates with a 150 mm water table depth were below $5x10^{-8}$ gms/$cm^2$-min. Under these conditions, sweet corn and dwarf corn yields were reduced 65-75 percent respectively. Williamson also found that there was a tremendous increase in the $O_2$ diffusion rates above $15x10^{-8}$ gms/$cm^2$-min where the soil moisture was not limiting growth.

It has been noted that light intensity and its associated photosynthetic and transpiration demand can have adverse effects on plants when a high moisture-low aeration condition prevail (Erickson, 1965). Lemon and Wiegand (1962) showed that there is also a characteristic increase in the critical $O_2$ concentration as the temperature increases. Thus, as light intensity and higher air temperatures put more demand on the metabolic activities of the plant, plant respiration increases. The higher respiration increases the utilization of $O_2$, increases the $CO_2$ concentration, and increases the $O_2$ absorption demand at the root surface. Since biological processes are more temperature sensitive than physical processes such as diffusion, diffusion is more likely to be the limiting process as the temperature is increased in the absorption of $O_2$ by the plant. This becomes understandable when one realizes that the diffusion path from soil surface to root surface is completed via the water films surrounding the root hairs. This film may constitute only a fraction of the total length of the path, but its effective length is increased more than 10,000 fold by virtue of the smaller diffusivity of $O_2$ in water than in air. Letey and Stolzy (1967) concluded that a film thickness of 0.08 to 0.05 mm would limit root growth in media containing 20 to 50 percent air porosity and atmospheric $O_2$. Hillel (1982) discusses the different methods of measuring aspects of soil aeration.

It is thus evident that the degree of soil aeration affects the growth potential of growing crops. The water logging of the soil profile increases the effective thickness of water films surrounding the plant roots. The water film thickness affects the effective length of diffusion through which $O_2$ must travel by as much as 10,000 times when compared with diffusion through air. Temperature and the high moisture-low aeration condition have an adverse effect on crop growth and yield.

## 2. Affect of Water Table Depth on Root Growth

How a plant grows and the environment in which the growth occurs affect the outcome of the plant and its yield. The distribution and depth of roots depend on many factors such as plant species, stage of growth, fertilizer distribution, tillage treatments, physical barriers such as hardpans, chemical barriers such as acid subsoils, and the soil water regime during root development (Allmaras et.al. 1973).

Roots grow in the upper crust of the soil profile and penetrate and spread out as they mature. The depth and concentration of the roots is important information, useful in establishing the proper placement of the static water table in subsurface irrigation. Bloodworth et.al. (1958), in their work on root distribution of crops using undisturbed soil cores, found that 90 percent of grain sorghum roots were concentrated in the top 300 mm of the soil. Mengel and Barber (1974) found the highest percentage of corn root distribution, 80 percent, to be in the upper 400 mm of the soil profile. They also observed little evidence of root growth limitation by moisture or aeration stresses on corn grown in a silt loam soil having tile one meter deep spaced twenty meters apart. Williamson and Kris (1970), however, concluded that the root zone will be restricted by the water table. A study done by Williamson et.al. (1969) with millet indicated that total root weight increased with increasing depth of the water table to a maximum at 610 mm. Although most roots were in the top 150 mm, the highest shoot yields were obtained from tanks with water tables at 760 to 1020 mm.

Chandra (1973) concluded that final yields were not at all related to the amount of root growth near maturity but were strongly related to the total root length as well as to the depth distribution of roots during the vegetative phase of growth. Evans et.al. (1985) concluded that crop yield reductions of more than 50 percent may develop from stress caused by excessive soil-water conditions on poorly drained soils. Greater depth to the water table apparently permits more soil aeration and nutrient uptake for greater root development. Passioura (1981) found that the root system of cotton growing in the subsoil of a drying profile grew much faster than those growing in a well-watered profile. The total length of the drought root system was substantially greater than the well-watered one. The most likely explanation for this was that drought affects the growth of the shoot more than it does photosynthesis, so that the amount of assimilation available for root growth was thereby increased. The increased root development helps match the plant's water supply to the evaporative demands on its leaves.

High water table affects the availability of moisture. Kramer (1965) showed that having a water table too high or in a flooded condition can hinder upward water movement in the plant root system. He found that saturating the soil with water caused a reduction in water movement through the root system of tobacco to 60 percent of the original rate in an hour and to 25 percent in three hours. Injury due to deficient aeration when flooding occurs for longer than 24 hours can result in serious and often irreversible symptoms such as epinasty (the downward curvature of the petioles), yellowing, and finally death of the lower leaves. Kramer (1965) and Williamson (1964) found that corn plants grown with a 152 mm (6 inch) water table were slightly chlorotic and somewhat smaller than were plants grown with deeper water tables. It was also noticed that the corn plants remained chlorotic throughout the growing season, and that the smallest diameter corn stalks were associated with plants grown at a 152 mm (6 inch) water table depth.

The optimum water table depth is dependent on the crop, stage of growth, and soil type. Williamson and Kriz (1970) related yields for a variety of crops to the position of varying piezometric water table depths in varying soil textures. They compared water table depth to the relative yield, where 100 percent relative yield equaled maximum potential yield if no crop input parameters were limiting. They concluded that the severity of injury for corn as it was actively growing was dependent on the growth stage and the time of year during which excessive high soil moisture took place. Purvis and Williamson (1972) concluded that the flooding of corn for one day had no visible effect on growth and yield. However, the flooding of corn for more than one day in the early growth stages caused reduction in yields.

The desire to look quantitatively at stress due to excess water or lack of water has resulted in the development of a number of models. The concept of Excess

Soil Water ($SEW_{30}$) was discussed by Wesseling (1974) and Bouwer (1966). It was originally defined by Sieben (1964) to evaluate the influence of high fluctuating water tables during the winter on cereal crops. The value of $SEW_{30}$ is equal to the length of time in days the water table stayed in the top 30 cm of soil. Computing a range of $SEW_{30}$ values and matching yield reduction to $SEW_{30}$ values, the yield loss could be predicted for the crop grown. The use of the $SEW_{30}$ concept assumes, however, that the effect on crop production of a 50 mm water table depth for one day duration is the same as that of a 250 mm depth for five days. This seems unlikely as pointed out by Wesseling (1974).

At the other extreme is a water table too deep to allow the majority of the roots adequate moisture. The plant can compensate somewhat for this condition. Reicosky et.al. (1972) indicated water uptake over a static water table may not be related to root distribution. They found that a small amount of roots near the capillary fringe absorbed most of the water. This may be compared perhaps to trickle irrigation where water is placed at a very specific location and reaches only part of the root system. However, forcing a plant to extend its rooting depth and distribution can have positive effects. More nutrients become available to the plant and less irrigation water is needed because the volumetric soil water content available to the plant is increased. Hiler (1969) used early season drought stresses to stimulate downward development of the root system.

Hardjoamidjojo and Skaggs (1982) incorporated the Stress Day Index (SDI) proposed by Hiler (1969) as a water management parameter in the simulation model, DRAINMOD, to quantify the effects of too little or too much water on corn yields. They compared actual yields with predicted yields. The predicted and measured results were in good agreement. Based on the predicted yields, DRAINMOD could then be used to design a subsurface irrigation and drainage system to decrease water stresses that hinder production.

It is apparent that a water table needs to be positioned to allow for maximum root length and depthwise distribution to increase nutrient uptake and soil aeration. The water table should also be positioned in the soil profile so that upward flux of the water can supply sufficient water to the root zone. Flooding the root zone can result in a decrease of water movement into the root system and can produce a chlorotic effect in the corn plants and thus a reduction in yields (Williamson, 1964).

## 3. Soil Nitrogen

The flooding and/or water logging of soils leads to a series of undesirable events involving soil nitrogen. Fertilizer effectiveness is reduced, nitrification stops and denitrification takes place rapidly. Allison (1965) concluded that of the number of pathways nitrogen can be lost in the soil profile, most are minor except denitrification and leaching.

Denitrification is the process of nitrogen, in the form of nitrate ($NO_3$), being lost from the soil as nitrogen gas ($N_2$). This loss of nitrogen due to denitrification is attributed to the activities of anaerobic denitrifying bacteria that utilize oxidized forms of nitrogen. The bacteria demand oxygen to carry on their metabolic processes. When the $O_2$ supply is decreased because of a high water table condition, the denitrifying bacteria remove $O_2$ molecules from the available nitrogen ($NO_3$) ions. Nitrate, upon losing the $O_2$ molecule, becomes free nitrogen and escapes into the atmosphere. Williamson and Willey (1964) found that the beneficial presence of $NO_3$ lasts for only a few weeks during a normal growing season. In their study, denitrification and leaching of nitrate resulted in deficient nitrate within four weeks after nitrogen application. Alternate submergence and aeration has the effect of rapidly depleting the soil of available nitrogen through the denitrification process (Patrick and Wyatt, 1964).

Leaching loss of nitrogen from the soil system is dependent on the nitrate ions available and the quantity of water passing through the soil profile. Leaching losses of 70 percent of the applied nitrogen have been reported under conditions of overapplication of sprinkler irrigation (Johnston et.al. 1965).

In a study on water table control on organic soils, yields of onions, carrots, potatoes, peppermint and corn were reduced with a water table less than 400 mm, and crop response to nitrogen was also limited with the water table less than 400 mm (Harris et.al. 1962). Because the process of denitrification with a 400 mm or higher water table resulted in a limited crop response to nitrogen, it stands to reason that controlling the depth of the water table at a depth deeper than 400 mm is important in maintaining the nitrogen level in the root zone of the above plants in organic soil.

4. Salts

Consideration should be given to the concentration of soluble salts and sodium in the water supply and soil profile where they pose a problem during irrigation. The practice of subsurface irrigation can promote the concentration of salts in the surface soil (Renfro, 1955). The salts accumulate at those depths where roots absorb water for the evaporatranspiration process. The osmotic pressure of the soil solution within the capillary zone increases as salts accumulate. This reduces the availability of water in the root zone area.

When adequate drainage is maintained, late season winter and spring rains, snow melt or high annual rainfall can wash much of the surface accumulation of salts downward in the soil profile (Kriz and Skaggs, 1973).

Concentrations of salts are measured by the conductivity of the saturated extract (Williamson and Carrekar, 1970; U.S.D.A. Handbook No. 60, 1954). When the conductivity of a saturated extract is more than four mmhos per cm in the soil profile, plant growth (or water uptake) may be limited for some crops (Long, 1965).

Therefore, soluble salts and sodium can be a problem in areas low in annual rainfall and snow melt. However, because of the amount of annual rainfall and snow melt in the state of Michigan, salt accumulation during subsurface irrigation has never been identified as a problem.

## C. Management of The Water Table

A subsurface irrigation and drainage system can eliminate part of the risk associated with growing a crop. Risk associated with excess soil water and drought conditions can be greatly decreased because of the ability to irrigate and drain excess soil water. Good management of such a system will not only increase average yield but also reduce the yearly variations in yields. The position of the water table, the timing of water table establishment at the base of the root zone, and the shape of the water table are critical factors determining the success of water table management.

1. Water Table Position

The proper position of the water table is a function of the management ability of the farmer, soil texture, and type of crop being grown.

Williamson and Kriz (1970) concluded that coarse-textured soils require a higher water table for optimum yields than do fine-textured soils because moisture will move higher above the water table in a fine-textured soil by capillary action. This upward flux of water at any point in the soil is dependent on the depth of the water table, the evapotranspiration rate of the crop planted (i.e., plant water uptake rate), soil matric potential, and soil texture. The deeper the water table, the farther the water must move through the capillary zone to reach the roots. Skaggs (1981) concluded that the water table elevation which should be maintained during subsurface irrigation depends on the depth and distribution of plant roots and the rate water can be transmitted upward from the water table into the root zone. A deep water table may place the water out of reach of the crop roots. A shallow water table will produce poor soil aeration, decreased plant growth, and potentially decreased yields.

Recommendations for optimal water table position vary among researchers. Williamson and van Schilfgaarde (1965), Williamson and Kriz (1970), and Vissir (1958) reported that the static water table depths giving optimum yields are generally 760-860 mm for corn in fine sandy loams and loam soils. Jensen et.al. (1980) reported that for most soil types the water table should not rise closer to the soil surface than 500 mm for most crops and should fall to the design water table depth within one or two days if the water table rise was due to rain or overpumping. Williamson (1964) noted a decline in soybean yields when the water table was at a depth of 760 mm from the surface as compared to 460 mm. It was further noted that this was due to a drying out of the top layer of soil where a majority of the soybean roots were located. Williamson and van Schilfgaarde (1965) found in four experiments that soybeans grown in Norfolk and Seneca fine sandy loams and Bayboro loam soils were found to have a maximum yield at a water table depth of 460 to 620 mm. Woolley (1965) mentions a conclusion of Williamson that most agricultural crops grow well in the upper 375 mm of soil if it is well drained.

Two approaches have been used to manage a subsurface irrigation system. The first method is to maintain a constant water table at some depth below the soil surface. The water table is allowed to fluctuate only one or two inches and is easily controlled by the use of a float switch which turns the irrigation pumps on and off. Management is greatly simplified. One disadvantage of this method is that limited storage is available for rainfall if the water table is held too high. As a result, most rainfall that occurs during the irrigation season drains from the profile. Williamson and Kris (1970) looked at this approach and related yield to a variety of constant water table depths. They considered approximately thirty different crops and computed percentage of the maximum potential crop yield achieved with various water depths on a variety of soil types.

The second method takes the approach of raising the water table to the desired level and then shutting off the pumps. The water table is allowed to decrease through losses of seepage and evapotranspiration to some allowable limit (i.e., 203.2 to 457.2 mm of fluctuation). Once the limit is reached, the irrigation pumps are turned back on. This approach has greater potential to store and utilize rainfall that may occur when the water table is in the deeper range. Less water may be needed as a result, and pumping costs are minimized. Skaggs (1981) reported that when using this method the limit to which the depth of the water table is allowed to fall must be managed closely. Problems will occur if the water table is allowed to fall too far which may cause the soil profile to dry out. The time necessary to raise the water table once again can create a lag time between 80-100 hours for 18 meter tile spacing on a sandy loam soil. (Lag time is the difference in time between the time the pumps are started to the time it takes to get a response or rise in the water table midway between the tile laterals.) A large evapotranspiration rate could cause the lag time to be even longer, possibly stressing the crop. If the tile lateral or ditch lateral spacing were further apart than recommended by the design, the lag time would be still longer because the distance the water must travel is greater.

Evans et.al. (1985) recommends putting the water table at the greatest depth for either method used. This level will provide the greatest storage potential and the most efficient use of rainfall. It is important not to let the water table drop too far because of the lag-time it can take to pump the water table to an effective level for the crop to use it. The water table depth should be monitored constantly.

## 2. Water Table Shape

An understanding of the shape of the water table during the drainage and subsurface irrigation modes can help the irrigator monitor and manage his irrigation system. This can be accomplished by placing monitoring stations evenly spaced between two drainage tile lateral and/or lateral ditches (Skaggs et.el. 1972). PVC tubing is often used and placed at a depth of 1.0 to 1.2 meters. The changing water table can then be measured in reference to its depth from the surface.

It is a proven fact (Skaggs 1981) that the Dupuit-Forchheimer assumptions hold true and that the water table assumes an elliptical shape for the evapotranspiration condition. When the subsurface irrigation-drainage system is in the drainage mode, a water table is created that is lower at the tile/open ditch lateral than at the midpoint between laterals (Figure 3.1). Neal (1934) and Tisdall (1942) give specific data from a silt loam soil showing a curvilinear water table between drains spaced 13.7 to 38 m apart with the average water table 183 mm lower at the drain than at the midpoint.

If the irrigator/manager shuts the drainage system off when the water table midway between the drains reaches a certain depth, the water table there would continue to recede. The lower water table over the laterals would be filled by water midway between the tile laterals due to the hydraulic gradient toward the tile or ditch laterals. If subsurface irrigation were resumed, the water table would not rise immediately midway between laterals. Skaggs et.al. (1972) showed from field studies that for initially draining profiles, the water table elevation midway between drains continued to recede after water input was initiated.

3. Timing of irrigation

An important consideration is when to establish and when to release the water table for subsurface irrigation. Because crops can vary in their water consumption rate throughout the growing season, the irrigator must know at which times water demand will be greatest. Williamson and van Schilfgaade (1965) showed that as soybean plants matured, the soil moisture decreased over time at established water table depths of 305, 457, 610, and 762 mm. Lucas and Vitosh (1978) report that the greatest benefit from irrigation for corn is prior to tasseling and then through the pollination and silking stages.

It is important that the irrigator not let the static water table fall more than a few feet below the ground surface or let the soil profile dry out too much before starting to establish the water table at the desired level. A deep water table will require a longer time to pump the water table up to the root zone, and a dry soil profile will require a large volume of water per unit of rise of the water table height. Evans et.al. (1985) report that a drying soil profile decreases the hydraulic conductivity drastically. They report that a soil which normally required two to three days to move water from the drain to midway between the drains in a wet soil, may take two to three weeks to travel that same distance once the soil drys out. Skaggs et.al. (1972), observed that from the time the draining of the soil profile was stopped and the pumping of water resumed, the time-lag was as much as 2.5 days before the water table began to rise at the midpoint between lateral tile lines.

Information is lacking on the end of season discontinuation for subsurface irrigation. Sprinkler irrigation can be discontinued on corn when the grain is in full dent stage and moisture is 35 percent. At this stage the black layer forms at the base of the kernels. Subsurface irrigation may be discontinued much earlier. This is because the water table has provided and will continue to provide moisture to the soil profile. This soil water will provide enough moisture to bring the growing plant through to maturity, depending on soil type, for several days to a few weeks. A heavier soil will absorb and hold more plant-available water than a lighter sandy soil. This is a decision the irrigator/manager must make based on his knowledge of the soil type, maturity of the crop, and expected weather conditions.

## D. Energy and Efficiency

The energy cost and the efficiency of an irrigation system are important considerations when choosing which type of system to use. Subsurface irrigation offers potential for energy savings when contrasted to sprinkler irrigation, because it does not require delivery of water under high pressure but employs the use of gravity to move the water. The type of water supply, ground water or surface water, affects the total hydraulic head that a system must generate. Energy required for pumping water makes up a large portion of the total agricultural energy requirements where irrigation is used. Irrigation energy requirements may be reduced by a) improving pumping plant efficiencies, b) improving irrigation efficiency so that less water is required, and c) lowering the pressure of the system (Smith, 1983).

Gilley and Watts (1977) illustrated that seasonal pumping energy required for irrigation is dependent on the volume of water pumped and the hydraulic head against which it is pumped. The energy required for pumping irrigation water may be calculated from the following equation:

$$PE = CDH \qquad (3.8)$$

where PE = pumping energy required in kw-h/ha (kilowatt hours per hectar); C = 0.2717 (conversion factor); D = depth of water pumped (cm); and H = total hydraulic head against which water is pumped (m).

Larson and Fangmeier (1978) found that energy requirements for sprinkler irrigation were five to twelve times greater than for surface irrigation when the water supply was a surface source. When the source of irrigation water was ground water, sprinkler irrigation energy requirements were six to seven times greater than for surface irrigation. Smith (1983) found that subsurface irrigation required only about 6 to 9 percent of the energy required for sprinkler irrigation systems operating at 340 and 690 kpa (50 and 100 psi) respectively. When a deep well water supply was assumed, subirrigation offered a 20 to 40 percent energy savings for two of three sites and had equal energy requirement with sprinkler irrigation for a third site.

The amount of water used during the growing season with

subsurface irrigation varies with crop type, stage of crop growth, depth to the impermeable layer, seepage losses, and location. Knowledge of the consumptive use of water on a daily or weekly basis is necessary to manage the water application rate to the crop.

Massey et.al. (1983) and Strickland et.al. (1981) each studied the energy and water use of subsurface and center pivot irrigation. It was noted that the subsurface irrigation used 40 to 80 mm more water than the center pivot system. A number of reasons account for why a subsurface irrigation system would use more water. Natural rainfall had reduced storage availability and increased drainage and surface runoff over that of a sprinkler system. This made less efficient use of natural rainfall and required more water to be pumped. Seepage losses occur vertically and laterally. A significant volume of water must be pumped to raise the water table near the root zone.

Water table location in the soil profile also affect cost and water use. Benz et.al. (1981) found small increases in water table depth beyond the optimum depth, 1.3 m, increased the water and thus energy requirements on corn and sugar beets. By allowing the water table to drop 0.2 to 0.3 m below the optimum water table depth, 260 mm of water must be pumped to raise the water table back to the optimum depth for maximum corn dry matter and grain yield. Subsurface irrigation requirements can be reduced by controlling the system such that the midpoint water table is allowed to fluctuate within limits. Loss of water by evapotranspiration causes the water table between the drains to be drawn down for a period of time each day before beginning to rise later (usually during the night) as the inflow rate exceeds evapotranspiration and seepage losses. A model based on a numerical solution to the Boussinesq equation showed that the irrigation requirement was decreased by about 7 percent when the water table was allowed to fluctuate compared with a constant water level control for five simulations (Smith, 1983). Water input rate should be sufficient so that the water table will rebound to its initial level before the evapotranspiration demand for the next day begins.

Subsurface subirrigation can therefore offer substantial savings in energy cost when compared with center pivot irrigation systems. This is due in part to the fact that gravity and/or low pressure pipe flow are utilized to move water into the soil profile rather than high pressure. This may be offset, however, by the amount of water needed to be pumped. A greater amount of water may be needed for subsurface irrigation versus center pivot irrigation. The depth of the impermeable barrier, soil surface, seepage losses, and possible runoff from rain must be evaluated. Having an impervious barrier which is very deep and allows the water table to fall substantially below the root zone and subsurface tile can result in additional water being needed to bring the piezeometric water surface within the root zone and therefore increases the cost of subsurface irrigation.

## E. Sugarbeets Under Irrigation

Sugarbeets (Beta Vulgaris) have been a major crop in many areas of the United States for production of sugar. The objective of subirrigation of sugarbeets is to increase the weight and sugar content of the beets.

Factors which affect beet sugar content and growth are plant population, nitrogen levels in the soil profile, and available moisture. Robins et.al. (1956) and Loomis and Haddock (1963) found that sugar content was significantly reduced at increasing nitrogen fertilization rates. Haddock (1947) found that additional nitrogen increased the weight yield of the sugarbeet root and simultaneously decreased the sugar percentage. Deficiencies in either nitrogen or moisture resulted in a lower rate of root growth and an increase in sucrose concentration. The increase in sucrose concentration when both nitrogen and water are deficient is due to a reduced rate of dry matter accumulation. Loomis and Haddock (1967) and Henderson et. al. (1968) indicated that nitrogen deficiency and drought stress reduced growth and increased (on a fresh basis) the sucrose concentration in roots. However, there is a need to manage soil nitrogen levels to achieve significant root weight at harvest.

Archibald and Haddock (1959) found that plants kept moist all season by sprinkler irrigation resulted in the highest yield. He also found that beets kept moist all season tended to mature early and were generally higher in sucrose than those from plots which were dry for an extended period of time. Loomis and Haddock (1967) reported that sucrose yields are not increased and may be reduced significantly by single, brief cycles of wilting and almost invariably are lowered by repeated wilting apparently due to reduction in leaf area and rate of photosynthesis. Extended periods of drought preceding harvest resulted in substantial reductions in sucrose percentages, and it appears advisable to continue with moderate irrigation until shortly before harvest. Beet purity and sucrose yields were increased by nitrogen deficiency but not by moisture stress. Archibald and Haddock (1959) showed that the lower the available nitrogen supply of a soil, the more seriously will excess irrigation water depress yields. The more abundant the available nitrogen supply in a soil the smaller the reduction in yield will be from excess water application.

A recommendation about when to irrigate sugarbeets is made by Loomis and Haddock (1967), Haddock (1947) and Brewbaker (1934). They recommend irrigation practices be directed toward rapid stand establishment and early attainment of a full leaf canopy. Brewbaker (1934) found that larger beet yields were obtained with an early first application and a very late last application of water, with applications made at biweekly intervals using overhead irrigation during the summer. Midsummer irrigation was sufficient to avoid periodic water stress which might reduce root growth and the photosynthetic effectiveness of the foliage canopy.

Sugarbeets are a deep rooting plant with a large tap root. Water is extracted most rapidly from the first 0.66 m of soil, but with deep, well drained soils, appreciable amounts of water will also be obtained from depths of 1.22 to 1.52 m. Loomis and Haddock (1967) state that 60 percent of the total seasonal water used is commonly acquired from the top 0.66 m of soil. Henderson et.al. (1968) found that with a water table at approximately one meter, the top 0.66 meters of soil became very dry with subsurface irrigation. Most of the water used by the crop comes from stored moisture in the soil. When this is largely depleted, nearly all of the water is supplied by upward rise from the water table. Reichman et.al. (1977) found in his test with a sandy loam soil, that a shallow water table at approximately 0.86 to 1.10 meters provided all the moisture the sugar beets needed (illustrated by no increase in root weight when the subsurface irrigated plot was compared with an overhead irrigated plot). Follett et. al. (1974) found that the effective root zone for beets in a sand soil in irrigable areas of North Dakota is only 0.61 to 0.92 meters.

In conclusion, sugarbeets need an adequate supply of soil moisture and soil nitrogen to maintain good yields of sugar and weight of beets harvested. Water management should be aimed at rapid stand establishment and early attainment of leaf canopy. Soil moisture should be readily available until shortly before harvesting. Establishing a water table using subsurface irrigation at approximately one meter to 0.61 meters will provide the moisture the growing crop will need in a sandy loam to loamy sand soil.

## IV. PROCEDURE: FIELD INVESTIGATION

### A. Site Selection

This study was prompted by the interest of a major drainage tubing manufacturer, Advance Drainage Systems, Inc. (ADS)*. They were interested in field measurements of the rate and uniformity of water table elevation response during subsurface irrigation. Names and locations of selected farmers who were operating systems were provided by the company. Four systems were selected for study on the following farms:

1. The C. Iott farm, near Deerfield, MI;
2. The J. Ellenbaum farm, near Pigeon, MI;
3. The B. Singer farm, near Unionville, MI (two systems).

The purpose of the study was to determine the water table response while irrigating through subsurface tile drains and to study water movement under subsurface irrigation and drainage conditions. Schematic sketches of the field installations are shown in Figures 4.1, 4.3, 4.6 and 4.9. Criteria for selecting the fields to be studied were:

---------

* Advanced Drainage Systems, Inc.
3300 Riverside Drive
Columbus, OH 43221

1. To investigate system performance in a range of soil types;

2. To limit systems selected to systems at least two years old to minimize soil disturbance effects resulting from the installation of the subsurface irrigation and drainage system;

3. To select farmers who would keep records regarding system operation including such things as when irrigation pumps were turned on, how long the pumps were run, when the system was put into the drainage mode, etc.

## B. Site Descriptions

The predominate soil series in the study regions are classified in Michigan Soil Associations 63,69,71 and 74 (Soil Association Map Of Michigan, 1981). The soils of these associations were developed under poor natural drainage conditions from loam, clay loam, or sandy loam parent material. Strong gleying* and/or mottling is associated with these soils and naturally poor drainage is a principle hazard to crop production.

---

* Gleying results from the chemical reduction of iron in an anaerobic soil condition and is visually recognized by the gray color in the soil profile. It signifies a high water table condition.

These can become some of the most productive in the state of Michigan when subsurface drainage is utilized to control excessive moisture and improve soil aeration.

1. Field Site A

Site A (C. Iott farm) was in a field two kilometers southeast of Deerfield, Michigan (Figure 4.1). Total tillable area consisted of approximately 12.7 ha (31.5 ac). One half of the area was subsurface irrigated, and the other half was a tile drained but non-irrigated area. The legal description of the irrigated plot was the N 1/2 of the SE 1/4 of the SW 1/4, and the non-irrigated plot was the S 1/2 of the NE 1/4 of the SW 1/4 of section 18, R. 6E. T.7S, Monroe County (USDA, Soil Survey, Monroe County, 1980).

The field drained into a ditch bordering the east boundary. The ditch in turn drained into the Raisin River. The field slope was less than one percent. The soil texture that predominates was a loamy sand (Granby Loamy Fine Sand, Figure 4.2). A loamy sand ridge ran across the field in a north-south direction, located two thirds of the way upslope from the east boundary. The field had two small depressions which would pond water when the water table was raised too high by subsurface irrigation. The field dimensions were approximately 402 m wide and 402 m long.

