SUGGESTED SHORT TITLE

SUBSURFACE DRAIN PERFORMANCE ON QUEBEC LOWLAND SOILS

THE PERFORMANCE OF SUBSURFACE DRAINAGE SYSTEMS
ON TWO SAINT LAWRENCE LOWLAND SOILS

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ABSTRACT

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THE PERFORMANCE OF SUBSURFACE DRAINAGE SYSTEMS ON TWO SAINT LAWRENCE LOWLAND SOILS

Measurements of water table positions, hydraulic conductivity, drainable porosity, subdrain outflow, maize yield and trafficability were made on fields which had experimental subdrains at several depths and spacings.

Hydraulic conductivities from subdrain performance agreed satisfactorily with values from auger holes. Subdrain outflow rates as high as 76 mm/day were observed. Volumetric sampling at field capacity was the most suitable of the 4 methods which gave drainable porosities ranging from 3 to 20 per cent.

Water tables fell remarkably quickly, after rainfalls or irrigations, for subdrain spacings as wide as 36.6 m.

Maize yields for Ste. Rosalie clay during 1967 - 70 were not affected by depth or spacing of subdrains. Yields for Soulanges fine sandy loam were significantly affected by subdrain spacings in the two years with higher than normal rainfalls in April, May and June.

RESUME

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COMPORTEMENT DE SYSTEMES DE DRAINAGE SOUTERRAIN DANS DEUX SOLS DE LA PLAINE DU ST-LAURENT

On a fait des mesures de niveau de nappe d'eau libre, de conductivité hydraulique, de porosité drainable, d'écoulement des drains, de rendement de maïs et de mobilité de machines aratoires dans des champs ayant des lignes de drains dont l'écartement et la profondeur variaient.

Les valeurs de conductivité hydraulique déterminées par la méthode du débit au drain coincidaient avec celles trouvée par la technique du trou de sondage. On a observé des débits au drain de 76 mm/jour. L'analyse volumétrique d'échantillons à la capacité au champ fut la meilleure des 4 méthodes utilisées pour déterminer la porosité drainable dont la valeur a varié de 3 à 20%.

Le rabattement des nappes fut assez rapide à la suite de pluies ou d'irrigations dans le cas d'écartement aussi élevé que 36.6 m.

Au cours de 1967-70, dans l'argile Ste-Rosalie, il n'y eut pas de variation dans les rendements de maïs due à l'écartement ou à la profondeur des lignes de drains. Dans le loam fin sableux les rendements ont varié de façon significative avec l'écartement des lignes de drains au cours des deux années ayant des précipitations supérieures à la moyenne en avril, mai et juin.

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LIST OF SYMBOLS

Unless otherwise defined in the text the descriptions given below apply to these symbols throughout the text. It is understood that the units applied to a symbol should be consistent in any one equation.

a	Depth from the soil surface to the bottom of a drain tube (the trench depth).
b	Vertical distance from the water table at mid-spacing between subdrains to the impervious soil layer.
c	a constant
d	The vertical distance from drain tube center to the impervious soil layer.
d_e	Hooghoudt's equivalent depth of soil, below the drain center, through which flow to drains occurs.
f	Drainable pore space, usually expressed as a percent or a decimal fraction of soil volume.
g	Acceleration due to gravity; grams.
h	Height of water table at mid-spacing, above subdrain centers.
h_o	h at some reference time zero.
h_t	h at some time t days after h_o.
i	Hydraulic gradient, ft/ft or m/m.
j	Kraijenhoff van de Leur's reservoir coefficient.
K	Hydraulic conductivity of saturated soil.
L	Horizontal spacing distance between subdrain centers.
m	Meters

n	Number of items.
Q	Discharge rate, Volume per unit time.
r	Radius.
R	Drainage rate, volume of outflow per unit area of land drained per unit time, in/day or mm/day usually.
s	Slope.
S	Shape factor.
t	time : also thickness of ponded water above soil surface.
v	Velocity.
V	Volume.
w	Height of capillary fringe above a water table.
x	Horizontal distance from some vertical reference plane.
y	Vertical distance above some horizontal reference plane.
$\bar{y}$	The average initial depth of the saturated flow stratum $\bar{y} = d + h_o/2$
z	Vertical distance from subdrain centers to the water table at any position x.