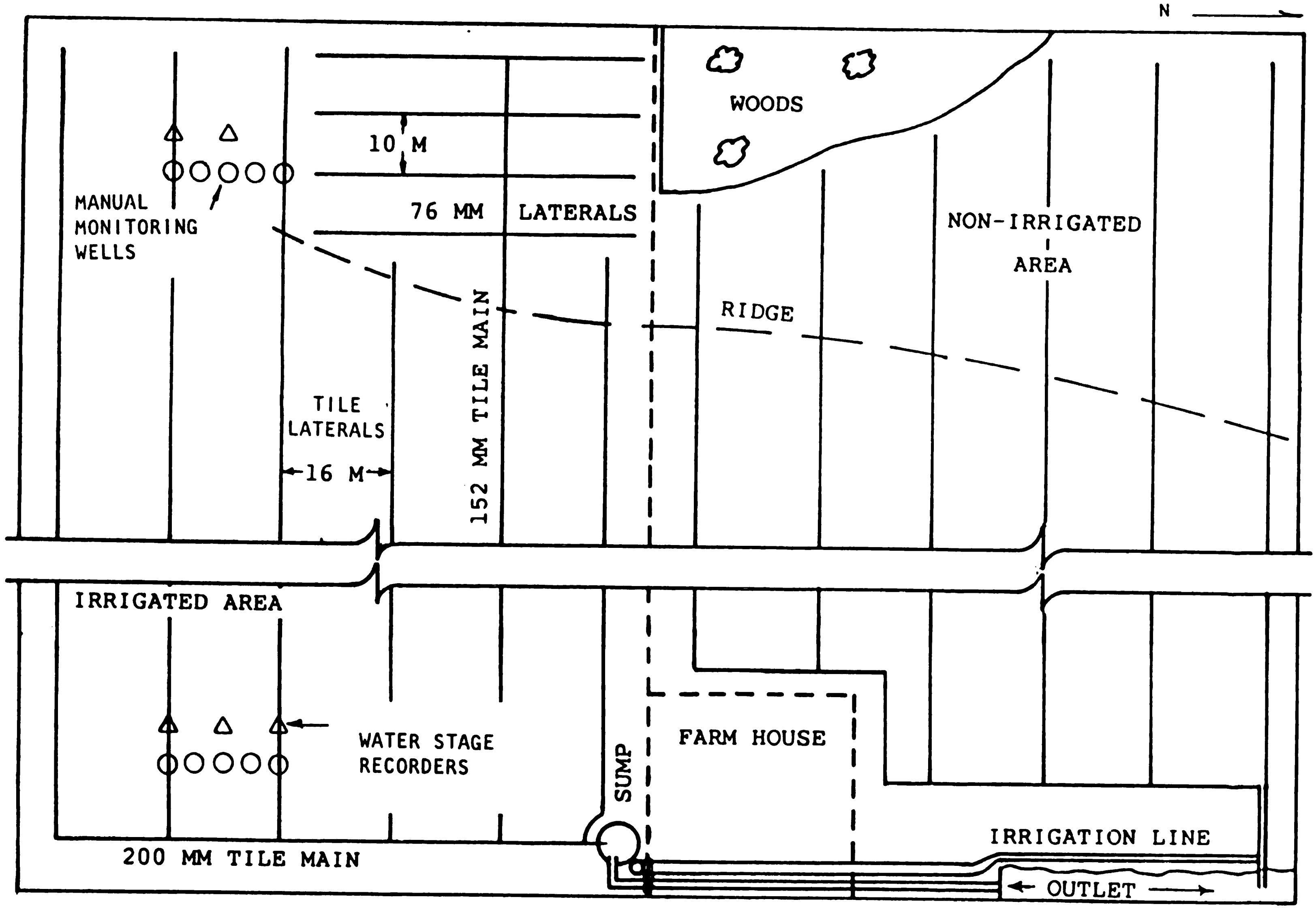


Figure 4.1 Schematic diagram of Site A, sandy loam soil

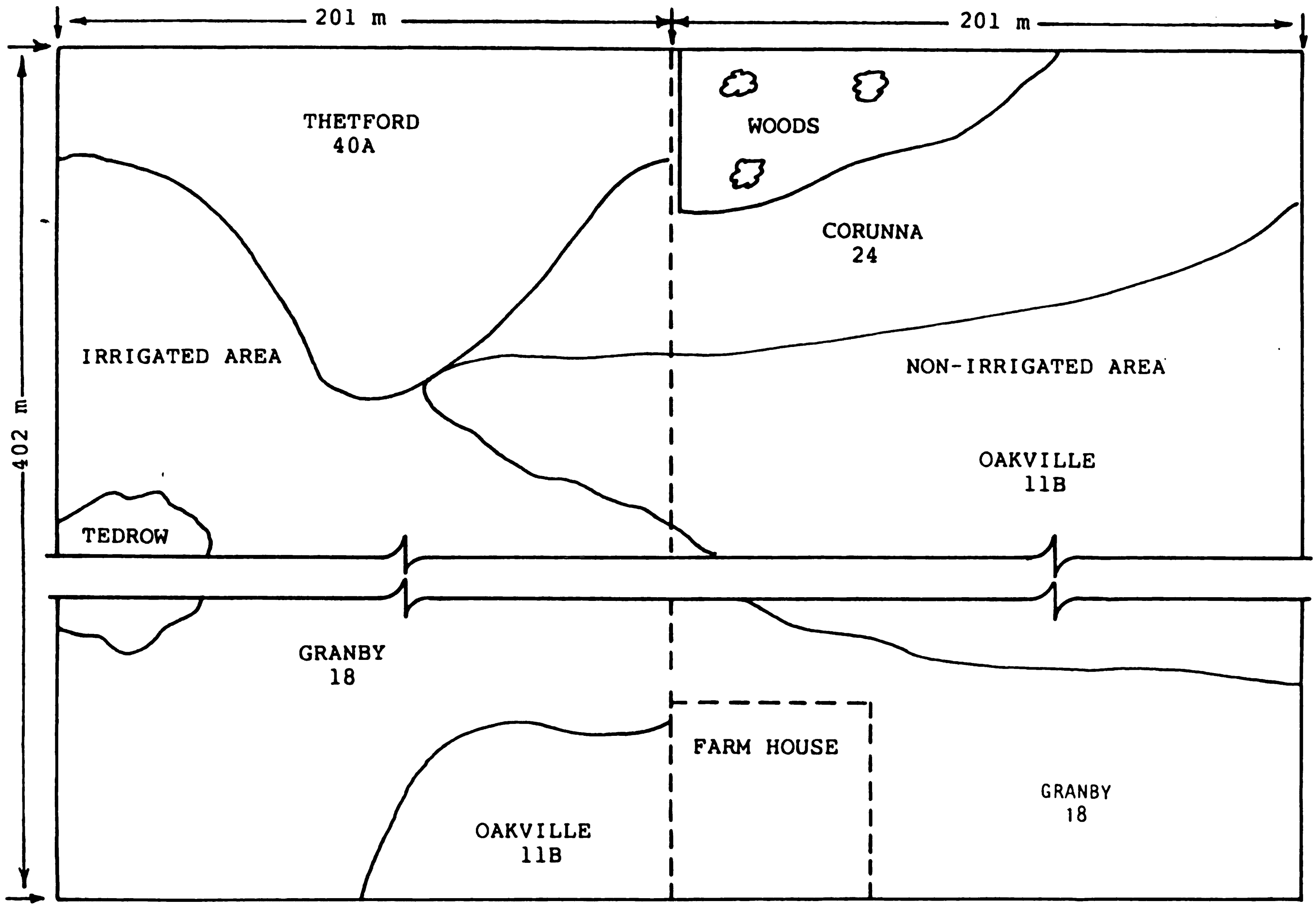


Figure 4.2 Schematic of soil types on Site A

The layout of the subsurface irrigation and drainage system ran east-west with laterals parallel to the major slope of the field (Figure 4.1). Alternate laterals were of old clay drain tile, 100 mm in diameter, installed many years before at 32 m spacings. Prior to the study, the spacing between the clay tile was split with 76 mm (3 inch) pin-hole corrugated plastic tubing. Tile were placed approximately 0.8 m deep on a 0.1 percent grade. Tile lines were run into the loamy sand ridge and terminated. Behind the ridge was a smaller drainage system of 76 mm (3 inch) corrugated plastic tubing spaced at 10 m. This small drainage system was serviced by a 150 mm main which was connected to the 200 mm field main. The drainage main ran the length of the subsurface irrigated area on the east boundary and was connected to the water level control structure which was 1.2 m in diameter. The total variation in field surface elevation between the monitoring locations was 0.3 meters (except on the narrow ridge which was higher). The water table elevation for the entire field was controlled by the one structure.

There was no visible surface runoff during the growing season indicating all excess soil water left the site through the tile system. The fertilizer, herbicide, plant variety, and plant population were the same for the irrigated and non-irrigated sites. A yield check was taken well away from the edge of the irrigated site to avoid having lateral seepage affect the non-irrigated yield.

Yield checks were conducted according to the method established by the National Corn Growers Association.

The Granby loamy fine sand is a mollisol, with the subgroup being a typic haplaquoll, a sandy mixed mesic soil. Small areas of Tedrow and Oakville loamy fine sand were also present having ochric epipedons with no subsurface horizons. The Tedrow was classified as a typic udipsamment and the Oakville was classified as a typic haplaquent. Both were sandy, mixed mesic soils. A Thetford loamy sand existed in the irrigated part of the field. It is classified as an alfisol, with the subgroup being a psammaquentic hapludalf, a sandy, mixed mesic soil and poorly drained. The Granby was a poorly drained soil, while the Tedrow was somewhat poorly drained and the Oakville was a well drained soil. A water table was established under the Oakville soil at a depth greater than 1.5 m near a ridge (Figure 4.1) and 0.5 m near the farm house. During subsurface irrigation, wet sand could be pulled up with a 1.5 m auger.

Borings were taken with a hand auger to a depth of 1.5 m. No clay barrier was encountered. Either a clay barrier existed at some depth to perch a water table or else a naturally high water table caused the excessive soil moisture condition for which artificial drainage was needed.

Water for Site A was pumped from the Raisin River. A 150 mm buried aluminum irrigation main ran 2439 meters from the river to the field. This main line was shared with a sprinkler irrigation system used by a neighbor to irrigate an established apple orchard. The operating head on the irrigation main varied according to the choice of pumps the farmer used (the farmer had a choice of three different pumps), the amount of water needed for either the subsurface irrigation system or the overhead sprinkler system and the pump rpm.

Prior to irrigation a fixed height overflow pipe was installed and bolted on the end of the tile outlet in the water level control structure. Application of irrigation water was initiated by raising the water level in the structure by pumping water into it. The water level in the control structure was periodically brought up to a constant elevation and held for a short time. Water moved through buried tile lines into the soil to raise the water table. Pumping was not continuous and the water table was allowed to drift downward as plants used moisture and other possible losses occurred. The crop grown on the field during the 1983 study year was corn, with tomatoes the year before.

### 2. Field Site B

Site B was owned by J. Ellenbaum and was located three kilometers south of Pigeon, Michigan. The legal description of the site was the NE 1/4 of the SE 1/4 of section 28, R.10E. T.16N, Huron county (USDA, Soil Survey, Huron County, 1980). The field drained into the Pigeon River via the West Branch Drain, which in turn drained into the Saginaw Bay. The field sloped to the northwest at less than 1% slope. The field was approximately 402 meters wide by 402 meters long (16.2 ha), with 15 ha (37 acres) tilled (Figure 4.3).

The layout of the subsurface irrigation and drainage system laterals was a north-south gridiron (Figure 4.3) with 20 meter (66 ft) spacing and tile lines diagonal to the slope. The drainage system was installed in the 1950's and consisted of 100 mm diameter clay tile laterals, with the tile depth 0.6 meters at the north end and 0.7 meters at the south end.

The field was divided into three zones for water table elevation control, each having about 457 mm (1.5 feet) change in the soil surface elevation. Water level control structures were spaced at selected elevation increments along the tile main. An overflow pipe in the control structures allowed excess water to move from the higher elevation zone to the next lower zone. This theoretically allowed control of the water table height over the entire field in three increments. The tile main sloped toward the west which allowed water to be put in at the east end of the main. Zone 3 had a control structure with a valve attached to the outlet and a valve attached to the tile main on the west side of the structure. The valve attached to the west tile main could be shut off to prevent water from entering

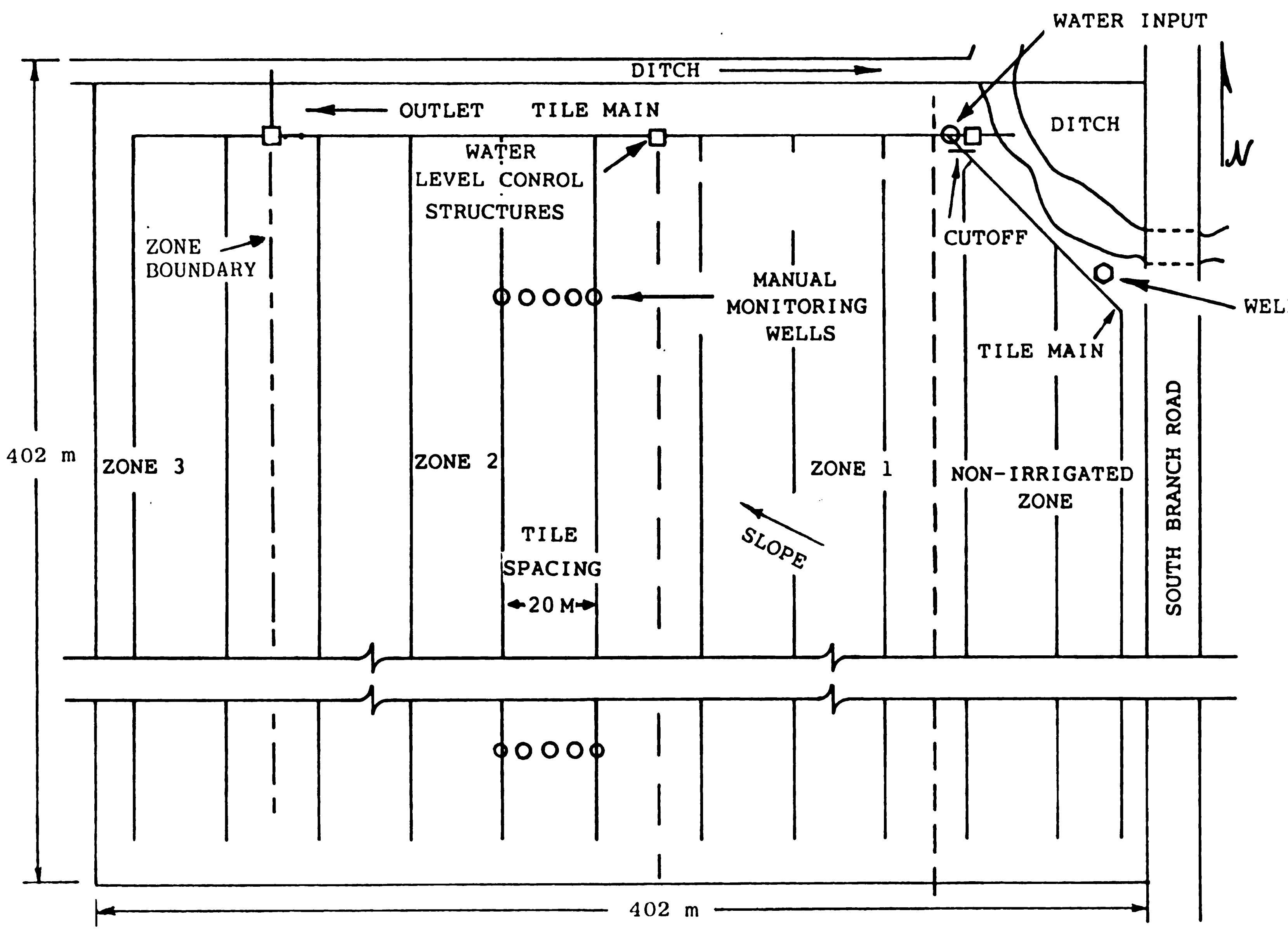


Figure 4.3 Schematic of Site B, clay loam soil

zone 3 or left open to irrigate zone 2. In this experiment, the water level in zone 3 was set lower than zone 2, from which it received its irrigation water. A second valve at the outlet of zone 3 controlled the water from being lost. Surface runoff from excess rain was directed into the West Branch Drain.

The soils (Figure 4.4) were Kilmangh clay loam and Shebeon clay loam (Michigan Soil Association group 74). These soils are Alfisols. The subgroup for the Shebeon was an aeric ochraqualf, clay loam mesic, and the Kilmangh was an aeric haplaquept, clay loam mesic. The Shebeon and Kilmanngh loam soils were classified as poorly drained. Borings were taken with a hand auger. A very dense clay barrier existed at approximately 1.2 m below the surface. Artificial drainage was needed to remove excessive soil moisture so that early spring planting and harvesting were possible. Without artifical drainage, a perched water table condition would exist.

Application of irrigation water was initiated by running water into a riser pipe connected to the tile main at the upper end of the field. The water then moved through buried tile laterals and out into the soil profile. Water moved to lower zones by overflowing control structures along the tile main. Water table elevations were stair-stepped down to follow the change in the soil surface elevation. Excess water was allowed to overflow the last water level control structure and flow into a

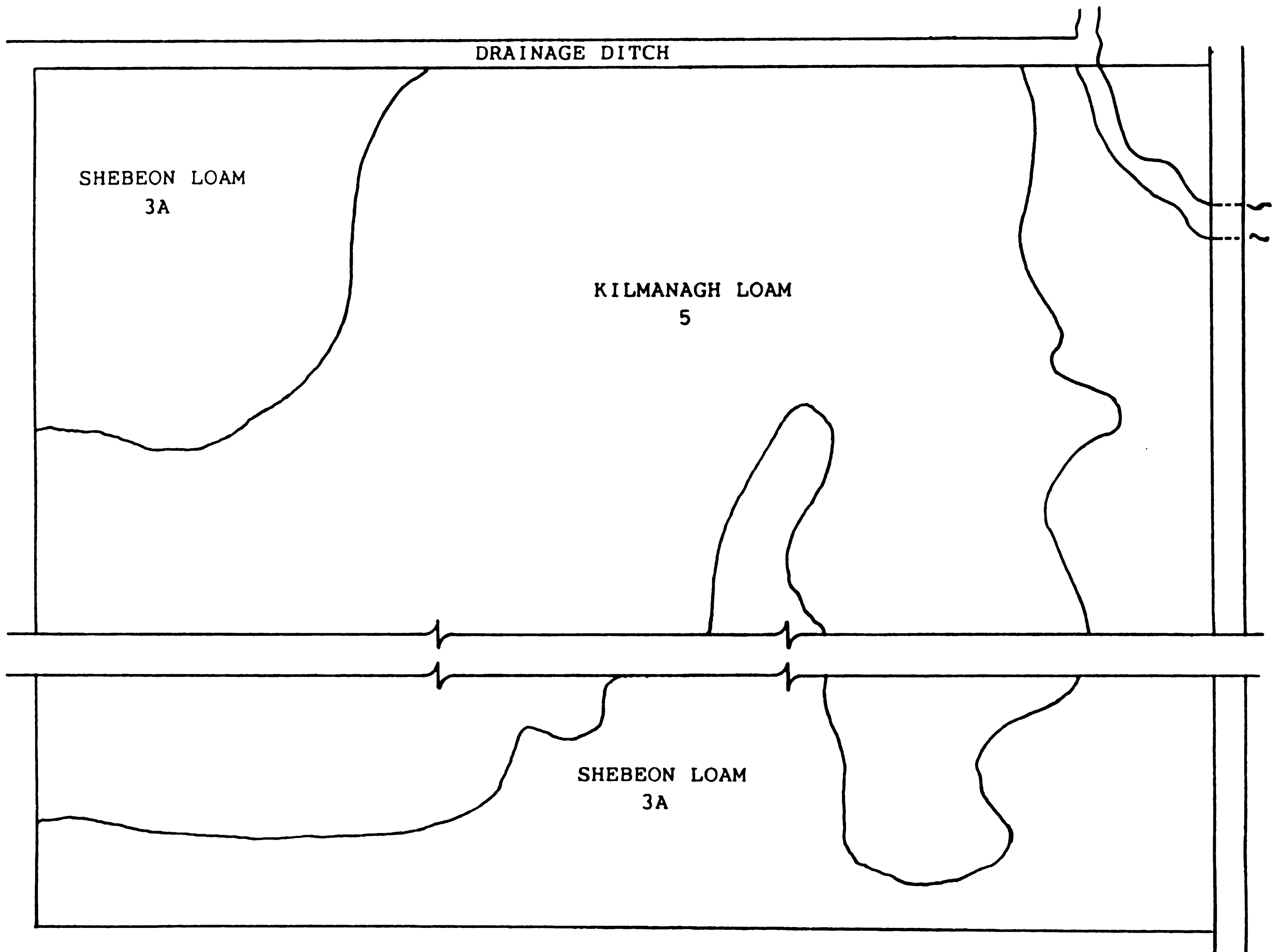


Figure 4.4 Schematic of soil type on Site B:

drainage ditch. The water supply came from a 127 mm diameter well with a 100 mm diameter submersible pump. The irrigation water was pumped with a three phase, 11.2 kw submersible pump. Well depth was approximately 85 m. The capacity of the well was approximately 380 liters per minute (100 gals/min). The well was located in the northeast corner of the field.

A non-irrigated plot was set aside along the east side of the field to compare irrigated to non-irrigated yields (Figure 4.5). This was accomplished by shutting off a section of the tile main line, thus allowing no water to flow into the non-irrigated field plot via the tile laterals when subsurface irrigation was begun. No monitoring of the water table was done on the non-irrigated plot. Plant population, plant variety, herbicide program, planting date, soil texture and the fertilizer program were the same for the irrigated and non-irrigated plots. Yield checks were taken in the non-irrigated plot well away from the irrigated plot to avoid having any lateral water movement influencing the yield check. The crop grown in the site was sugarbeets with 760 mm (30 inch) row spacing. A population count of growing plants was taken in both the irrigated and non-irrigated plots approximately six weeks after emergence.

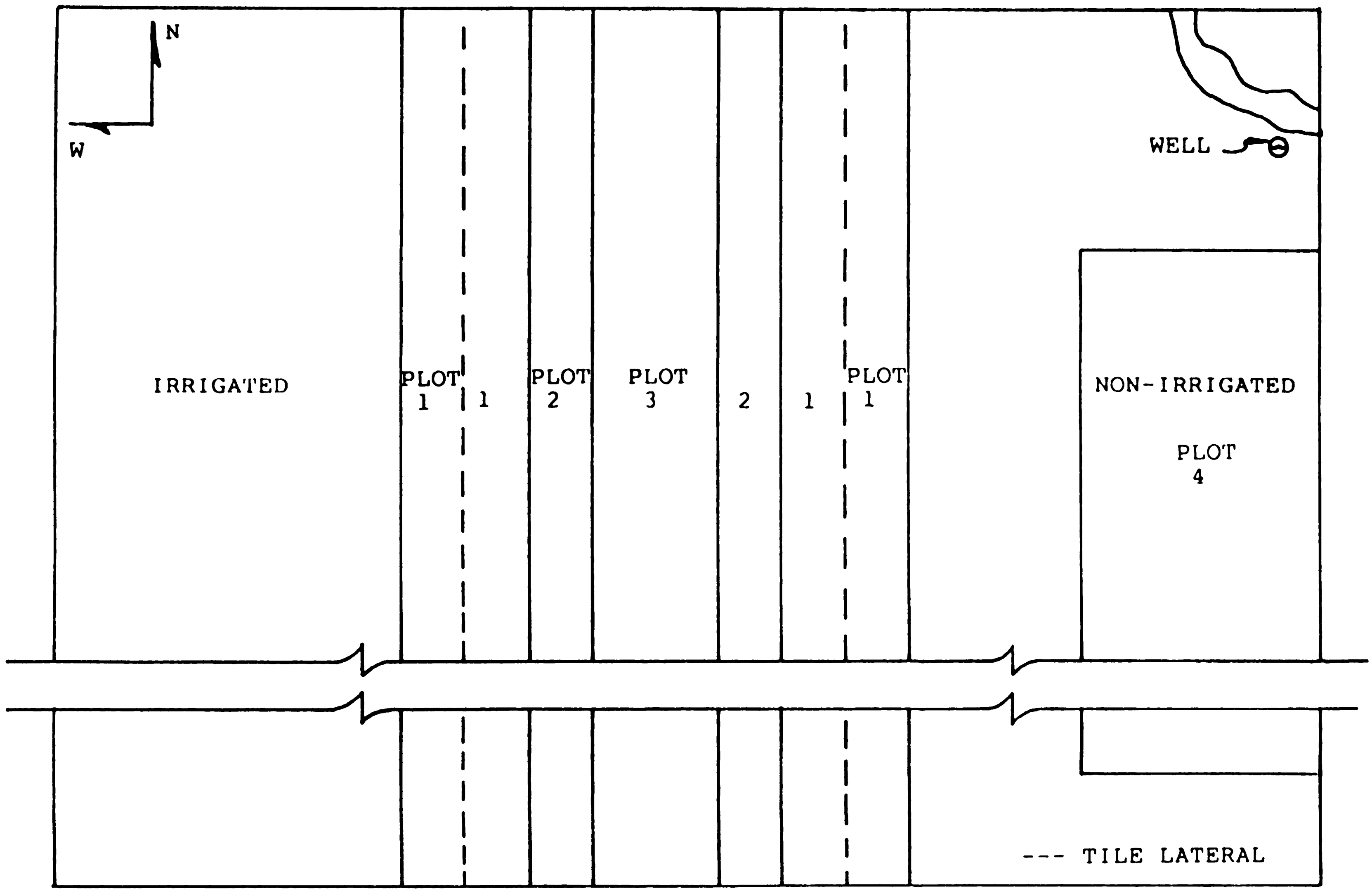


Figure 4.5 Location of harvested plots on Site B (not to scale)

3. Field Site C

Two field sites were selected on the B. Singer farm. Site C was located approximately two kilometers from Saginaw Bay and three kilometers southwest of Sebewaing, Michigan. Its legal description was the SW 1/4 of the SE 1/4 of section 28, R. 8E. T. 15N (USDA, Soil Survey, Tuscola County, 1984). A schematic sketch of the field is shown in Figure 4.6.

The soil texture that predominates is a sandy clay loam named Wisner loam. Wisner loam is a typic glossaqualf, with a texture finer than loamy fine sand. It is an Alfisol with an aquic moisture regime. Gleying is very common in this soil, indicating that the soil has been saturated over an extended period of time. The field required only one water table control zone. Dimensions were approximately 402 m wide by 402 m long, having a total area of 16.2 ha (40 ac), with approximately 14.2 ha (35 ac) tiled.

Because of the proximity to Saginaw Bay, bay water backed up in the drainage ditches and a naturally high water table existed. The bay maintained approximately one meter or more of water depth in the drainage ditches year around during this study. The top width and total depth of the ditch along the south side was six meters and approximately four meters respectively. Drainage water from the field was removed by an electrically powered vertical shaft centrifugal pump (Figure 4.7) in a 3.6 m deep sump which

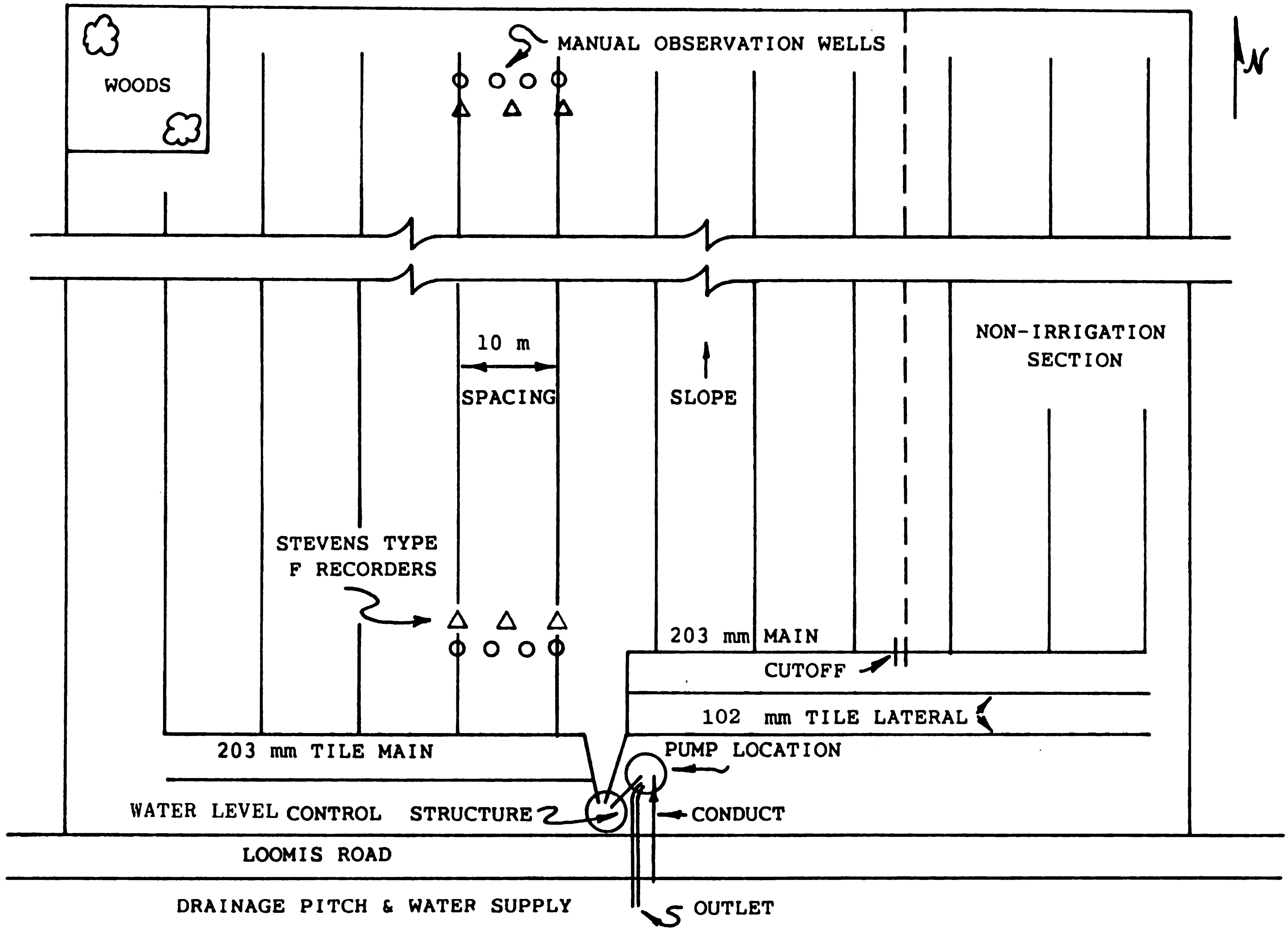


Figure 4.6 Schematic diagram of Site C, sandy clay loam.

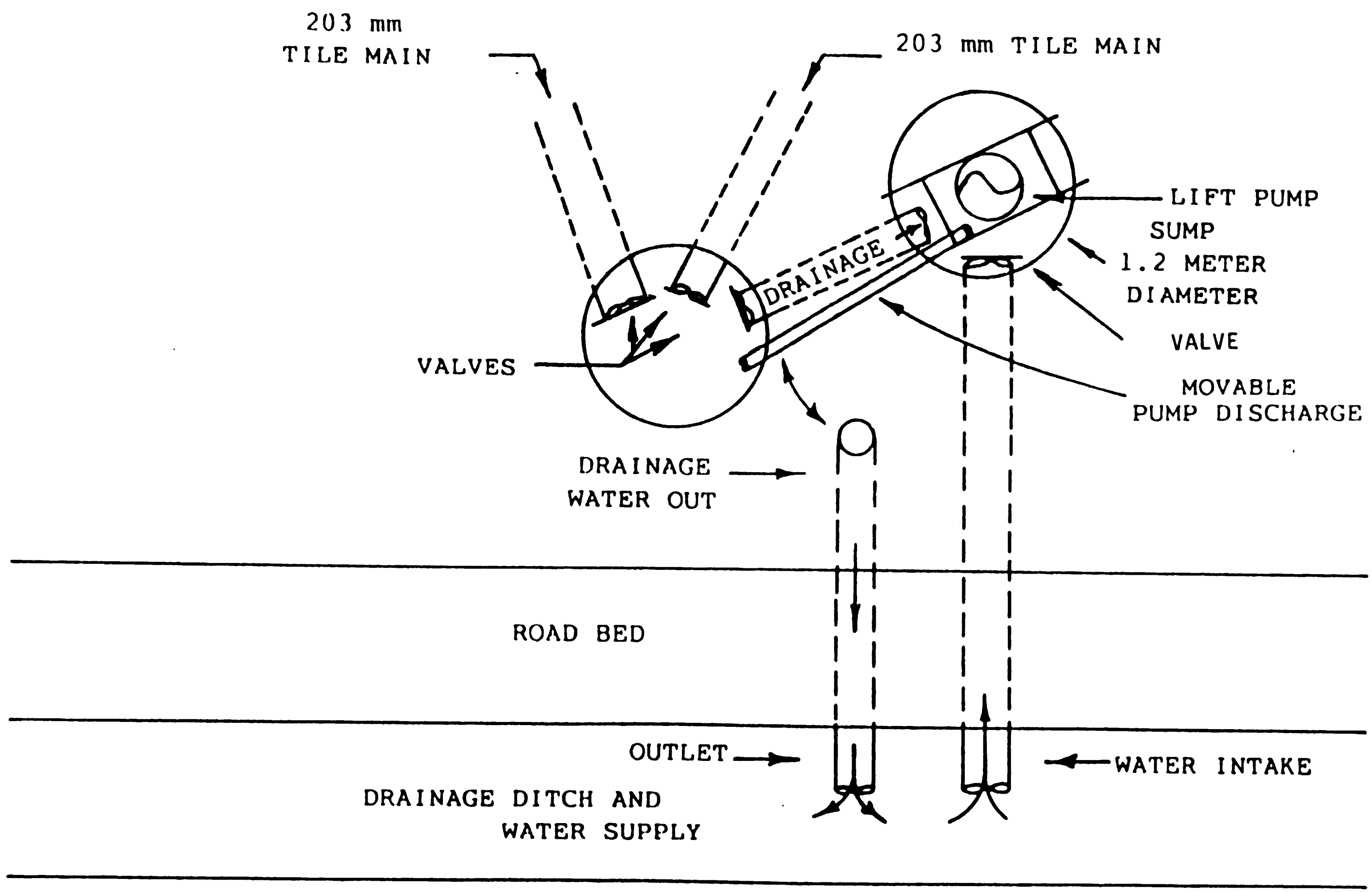


Figure 4.7 Schematic of water level control structure and pump setup, Site C.

served both as an irrigation and drainage lift pump. The pump had a variable speed belt-pulley that the farmer/manager could adjust to increase or decrease the amount of water supplied to the field. Irrigation was initiated by opening the irrigation intake pipe from the ditch to the pump sump, closing the tile outlet valve directing the flow from the pump into water level control structure and opening one or both valves on the tile mains extending out into the field (Figure 4.7). The valves were rubber-lined metal plates that closed over the tile main ends. The tile mains had to be either totally open or totally closed. The farmer determined when irrigation water for the crop was needed based on his understanding of the crop water use and soil moisture conditions.

Irrigation water was brought from the bottom of the drainage ditch to the pump sump via a 254 mm (10 inch) conduit. Each of the two 203 mm (8 inch) tile mains transported water back to about one half of the field. The water then moved through buried tile laterals into the water table. The tile laterals themselves were alternating clay tile and perforated corrugated plastic pipe, 100 mm in diameter and spaced 10 m (33 feet) apart. The tile depth was approximately 0.66 m at the north end and 1.0 meter at the south (outlet) end. The subsurface irrigation-drainage system laterals ran in a north to south direction on a gridiron layout (Figure 4.6).

To create a non-irrigated zone, the upper end (Figure

4.6) of one tile main was interrupted and capped off. A 380 mm sump was installed on the non-irrigated side of the tile main just above the capped tile main. A submersible pump was then installed in the sump to remove all drainage water coming from the tile laterals in the non-irrigated zone. This resulted in isolating the non-irrigated zone as a separate area with subsurface drainage only.

The field was divided and seeded at two different rates with emergence counts taken to determine actual plant populations. Figure 4.8 shows that the irrigated area was split in half, with the west half having a higher population (66,700 plants/ha) than the east half (63,400 plants/ha). The population for the non-irrigated area was 63,400 plants/ha, the same as the lower population of the irrigated area.

The vertical shaft centrifugal pump was belted to a 3.75 kilowatt electric motor. The pulley on the electric motor was adjustable to achieve different pump speeds to increase or decrease the pumping volume. A timer was connected to the pump to record the amount of actual running time. The instantaneous pumping rate was measured periodically using a catch bucket and stop watch to calculate total discharge.

4. Field Site D

A fourth monitoring site (site D) was also located on the B. Singer farm located approximately three and one half

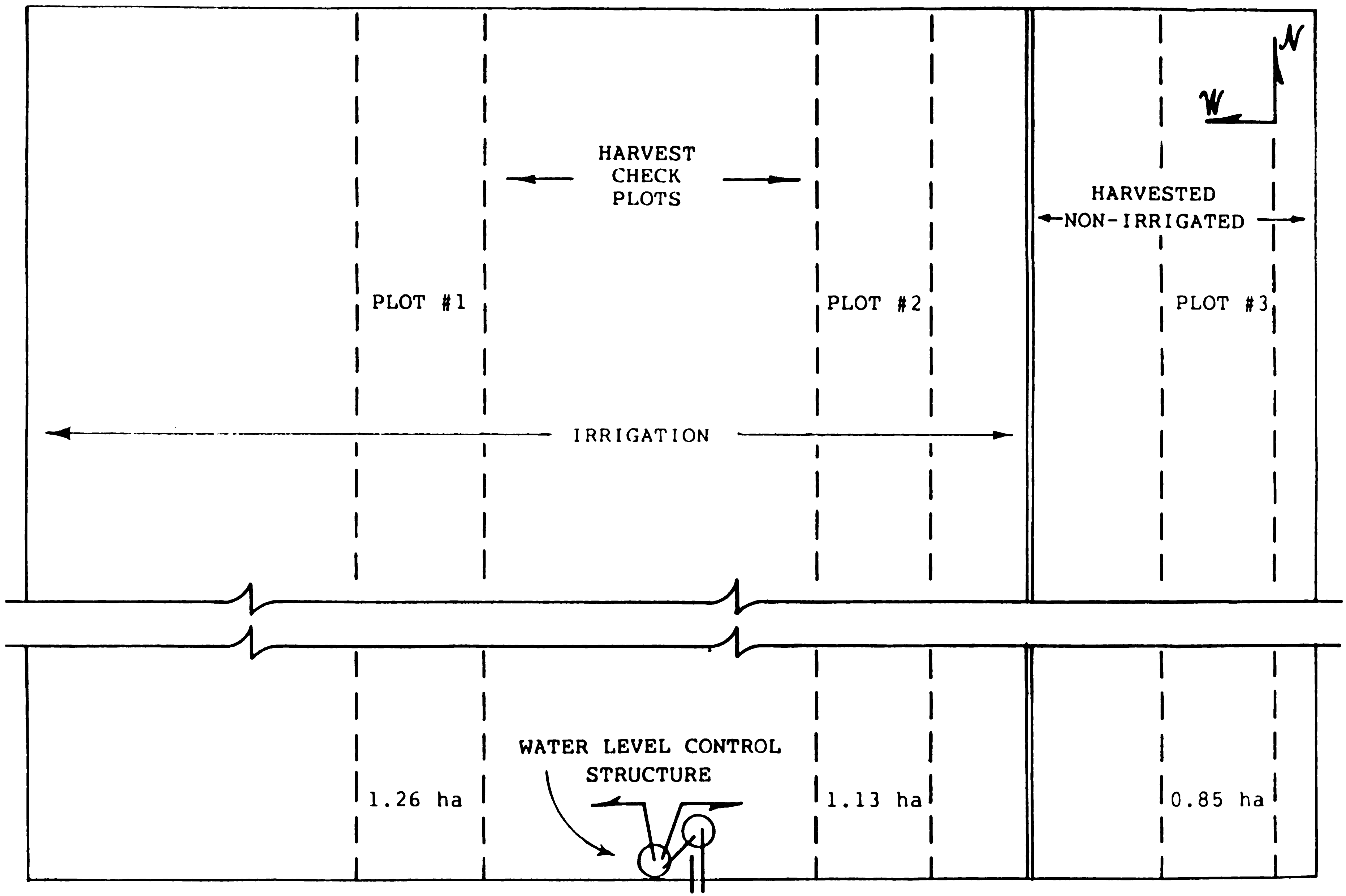


Figure 4.8 Harvested plots for yield checks on Site C

kilometers southwest of Sebewaing, Michigan, in Tuscola County (Figure 4.9).

The legal description was the NE 1/4 of the SW 1/4 of section 32, R. 8E. T. 15N. (USDA, Soil Survey, Tuscola County, 1984).

The soil texture that predominated is a Wisner loam. Because of the seasonally high water table, gleying as well as mottling were present. The clay barrier is approximately two meters from the surface.

The proximity of the Saginaw Bay provided a year around supply of surface irrigation water as for Site C. Site D was also very flat, with the total area in one water table elevation control zone. Tile laterals were 100 mm diameter, concrete tile spaced 20 m (66 feet) apart. The gridiron tile system was approximately one meter deep with laterals laid out in a north to south direction. Drainage water was run into a three meter deep sump, 1.22 m in diameter. A 0.56 kilowatt, submersible pump was utilized during drainage to lift the water to a second vertical pipe which had a 203 mm (8 inch) conduit running from the bottom of it under a road into the bottom of a drainage ditch (Figure 4.9).

Water was delivered to the artificial drainage system for irrigation by reversing the process. Water flowed from the ditch through the 203 mm conduit into the second sump. The pump was shifted from the first sump to the second, and the water was lifted and deposited into the sump

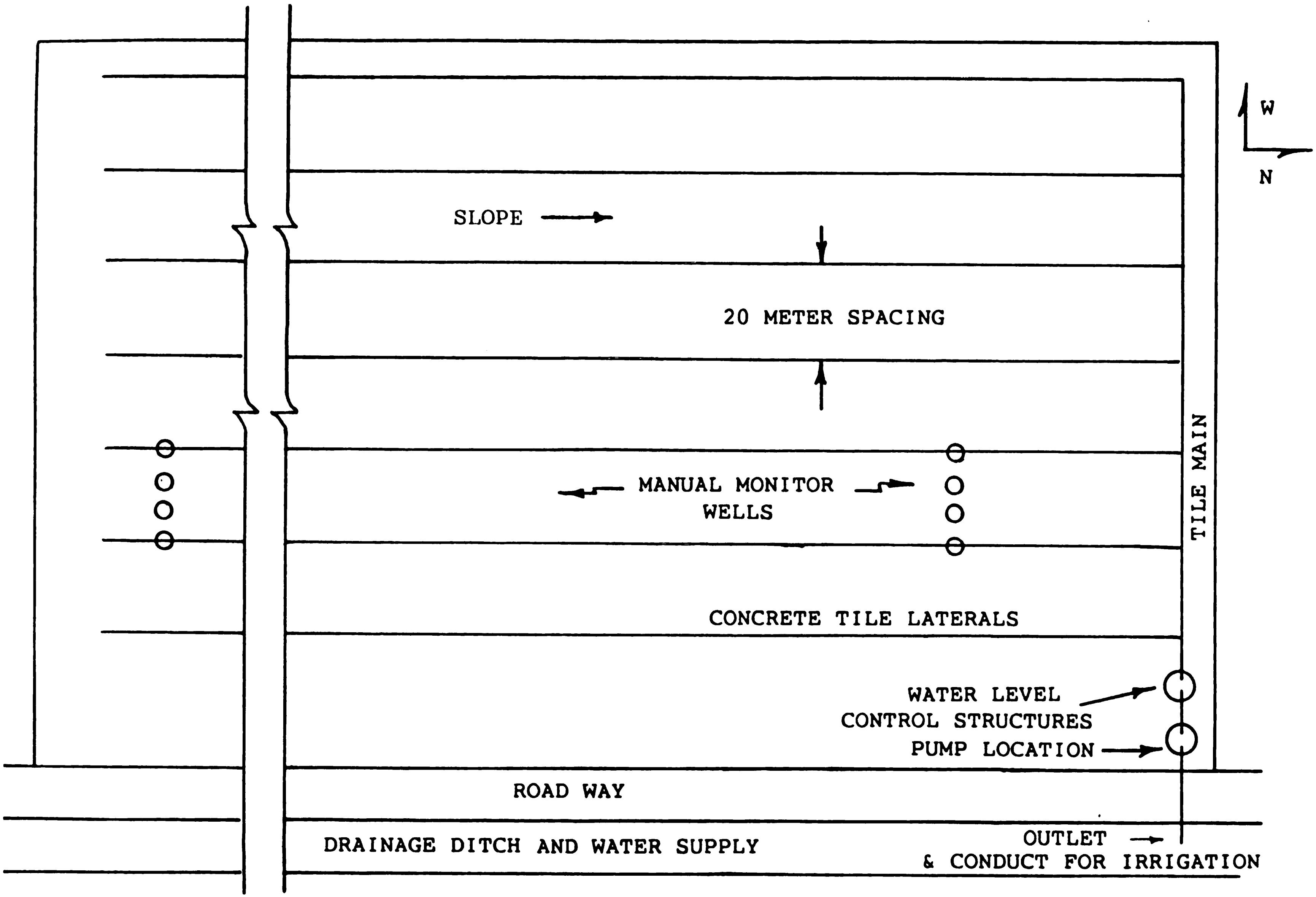


Figure 4.9 Schematic diagram of Site D, sandy clay loam

which was connected to the tile main. The water then moved through buried tile laterals and into the soil.

The water level was controlled by turning the pump on and off with no provision for varying flow rate. A timer was connected to the pump to record the amount of running time on the pump. Water volume being pumped was measured periodically using a bucket and stop watch procedure to calculate the total discharge rate.

### C. Water Table Monitoring

The movement of the water table under subsurface irrigation and drainage conditions was measured using a series of perforated vertical monitoring tubes placed in the soil profile. Tubes were placed at each end of two adjacent tile lines as shown in Figures 4.1, 4.3, 4.6 and 4.9. Two different types of tubes were used. One type was 13 mm PVC tubing approximately 1.2 m deep. The water level was recorded manually in the wells on all four field sites using a blow tube of flexible rubber (Figure 4.10). The second set of wells were 76 mm diameter PVC tubing placed approximately 1.5 meters deep. The water level in each large diameter observation well was continuously recorded with Stevens Type F water stage recorders.

Traces of water level vs time were obtained with Steven Type F water level recorders (Figure 5.11) for the 1983 growing season on Sites A and C. Manually recorded

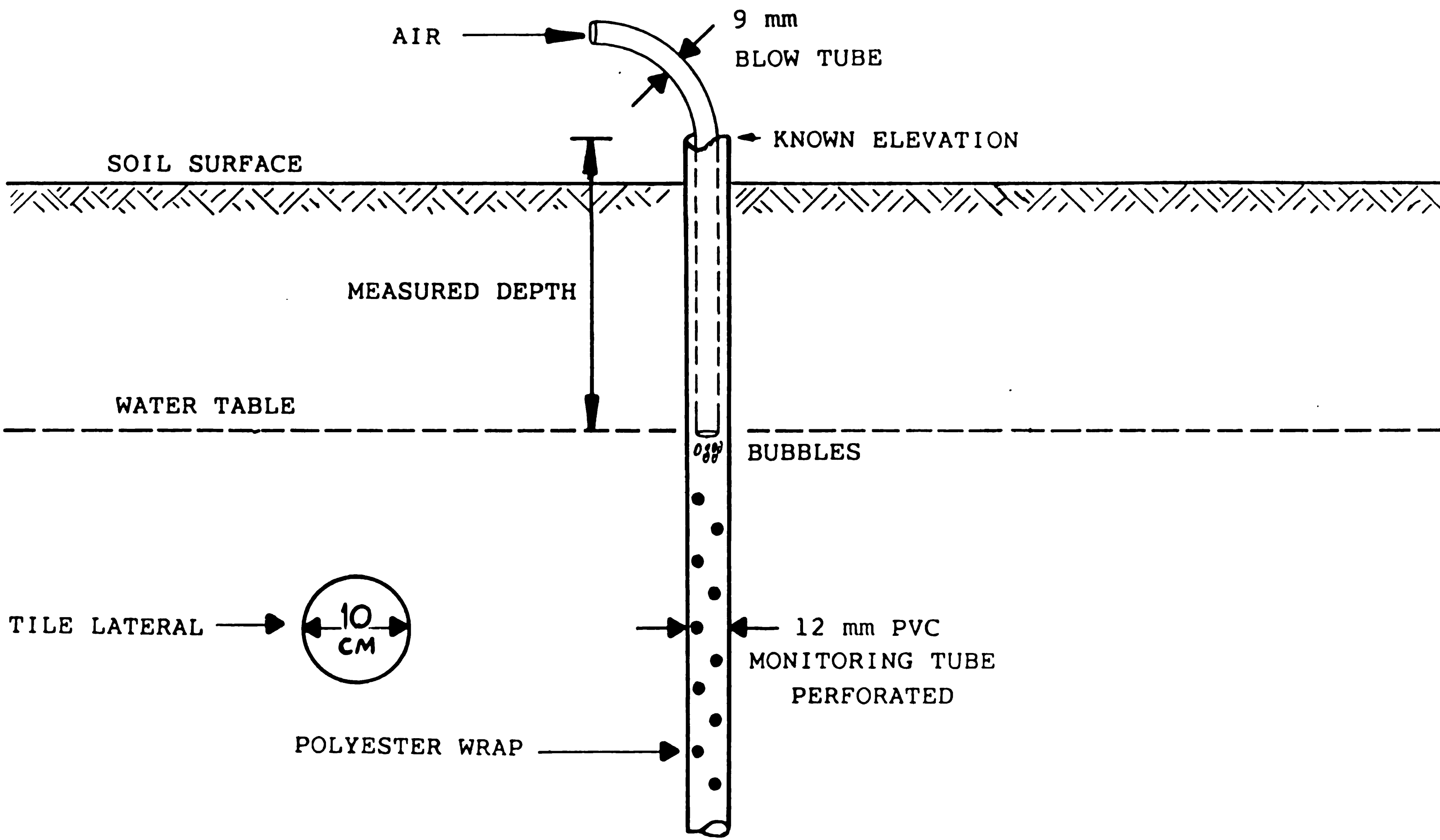


Figure 4.10 Illustration of a blow-tube used to monitor water table depths manually.

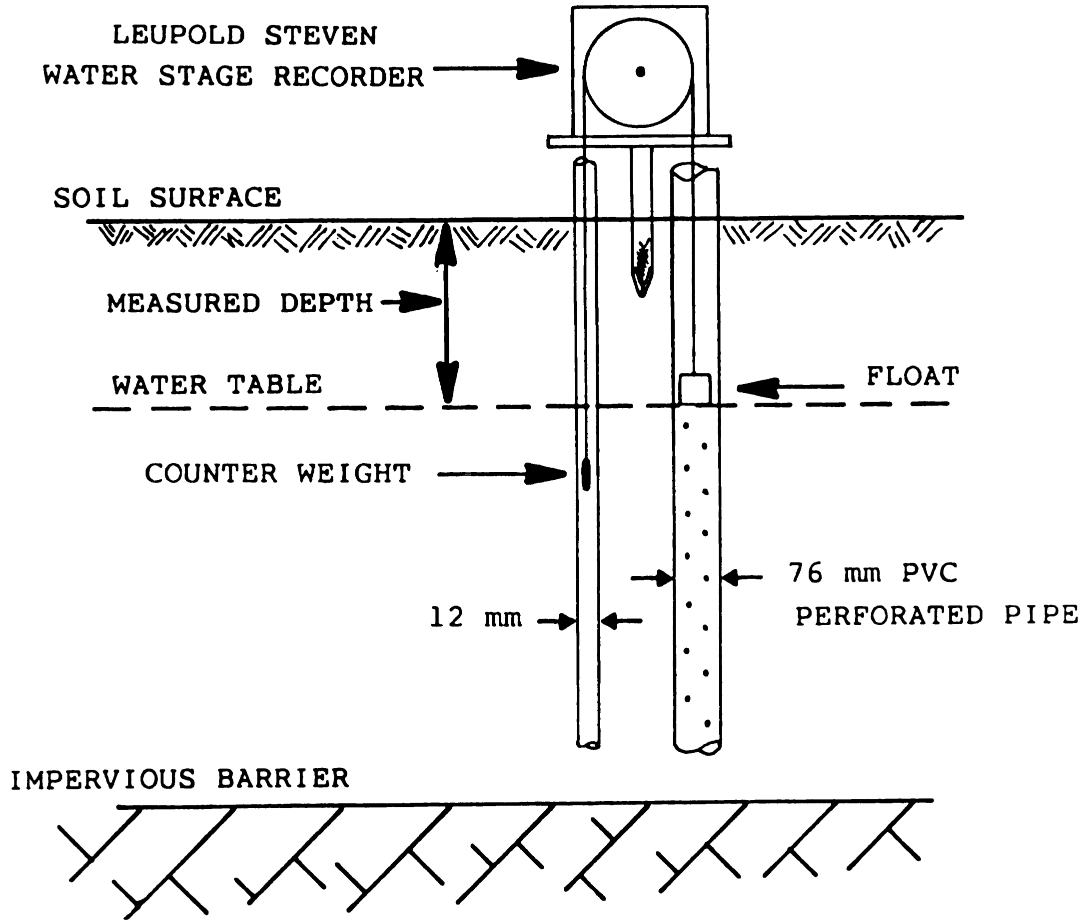


Figure 4.11 Schematic of Leupold Stevens Water Stage Recorder for measuring changing water table elevation.

water table records were obtained on all Sites A, B, C and D. The water levels at each site were managed by the farmer according to his normal management practices. Where continuous records using water level recorders were obtained, events such as the rise in the water table versus the time when the farmer initiated subsurface irrigation were recorded along with diurnal variations over and between tile laterals. To characterize the response of the system to irrigation and drainage, events having a rising water table or a descending water table were analyzed from the water level recorder charts. The response of the water table to drainage conditions was recorded when irrigation water was allowed to drain out of the tile system.

### D. Saturated Hydraulic Conductivity

The saturated hydraulic conductivity (K) was determined using a Velocity Head Permeameter developed by Dr. G. E. Merva, Michigan State University. Results are presented in Table 1. Depth of the measurements ranged from 15 to 50 cm in both the horizontal and the vertical direction for Sites B, C and D. A depth greater than 50 cm should have been measured for saturated hydraulic conductivity. However, this was not accomplished due to lack of foresight on the researcher's part. A depth of about 70 to 80 cm would have given K values closer to the depth of the tile lateral. At Site A, the sandy soil profile slumped into the borehole so the velocity head permeameter could not be used, and hydraulic conductivity was taken from the estimate in the USDA, Soil Survey Book, Monroe County, 1984.

## E. Crop Yields and Planting Inputs

Final yields were reported in Table 2 for each site. Corn yields were measured using methods established by the National Corn Growers Association on Sites A, C and D and expressed as yield at 15.5 percent moisture. Yields for sugarbeets were measured on Site B. A tare was subtracted for the soil and residue removed from the sugarbeets as they were unloaded at the processing plant. A second tare would also account for the weight of the remaining soil left on the sugarbeet during storage which was estimated at 5% of the total weight and subtracted from the yield. Plant populations were determined through an emergence count (Table 3). Data on crop inputs including corn varieties, fertilizer and herbicides were obtained from the cooperating farmers (Table 4).

## F. Available Soil Nutrients

Soil fertility influences the performance of a growing plant. Soil samples were taken from each of the fields used in the experiment and sent to the soils lab at Michigan State University. Phosphate, potassium and soil Ph were measured and are recorded in Table 7.

r
f
m
t
t
t
s
a

sp
sp
cr
po
lo
te
ir
de
ir
ca
in
re
co

aft

## G. Evapotranspiration

Evapotranspiration (ET) was estimated for corn using a modified version of the Penman equation in a spread sheet format as described by Vitosh (1984). The program utilizes minimum and maximum temperatures during each growing day, the geographic location within the state of Michigan, and the crop coefficient (KC) which relates evapotranspiration to stage of crop growth for the estimation of ET. The stage of crop growth is calculated from the emergence date and genetic growing period of the corn variety.

By inserting the appropriate coefficients into the spread sheet, accurate calculations of the crop evapotranspiration (ET) at each stage of growth for a specific crop, location, date, and mean daily temperature are possible. Once the spread sheet is set up for crop and local conditions, entries of any deviation in daily temperature from the long term mean and any rainfall or irrigation amount on the date it occurs can be made. Root depth, profile moisture content and the amount of irrigation that may be added on any day are automatically calculated. A graphic display of the daily moisture content in the soil profile is shown. The computer program begins reducing evapotranspiration rates when soil moisture content is less than 50% of the available moisture.

The calculations for evapotranspiration were begun after a major rainfall event. Because soil moisture was assumed to be at field capacity following the rain, potential evapotranspiration was also assumed. Because subsurface irrigation seeks to establish a water table in or near the root zone, it was assumed that after irrigation commenced, the available water supply to the plant would always be greater than 50% available soil moisture, and ET would never be limited. Therefore, the ET rate that was potentially possible for the crop being grown was calculated.

## H. Precipitation

Precipitation amounts and date of rainfall events were obtained from two sources. The first source was the field location where local rainfall data was recorded by the farmer through the use of a rain gauge set up above the crop canopy. The farmer was to record any precipitation each morning in a record book for his field location. The second source was the nearest weather station. The rainfall amounts and their corresponding dates were compared. A check on a rainfall event was made from the water stage recorders for Site C. When the water stage recorders showed a rapid water table rise and this coincided with the weather station records for rainfall while the farmer's recorder revealed no rainfall for that date, rainfall was assumed and the weather station record was utilized. However, every effort was made to use the farmer's rainfall record because of the possibility of local variation in rainfall. These values were compared with local rainfall data recorded from other local weather stations like airports.

The amount of drainage water which was removed from the system was not measured due to the nature of the subsurface irrigation systems designed and installed by the farmers. The farmers would drain the systems whenever they felt excessively high water table conditions would result from rainfall amounts. The water stage recorders measured water table elevation as it changed over time, including ET induced fluctuations and changes due to irrigation and drainage.

Sites A and B did not result in a total water volume being recorded. The reason was that the farmers at each site took liberties to vary the pumping rate as crop and precipitation dictated and failed to record changes in pump output operating pressure, pump rpm, and the length of time the pumps were operated.

# V. RESULTS AND DISCUSSION

Water table elevations at four sites were monitored during subirrigation. At two sites, Sites A and C, both continuous and discrete data were collected. Leupold Stevens Type F water stage recorders were used to automatically monitor the water table elevations near and midway between tile lines at selected locations in each field (Figure 4.10). At Sites B and D the water table was monitored manually utilizing monitoring tubes at locations interspaced between parallel tile laterals. A blow tube was used to determine water table depth from the datum selected for each site (Figure 4.11).

## A. Site A

The results of the field evaluation to determine the response of the water table at Site A yielded very little reliable data. The data was not adequate because of the following reasons: 1) the time of pump start-up, discontinuation of irrigation, and other information such as pump speed and pressure were not recorded; 2) the soil at the site, a loamy fine sand, moved into the tubes housing the float and counter weight, causing them to stick, resulting in no data; 3) measurements made by two water stage recorders using 30 day timing clocks were not consistent with each other on water table fluctuations from a predetermined datum; and 4) cables connected to a number of floats and counter weights jumped the pulleys driving the drum which contained the charts for recording water table change.

## B. Site B

The results of the field evaluations to determine the response of the water table at Site B are recorded in Figures 5.1 through 5.4. All measurements were made manually. The positions of the monitoring tubes are noted in Figure 5.1 through 5.4 by the vertical arrows at the top of the figures. The tubes were spaced at five meter intervals between two parallel tile laterals, with a tube near each lateral. The tile lateral spacing was 20 meters. A clay barrier existed at approximately 100 cm or greater below the soil surface. A datum, which was the top of the supply well outlet pipe, was used as a common reference. The bottoms of the monitoring tubes were approximately 77 cm and 100 cm below the soil surface at the north and south end respectively. The tile lateral depth varied from 42 to 47 cm below the soil surface at the north end of the field and approximately 83 cm below the soil surface at the south end of the field.

Figures 5.1 and 5.2 show the Site B water table elevations at the north end of the field, close to the water supply, for different observation days. Figures 5.3 and 5.4

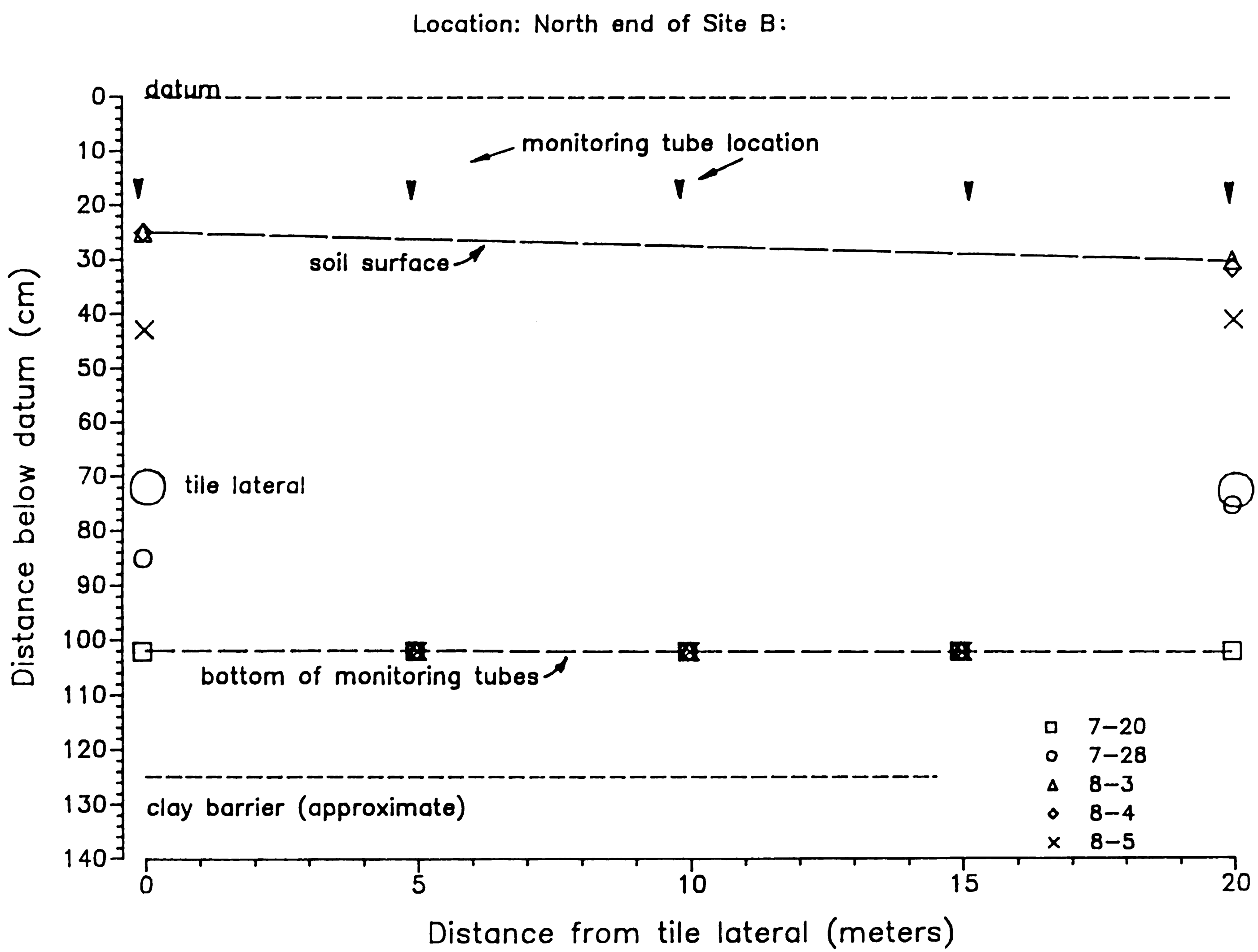


Figure 5.1 Water table elevations on five dates, north end, Site B, early season.

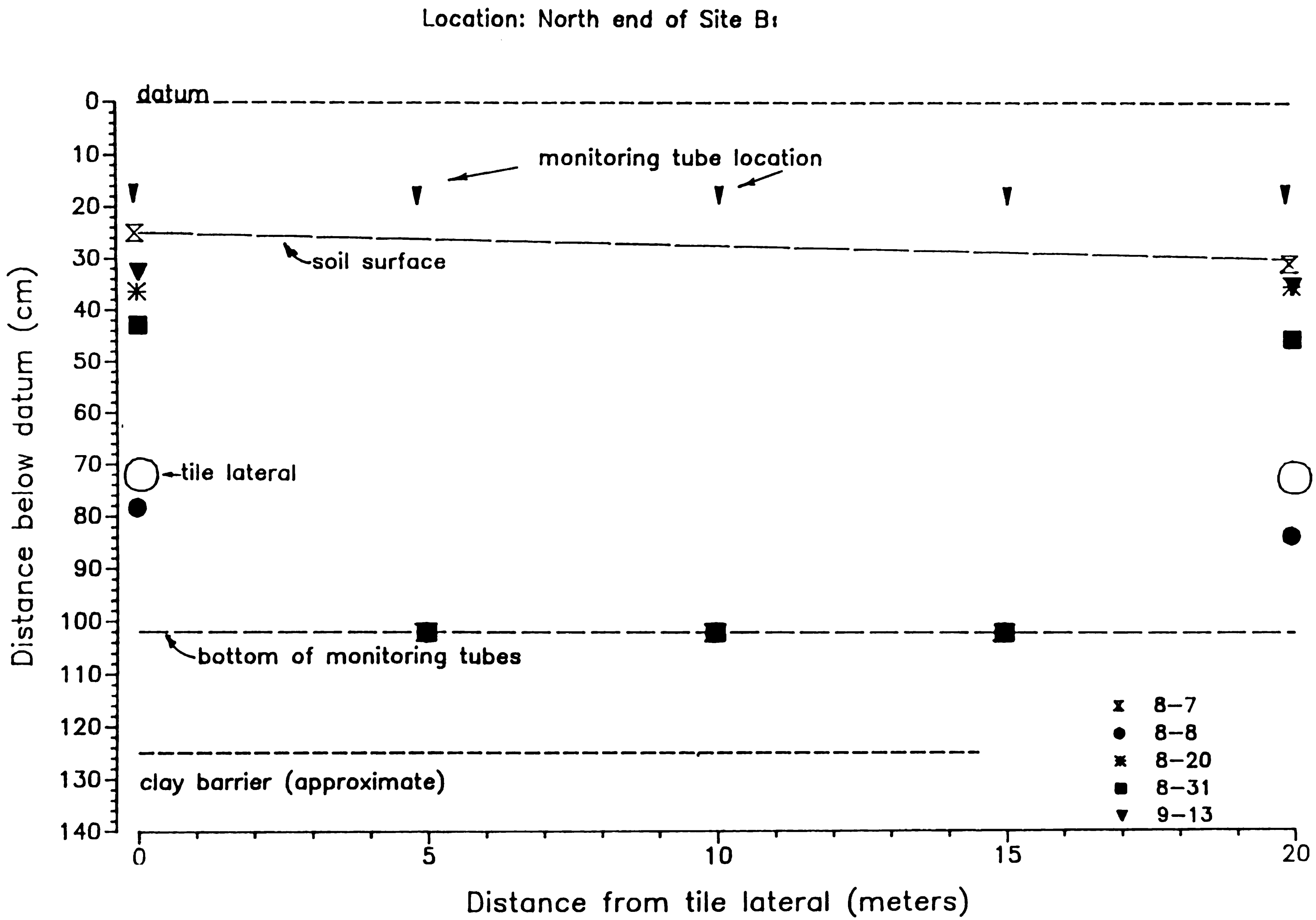


Figure 5.2 Water table elevations on five dates, north end, Site B, late season.