LIST OF ABBREVIATIONS

The following abbreviations have been used in the text. Abbreviations for units of measurement have been used in lower case and without periods.

ac	acres
ASAE	American Society of Agricultural Engineers
ASCE	American Society of Civil Engineers
ASTM	American Society for Testing Materials
bu	bushels
cm	centimeters
cc	cubic centimeters
DF	Degrees of Freedom
ft	foot, feet
F	Variance ratio
g	grams : and acceleration due to gravity
ha	hectare
hr	hour
in	inches
I.D.	inside diameter
Igpm	Imperial galons per minute
kg	kilogram
km	kilometre
ln	natural logarithm

lbs	pounds
m	meters
mm	millimeters
MS	Mean Square
no.	number
O.D.	outside diameter
psi	pounds per square inch
rep	replicate
sec	seconds
SS	Sum of Squares
USgpm	United States gallons per minute
vs	versus
yr	year

CHAPTER I

INTRODUCTION

There is a great need for the installation of subsurface drains in much of the St. Lawrence lowlands if the food production capabilities of these lands are to be achieved. In a Royal Commission on Agriculture in Quebec Report, April (1967) shows that although the Province of Quebec comprises 335.5 million acres, only about 16.8 million acres, or 5 per cent, is considered usable as farm land. Of that, only 5.2 million acres, or 1.5 per cent of the total area of Quebec, are of sufficient quality to be cultivated for annual crops or the planting of improved pastures and hay crops. April (1967) and Jutras (1967) show that 3.2 million acres, or about 60 per cent of the cultivable land needs subsurface drainage improvement for its crop production potential to be realized.

Much of this potentially productive land is in the region known as the St. Lawrence lowlands. This is also the region in Quebec with the best climatic regime for crop production (April 1967, Ouellet 1966). When compared with the rest of Canada, Quebec is the province with the largest total land area and the second largest population, but it ranks fifth in area under cultivation and first for food and feed imports. April (1967) stated that the productivity of farm land in Ontario was greater than that in Quebec by 26 per cent, and that one of the foremost causes of the low productivity of Quebec farm land was poor drainage. Thus he recommends that land drainage improvement be given priority.

It is recognised that much of the land in the Ottawa and St. Lawrence lowlands of eastern Ontario also needs subsurface drainage improvement to reach its crop production potential. The need for subsurface drainage in the St. Lawrence lowlands of Ontario and Quebec appears to exist primarily because of the following features: the total annual precipitation exceeds the annual evapotranspiration by 12 to 28 inches per year; most of the precipitation and snow melt occurs at rates slow enough that the soil profile is often saturated before surface runoff commences; much of the potentially fertile land is formed on clay sediments with low hydraulic conductivity; the relatively flat topography restricts the hydraulic gradient to rivers and watercourses; and most of the St. Lawrence lowlands region is less than 200 feet above sea level. As a result of these features, natural water tables are within a few feet of the land surface. During periods of excess rainfall or snowmelt natural or perched water tables rise into the root zone or to the soil surface. Unfortunately the economic crops of the temperate regions do not grow well with saturated root zones.

Prior to 1965 only about 42,000 acres of land in Quebec had subsurface drains installed. Since 1965 rates of installation of subsurface drains have increased rapidly from about 3 million feet per year in 1965 to 15 million feet per year in 1970 (Fisk, 1971). This increase in rate of installations is encouraging. However, if 15 million feet of sub-drains were installed per year on systems with an average spacing between laterals of 52 feet only 18,000 additional acres would be drained per year and 180 years would be required to install subdrains on 3.2 million acres.

At current installation rates of about 850 feet per acre (i.e. average spacings between parallel lateral drains of about 52 feet) and at current drain tube prices and installation costs, the average total costs of subsurface drainage installations is about $ 170 per acre. To install subdrains on 3.2 million acres at these prices would cost $ 544 million. The above figures show the scope of the subsurface drainage problem in Quebec.

In order to maximize the drainage benefits for the large amount of money that must be spent on drainage construction more must be learned about the effects of drains under the climatic conditions of the region; on the movement of soil water; on crop yields; and on the soil surface conditions which could improve the mobility of tillage, planting, harvesting and field haulage machines.

While theories about flow to subdrains have been developed, few measurements of the field parameters to be used in these drainage design equations have been made for the St. Lawrence lowlands. Subsurface drainage design has progressed conservatively here, as in other regions, based on experience and tradition, since the days when trenches were dug by hand. With hand dug trenches there was an understandable tendency not to install sub-drains deeper than about 2.5 feet except where it was necessary to dig deeper through a ridge to keep the drains on grade. The shallowness of outlets at rivers or ditches has also restricted depths for subsurface drains and thus affected the design of drainage systems.