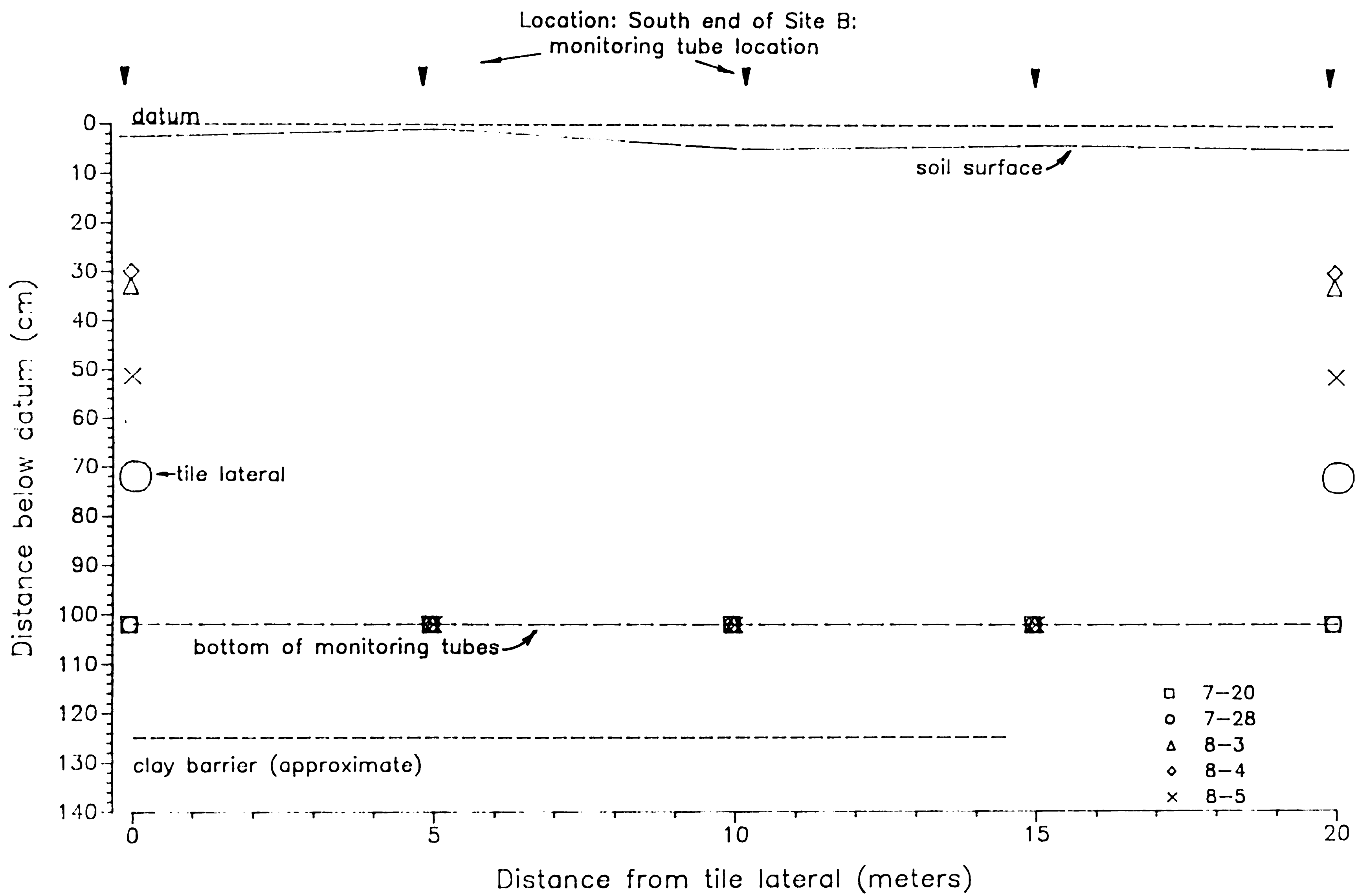


Figure 5.3 **Water table elevations of five dates, south end, Site B, early season.**

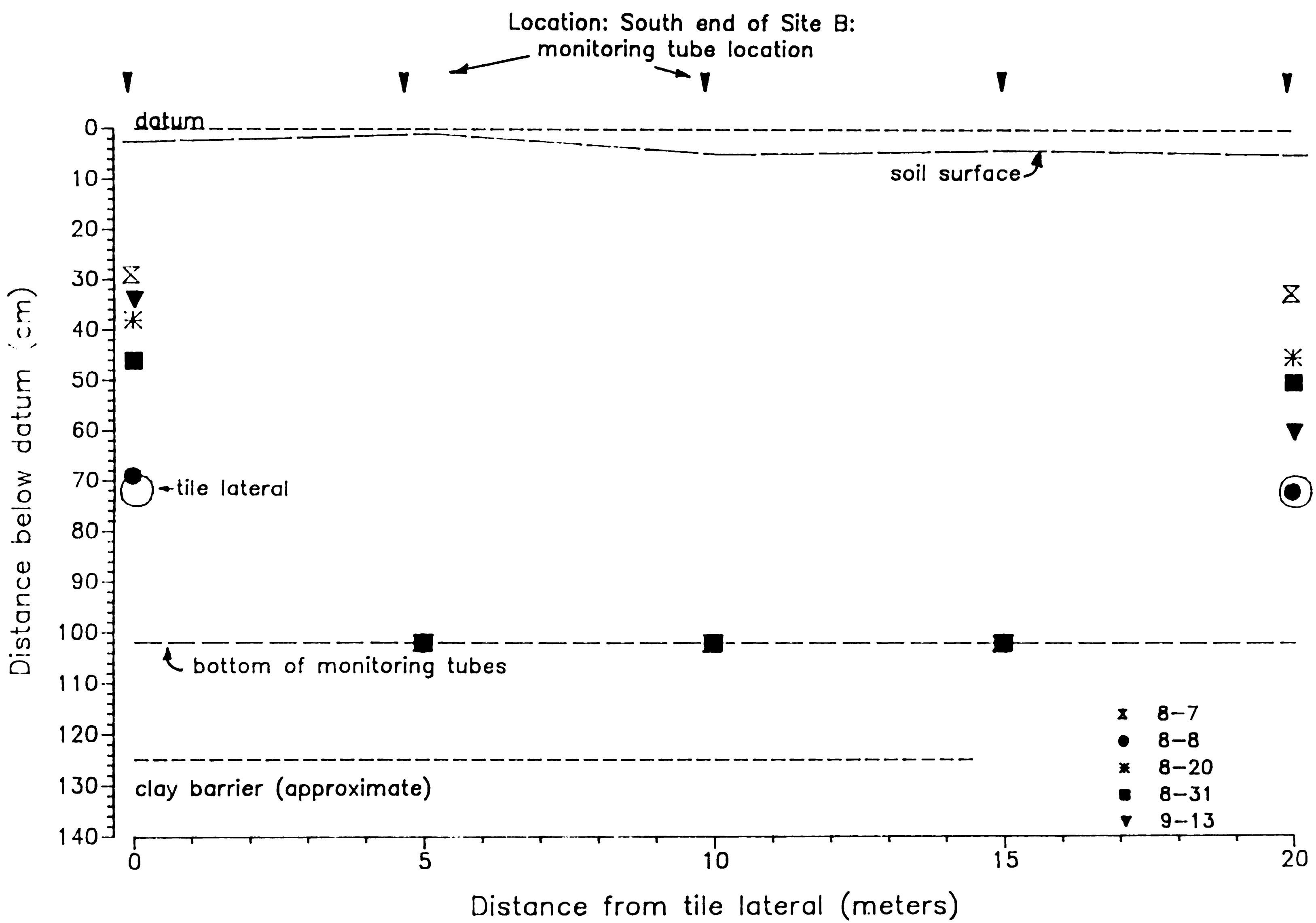


Figure 5.4 Water table elevations on five dates, south end, Site B, late season.

present the elevation of the water table at the south end of the field, away from the water supply but located on the same laterals as monitored at the north end. Figure 4.3 shows the location in the field where these measurements were taken. Data was recorded for 56 days during irrigation, from 7/20 through 9/13. Prior to the beginning of monitoring, the system was in the drainage mode. The water table elevation was below the tile laterals. When subsurface irrigation was initiated, the water level was raised in a riser pipe on the tile main to an elevation near the soil surface. The farmer did not record the initial start-up time and date of irrigation nor when the pump was shut off. However, irrigation was initiated either before or on 7/28. Irrigation water input was operated in an on-off sequence prior to 8/8, then continuously from 8/9 through 9/13.

The water table elevation at the north end (Figure 5.1) reveal a rise near the tile lateral on 7/28 and by 8/3 was on the soil surface. It was held there through 8/4, allowed to decrease below the surface on the 5th, and brought back to the soil surface until August 7 when the pump was shut off. The water table then decreased below the tile laterals by August 8 (Figure 5.2). From August 3 - 7, water above the tile laterals was visibly noted. Water was puddled on the soil surface over the tile lines at the north end of the site.

At the south end (Figure 5.3), the water table showed a lag in the time of rise. The water table did not show a response on July 28 as the north end had done. However, by the time of the next observation on August 3, the water table had risen to approximately 27 cm below the soil surface, similar to the rise in height at the north end. It could also be noted that as one proceeded south from the north end, the puddled water ceased and only capillary soil moisture appeared over the tile laterals. This can be understood by analyzing Figures 5.1 and 5.4. The water table at the south end never came to the soil surface. The soil sloped upward, making the water table approximately 27 cm below the surface but at the same elevation as the north end. Capillarity moved moisture upward 27 cm from the water table to the soil surface.

The observations on August 8 revealed the water table dropped below the tile laterals at the north end of the field and dropped to just above the tile laterals at the south end. This was a decline of approximately 48 to 58 cm at the north end and 40 cm at the south end in about a 24 hour period. At this point the water supply had been turned off, and water flowed away from over the tile laterals to cause the decline. Reasons for the rapid decline may have been that water was being removed by evapotranspiration over and near the tile lines by the crop and/or water was lost as leakage near the outlet pipe.

The exact time when the irrigation water was turned back on was not recorded. The exact date of the beginning of the water table rise before August 20th at the north (Figure 5.2) and south ends of the field (Figure 5.4) was not known. However, the water table over the tile laterals was held between 0 to 15 cm below the soil surface at the north end and 30 to 40 cm below the soil surface at the south end until September 13th.

Figures 5.5 and 5.6 illustrate the difference in water table elevation at the two extreme ends of the field, but over the same tile lateral. The break in the water table elevations, as shown in the figures, represents a time period during which the rate of rise of the water table was unknown. The figures allow some insight into the effect of distance from the water source and friction in the tile lateral on the loss of water table height.

Figure 5.5, representing the west tile lateral of the area of the field being monitored, shows a fairly uniform water table response at both ends of the field. There was a delay in the initial water table response at the south end, but by 8/3 a uniform response was seen.

Figure 5.6, representing the east tile lateral of the area of the field being monitored, showed less agreement in responses at both ends of the field. This may have been a measurement error or head loss due to friction in the pipe.

In checking the decrease in the water table elevation over the length of the tile lateral as a result of friction, the Manning formula for open channel flow in field drainage tile is often used (Schwab, 1966). The Manning formula is normally applied to tile drainage because very seldom are the tiles flowing full of water. With subsurface irrigation, however, the field tiles are filled with water and pipe flow condition occurs rather than open channel flow. The Hazen - Williams formula as outlined by Finkel (1982), therefore, applies. The Hazen - Williams formula is historically a proven formula and has been used for many years to describe head loss during pipe flow.

The Hazen - Williams formula is:

$$h_l = (Q/C)^x * K_1 L/D^m \text{ ......................... } 5.1$$

where $h_l$ = head loss (m) through L distance; L = length of pipe (m); Q = flow rate ($m^3$/sec); D = internal diameter of the pipe (m); $K_1$ = 10.59 (SI units); C = roughness coefficient; m = 4.87 and x = 1.87.

Q was calculated by taking the rate of water input (0.0063 $m^3$/sec) and dividing it by the number of tile laterals in the irrigated portion of the field.

Because it was difficult to calculate the head loss in a concrete tile lateral with water being removed through perforations or joints, the exact amount of water removed as it flowed down the tile lateral was unknown. Therefore, it was assumed that the total volume of water entering the tile lateral from the tile main was transported the full length of the tile. Maximum head loss could then be calculated assuming no water loss. The following parameter values used were L = 372 m, Q = 0.0004 $m^3$/sec, D = 0.1 m, $K_1$ = 10.59, C = 110 for old concrete tile (Finkel, 1982), m = 4.27 and x = 1.87. The

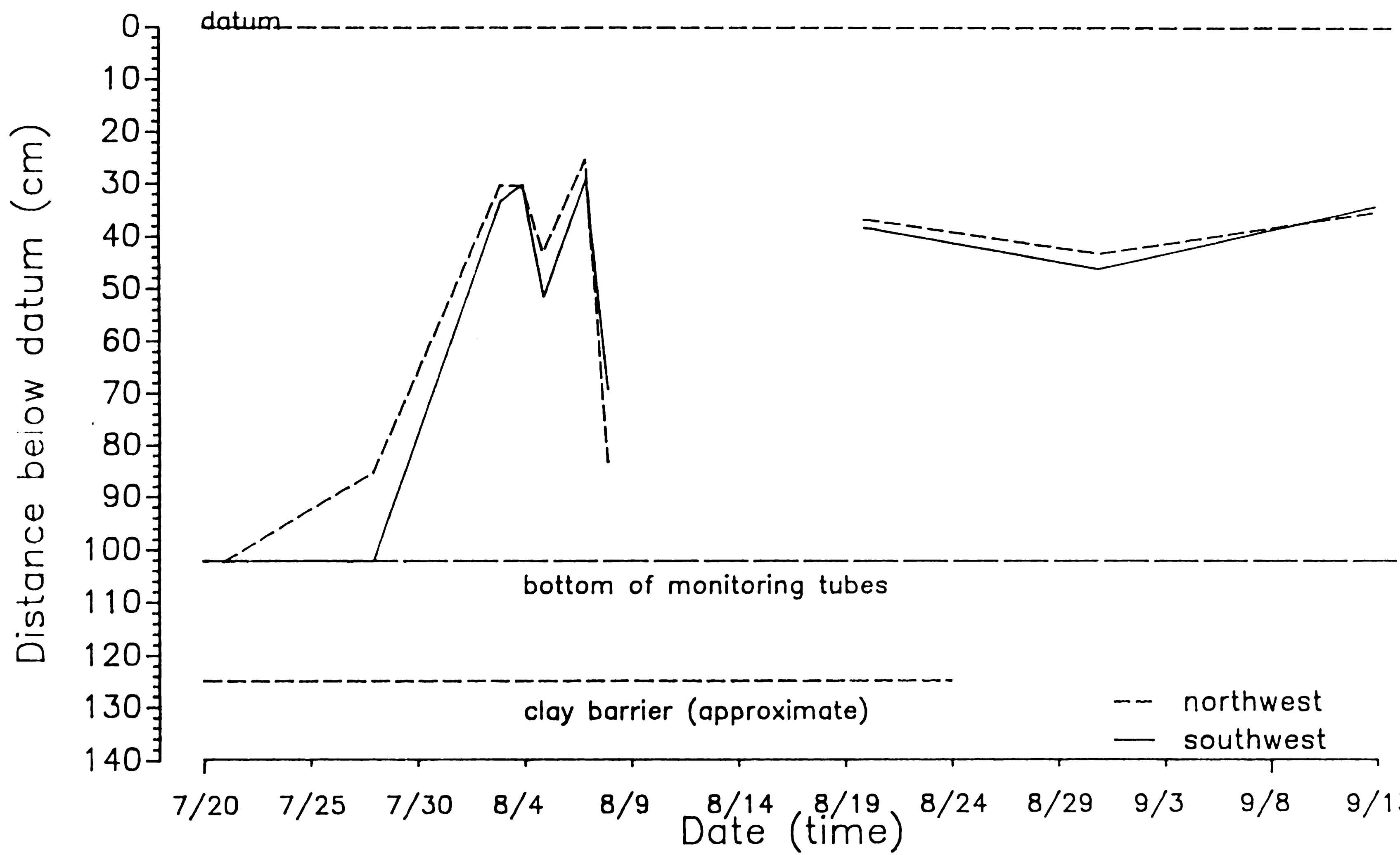


Figure 5.5 Water elevation over the west tile line monitored at both ends of the field, Site B

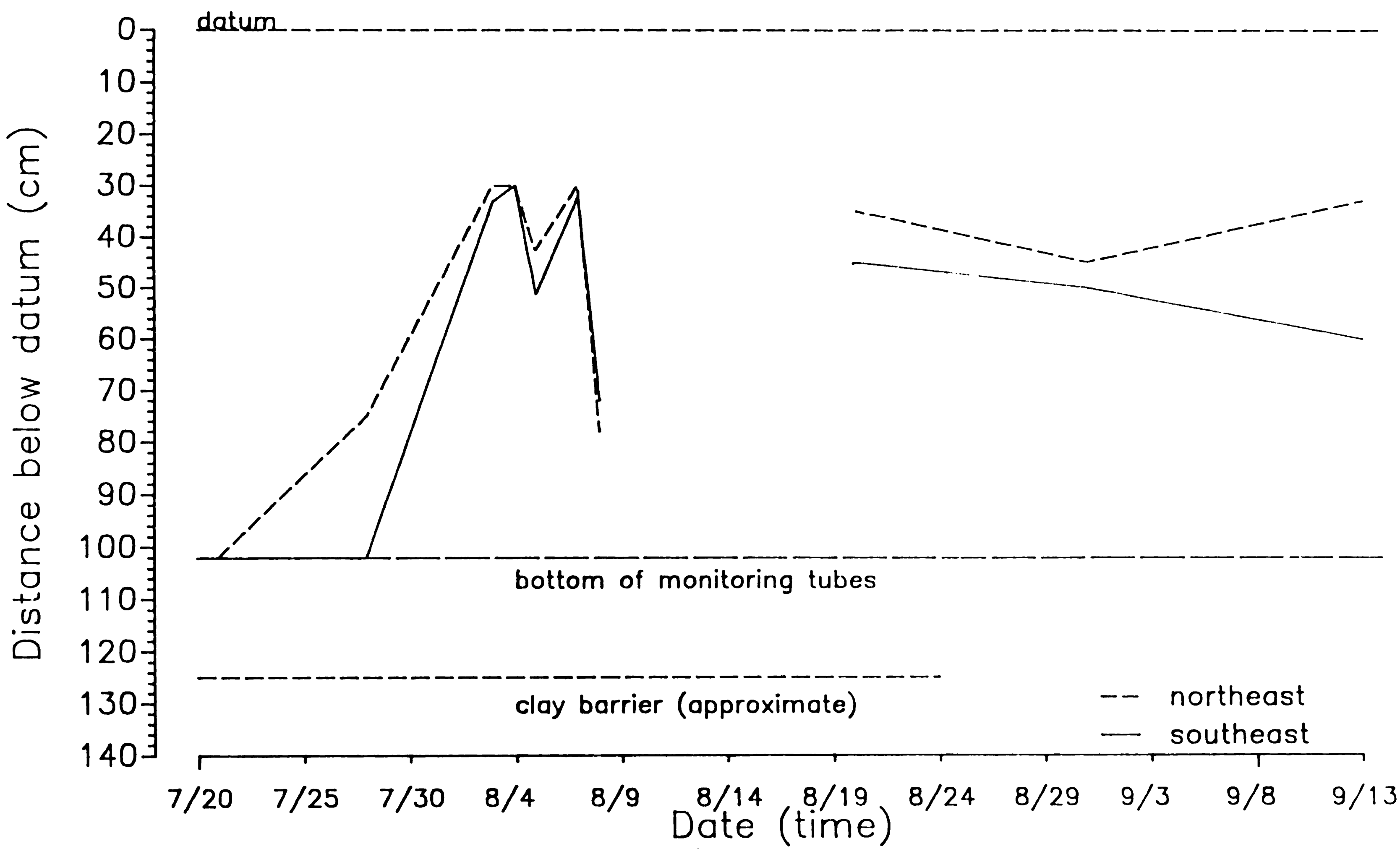


Figure 5.6 Water elevation over the east tile line monitored at both ends of the field, Site B

result was that $h_l$ = 0.02 m (2 cm) of head loss when Q was transported for L distance.

In actuality, irrigation water is lost into the soil profile as it moves down the tile lateral during subsurface irrigation. As a result, the actual head loss due to friction would be less than 0.02 m. Because 0.02 m is a very small amount of head loss due to friction, it can essentially be assumed to have no influence on the water table height over the tile laterals.

Monitoring tubes five meters off each tile lateral revealed no water table during 56 days of monitoring. At no point during subsurface irrigation was a water table established between the tile at either end of the field. The water table came up over the tile lateral but fell off within the first five meters from the tile indicating a large hydraulic gradient existed in the vicinity of the tile laterals.

Factors which affect whether lateral movement away from the tile lateral will raise the water table are the rate of vertical and lateral movement and the ET rate. The lateral hydraulic conductivity and the hydraulic gradient created by the water table over the tile laterals determine the flux away from the tile.

Estimated evapotranspiration for sugarbeets in the month of August varied from 3.8 mm to 5.5 mm per day and averaged 4.6 mm (0.18 inches) per day. The well providing the water supply produced approximately 378 liters per minute (100 gpm) or about 545 $m^3$ per day. If ET averaged 4.6 mm per day and was calculated for 13.7 ha (non-irrigated area omitted), the total ET for the irrigated area equals approximately 600 $m^3$ per day. The well water supply rate was below the ET requirement, but only by 55 $m^3$ per day (about 10 percent). A fraction of the total possible area, an area less than five meters on either side of each tile line received water. When the area between the tile laterals is not considered irrigated, the well produced more than enough water for those areas being irrigated. Some of the excess ponded water over the tile laterals actually ran off as surface runoff at the north end of the field. This runoff was not measured.

The difference in the vertical and lateral movement of the water table in the soil profile may be explained in part by the difference between the vertical and lateral hydraulic conductivities. The saturated hydraulic conductivity values recorded in Table 1 show that the saturated vertical conductivity at 30.5 cm depth, range from 2.3 to 7.7 cm/hr compared to 0.3 cm/hr for the saturated lateral hydraulic conductivity. Thus, the vertical conductivity was 13 to 25 times greater than the lateral conductivity. The lateral conductivity at the 50 cm depth was also quite slow, ranging from 0.3 to 0.4 cm/hr. Measurements using the reverse auger hole method as described by Reeves (1982) showed a hydraulic conductivity of 0.1 to 0.2 cm/hr for saturated horizontal flow. Equation 3.1, Darcy's law (Hillel, 1982), was used to calculate the flux rate or volume of water flowing through a

Table 1. Saturated hydraulic conductivity utilizing velocity head permeameter.

| Field site | depth (cm) | Lateral (cm/hr) | vertical (cm/hr) |
|---|---|---|---|
| A | | -* | -* |
| B | 30.5 | 0.3 | 7.8 |
| | | 0.3 | 2.3 |
| | | 0.3 | - |
| | | 0.3 | - |
| | 50.0 | 0.4 | -# |
| | | 0.3 | - |
| | | 0.3 | - |
| C | 15.2 | 5.1 | 3.2 |
| | | 5.2 | - |
| | 50.0 | 4.5 | 3.2 |
| | | 4.2 | 3.2 |
| | | - | 3.5 |
| D | 30.5 | 4.7 | 10.8 |
| | | 4.7 | 9.0 |
| | | 3.6 | 6.7 |
| | | 3.9 | - |
| | 50.0 | 6.0 | -# |
| | | 7.3 | - |
| | | 5.6 | - |

* Because of sidewall slump and the existence of a water sand environment, the velocity head permeameter and the reverse auger hole method were not feasible.

# Vertical hydraulic conductivity was not taken at this lower depth.

unit cross-sectional area per unit of time. If the soil properties were such that the hydraulic conductivity was very small, the volume of water (flux) moving laterally through a cross-sectional area of soil profile would be small.

If one looks at the evapotranspiration (ET) rate in relation to the hydraulic conductivity needed to sustain ET, a comparison between the measured K ($K_{mea}$) and the calculated K ($K_{cal}$) value can be made. If the $K_{cal}$ needed to sustain ET is larger than $K_{mea}$, a water table should not have been established at least five meters off the tile lateral.

Calculating the total evapotranspiration volume ($ET_v$) with an ET rate of 0.0046 m/day over an area of 5 $m^2$,

$$ET_v = 0.0046 \text{ m/day} \times 5 \text{ m} \times 1 \text{ m} \quad \text{..........(5.2)}$$

$$ET_v = 0.023 \text{ m}^3\text{/day/ } 5 \text{ m}^2 \text{ area.}$$

Calculating the lateral flux into the soil over the tile lateral where the water came up to the soil surface, the soil must conduct the full amount, 0.023 $m^3$/day, through an area 1 m by 0.8 m (depth of tile below surface) to supply ET. Flux (q) at the tile,

$$q = \frac{0.023 \text{ m}^3\text{/day}}{1 \text{ m} \times 0.8 \text{ m}} \quad \text{........................(5.3)}$$

$$q = 0.03 \text{ m/day}$$

Calculating the required hydraulic conductivity (K) to move 0.03 m/day using Darcy's Law:

$$K_{cal} = \frac{q\ L}{\Delta H} = \frac{0.03\ m/day * 5\ m}{0.8\ m} \quad \text{..........(5.4)}$$

$$K_{cal} = 0.2\ m/day$$

where L = 5 m (distance to the monitor tubes), q = 0.03 m/day and $\Delta H$ = 0.8 m (height of water table above tile and at the soil surface).

Therefore, to sustain an ET rate of 0.0046 m/day, with a lateral flux calculated at 0.03 m/day, a $K_{cal}$ value of 0.2 m/day is required.

The $K_{mea}$ from the velocity head permeameter averaged 0.072 m/day (0.03 cm/hr, Table 1).

The measured hydraulic conductivity value is 2.6 times smaller than the calculated K value for the assumptions considered. Water moving laterally could be drawn upward to replace water used by the crop before it moves to a monitoring site five meters from the tile lateral.

The hydraulic conductivity was small enough to explain the fact that insufficient water moved laterally to supply daily ET, let alone supply water to establish or maintain a water table.

Deep seepage was considered negligible in its affect on lateral water movement. Soil borings were obtained during the early part of the spring when the field was too wet for field operations. Approximately six borings taken around the field to a depth greater than 125 cm all resulted in an almost dry, slowly permeable subsoil being encountered. Therefore, very little deep seepage was evident.

The conclusions resulting from the monitoring of the water table movement for the type of conditions at Site B are as follows: 1) The hydraulic conductivity, with values between 0.1 to 0.4 cm/hr, became the limiting factor in water not moving fast enough laterally to establish a water table five meters off the tile lateral; and 2) water supply was approximately 10 percent below the capacity required to irrigate the total area. However, it was adequate because the area between tile laterals was not being provided with subsurface irrigation water.

## C. Manual Water Table Response for Site C and D

Manually determined water table elevations resulting from a constant water level in the head control structure are given in Figure 5.7 for Site C, and in Figure 5.8 for Site D. The figures represent the monitoring locations furthest from the water source and control structure. The area midway between the tile laterals was believed to represent the position slowest to respond to subsurface irrigation. This location was slowest to respond because of the distance from the tile laterals, effects of the soil properties and the influence of evapotranspiration.

Measurements were taken manually from monitoring tubes interspaced between tile laterals as shown in Figure 4.6 and 4.9. Sites C and D had a 10 meter and 20 meter tile spacing, respectively. Prior to the beginning of the test, the water table elevations were below the tile laterals for each site. When irrigation was initiated, the water table in the control structure was raised to a constant elevation. It was then held at that elevation until the farmer decided to lower the water table due to excessive irrigation water and/or rainfall.

Figure 5.7 shows the water table between laterals at the north end of the field for several manual observations after initiation of water input on Site C. Subsurface irrigation was initiated on 7/18 at 0800 hours with an irrigation rate of approximately 1000 liters per minute (265 gpm). A constant head was maintained in the head control structure 72 cm above

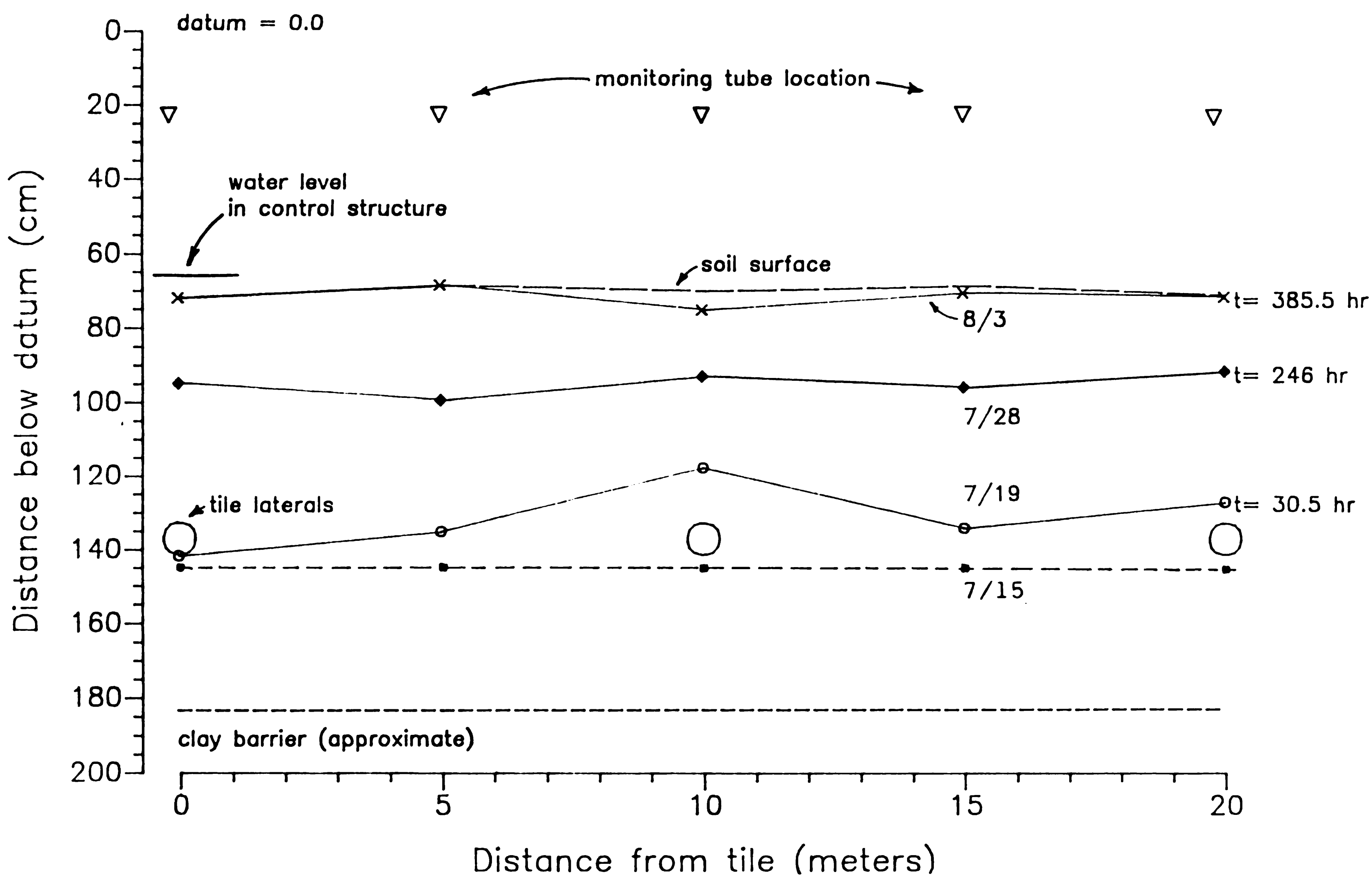


Figure 5.7 Water table elevations at various times across three laterals, furthest from control structure, Site C.

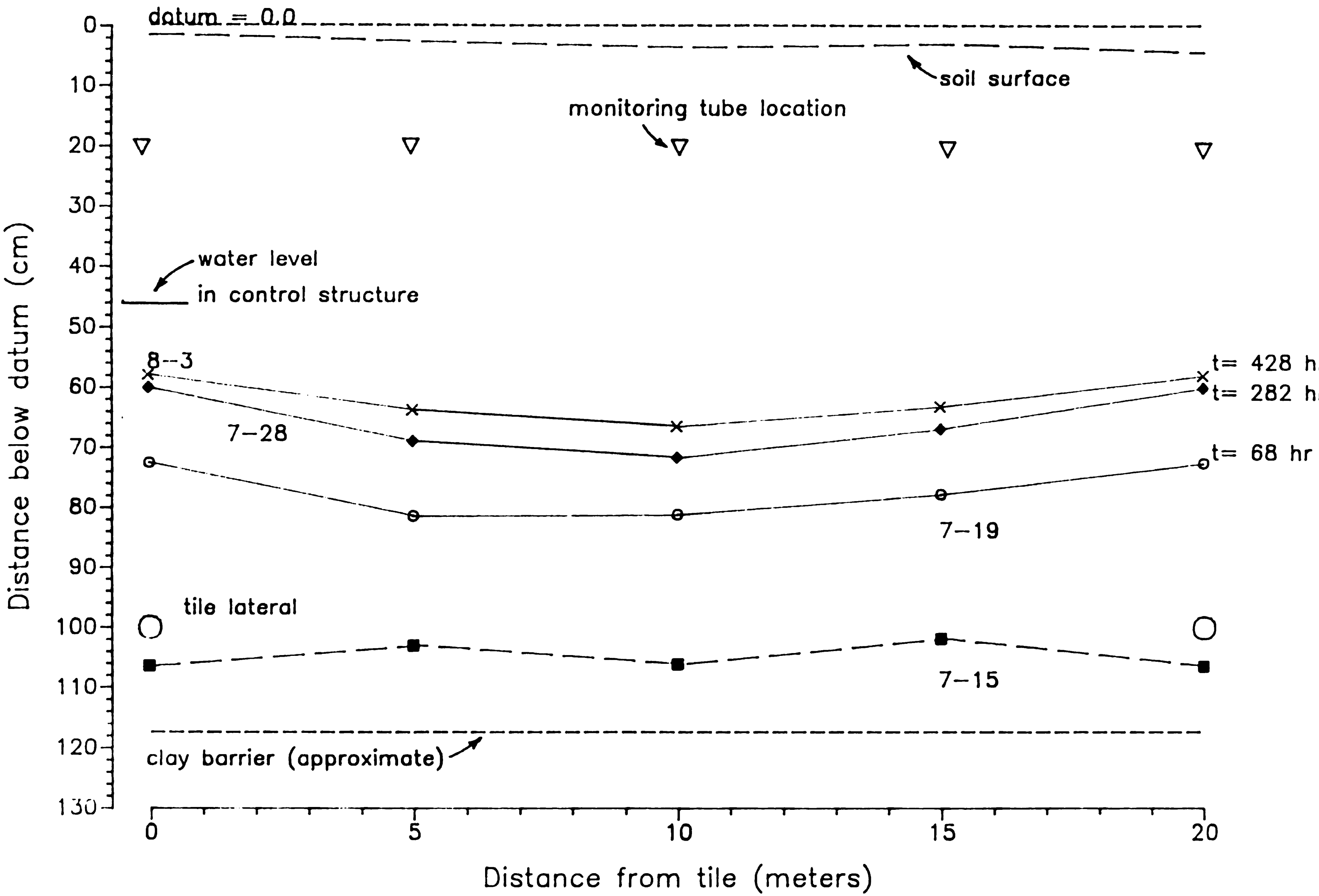


Figure 5.8 Water table elevations at various times across two laterals, furthest from control structure, Site D.

the tile center at the position in the field where the monitoring took place. The average depth of the monitoring tubes was approximately 77 cm below the soil surface. The water table prior to 7/15 was somewhere below the bottom of the monitoring tubes. The data for 7/19 was the first measured water table profile 30.5 hours after irrigation was initiated and reveals a rising water table near the tile. The water table was approximately 67 cm below the soil surface at this time. From 7/19 to 7/28, the water table rose 38 cm in 212.5 hours (0.18 cm/hr) midway between the tile laterals at the north end of the field. Between 7/19 and 8/3, it rose an average of 63 cm in 355 hours (0.18 cm/hr).

Figure 5.8 shows the rise in the water table at Site D. The supply of irrigation water was approximately 500 liters per minute (132 gpm). A constant head was maintained 54 cm above the tile center. This water column provided the head to move water through the tile. The tile laterals were approximately 100 cm below the soil surface. Subsurface irrigation was initiated on 7/16, at 1600 hours. On 7/15 the water table profile was known to be below the tile lateral and greater than 106 cm below the soil surface, the depth of the monitoring tubes. As a result of not knowing the exact water table depth at initiation of irrigation, the height of the water table change was referenced to the water table reading on 7/19. The water table reading on 7/19 showed a concave upward shape 68 hours after initiation of irrigation, being higher over the tile laterals than midway between. Midway between tile laterals, the water table by 7/28 had moved upward uniformily. It had progressed 11 cm from the previous monitored position (7/19) in 214 hours (0.05 cm/hr). By 8/3 the water table rose another 15 cm in 360 hours from 7/19 (0.04 cm/hr). The slow rate of rise can be attributed to the lower pumping rate and a wider tile lateral spacing.

For subsurface irrigation with a constant evapotranspiration rate at the surface, the steady state water table takes the general shape given in Figure 5.9. Skaggs et.al. (1972) utilized an approximate algebraic expression developed by Fox et.al. (1956), which utilized the Dupuit-Forchheimer assumptions describing the water table. The equation may be written in the following form to determine the tile or ditch spacing required to not exceed a preset maximum difference in the water table elevation directly over and midway between the tile laterals, $h_1 - h_2$:

$$L = \left( \frac{4K}{u} * (h_1^2 - h_2^2) \right)^{0.5} \qquad \text{...............(5.5)}$$

where L = the distance between tile laterals; K = the lateral hydraulic conductivity; u = the evapotranspiration rate; and $h_1$ and $h_2$ = the distance of the water table above the impermeable layer at the tile lateral and midway between the tile laterals, respectively.

A procedure developed by Bower and van Schilgaarde (1963) for predicting the rate of fall of the water table in tile drained soil can also be applied to a rising water table.

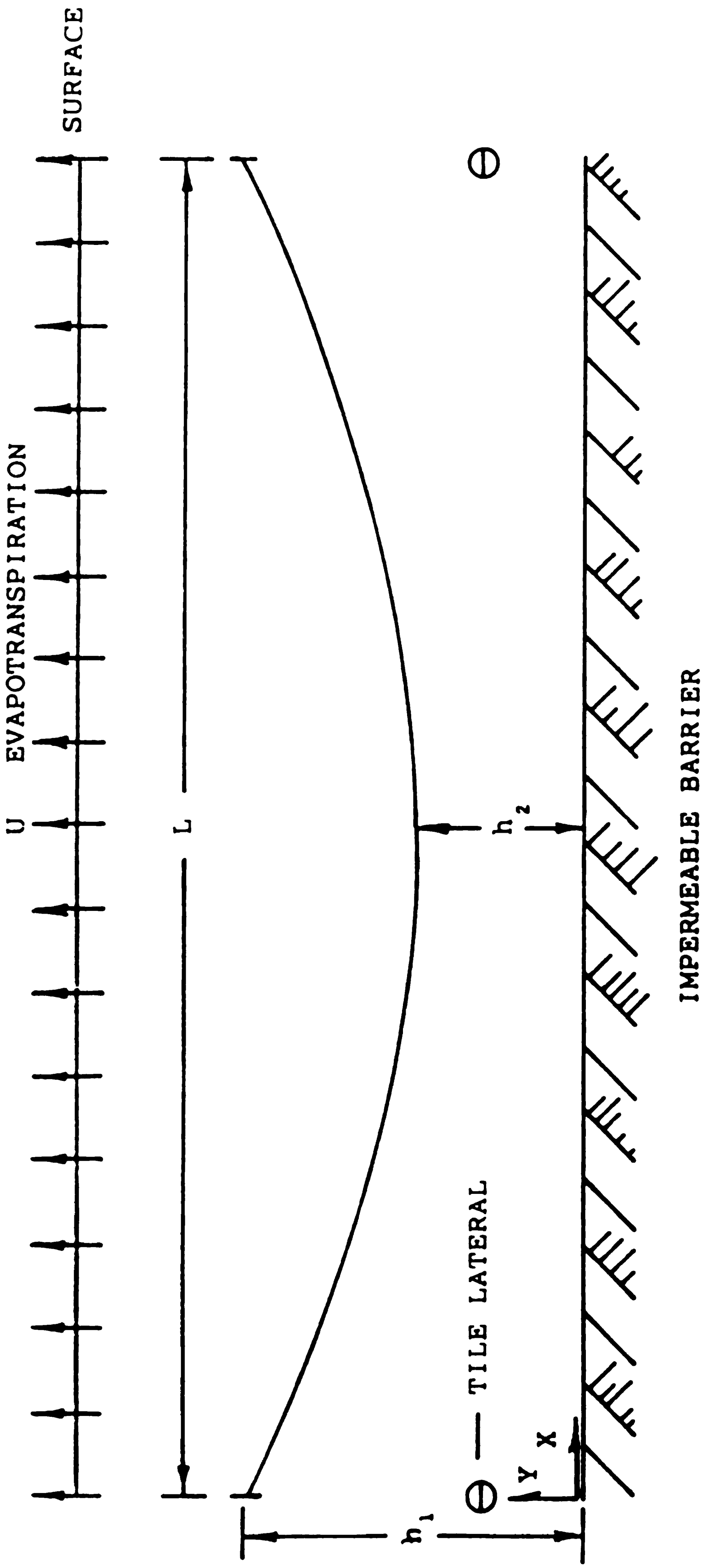


Figure 5.9 Schematic of water table profile during subsurface irrigation.

Skaggs et.al. (1972) characterized the upward water movement of the water table under subsurface irrigation conditions by utilizing an equation derived from the methods of Bower and van Schilfgaarde. If the water table rises uniformly without change of shape, the flux is uniform and can be expressed by

$$\frac{dm}{dt} = \frac{u}{f} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5.6)$$

in which m = the height of the water table above the center of the tile at the midpoint between drains; t = time; u = the instantaneous subsurface irrigation water input rate or upward flux minus the evapotranspiration rate (units of length/time) and f = the fillable porosity.

The fillable porosity (f) needed for Equation (5.6) was determined according to the method outlined by Vomocil and Black (1965):

$$AFP_{60\ cm} = \frac{Sat.Wt}{Vol} - Wt_{60\ cm} \quad \ldots\ldots\ldots\ldots\ldots\ldots (5.7)$$

where $AFP_{60\ cm}$ = air fillable porosity at 60 cm of tension (%); Sat.Wt = the saturated weight (gms); Vol = volume of the soil core ($cm^3$); and $Wt_{60\ cm}$ = weight (gms) at 60 cm of tension.

Soil cores were taken on Site C and D at a depth of 30 - 38 cm and 68 - 76 cm two years after the field data on water table were collected. The values for fillable porosity were calulated and listed in Table 2.

Table 2. Fillable Porosity at Two Depths, Site C & D

| Core number | Saturation wt (gm) | Tension table, 60 cm @ 48 hr (gm) | Oven dry wt (gm) | Ring wt (gm) | Density ($gm/cm^3$) | Total Porosity (%) | Fillable Porosity (%) |
|---|---|---|---|---|---|---|---|
| 30 -38 cm depth Site C | | | | | | | |
| 1201 | 895.7 | 868.2 | 757.9 | 159.5 | 1.7 | 39.7 | 7.9 |
| 1205 | 899.0 | 866.5 | 762.4 | 159.5 | 1.7 | 39.3 | 9.4 |
| 1209 | 878.1 | 836.0 | 735.7 | 159.5 | 1.6 | 41.0 | 12.1 |
| 1210 | 894.2 | 858.6 | 749.5 | 159.5 | 1.7 | 41.6 | 10.2 |
| 1211 | 879.4 | 844.4 | 734.9 | 159.5 | 1.6 | 41.6 | 10.1 |
| | | | | | | | Average = 9.9 |
| 68 - 76 cm depth Site C | | | | | | | |
| 1216 | 873.7 | 837.2 | 721.8 | 159.5 | 1.6 | 43.7 | 10.5 |
| 1217 | 864.1 | 833.0 | 720.4 | 159.5 | 1.6 | 41.3 | 9.0 |
| 1221 | 872.8 | 838.2 | 728.1 | 159.5 | 1.6 | 41.6 | 10.0 |
| 1224 | 861.0 | 828.5 | 711.2 | 159.5 | 1.6 | 43.1 | 9.4 |
| 1225 | 855.8 | 813.6 | 700.1 | 159.5 | 1.5 | 44.8 | 12.1 |
| | | | | | | | Average = 10.2 |
| 30 -38 cm depth Site D | | | | | | | |
| 1430 | 888.5 | 861.3 | 756.1 | 159.5 | 1.7 | 38.1 | 7.8 |
| 1438 | 878.3 | 848.3 | 743.1 | 159.5 | 1.6 | 38.9 | 8.6 |
| 1441 | 871.9 | 835.5 | 732.1 | 159.5 | 1.6 | 40.2 | 10.5 |
| 1449 | 867.5 | 828.6 | 714.9 | 159.5 | 1.6 | 43.9 | 11.2 |
| 1450 | 863.5 | 821.0 | 712.9 | 159.5 | 1.6 | 43.3 | 12.2 |
| | | | | | | | Average = 10.0 |
| 68 - 76 cm depth Site D | | | | | | | |
| 1427 | 885.3 | 854.3 | 744.7 | 159.5 | 1.7 | 40.5 | 8.9 |
| 1428 | 849.1 | 819.7 | 717.8 | 159.5 | 1.6 | 37.8 | 8.5 |
| 1436 | 861.1 | 819.7 | 714.1 | 159.5 | 1.6 | 42.3 | 11.9 |
| 1446 | 848.5 | 806.1 | 689.0 | 159.5 | 1.5 | 45.9 | 12.2 |
| 1447 | 871.4 | 831.8 | 716.3 | 159.5 | 1.6 | 44.6 | 11.4 |
| 1448 | 861.5 | 825.6 | 722.2 | 159.5 | 1.6 | 40.0 | 10.3 |
| | | | | | | | Average = 10.5 |

A steady-state relationship such as Equation (5.5), can be used in Equation (5.6) to describe the rate of rise of the water table. Solving Equation (5.5) for u, substituting into Equation (5.6) and integrating between $t_o$, $m_o$, and t, m, yields the following equation (Skaggs et.al., 1972),

$$(t - t_o) = \frac{fL^2}{8K(d + y_1)} \ln \frac{\dfrac{2d + y_1 + m}{y_1 - m}}{\dfrac{2d + y_1 + m_o}{y_1 - m_o}} \quad .......(5.8)$$

in which $m_o$ = the between lateral water table elevation at t = $t_o$ measured from the center of the tile lateral; $y_1$ = the elevation of the water in the head control structure above the center of the tile line at the point in the field where the equation is being applied and d = the distance from the center of the tile lateral to the impermeable barrier. Equation (5.7) is only valid after the water table assumes a level or concave upward shape and begin to rise uniformly. The time at which the water table assumes a uniform, concave upward slope and rises uniformly is the time $t_o$. Therefore, the equation does not apply for the lag-time associated with a subsurface irrigation system between start-up and attainment of a uniform water table shape.

Utilizing the data from Figures 5.7 and 5.8 to determine an appropriate $t_o$ for Sites C and D, respectively, a calulated rise of the water table was made. Comparisons of the calulated and the measured rise in the water table at the midpoint between two adjacent tile laterals are given in Figure 5.10 for

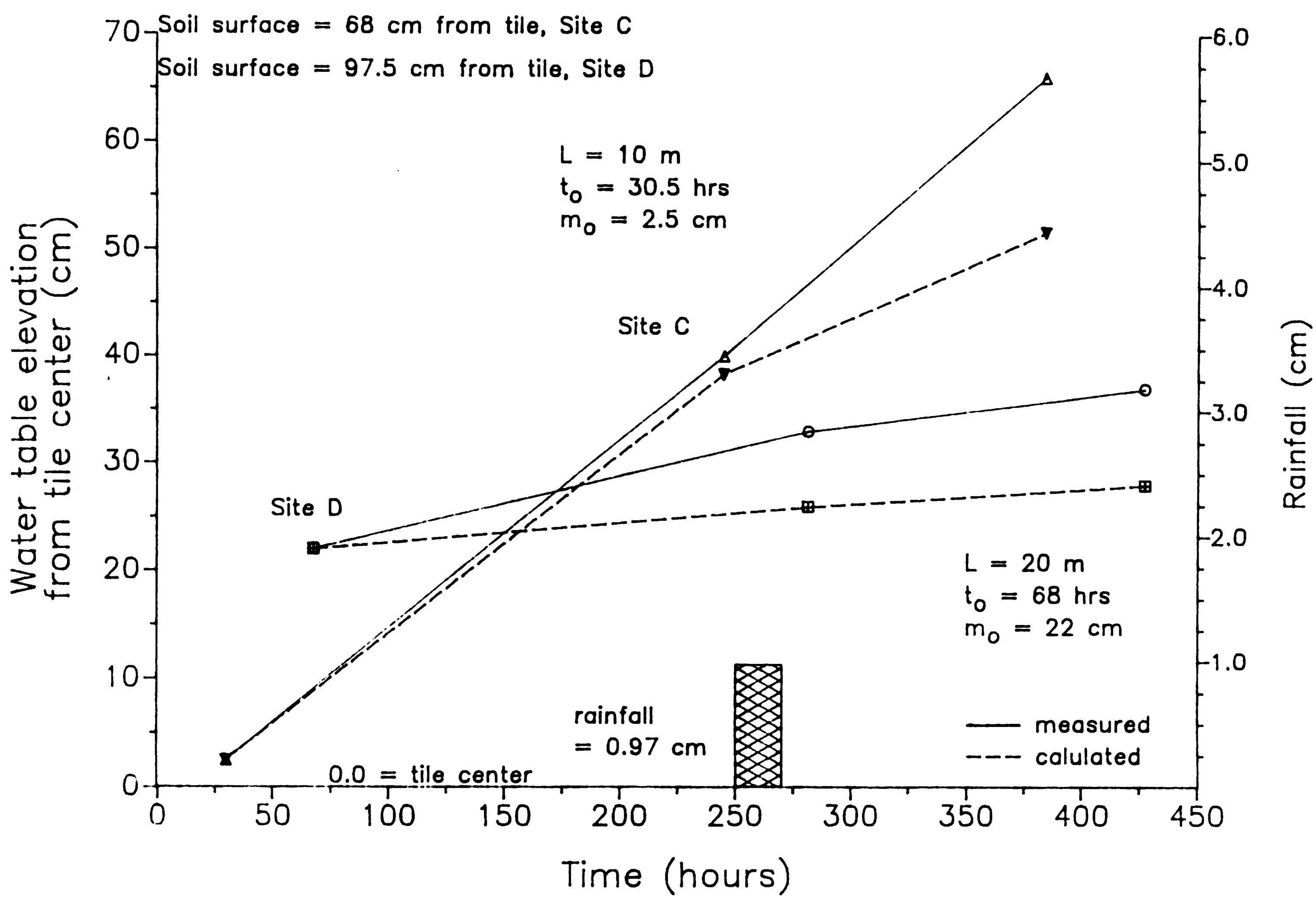


Figure 5.10 Calculated and measured water table rise, midway between adjacent tile lines for manual observations.

Sites C and D.

The value for $t_o$ was the first measured time when the water table assumed upward movement with a uniform surface shape during irrigation. The value of $t_o$ = 30.5 hours for Site C was where the water table had an approximately level shape during subsurface irrigation. The corresponding $m_o$ value between laterals was 2.5 cm. The values for the other parameters on Site C in Equation (5.7) were K =0.51 cm/hr, f = 0.102, d = 45 cm, $y_1$ = 72 cm and L = 10 m (Table 3).

For site D, $t_o$ = 68 hours when the water table was first measured having an approximately level and uniform shape during subsurface irrigation. The corresponding $m_o$ value was $m_o$ = 22 cm. The values for the other parameters in Equation (5.7) are K = 0.51 cm/hr, f = 0.105, d = 17 cm, $y_1$ = 54 cm and L = 20 m (Table 3).

The values for hydraulic conductivity (K) were taken from the U.S.D.A., Soil Survey of Tuscola County, Michigan. The reason these values were used instead of the K values from Table 1, were that the values represented a more realistic K value at the actual depths of the tile laterals for Sites C and D. The K values expressed in Table 1 represent a depth of only 50 cm (20 inches), while the tile laterals were actually deeper, varing from 66 - 100 cm (26 - 39 inches) depth. Site C and D contained a Wisner loam having a shallow clay barrier and therefore the depth of the clay barrier in relation to the tile lateral can have a controlling effect on water movement out of the tile.

Calculating the height of the water table (m) above the center of the tile at the midpoint between tile laterals using Equation (5.7) and comparing the results of the manually measured water table elevations, it can be seen how close the measured and calculated values are. In Figure 5.10, Site C shows very good agreement between the measured and calulated water table height midway between tile lines until approximately 250 hours after initial irrigation. Rainfall then contributed 0.97 cm of water to the soil profile and caused the measured water table height to increase beyond the calulated water table height.

Site D shows less agreement between the calculated and measured values (Figure 5.10). The calculated function shows a flatter rise in the water table height than the measured over time. Additional soil moisture from rainfall did not affect the water table as in Site C. This may have been due to the deeper depth of the static water table in relation to the soil surface. The greater depth of the static water table provided additional storage area and therefore, the affects of rainfall would not be as great. A second reason for the measured water table being higher than the calculated may have been the actual field hydraulic conductivity (K) may have been greater than measured K used to determine calculated height.

Table 3. Parameter values for Figure 5.10, where time (hours) is referenced from initiation of irrigation and water table elevation (cm) referenced from center of tile lateral.

Site C

| Measured Time (hr) | Measured Elevation (cm) | Calculated Time (hr) | Calculated Elevation (cm) | where |
|---|---|---|---|---|
| 30.5 | 2.5 | 30.5 | 2.5 | f = 0.102 |
| 246.0 | 40.0 | 246.0 | 38.0 | L = 10.0 m |
| 385.5 | 66.0 | 385.5 | 52.0 | K = 0.51 cm/hr |
| | | | | $y_1$ = 72.0 cm |
| | | | | $m_o$ = 2.5 cm |
| | | | | d = 45.0 cm |
| | | | | $t_o$ = 30.5 hr |
| | | | | t = x value (hr) |
| | | | | m = finding height (cm) of water table |

Site D

| Measured Time (hr) | Measured Elevation (cm) | Calculated Time (hr) | Calculated Elevation (cm) | where |
|---|---|---|---|---|
| 68.0 | 22.0 | 68.0 | 22.0 | f = 0.105 |
| 282.0 | 33.0 | 282.0 | 26.0 | L = 20.0 m |
| 428.0 | 37.0 | 428.0 | 28.0 | K = 0.51 cm/hr |
| | | | | $y_1$ = 54.0 cm |
| | | | | $m_o$ = 22.0 cm |
| | | | | d = 17.0 cm |
| | | | | $t_o$ = 68.0 hr |
| | | | | t = x value (hr) |
| | | | | m = finding height (cm) of water table |

Site C Water Stage Recorder Values

| Measured Time (hr) | Measured Elevation (cm) | Calculated Time (hr) | Calculated Elevation (cm) | where |
|---|---|---|---|---|
| 83.0 | 7.0 | 83.0 | 7.0 | f = 0.102 |
| 96.0 | 13.5 | 96.0 | 9.6 | L = 10.0 m |
| 120.0 | 15.0 | 120.0 | 14.2 | K = 0.51 cm/hr |
| 144.0 | 21.5 | 144.0 | 18.6 | $y_1$ = 72.0 cm |
| 168.0 | 24.5 | 168.0 | 23.0 | $m_o$ = 7.0 cm |
| 192.0 | 26.0 | 192.0 | 26.6 | d = 45.0 cm |
| 216.0 | 32.0 | 216.0 | 30.2 | $t_o$ = 83.0 hr |
| 245.0 | 37.5 | 245.0 | 34.3 | t = x value (hr) |
| 264.0 | 46.5 | 264.0 | 37.0 | m = finding height (cm) of water table |
| 288.0 | 52.0 | 288.0 | 40.0 | |
| 312.0 | 54.6 | 312.0 | 42.3 | |
| 336.0 | 58.5 | 336.0 | 45.0 | |
| 360.0 | 62.5 | 360.0 | 47.0 | |
| 384.0 | 56.4 | 384.0 | 49.0 | |
| 385.5 | 56.4 | 385.5 | 49.2 | |

Measurements of the water table should have been carried out at more frequent intervals after initial irrigation began. This would have given additional water table elevation points for comparison to the calculated elevation height soon after initiation of irrigation.

Additional observed water table elevations were available from the continuous record for Site C provided by the water stage recorders located midway between two tile laterals at the north edge of the field (Site D had manually measured water table height data only:).

Data points used from the continuous water stage charts were taken at about 24 hour intervals. Time was from 83 to 385.5 hours after initiation of irrigation during a fairly uniform rise in the water table (Table 3). The water stage recorder values were comparied to the calculated water table position taken from Equation 5.7.

The results of the comparison between the more frequently measured and calulated rise in the water table elevation on Site C show fairly good agreement from 83 to 385.5 hours for the data obtained from the water stage recorder (Figure 5.11). At about 250 hours into irrigation the measured and calculated water table elevations begin to separate. The measured elevation rose at a more rapid rate due to rainfall of approximately 0.97 cm, which was not accounted for in the calculated values.

The results of the measured and calculated water table elevations are as follows: 1) The measured and calculated

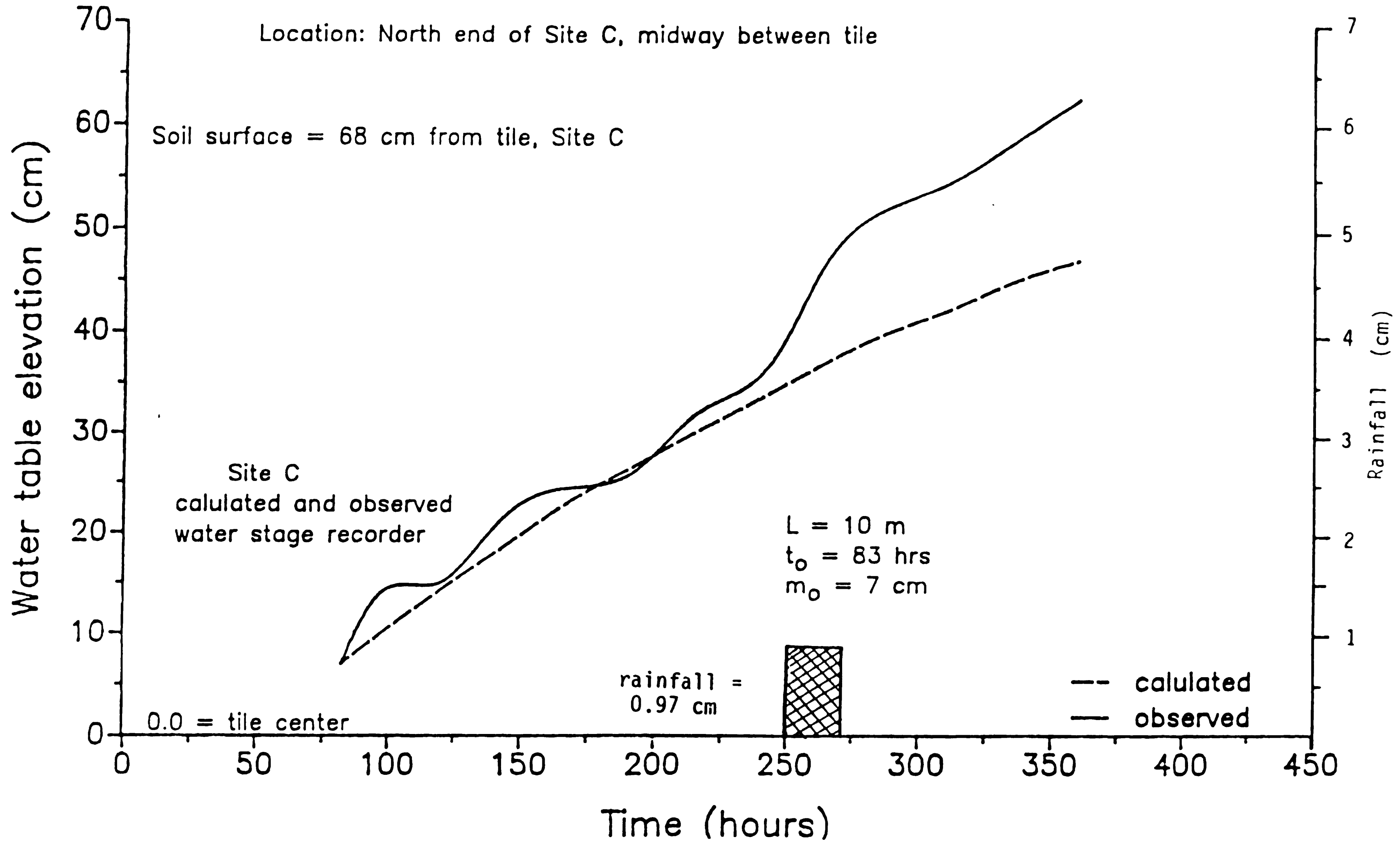


Figure 5.11 Water table rise from recorded tile lines verses calculated values, Site C.

water table elevations for Site C are in fairly good agreement as shown in Figure 5.10. The values for Site D are not so close and reflect discrepancy between the measured and the calculated rise in the water table height. 2) The results of earlier and more frequent water table readings from the water stage recorder on Site C shows good agreement with the calculated (Figure 5.11). The effect of rainfall is obvious when the measured water table height increases rapidly as a result of a 0.97 cm rain; 3) the rise of the water table on Site D is not as rapid as the rise in Site C. A smaller water supply was provided at Site D. Site D had a water supply of about 500 liters per minute (132 gpm) while Site C had 1000 liters per minute (265 gpm) over the approximate same area being irrigated. The farmer may wish to increase the pumping rate to increase the rate of the rise of the water table for Site D and 4) the ability to move water into the soil profile for the purpose of subsurface irrigation was adequate with the present tile spacing. The water table continued to rise despite water loss due to evapotranspiration.