With the development in recent years of machines which can efficiently install drain tubes to depths of 5 or more feet there is new scope for considering a greater range of depths in subsurface drainage design. Indeed, research on drainage performance should influence machine design rather than the reverse.

The cost per acre of subdrain installations is roughly proportional to the length of drain tube that needs to be installed per acre to provide adequate drainage (Fisk 1970). Thus, action that permits increased drain spacings without significantly increasing cost per unit length of drain will reduce the installation cost per acre - or increase the acreage that can be improved with a given amount of capital.

Theories of flow to subdrains in homogenous soils presented by Kirkham (1949), Luthin (1957), Houghoudt (1937), Van Schilfgaarde (1956; 1963) indicate that by increasing the depth of subdrains the spacing between drain laterals can be increased without reducing the drainage effect. For layered soils the spacing between subdrain laterals can theoretically be increased if the drain depth is increased providing the decrease in hydraulic conductivity with depth is not too rapid. Authors presenting theories of flow to subdrains indicate the need for local field experiments to determine soil, crop and climatic characteristics to be used with the theories for designing drainage systems.

Objectives

The objectives of this work were:

1. To make measurements in St. Lawrence lowlands fields having subsurface drainage systems to determine rates of flow of water to subdrains and rates of fall of water table possible on those fields.
2. To check the suitability of using some of the known theories of flow to subdrains for the design of subsurface drainage systems in the St. Lawrence lowlands region.
3. To measure the hydraulic conductivity and drainable porosity of two St. Lawrence lowland soils by different methods and comment on these methods

for obtaining values for these two variables for use in the drain spacing equations proposed in theories of flow to subdrains.

4. To show that peak drainage rates in this region are primarily limited by the discharge capacity of the drain tubes rather than by the hydraulic conductivity of the soil.

5. To test the hypothesis that crop yield in the field is greater for subdrained fields than for fields without subdrains.

6. To test the hypothesis that maize yield is relatively insensitive to subdrain depth and spacing.

7. To show that by placing subdrains at depths of 3.5 ft (1.1 m), or more the spacing between drains, for equal rates of lowering of the water table, can be greater than for drains at depths of 2.5 or 3.0 ft (0.76 or 0.91 m).

Scope

While much might be said about the drainage of undulating and hillside land, this thesis is restricted to relatively flat lands. Specifically the thesis will deal only with Ste. Rosalie clay and Soulanges fine sandy loam soils. The results will indicate what might be expected on some similar soils but conclusions will not be specific to other soils.

Contributions to Knowledge

This work provides the following contributions to knowledge:

1. With respect to Ste. Rosalie clay and Soulanges fine sandy loam
   (a) The yield of maize can be greater where subdrains have been installed.
   (b) The yield of maize is relatively insensitive to the depth and spacing of subdrains.
   (c) The use of drain spacing equations together with values of hydraulic

conductivity and drainable porosity can give reasonable results for selecting drain spacings.

2. Some Ste. Rosalie clay soils have hydraulic conductivities high enough to provide good drainage with subdrains spaced as wide as 120 ft (36.6 m). Drains placed at this spacing could provide cost reductions of 50%, or more, when compared with common traditional installations with 40 to 60 ft (12.2 to 18.3 m) spacings on these soils.

3. Flow rates to subdrain systems were observed in Ste. Rosalie clay as high as 76 mm/day (3.0 in/day) and in Soulanges fine sandy loam as high as 62 mm/day (2.4 in/day). These measurements have shown that higher rates of water flow through clay soils to drains than would hitherto have been expected without special pervious infill around and above the drain tubes can readily occur in nature.

4. If drain tube capacities are large enough, snowmelt may practically all pass through the soil and out the subdrains under some observed snowmelt conditions.

5. Water or ice held in the top 18 in (46 mm) of the soil profile increased considerably through the winter months but the increases were less on subdrained plots than on plots without subdrains.

6. Observations showed qualitatively better surface conditions for earlier springtime tillage and planting operations where drains were 3.5 ft (1.1 m), or more, deep than where drains were shallower than 3 ft (0.9 m).