Because of the good agreement between observed and calculated water table elevations using Equation (5.7), it was possible to predict the position of the water table in relation to the length of time irrigation had been on-going for Sites C and D. Subsurface irrigation is considered a viable practice with the present tile design and properties.

## D. Continuous Observations Using Water Stage Recorders on Site C

Continuous water level recordings using water stage recorders on Site C cover a time sequence from July 15, when monitoring was begun, to approximately August 29. July 15, 2:00 p.m., was the beginning of monitoring and this date and time were referenced as time 0.0. Hourly data was digitized from the continuous water level trace to form the computer plots displayed in Figures 5.12 - 5.25 for analysis. A zero reference level at the top of the head control structure which housed the valves for controlling the water level was used. The soil surface, depth of the fluctuating water table, depth of the clay barrier and depth of the tile laterals were referenced to this datum. The lateral tile spacing was 10 meters. The figures presented distinguish between the water table at the north and south end of the site and each display the water table movement near and/or midway between two parallel tile laterals. The north end of the field was the end furthest from the water supply and head control structure.

Rainfall data consisting of an approximate day of occurrence as recorded by the farmer/manager and cross-checked at nearby weather stations was plotted. The rainfall amount (cm) recorded is illustrated with a bar chart when rainfall occurred in Figures 5.1 through 5.25.

Irrigation was initiated just prior to tasseling of the corn on July 18, at 8:00 a.m., 66 hours after monitoring of the water table had begun. The water level in the head control structure was maintained 72 cm above the tile laterals where monitoring took place. The pumping rate was measured at 1000 liters per minute (265 gal/min) at that time.

At the north end of Site C, monitoring tubes for the water stage recorders were approximately 70 cm deep in the soil profile. This depth varied some, depending on the ground elevation change between the two parallel tile laterals monitored. The rise in the water table was first sensed 44.5 hours after the initiation of irrigation over the tile lateral. Midway between the tile lateral, the rise was noted 78 hours after the initiation of irrigation (Figure 5.12). Reasons for the lack of immediate response of the water table was due to; 1) the 360 m distance the water had to travel from the water source and filling of the tile laterals and soil profile around the tile and 2) the time required to raise the water table residing below the monitor tubes to a position where measurements in the monitor tubes could be made.

Figure 5.12 shows the water table above the tile lateral (dashed line) reaching the monitored depth between laterals of 135 cm, 69 hours after irrigation was begun. In an additional 9 hours, the rise of the water table midway between tile laterals was registered by the water stage recorder. The 9 hours difference between water table response over as comparied to midway between laterals represents the difference in time for the water table to reach the same elevation.

As expected, the water table over the tile lateral always responded quickest to any change in head at the control

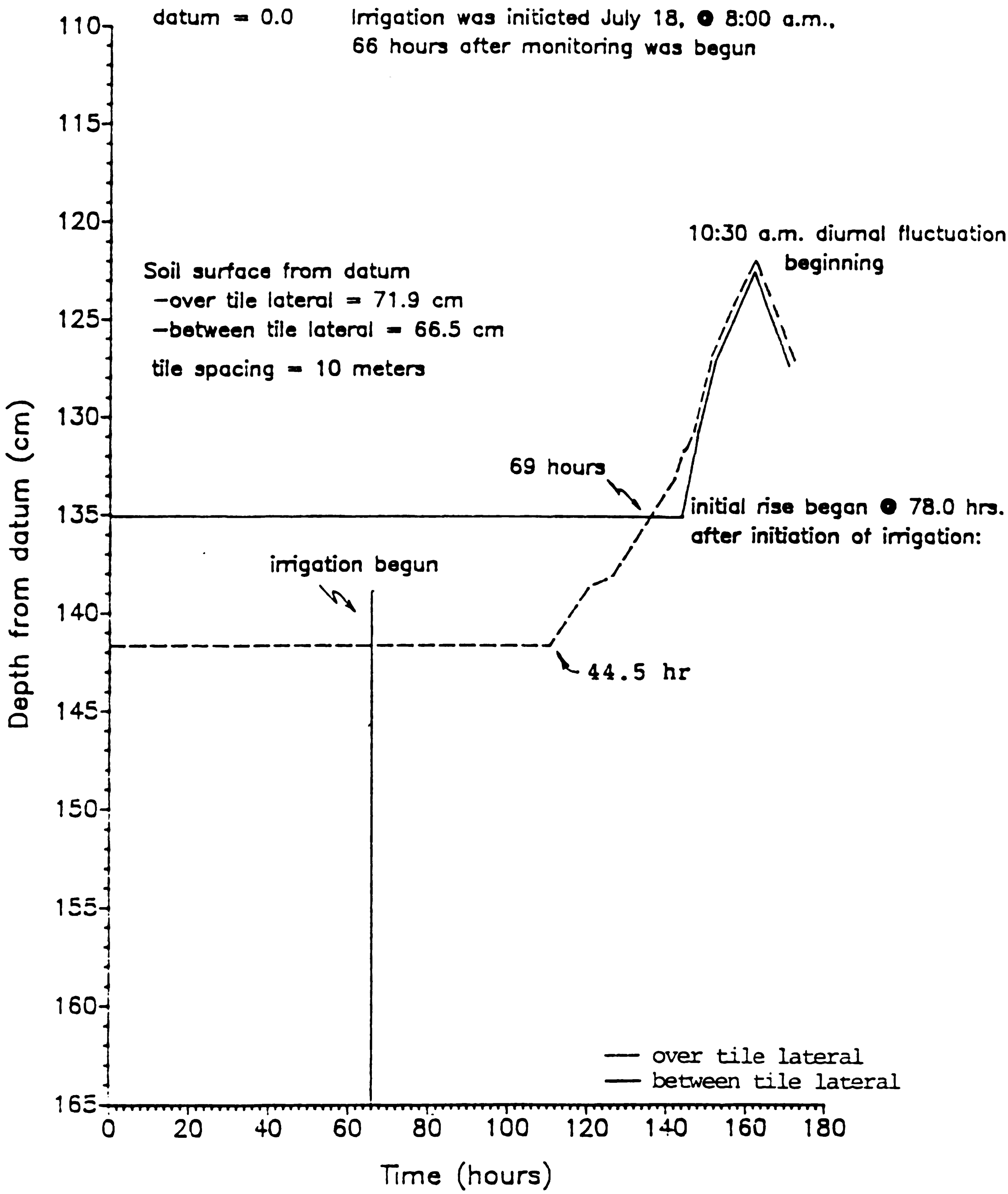


Figure 5.12 Initial water table movement over and between tile after onset of irrigation for Site C, north end.

structure. The driving force moving water to the middle of adjacent tile laterals was the hydraulic gradient created when water came up higher over the tile lateral than midway between adjacent tile.

The water table continued to rise uniformly for 98 hours (10:30 am) after the initiation of irrigation and averaged 53 cm (21 inches) below the soil surface at this time (Figure 5.12). Because irrigation was initiated during peak water use when the corn was beginning to tassel, the downward movement of the water table (10:30 am in the morning) revealed the beginning of diurnal fluctuations in late morning due to evapotranspiration as capillary moisture from the water table entered the root zone to replace ET.

Figure 5.13 shows the rise of the water table at the south end of the field, which was quite different than at the north end (Figure 5.12). The south end was nearest the water supply and closest to the drainage outlet. The monitoring tubes for the water stage recorders over and midway between two parallel tile laterals were 107 cm deep in the soil profile.

When the farmer closed the valve to keep the tile system from draining, the total drainage system continued to feed water into this area before irrigation had begun. This resulted in a gradual rise in the water level both between and over the tile lines at the lower (south) end of the field. The water table over the tile lateral (doted line) had a 12.5 cm higher starting-profile than between the tile lines. This is revealed in figure 5.13, where a gradual rise of the water

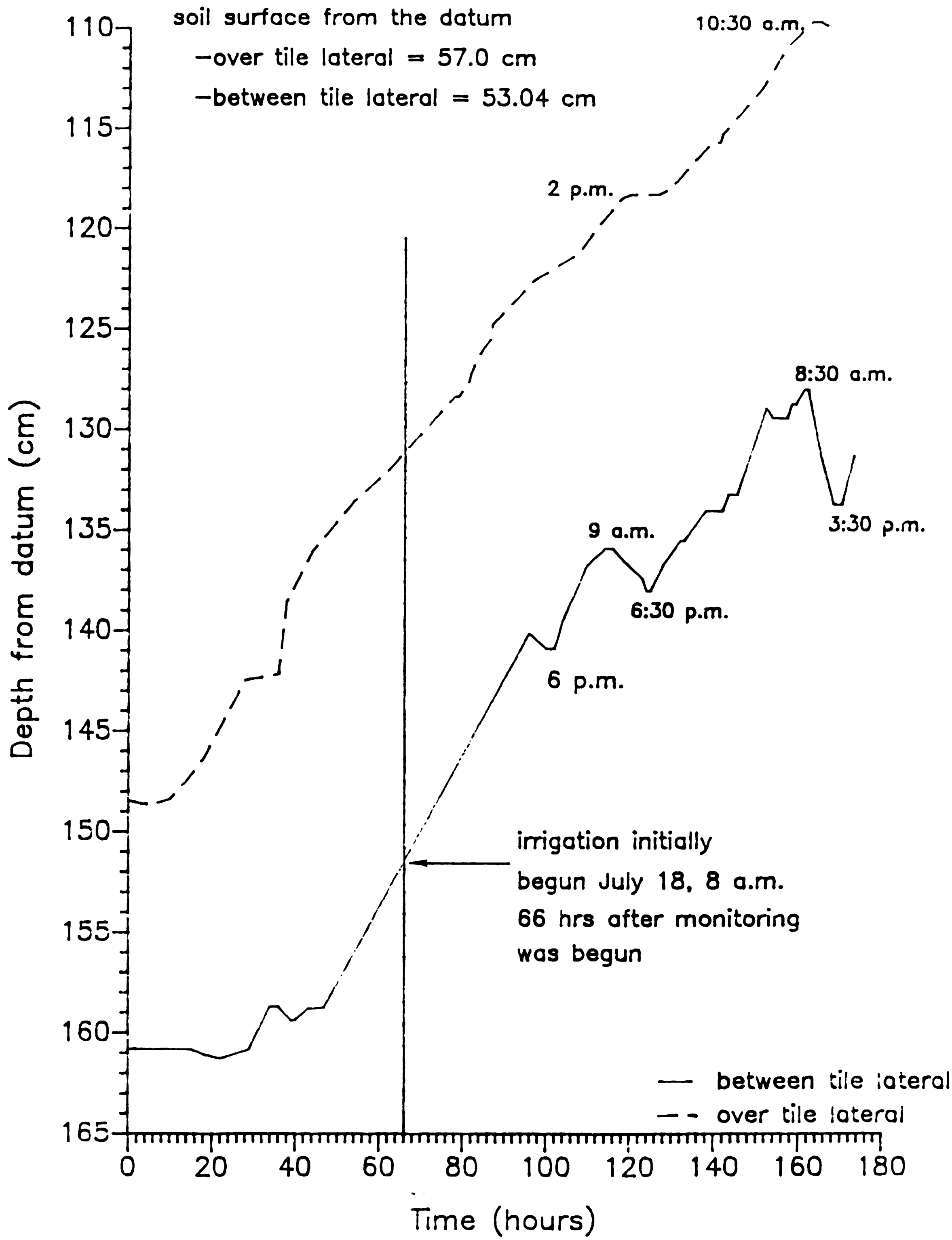


Figure 5.13 Initial water table movement over and between tile after the initiation of irrigation on Site C, south end.

table was seen before the initiation of irrigation at 10 hours after the initial monitoring time.

Diurnal fluctuations of the water table began approximately 98 hours into irrigation, with the water table being approximately 53 cm (21 inches) below the soil surface (Figure 5.14). The time on the curves (a.m. and p.m.) refers to when an inflection point occurred. The water table between and over tile laterals at the north end of the field rose and fell in a very rhythmic pattern. This resulted as a consequence of drawdown attributed to the upward movement of water from the water table to replace soil moisture lost by evapotranspiration (ET). The time drawdown began was usually between 0830 and 1030 hours and fell anywhere from 5 cm to as much as 15 cm during the day. The rebound of the water table began between 1730 and 1930 hours. It was interesting to note that the water profile above and between the tile laterals responded almost alike in the daily fluctuations. Each day, the rebound exceeded the rise the previous day by about 2 cm. The peaks between tile lagged the peaks over tile by about one hour each day. Rainfall resulted in not much of a rise in the water table the day it rained (Figure 5.14). Because the water table rose to a greater height after each decline, a continuous rise in the water table toward the surface was evident, even though ET was estimated to be between 0.38 to 0.50 cm/day. The pumping rate was approximately 1000 liters/minute (265 gal/min) during this time. This pumping rate was equivalent to an outflow or ET rate of 0.44 cm/day over the field.

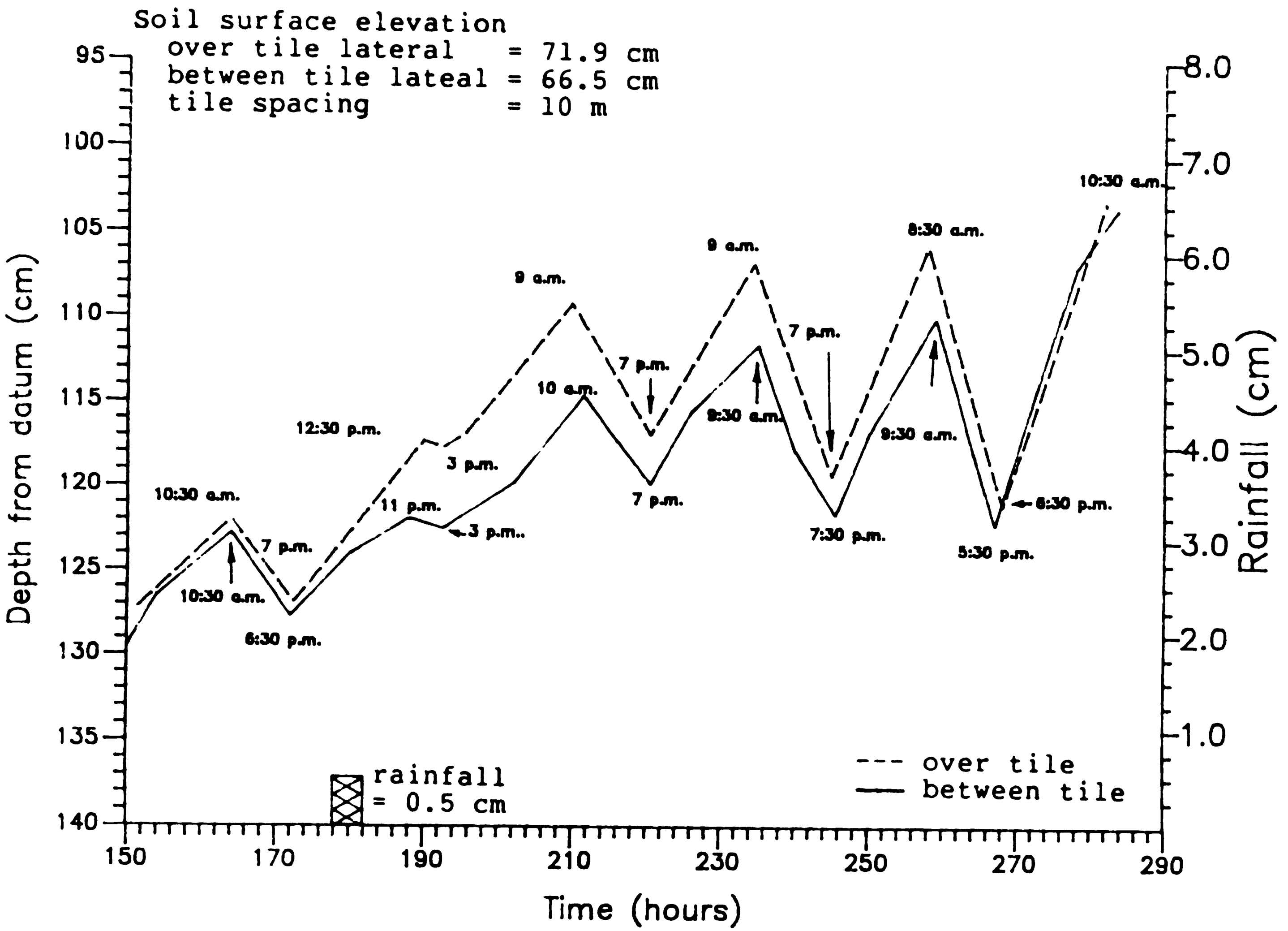


Figure 5.14 Diurnal fluctuations over and between tile laterals as effected by ET, north end, Site C.

During this same period, the water table fluctuations at the south end of the field showed a different response (Figure 5.15). Daily fluctuations due to evapotranspiration over the tile line were almost non- existent, while between the tile laterals, the water table showed fluctuation, but not as great as those shown in Figure 5.14 for the other end of the field.

Rainfall contributed to the steady increase of the water table toward the soil surface without a decrease caused by evapotranspiration. The effect of rainfall on a rising water table over and midway between adjacent tile laterals can be seen in Figures 5.14, 5.16 and 5.17. In Figure 5.14, a 0.5 cm rainfall 7.7 days (185 hours) into monitoring was enough to avoid a decrease in the water table due to daily evapotranspiration. The water level came up more over the tile than midway between tiles. Figure 5.16, for the north end of Site C, shows the same result for a 0.97 cm rainfall. The water table showed a 10 cm upward surge in less than 30 minutes, while midway between the tile laterals, the upward surge was only 4 cm in 60 minutes. The magnitude of the surge upward may have resulted from surface or rain water moving down along the monitor tube during and/or after the rain. The water surge upward was followed by approximately 8 cm decrease over the tile lateral and 1 cm decrease midway between tile lines. The decrease was less than the rise, and the water table continued to move upward.

The south end of the site for this same time period and rainfall, Figure 5.17, again showed a similiar response to rain

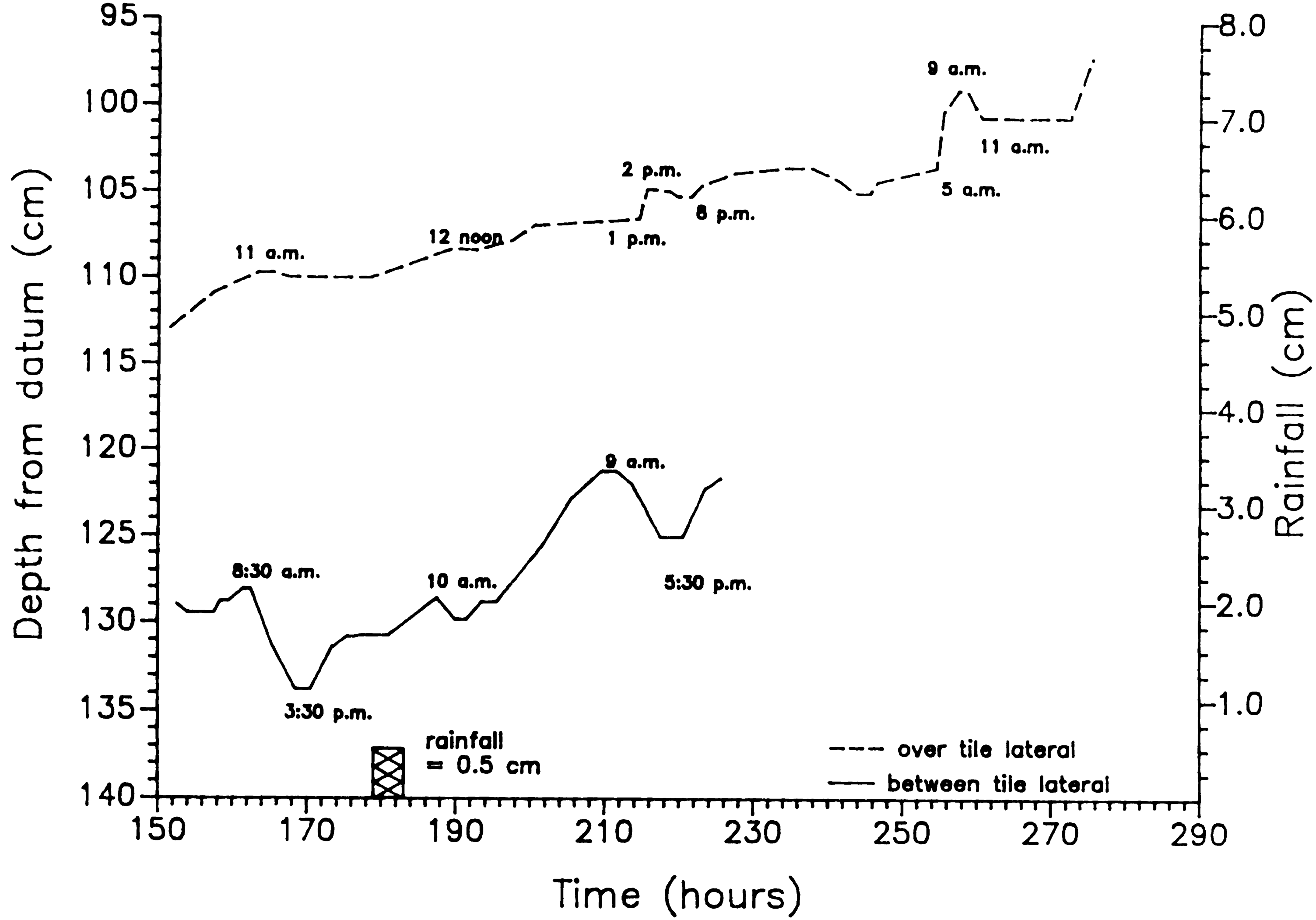


Figure 5.15 Fluctuating water table as effected by ET, south end of field, Site C.

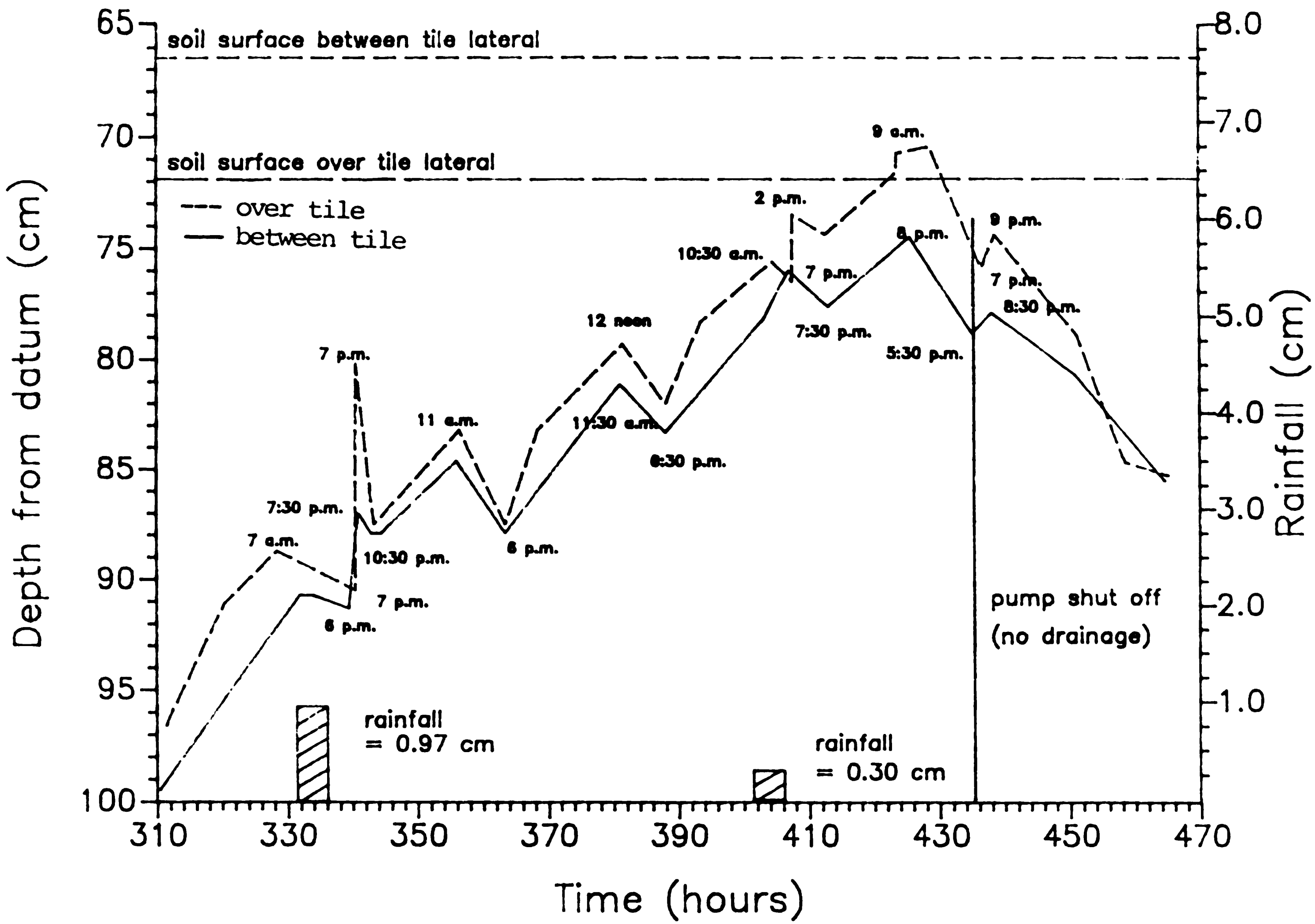


Figure 5.16 Water table between and over tile laterals on Site C, north end.

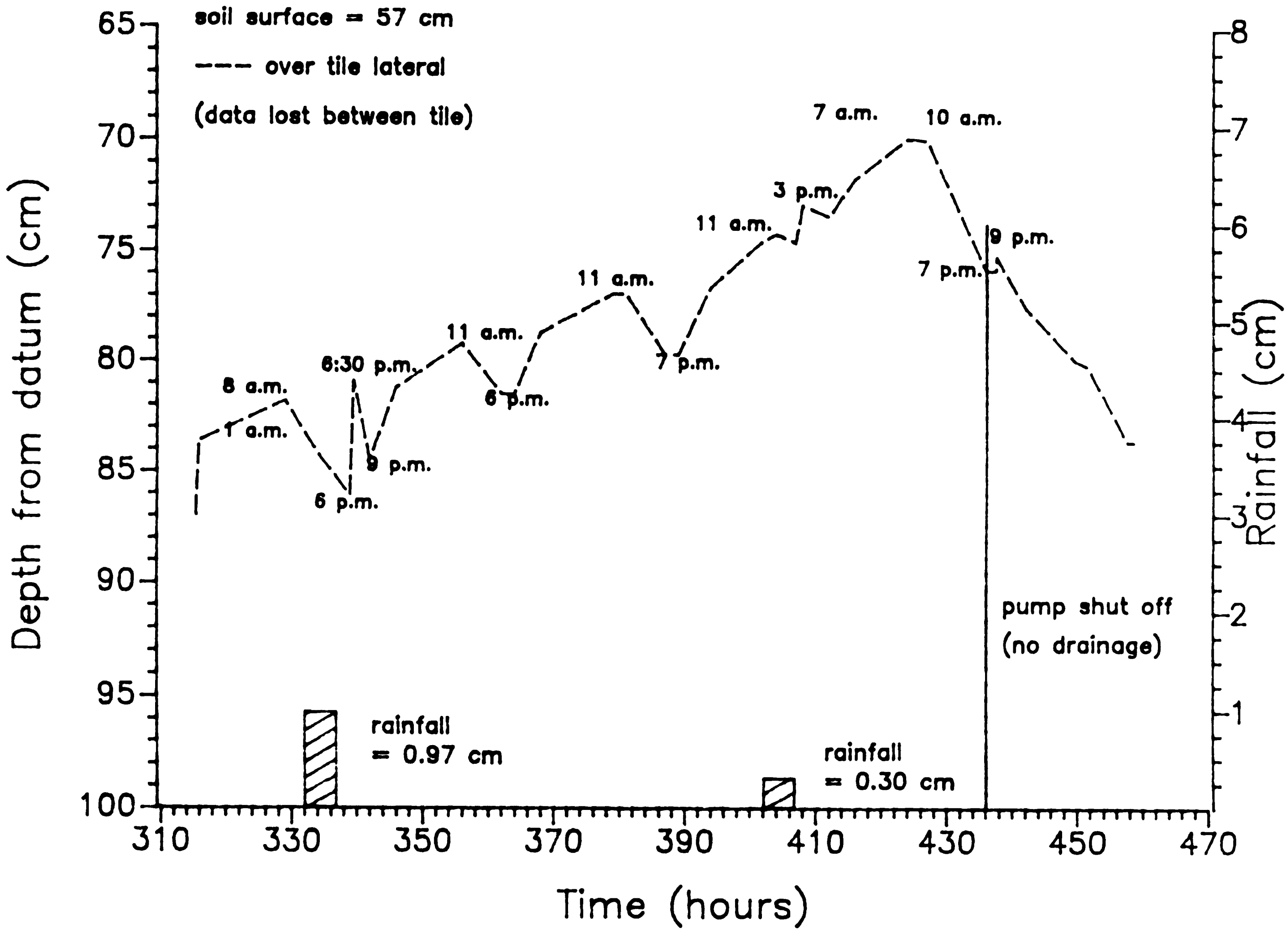


Figure 5.17 Influence of rain over tile lateral, Site C, south end.

over the tile lateral. The water stage recorder between the tile laterals jumped its chain on which the float and counter-weight were hanging and as a result no recordings were obtained midway between laterals. The water table over the tile lateral recorded a 5.0 cm upward movement within 30 minutes and decreased by 4.0 cm in almost equal time due to a 0.97 cm rain. It seems apparent that rainfall increases the water table over the tile lateral, but recedes almost as quickly as the hydraulic gradient moves the water horizontally toward the midpoint.

The implications of the magnitude of the rise and fall implies; 1) the realism of the response additional water can have on bringing the water table upward in a subsurface irrigation system; 2) a very quick surge may reflex water moving along the monitor tubes and 3) the height of the water table will increase toward the soil surface when irrigation water is applied at 1000 liter/min (265 gal/min) despite the diurnal fluctuations downward.

As the water table neared the soil surface, capillary soil moisture became apparent. When the water table reached the surface and resulted in a ponded water condition over the tile lateral, the irrigation pump was shut off (Figure 5.18).

The effect of discontinuing irrigation water and allowing no drainage, is shown in Figure 5.18. The water table began to decline. The curves consisted of steeply declining segments that occurred during the period of evapotranspiration from approximately 0900 to 1730 hours followed by relatively flat

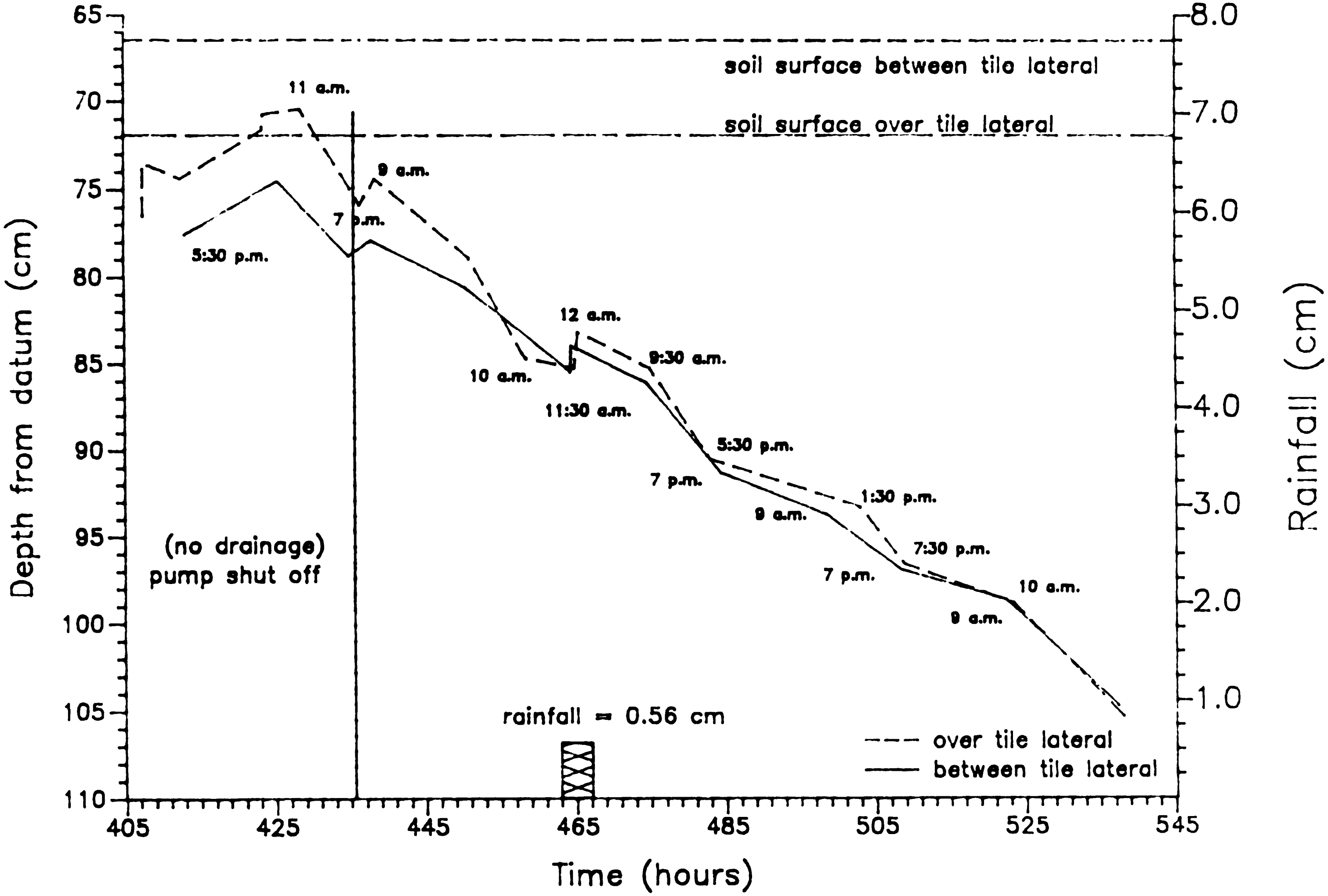


Figure 5.18 Decreasing water table due to evapotranspiration, Site C, north end.

segments from approximately 1730 to 0900 hours. A rate of water table decline of 0.30 cm/hour or 7.2 cm/day was observed. (A similar rate of decline for the water table later in the growing season was seen in Figure 5.25, where the water table fell 0.28 cm per hour or 6.7 cm per day after irrigation was terminated and no drainage allowed after drainage was discontinued). Estimated ET averaged 0.40 cm/day (0.16 inches/day) during this particular time. If the drawdown rate was approximately 7.2 cm/day during average ET rate of 0.40 cm/day, one cm of ET causes the water table to decline approximately 18 cm in the soil profile. The daily amount of drawdown depended on the water table elevation, rainfall, evapotranspiration rate and stage of crop growth. A 0.56 cm rainfall was recorded during this period and slowed the decline in the water table. It produced a flattening of the water table curve followed by a 1.5 cm rise.

At 546 hours into the monitoring process, the farmer wished to reverse the declining water table. Irrigation was resumed at 0900 hours on August 7. The water table response is shown in Figures 5.19 and 5.20.

The response of the water table to irrigation was within 0.5 hr for both ends of the field over the tile lines. The rise of the water table was not due entirely to the pump start-up. A rainfall of 1.8 cm occurred which contributed to the overall rise of the water table. Comparing the rate of water table rise in Figures 5.19 and 5.20 with the rise in Figures 5.12 and 5.13 for the beginning of initial irrigation

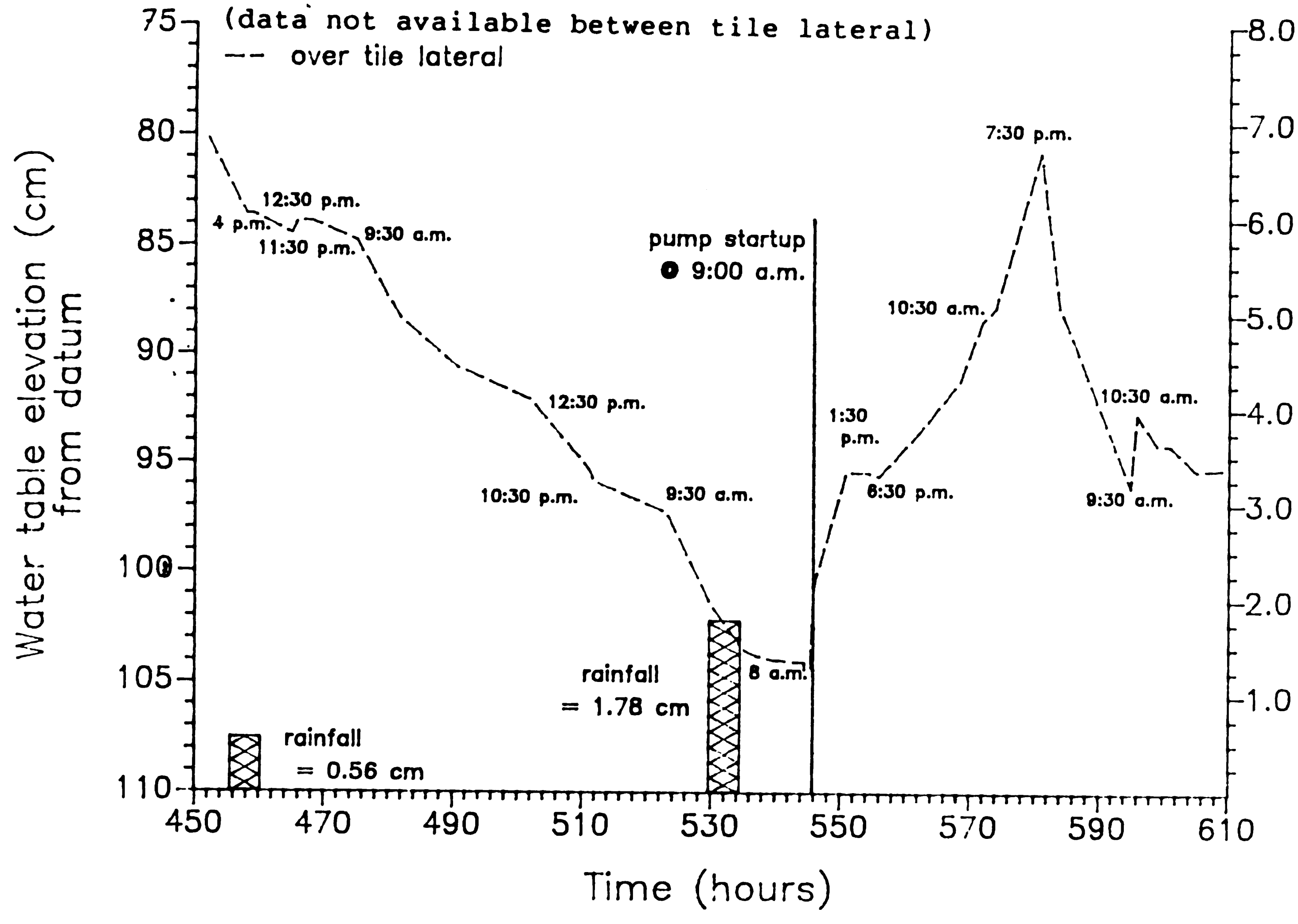


Figure 5.19 Water table response to ET and pump start-up over the tile lateral, Site C, south end.

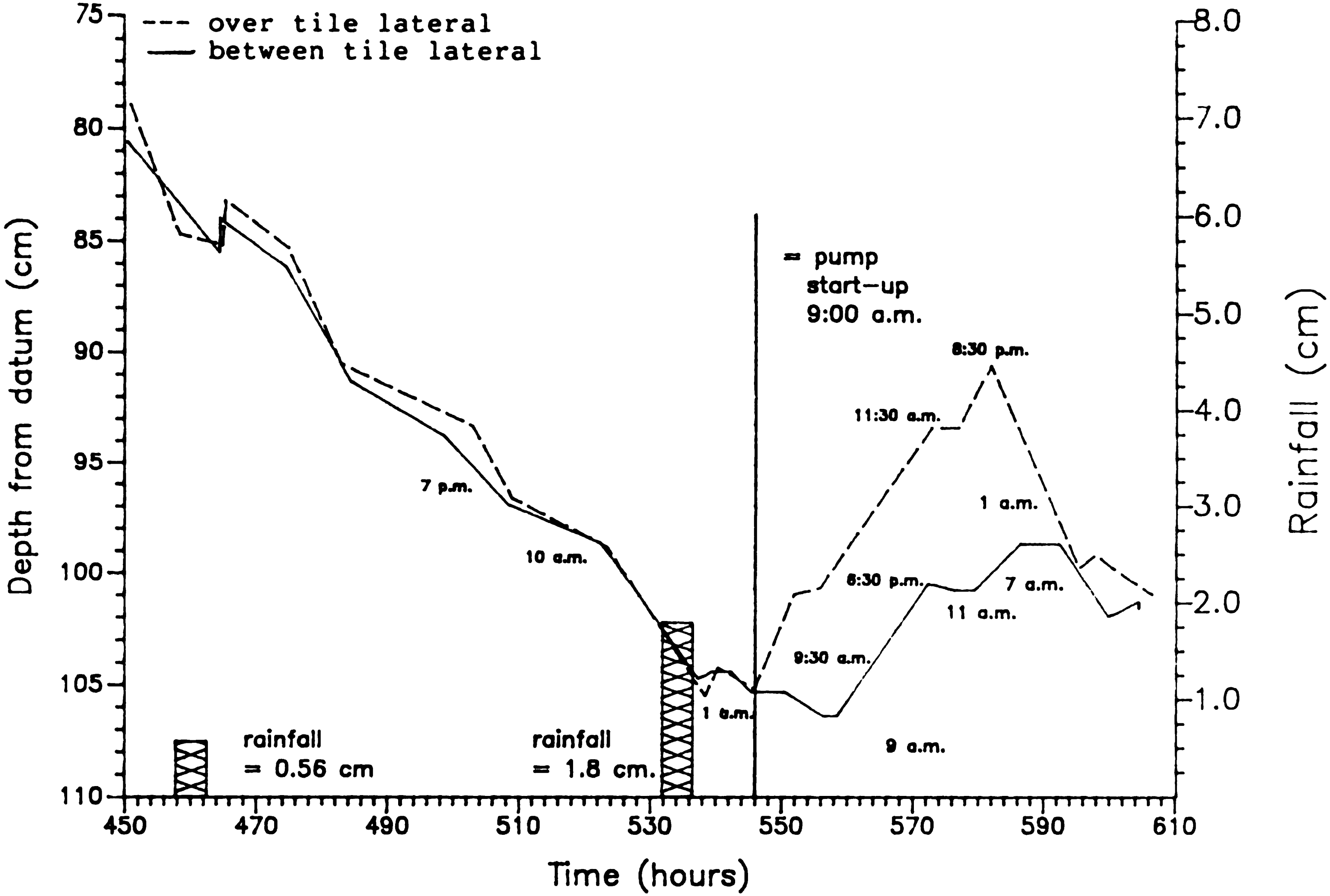


Figure 5.20 Water table response over tile lateral, Site C, north end of field.

was therefore not possible. The water table at the south and north end rose to within 23 and 18 cm from the soil surface, respectively. Thus the south end showed a higher rise of the water table due to the rainfall and the hydraulic pressure created when the water level was raised in the head control structure.

The water table midway between the tile laterals, furthest from the control structure of the subsurface irrigation system (Figure 5.20), took 12 hours to respond to resumed pumping when the water table was initially 37.5 cm below the average soil surface. Forty hours after irrigation was resumed, the water table between the tile had risen a total of 8.0 cm, which was at a rate of 0.2 cm/hr (4.8 cm/day). The water table between tile lateral never peaked as high as that over the tile laterals. The maximum height wver the tile was 18 cm below the soil surface as compared to 27 cm between tile. A 9 cm difference (3.5 inches) in height between the two water table curves existed. A second event involved a second pump start-up event later in the growing season, 35.7 days (856.5 hours) into the monitoring of Site C, is shown in Figures 5.21 and 5.22. An almost immediate response by the water table over the tile lines could be observed at both ends of the field. Midway between the adjacent laterals, the rate of rise was slower. An actual decline or receding was observed until 5 hours into irrigation, at which point the water table began to rise.

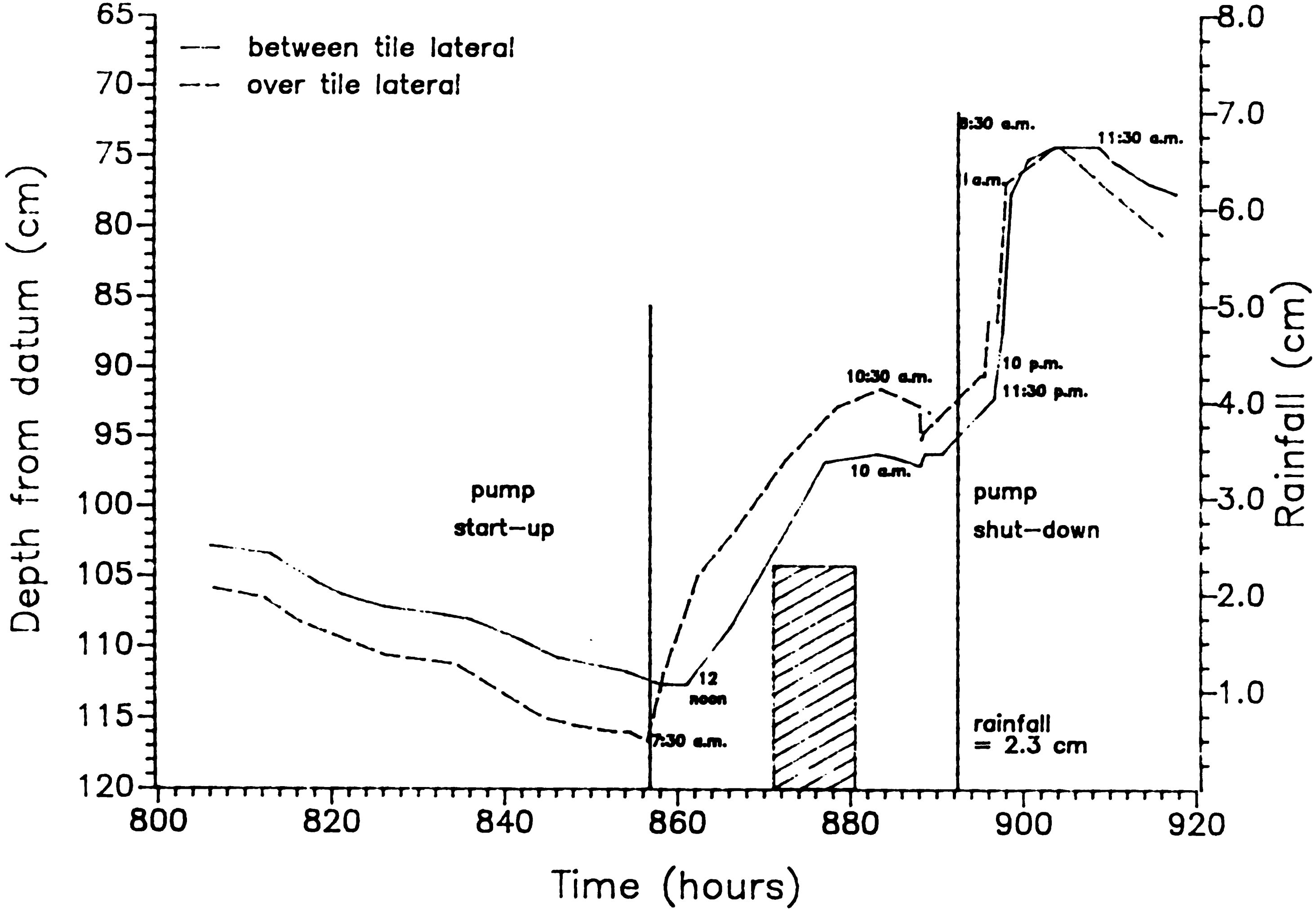


Figure 5.21 Lag-time over as compared to between tile laterals when irrigation resumed, Site C, south end.

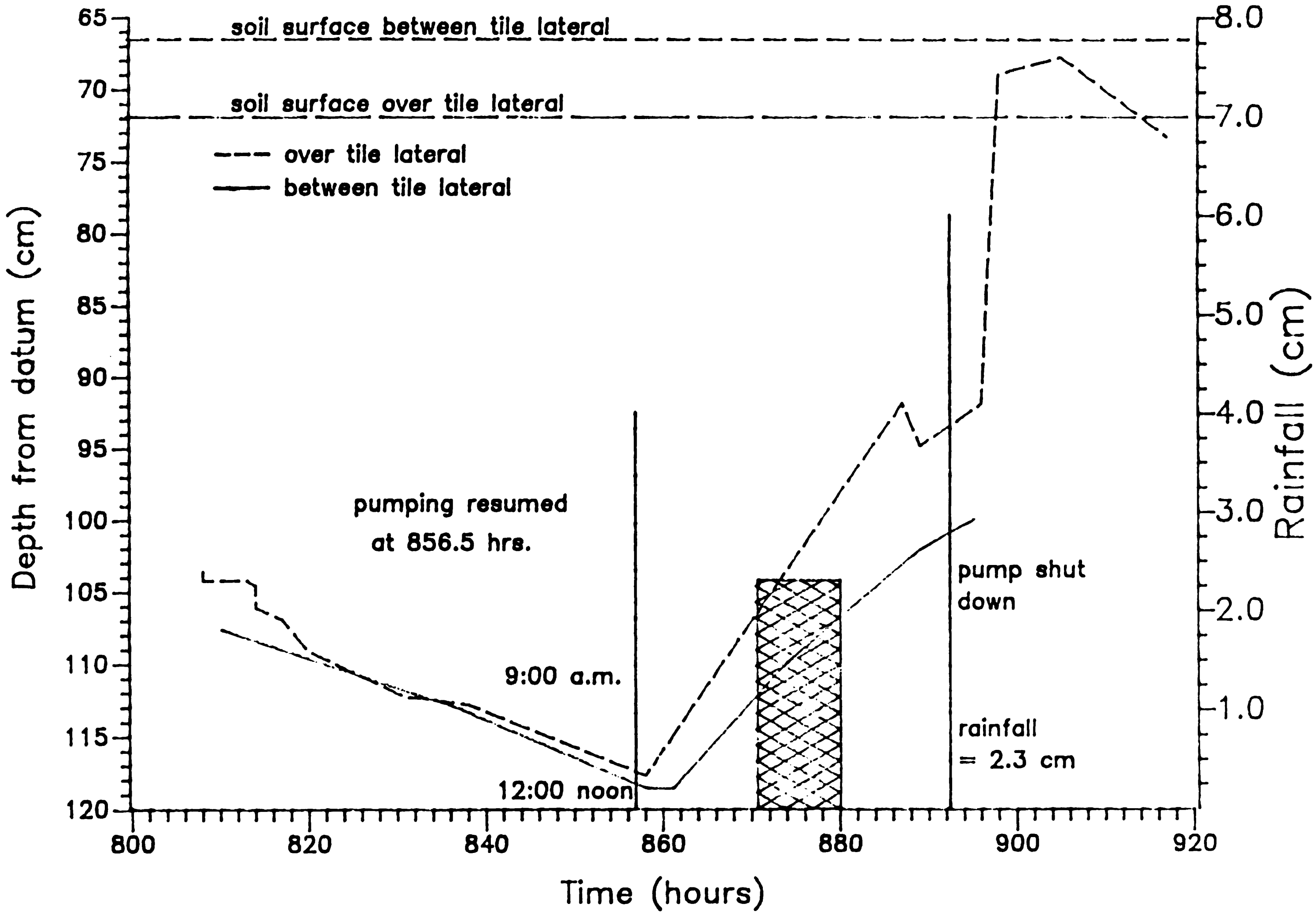


Figure 5.22 Lag-time over as compared to between tile laterals when irrigation resumes, Site C, north end.

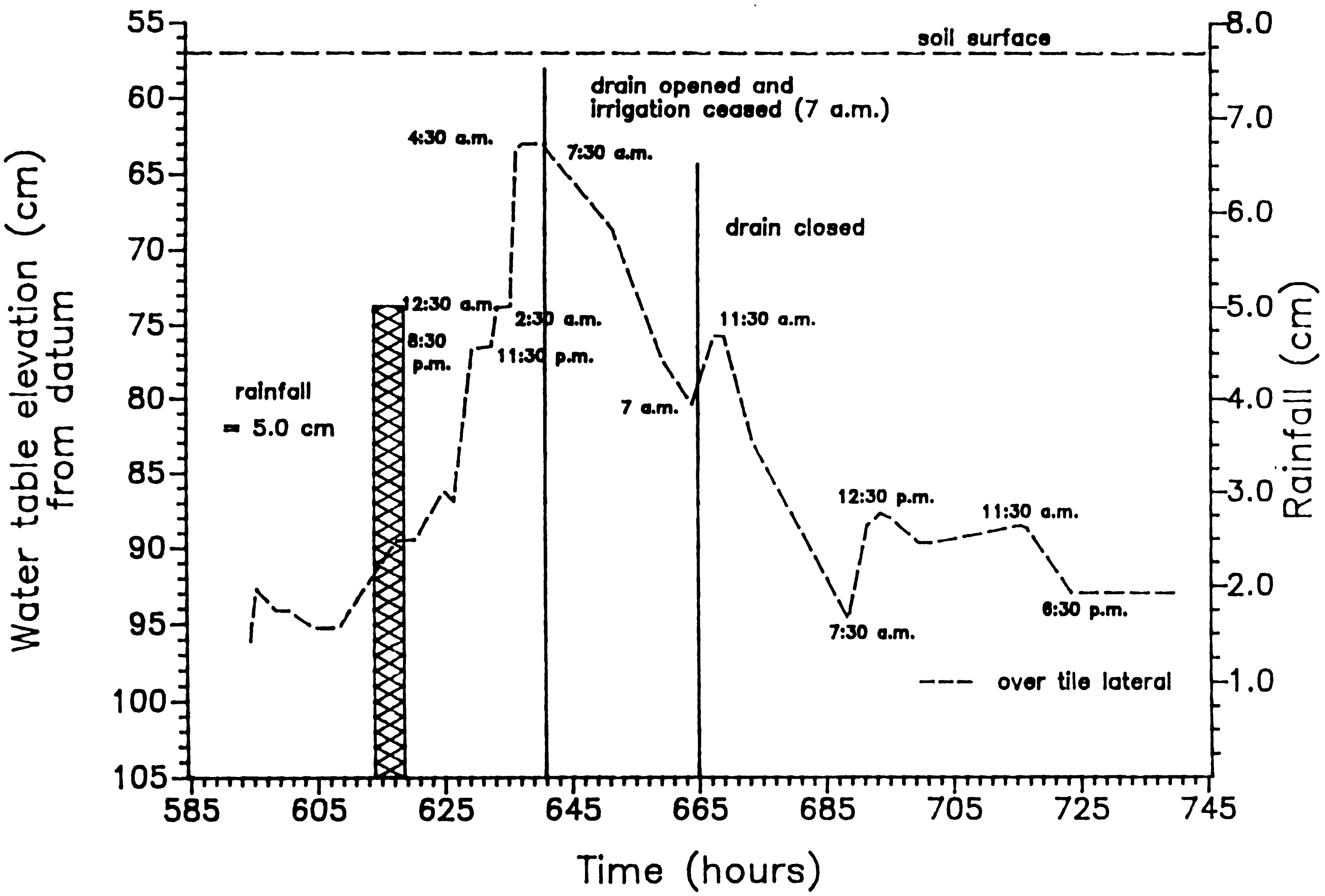


Figure 5.23 Water table response to rainfall and drainage over the tile, Site C, south end.

The effect of a rainfall event in Figures 5.23 and 5.24 shows a rapid rise in the water table at both ends of the field when 5.0 cm were added. Irrigation was ongoing during this time. The water table rose 42.5 cm over the tile lateral in 95 hours. The water table came within 5 cm of the surface at the south end of the field (Figure 5.23) and actually ponded water over and between the tile laterals at the north end of the field (Figure 5.24). The water table between and over the tile lateral rose uniformly. At this point in time, the farmer ceased irrigation for the second time and opened the tile main to drain water from the soil profile. The amount of drainage water was not recorded. Skaggs (1981) discussed this situation when he noted that rainfall can be lost because of the lack of storage available in the soil profile as the water table nears the surface. Water can leave as excess run-off or be lost as overflow of the water control structures.

Once irrigation had ceased and the drain was opened to remove excess rainfall, within a 24 hour period the water table at the south end of the field over the tile lateral (Figure 5.23) fell 17 cm. The rate was 0.7 cm/hr or twice the rate at the furthest end of the field (0.3 cm/hr) on the same tile lateral. Once the drainage valve was closed, the water table first rebounded, then continued to recede. The water table receded at a rate of 19 cm in 19 hours which was twice the rate midway between tile.

During this same period of time the water table at the north end of the field decreased 7.2 cm both over and between

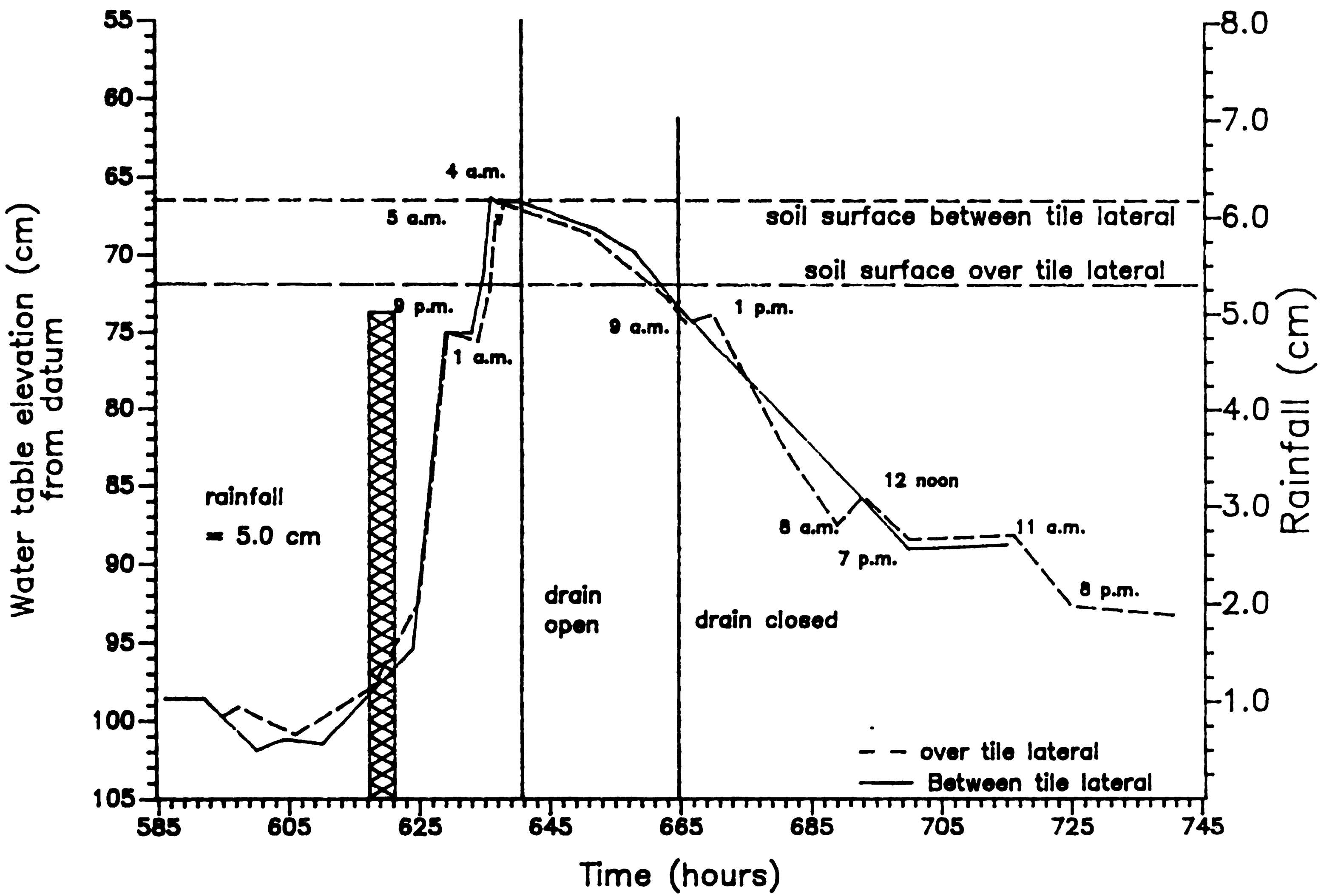


Figure 5.24 Water table response to rainfall and drainage, Site C, north end.

laterals (0.3 cm/hr) in response to the drain being open (Figure 5.24). The water table continued to decreased when the drainage value was closed after 24 hours due to redistribution of water midway between tile lateral toward the tile lines and evapotranspiration and other possible losses. The water table decreased an additional 14 cm in 28 hours (0.5 cm/hr) before it began to flatten.

The downward diurnal water table drop under closed drain conditions at the north end were approximately 4 to 5 cm per day over and between the tile laterals (Figure 5.25). No further water input occurred after 790 hours (August 17). The water table was allowed to decrease through ET and with no drainage.

Calculated Tile Spacing From Figure 5.14. For subsurface irrigation with a constant evapotranspiration rate at the surface, the steady state water table takes the general shape given in Figure 5.9. An algebaic expression previously mentioned, Equation 5.5 (page 100), which describe the water table can be used to determine the tile spacing required to give a maximum difference, $h_1 - h_2$, in the water table elevation directly over ($h_1$) and midway between ($h_2$) the tile laterals. $h_1$ and $h_2$ equal the distances of the water table above the impermeable layer over the tile and midway between the tile lines, respectively. This equation can then be used to assess; 1) the desired tile spacing (L) for drainage if the hydraulic conductivity (K), the evapotranspiration rate (u) and the expected water table height above the impervious barrier

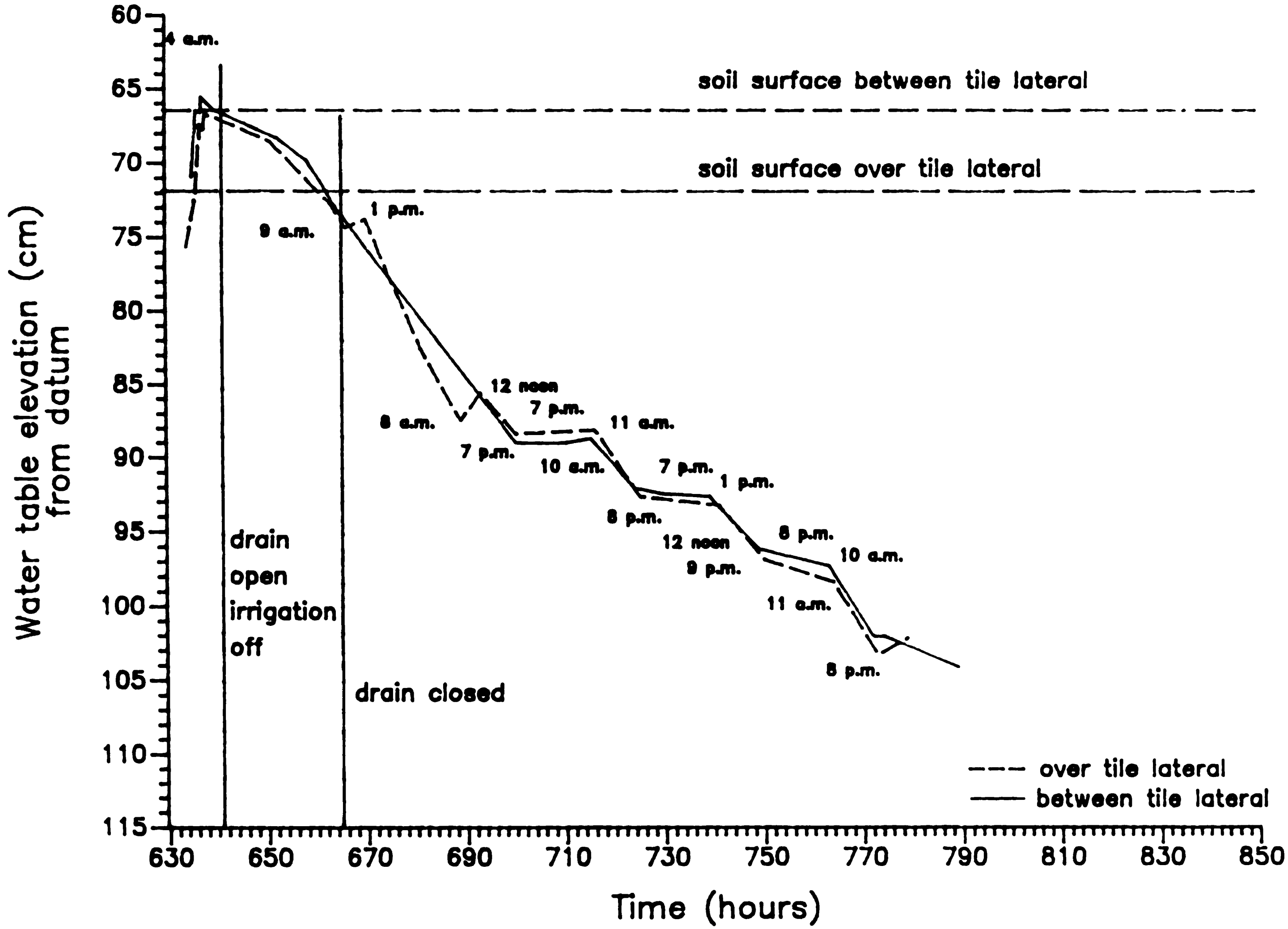


Figure 5.25 Water table drawdown associated with ET, Site C, north end.

either over or between tile laterals is known; 2) the expected water table response over and midway between the tile laterals of a drainage system already installed to determine if the present spacing is adequate and 3) the tile lateral spacing for subsurface irrigation when the water table elevation difference over and midway between the tile laterals is set based on allowable variation for a particular crop.

The design spacing for a particular soil can be computed by choosing an optimum water table depth and a maximum allowable variation (Skaggs et.al., 1972). Williamson and Kris (1970) give yield response of agricultural crops to a variety of constant water table depths. They showed optimum water table depths of 76 and 90 cm from the surface for corn on a loam and silt loam, respectively.

Data from Figure 5.14 was used in Equation 5.5 to evaluate the water table position with the present design and/or layout of Site C. An average K value of 4.2 cm/hr (Table 1) was determined from a velocity head permeameter. An average evapotranspiration rate of 0.5 cm/day was determined using a modified Penmann equation (Vitosh, 1984). The $h_1$ and $h_2$ values were determined from Figure 5.14 ($h_1$ = 76.7 cm, $h_2$ = 71.7). A theoretical tile spacing of 7.7 meters was calulated where an actual spacing of 10 meters existed in the field.

This agrees fairly well with the tile spacing that was presently in the field. The 10 m spacing showed that the water table could achieve a continuous rise dispite the loss of water through evapotranspiration. This was seen in Figure

5.14, where the fluctuations during high ET demand decreased the water table height in the soil profile, but the continuance of irrigation through the low ET time of day, resulted in the water table increasing approximately 2 cm more than the diurnal decrease from the previous day.

## E. Yield Results

Yield data for the irrigated and non-irrigated check plots were recorded in Table 4 for each field site. Table 5 shows the plant population at emergence for the irrigated and non-irrigated plots. Table 6 and 7 represent the crop type, variety, fertilizer and herbicide program, the soil ph, and available $K_2O$ and $P_2O_5$, respectively, for each site.

Site A had an irrigated and non-irrigated check plot for comparison (Figure 4.2). Plant population at emergence was 66,700 plants/ha, and the fertilizer and herbicide program was the same. The irrigated plot had a yield of 12,875 Kg/ha versus the non-irrigated plot yield of 10,955 Kg/ha (measured @ 15.5% moisture). The difference between the two plots, 1920 Kg/ha, was a 17.5% higher yield for the irrigated versus the non-irrigated plot. This was a significant increase in yield resulting from the addition of water by subsurface irrigation.

The sugarbeet yield data for Site B was recorded in Table 4. Plant population at emergence was 53,000 plants/ha for both the irrigated and non-irrigated plots (Table 5). There were four plots harvested, with one being a non-irrigated plot (Figure 4.5). Plot one represents the zone over and near the tile lateral, including the area of puddled water at the north end of the field and capillary soil moisture visible at the surface at the south end of the field. Four rows of sugarbeets (76 cm row spacing) on Table 4.

Table 4. Yield data (kg/ha @ 15.5% moisture, corn only).

| Field sites | Irrigated | Non-irrigated |
|---|---|---|
| A | 12,875 | 10,955 |
| B (plot 1) | 63,255 * | - |
| (plot 2) | 64,934 * | - |
| (plot 3) | 57,545 * | - |
| (plot 4) | - | 52,171 * |
| C (plot 1) | 10,092 | - |
| (plot 2) | 11,590 | - |
| (plot 3) | - | 10,574 |
| D | 11,945 | - |

* sugarbeets.

Table 5. Plant population at emergence (Plants/ha).

| Field sites | Irrigated | Non-irrigated |
|---|---|---|
| A | 66,700 | 66,700 |
| B | 53,000 | 53,000 |
| C (plot 1) | 66,900 | - |
| (plot 2) | 63,400 | - |
| (plot 3) | - | 63,400 |
| D | 65,200 | - |

Table 6. Crop type, variety, fertilizer and herbicide program.

| | Field Sites | | | |
|---|---|---|---|---|
| | A | B | C | D |
| Crop type | corn | sugarbeets | corn | corn |
| Variety | Pioneer 3744 | -* | Stauffer B606 | Stauffer 5650 |
| Fertilizer Program | | (kg/ha) | | |
| Nitrogen(actual) | 293 | 364 | 155 | 155 |
| $P_2O_5$ | 49 | 171 | 124 | 124 |
| $K_2O$ | 141 | 364 | 234 | 234 |
| Herbicide Program | | (liters/ha) | | |
| Atrazine | 1.2 | -* | - | - |
| Blade X | 3.5 | - | - | - |
| Sutan | 4.7 | - | - | - |
| Formula 40 | - | - | 0.6 | 0.3 |
| Brandville | - | - | 0.6 | 0.6 |
| Anthazine | - | - | 4.7 | - |

* Not available from the farmer.

Table 7. Soil ph and available soil nutrients of $K_2O$ and $P_2O_5$.

| Field Site | Soil ph | Available $K_2O$ (kg/ha) | Available $P_2O_5$ (kg/ha) |
|---|---|---|---|
| A | 6.5 | 550 | 890 |
| B | 7.2 | 490 | 206 |
| C | 8.1 | 426 | 6.0 |
| D | 8.0 | 122 | 75 |

Note: Nitrogen not available from soil lab.

each side of the lateral were harvested over two parallel laterals, for a total of 16 rows of beets in plot one.

Plot two represents the zone three to nine meters from two parallel tile laterals. The zone consisted of 16 rows. Eight rows were harvested along each lateral as shown in Figure 4.5. No surface moisture was observed in plot two which contained the area five meters off the tile laterals where no water table was found. Plot three was the 16 rows midway between the two laterals beginning nine meters from each of the two parallel tile laterals, or the area not included in plots one and two. At no time was a water table observed within 77 cm (bottom of monitoring tubes) from the soil surface in plot three. The non-irrigated plot was plot four.

Table 4 shows that the sugarbeet yield in plot one, closest to the tile lateral, was 2.6% less than the yield in plot two. This difference was not considered significant. It was possible, that the sugarbeets in at least some of the rows in plot one were too wet, which adversely affected their yield. Loomis and Haddock (1967) and Archibald and Haddock (1959) concluded that sugarbeets growing in the presence of lower available nitrogen and excessive soil moisture will have depressed yields. The excessive soil moisture which developed over the tile laterals could have caused a loss of soil nitrogen through denitrification. Observations in the color of the sugarbeet canopy during the growing season revealed a yellowing of the plants over the tile laterals compared with plants midway between the laterals. This yellowing effect was likely a result of a lower available soil nitrogen or a lower uptake of nitrogen by the plant.

Plot two had a larger yield than plot three by approximately 11.4%. It was surmised that the subsurface water table existed beneath a portion of plot two but dropped below the monitoring tubes five meters from the tile lateral. The water monitoring tubes placed five and ten meters out from the two parallel tile laterals never showed a water table. The yield advantage of plot two over plots one and three may have resulted from available soil moisture, available soil nitrogen being present and not removed by denitrification, and proper soil aeration.

Plot four had the lowest yield at 52,171 kg/ha, 18.6% less than plot two, the highest yielding plot. Plot three had no known water table and thus was expected to be like a non-irrigated area. However, plot three still exhibited a higher yield than plot four by approximately 5,374 kg/ha, 9.3%.

The fertilizer program was similar for the whole field (Table 6) and the fertility samples were not taken separately for the two soils but were a composite of the whole field. Table 5 shows the soil ph and available $K_2O$ and $P_2O_5$ for Site B.

Site C had two irrigated and one non-irrigated plot (Figure 4.8). Plots 1 and 2 had plant populations at emergence of 66,900 and 63,400 plants/ha, respectively, and the non-irrigated plot (plot 3) had a plant population at emergence of 63,400. The purpose for the differences in plant populations was to look at the affect subsurface irrigation would make on yield.

The results of the corn yield from two irrigated and one non-irrigated plot for Site C are recorded in Table 4. Plot 1, irrigated and having a higher plant population than plot 2, yielded less than plot 2 by approximately 1500 kg/ha. The non-irrigated plot, having an equal plant population as plot 2, yielded less than plot 2 by approximately 1000 kg/ha, but out yielded plot 1, which was irrigated and had a higher plant population, by approximately 482 kg/ha. Slightly increased plant populations greater than 63,400 plants/ha resulted in no increase in corn yield. The yield difference between the irrigated and non-irrigated plots was not that great.

Site D had no non-irrigated plot. The yield for the irrigated check was 11,945 kg/ha obtained with a plant population at emergence of 65,200 plants/ha.

## VI. Conclusions

The water table response during subsurface irrigation and drainage was investigated successfully on three of four sites. Water table response was affected by horizontal hydraulic conductivity, irrigation input rates, tile spacing, evapotranspiration (ET) and soil texture.

Horizontal hydraulic conductivity was a major component in water movement when attempting to establish a uniform water table over and between adjacent tile laterals. It was shown that a saturated horizontal hydraulic conductivity rate 0.3 cm per hour did not provide sufficent flow to establish a water table in a clay loam soil. Subsurface irrigation would not be recommended for similar hydraulic conductivity rates. Soils with horizontal hydraulic conductivities of approximately 4.2 cm per hour work well for subsurface irrigation with tile spacings at 10 meters.

Hydraulic conductivity rates for similar soil textures were shown to be different. The higher rates allow for wider tile spacing. Because of different hydraulic conductivities between field sites, an independent evaluation should be conducted for each field when designing for subsurface irrigation. Narrower or wider tile spacing will result, depending of the ability of the soil profile to conduct water horizontally when establishing a water table under the root zone of a growing crop with subsurface irrigation.

A reliable method of monitoring the water table is essential for knowing the depth from the water table to the root zone, and whether the water table is rising, falling or at equilibrium.

Monitor tubes should be placed at the tile lateral, and midway between tile laterals because this area was shown to respond the slowest. The tubes should be placed to a depth below the depth of the tile lateral, wrapped with a filter material and capped on the bottom to keep out sand and fine silt.

Drainage tile spaced at 10 meters in Wisner loam lowered the water table seven cm between tile lateral in 24 hours when the drain outlet was opened. For subsurface irrigation conditions in which the water table is held at shallow depth, the application of rainfall will result in a significant rise in the water table. Thus, subsurface irrigation systems will have to be designed such that adequate drainage is provided. Therefore, narrower tile spacing, larger tile mains and larger drainage coefficient need to be considered for removal of large amounts of water quickly. This decreases the risk of flooding and crop damage.

Presumably due to ET, diurnal fluctuations of the water table were observed as a sinuous rythmic falling and rising of the water table. This sinuousity makes it essential that manual water table observations always be made at the same time each day. Then observed trends will reveal a truer vertical water table movement on the sinuous curve.

An increase in the water table between adjacent tile lateral over the daily diurnal fluctuations caused by evapotranspiration is a positive indicator during subsurface irrigation. The irrigation input rate and tile spacing are adequate to increase the water table response toward the root zone to irrigate the crop.

Rainfall events brought the water table to the soil surface during subsurface irrigation. A water table nearing the soil surface decreases storage for infiltrating rain water. One management approach would be to allow the water table to fluctuate over a range to provide for greater utilization of rainfall. Allowing a decrease of the water table through ET to a predetermined depth from the soil surface results in greater storage of rain water. The water table must not be allowed to decrease to a depth where it can not be raised again. This practice provides a management tool for decreasing the likelihood of damage to the crop due to flooding. It will result in decrease irrigation water pumped when rain water is stored in the soil profile for the crop.

Good agreement was found between the calulated and actual field tile spacing for a given water table variation from over the lateral to half way between laterals using the approximate steady state approach. This approach, therefore, provides a means of designing tile spacing when a maximum difference in water table height above the clay barrier at a position over and midway between the tile laterals is known for a specific crop.

The yield response of corn and sugarbeets to subsurface irrigation was investigated. Results revealed that a granular soil texture produced a greater yield increase due to irrigation than heavier clay soils. Corn yields increased 17.5% over non-irrigated yield on a granular soil texture. Irrigated corn yield showed a 13.0% decrease when corn population was increased 5% on a sandy clay loam. Sugarbeets on clay loam soil showed a greater difference (18.6%) between irrigated and non-irrigated yield than corn (8.8%). It would be more beneficial to establish sugarbeets on the heavier clay soils than corn under subsurface irrigation. Benefits of subsurface irrigation need to be evaluated against installation, operation and maintence cost and the financial return on crop yields in the established crop rotation.

## VII. Recommendations

1. Establish a method and key locations which measure the average water table position in relation to the root zone of a particular crop and is easy to use by the irrigator.
2. Design a subsurface irrigation - drainage system based on horizontal hydraulic conductivity rates, water usage of crop grown, uniformity of the water table over as compared to midway between tile lateral and timely removable of excess water through drainage.
3. Timing of subsurface irrigation be adopted for each site based on crop need, rate of saturated horizontal water movement, minimum and maximum depth of the water table from the soil surface and length of time needed to build a water table.
4. Saturated horizontal hydraulic conductivity measurements be conducted on each soil horizon to the depth of the clay barrier and thus provide understanding of the region where saturated horizontal water flow occurs.
5. Monitor tubes be installed at close intervals in the region between and over tile laterals to provide a knowledge of the water table movement caused by rainfall, evapotranspiration, irrigation and drainage of excess water.
6. Drainmod be run on sites to characterize subsurface irrigation flux and the response of the soil water regime to various combinations of surface and subsurface water management.

# LIST OF REFERENCES

LIST OF REFERENCES CITED

Allison, F.E. 1965. Evaluation of incoming and outgoing processes that affect soil nitrogen. Soil Nitrogen Agronomy Monograph No. 10. Amer. Soc. of Agron. pp. 578-606.

Allmaras, R.R., A.L. Black and R.W. Rickman. 1973. Tillage, Soil environment and root growth. Proceedings of the National Conservation Tillage Conference, Des Moines, Iowa, pp 62-86.

Archibald, D.B. and J.L. Haddock. 1959. Irrigation practices as it affects fertilizer requirement, quality and yield of sugarbeets. J. Amer. Soc. Sugarbeet Technol. 10:344-355.

Benz, L.C., E.J. Doering, G.R. Reichman. 1981. Water table management saves water and energy. Trans. Amer. Soc. Agri. Eng., Vol. 24(2):995-1001.

Bloodworth, M.E., C.A. Burleson and W.R. Cowley. 1958. Root distribution of some irrigation crops using undisrupted soil cores. Agri. J. 50:317-320.

Bouwer, H. 1959. Theoretical aspects of flow above the water table in tile drainage of shallow homogeneous soils. Soil Sci. Soc. Am. Proc. 23:260-263.

Bouwer, H. and van Schilfgraade, J. 1963. Simplified method of predicting fall of water table in drained lands. Trans. Amer. Soc. Agri. Eng., Vol. 6:(4)288-291, 296.

Bouwer, H. 1966. Developing design requirements for parallel drains. Proceedings of the Drainage for Efficient Crop Production Conference, Amer. Soc. Agri. Eng., St. Joseph, MI 49085.

Bravo, N.M. and G.O. Schwab. 1975. Effect of openings on inflow into corrugated drains. ASAE Paper No. 75-2525, Amer. Soc. Agri. Eng., St. Joseph, MI 49085.

Brewbaker, H.E. 1934. Studies of irrigation methods for sugarbeets in northern Colorado. J. Amer. Soc. Agro. 26:222-231.

Chandra, K. 1973. Dynamics of corn root growth as affected by compact subsoil and its influence on crop response to irrigation. Unpublished Ph.D., Das, University of California, Davis.

Childs, E.C. 1947. The water table, equipotentials, and streamlines in drain lands. V. The Moving Water Table. Soil Sci. 63:361-376.

Criddle, W.E., and C. Kalisvaart. 1967. Subirrigation Systems in Irrigation of Agricultural Lands, Robert M. Hagan, Howard R. Haise, and Talcott W. Edministed(ed.), Agronomy 11:905-921. Amer. Soc. Agron., Madison, WI.

Doering, E.J. 1965. Change of permeability with time. Proceedings of the Drainage for Efficient Crop Production Conference, ASAE, St. Joseph, MI 49085.

Erickson, A.E. 1965. Short-term oxygen deficiencies and plant response. Proceedings of the Drainage for Efficient Crop Production Conference. ASAE, St. Joseph, MI. 49085.

Evans R., R.W. Skaggs, and W.N. Reynolds. 1985. Agricultural water management for coastal plain soils. North Carolina Agricultural Extension Service, North Carolina State University, Raleigh, North Carolina.

Finkel, H.J. 1982. Pipe Flow. Handbook of Irrigation Technology CRC Press, Inc., Vol.(1):172-186.

Follett, R.F., G.A. Reichman, E.J. Doering, and L.C. Benz. 1974. Effect of irrigation and water-table depth on crop yields. Agron. J., 66:304-308.

Fox, R.L., J.T. Phelan and W.D. Criddle. 1956. Design of subsurface irrigation systems. Agr. Eng. 37(2):103-108.

Grable, A.R. 1966. Soil aeration and plant growth. Adv. Agron. 18:57-106.

Gilley, J.R. and D.G. Watts. 1977. Possible energy saving in irrigation. Journal of the Irrigation and Drainage Division of ASCE, 103(Ir4):445-455.

Haddock, J.L. 1947. The influence of plant population, soil moisture, and nitrogen fertilization on the sugar content and yield of sugarbeets. Agron. J. 41:79-84.

Hardjoamidjojo, S. and R.W. Skaggs. 1982. Predicting the effects of drainage systems on corn yields. Agricultural Water Management. Vol. 5:127-144.

Harris, C.I., H.T. Erickson, N.K. Ellis, J.E. Larson. 1962. Water level control in organic soil and related to subsidence rate, crop yield and response to nitrogen. Soil Science Vol. 94:158-161.

Harris, D.G. and C.H.M. van Bavel. 1957a. Growth yield and water adsorption of tobacco plants as affected by the composition of the root atmosphere. Agron. J. 49:11-14,176-184.

Harris, D.G., and C.H.M. van Bavel. 1957b. Root respiration of tobacco, corn, and cotton plants. Agron. J. 49:182-184.

Henderson, D.W., F.J. Hills, R.S. Loomis, and E.F. Nourse. 1968. Soil moisture conditions, nutrient uptake, and growth of sugarbeets as related to method of irrigation of an organic soil. J. Amer. Soc. Sugarbeet Technol. Vol. 15:35-47.

Hiler, E.A. 1969. Quantitative evaluation of crop-drainage requirements. Trans. Amer. Soc. Agr. Eng., Vol. 12(3):499-505.

Hiler, E.A., R.N. Clark, and L.J. Glass. 1971. Effect of water table height on soil aeration and crop response. Trans. Amer. Soc. Agr. Eng., Vol. 14(5):879-882.

Hillel, D. 1980. Fundamentals of Soil Physics, Dept. of Plant and Soil Science. Univ. of Mass., Amherst, Mass. Academic Press, pp. 147-150.

Hillel, D. 1982. Introduction to Soil Physics, Dept. of Plant and Soil Science. Univ. of Mass., Amherst, Mass. Academic Press.

Hooghoudt, S.B. 1937. Bifdregon tot de kennis van eenige natuurkundige grootheden van degrond, 6. Versl. Landb. Ond. 43:461-676.

Jensen, M.E. 1980. Design and operation of farm irrigation systems. ASAE. Monograph, No. 3. Chapter 7, pp 242. Drainage Requirements and Systems.

Johnston, W.R., F. Ittihidieh, R.M. Daum, A.F. Pillsbury. 1965. Nitrogen and phosphorus in tile drainage effluent. Soil Sci. Soc. Am. Proc. 29:287-289.

Kirkham, D. 1958. Seepage of steady rainfall through soil into drains. American Geophysical Union Transactions, 39:892-908.

Kramer, P.J. 1965. Effects of deficient aeration on the roots of plants. Proceedings of the Drainage for Efficient Crop Production Conference. ASAE, St. Joseph, MI. 49085.

Kriz, G.J. and R.W. Skaggs. 1973. Water management using subsurface drains. Journal of Soil and Water Conservation. Sept.-Oct., pp. 216-218.

Larson, D.L. and D.D. Fangmeier. 1978. Energy in irrigation crop production. Trans. Amer. Soc. Agri. Eng., Vol. 21(6):1075-1080.

Lemon, E.R. and Erickson, A.E. 1952. The measurement of oxygen diffusion in the soil with a platinum microelectrod. Soil Sci. Soc. Am. Proc. 16:160-163.

Lemon, E.R. and Wiegand, C.L. 1962. Soil aeration and plant root relations: II. Root respiration. Agron. J. 54:171-175.

Letey, J. and L.H. Stolzy. 1967. Limiting distance between root and gas phase for adequate oxygen supply. Soil Sci. 103:404-409.

Linville, D.E. August, 1983. Impact evaluation on increased water use by Agriculture in Michigan. Research Report no. 449, Michigan State University, East Lansing, MI, 48824.

Long, W.F. 1965. Drainage design for irrigated lands. Proceedings of the Drainage for Efficient Crop Production Conference, ASAE, St. Joseph, MI. 49085.

Loomis, R.S. and J.L. Haddock. 1967. Sugar, oil, and fiber crops. Part 1- Sugarbeets in Irrigation of Agriculture Lands, Robert M. Hagan, Howard R. Haise, and Talcott W. Edminister(ed.), Agronomy 11:640-648. Amer. Soc. Agron., Madison, WI.

Lucas, R. and M. Vitosh. Dec. 1978. High corn yields with irrigation. Farm Service Series, Cooperative Extension Service, Michigan State University.

Luthin, J.N. 1959. The falling water table in tile drainage. II. Proposed criteria for spacing tile drains. Trans. Amer. Soc. Agri. Eng., Vol. 2:(1)44-47,51.

Massey, F.C., R.W. Skaggs and R.E. Sneed. 1983. Energy requirements of irrigation systems- Subirrigation versus sprinkler irrigation. Trans. Amer. Soc. Agri. Eng., Vol. 26:126-133.

Mengel, D.B. and S.A. Barber. 1974. Development and distribution of the corn root system under field conditions. Agronomy Journal 66:341-344.

Michigan Data. 1982. National Resources Inventory. USDA, Soil Conservation Service, 1405 S. Harrison Road, East Lansing, MI 48823.

Moody, W.T. 1966. Nonlinear differential equation of drain spacing. Journal of the Irrigation and Drainage Division, ASCE, Vol. 92, NOIR2, Proc. Paper 4835, pp. 1-9, June.

Neal, J.H. 1934. Spacing and depth of tile drains. Agricultural Engineering. Vol. 15, pp. 194-197, 229-232.

Passioura, J.B. 1981. Water collection by roots, photosynthesis and biochemistry of drought resistance in plants. Academic Press Australia.

Patrick, W.H. and R. Wyatt. 1964. Soil nitrogen loss as a result of alternate submergence and drying. Soil Sci. Soc. Am. Proc. 28:647-653.

Purvis, A.C. and R.E. Williamson. 1972. Effects of flooding and gaseous composition of the root environment on growth of corn. Agron. J. 64(5):674-678.

Reeve, R.C. 1982. Soil permeability--Auger-hole method, Technical Note No. 2.118, July, Advanced Drainage System, Inc., Columbus, Ohio 43221.

Reichman, G.A., E.J. Doering, L.C. Benz, and R.F. Follett. 1977. Effects of water-table depth and irrigation on sugarbeet yield and quality. J. Amer. Soc. Sugarbeet Technol. 19:275-287.

Reicosky, D.C., R.J. Millington, A. Klute, and D.B. Peters. 1972. Patterns of water uptake and root distribution of soybeans (Glycin max) in the presence of a water table. Agron. J. 64:292-297.

Renfro, G.M., Jr. 1955. Applying water under the surface of the ground. U.S.D.A. Yearbook.

Richards, L.A. 1931. Capillary conductivity of liquid through porous media, Physics New York, 1:318-333.

Robins, J.S., C.E. Nelson, and C.E. Domingo. 1956. Some effects of excess water application on utilization of applied nitrogen by sugarbeets. J. Amer. Soc. Sugarbeet Technol. 9:180-188.

Schwab, G.O., Frevert, R.K., Edminster, T.W. and Barnes, K.K. 1981. Soil and Water Conservation Engineering, Thrid Edition, John Wiley and Sons, Inc.

Sieben, W.H. 1964. Het verband tussen ontwatering en opbrengst bij de jonge zavelgronden in de Noordoostpolder. Van Zee tot Land. 40, Tjeenk Willink V, Zwolle, The Netherlands.

Skaggs, R.W. 1978. A water management model for shallow water table soils. Report No. 134, Water Resources Research Institute, N.C. State Unversity, Raleigh, pp 17.

Skaggs, R.W. 1979. A water management model for shallow water table soils. Report No. 134, Water Resource Research Institute, N.C. State University, Raleigh, pp. 178.

Skaggs, R.W. 1981. Water movement factors important to the design and operation of subirrigation systems. Trans. Amer. Soc. Agri. Eng., Vol. 24(6):1553-1561.

Skaggs, R.W., G.J. Kriz and R. Bernal. 1972. Irrigation through subsurface drains. Journal of the Irrigation and Drainage Division, ASCE, 90:363-373.

Skaggs, R.W., G.J. Kriz and R. Bernal, 1973. Field evaluation of transient drain spacing equation. Trans. Amer. Soc. Agri. Eng., Vol. 16(3): 590-595.

Skaggs, R.W. and Y.K. Tang. 1979. Effects of drain diameter openings and evelopes on water table drawdown. Trans. Amer. Soc. Agri. Eng., Vol. 22(2):326-333.

Smith, M.C. 1983. Subirrigation system control for water use efficiency. Masters Thesis. Dept. of Biological and Agricultural Engineering, N.C. State University, Raleigh, N.C.

Soil Association Map of Michigan. Michigan State University Extension Bulletin E-1550. East Lansing, Michigan. Dec. 1981.

Strickland, E.E., J.T. Ligon, C.W. Doty, and T.V. Wilson. 1981. Water and energy requirements for subsurface and center-pivot irrigation. Amer. Soc. Agri. Eng., Paper No. 81-2069, ASAE, St. Joseph, Mi 49085.

Tang, Y.K. and R.W. Skaggs. 1977. Experimental evaluation of theoretical solutions for subsurface drainage and irrigation. The American Geophysical Union, Paper No. 7W0687, Vol. 13(6):957-965.

Tisdall, A.L. 1942. Drainage investigations in the horticultural soils of the Murry Valley. Pamphlet No. 113, Council for Sci. and Ind. Res., Melbourne, Aust.

Unger, P.W. and Danielson, R.E. 1965. Influence of oxygen and carbon dioxide on germination and seedlings development of corn (Zea mays L.). Agron. J. 57:50-58.

U.S.D.A. 1954. Diagnosis and Improvement of Saline and Alkali Soils. Agriculture Handbook No. 60, Feb.

U.S.D.A. 1980. Soil and Water Resources Conversation Act. Appraisal Review Draft, Part 1.

U.S.D.A. 1980. Soil Survey, Huron county, Michigan, pp. 66.

U.S.D.A. 1980. Soil Survey, Monroe county, Michigan, pp. 62.

U.S.D.A. 1984. Soil Survey, Tuscola county, Michigan, pp. 69-73; Table 18, page 173.

Vissir, W.C. 1958. Delandouwwaterhuishouding in Netherlands. Comm. Onderz. Landb. Waterhuish. Ned. Tno. Rapport nr. 1. 231p.

Vitosh, M. 1984. Irrigation scheduling for potatoes in Michigan. American Potatoe Journal, Vol. 61: 205-214.

Vomicil, J.A. and Black et.al.(ed.). 1965. Methods of Soil Anslysis: Part I. Porosity. Agronomy, 9:299-314.

Wesseling, J. 1974. Crop growth and wet soils. Institute for Land and Water Management Research, Wageninger, Netherlands, pp. 7-37.

Williamson, R.E. 1964. The effect of root aeration on plant growth. Soil Sci. Soc. Am. Proc., 28:86-90.

Williamson, R.E. and J.R. Carrekar. 1970. Effect of water table levels on evapotranspiration and crop yield. Amer. Soc. Agr., Vol. 13:168-70,176.

Williamson, R.E. and G.J. Kris. 1970. Response of agricultural crops to flooding, depth of water table and soil gaseous composition. Trans. Amer. Soc. Agr. Eng., Vol. 13(1):216-220.

Williamson, R.E. and J. van Schilfgaarde. 1965. Studies of crop response to drainage. II. Lysimeters. Trans. Amer. Soc. Agr. Eng., Vol. 8:98-101.

Williamson, R.E. and C.R. Willey. 1964. Effect of depth of water table on yield of tall fescue. Agron. J. 56:585-588.

Williamson, R.E., C.R. Willy, and T.N. Gray. 1969. Effect of water table depth and flooding on yield of millet. Agron. J. 61:844-847.

Wooley, J.T. 1965. Drainage requirement of plants. Drainage for Efficient Crop Production Conf., Amer. Soc. Agr. Eng., Proc., Chicago, Ill.:1-5.

Worm, B.G., J.T. Ligon, T.V. Wilson, C.W. Doty, and E.E. Strickland. 1982. Economic evaluation of subsurface and center pivot irrigation systems. Proc. of the Specialty Conference on Environmentally Sound Water and Soil Management. ASCE, Orlando, FL.