7. The experimental design with a diagonal subdrain between 2 parallel drains to give a linear increase in subdrain spacing does not give consistent values of hydraulic conductivity when a falling water table

money on extra field measurements to give more precise designs for each farm. Measurements relating rate of water table fall to soil type, with only occasional measurements of hydraulic conductivities and drainable porosities, could provide a more economical and satisfactory guide to the design of subsurface drainage systems for the St. Lawrence lowlands region.

7. Observations showed qualitatively better surface conditions for earlier springtime tillage and planting operations where drains were 3.5 ft (1.1 m), or more, deep than where drains were shallower than 3 ft (0.9 m).

8. The experimental design with a diagonal subdrain between 2 parallel drains to give a linear increase in subdrain spacing does not give consistent values of hydraulic conductivity when a falling water table equation is used for different spacings. It appears that this experimental design is affected by some flow from the wide spacing end to the narrow spacing end of the plot, even though the gradients to the subdrains are much greater than the longitudinal gradients.

9. If drainable porosities are to be determined from soil samples by measuring the field capacity and saturation water contents, the field capacity value should be obtained by sampling the soil in the field at a time when the soil is at field capacity rather than using the moisture content for suctions of 0.10 or 0.33 bar obtained with the pressure plate or suction table apparatus.

CHAPTER II

REVIEW OF LITERATURE

Bouwer (1965) states that "the objective of artificial drainage of agricultural land is to help maximize the net profit from the farming enterprise." In cool moist climates such as prevail in the St. Lawrence lowlands this objective requires the orderly removal of water that is excess to profitable crop production. It is seen that fully specified drainage design would require quantification of agronomic crop requirements; prediction of system performance; physical specification of the soil medium; and economic evaluation of alternatives. Some pertinent information from literature relating to these requirements is presented here. In addition to literature referred to in this chapter, other references will be cited at appropriate points in other chapters.

Agronomic Requirements

From the standpoint of determining the required rates of removal of excess water, it would be good if agronomic requirements could be stated as the number of hours of root zone saturation a crop can stand, or the number of millimeters of root zone depth that should never be saturated and the number of millimeters per day of additional root zone depth that should be drained below the saturation water content after a precipitation or snowmelt event. Some experiments have been conducted to try to specify limiting and optimum root zone moisture conditions at different stages of plant growth. Hoveland and Webster (1965) have found that among several clovers, ball and white clover were the most resistant to flooding damage, and that these two clovers could be flooded three days out of every ten for a three-month period without suffering reduction in yield.

Harris et al (1962) reporting on a controlled water table field study on organic soils in Indiana, U.S.A., noted a great reduction of onion, potato, carrot and maize yields when the water table was kept at a depth of 16 inches. Yields were much higher for water tables 24 inches deep or deeper. Yields were very similar for water tables at depths of 24, 32 and 40 inches. Crop response to additional nitrogen was limited primarily to the 16 inch water table condition with potatoes and maize showing the greatest yield increase.

De Boer and Ritter (1970) observed damage to crops during the 1967 season when higher than normal June rainfalls caused pondings in crops planted in depressonal areas in North Central Iowa. The maize was approximately 12 inches high at the time of flooding. Flooding of $2\frac{1}{2}$ days caused severe reduction in yields. All maize plants were killed after $3\frac{1}{2}$ to 4 days of inundation. The average yields of maize from areas partly damaged by short term inundation were only 57% of the yields from undamaged areas. Observations of some 1966 pondings showed all soya bean plants killed after 3 days of flooding.

Williamson and King (1970) reviewed the findings of several experiments on depth of flooding and crop response. They indicate that it is difficult to transfer results from one location to another because of different soil types and climatic conditions. A water table depth of 15 cm below the surface has produced maximum yield for some crops under certain conditions while other crops have performed best with the water table at 150 cm or more. They indicate that when a water table rises above some of the root system during a growing season and remains at a higher than normal level for more than one or two days severe root pruning results.

Van Schilfgaarde (1970) states that in the Netherlands, many years of observations have established that where a drainage system has a capacity to remove 7mm of surplus precipitation per day good results are obtained with an average depth to water table of 20 to 30 cm for grassland, 40 to 50 cm for cropland, and 60 to 70 cm for truck crops. Since the Netherlands has long duration low-intensity precipitation, the soil is seldom saturated to the surface when the above criteria are met.

Woolley (1965) indicates that drainage affects plant growth only indirectly through its effect on the root environment; root respiration; growth of micro-organisms and on chemical reactions associated with nutrient up-take. Other environmental aspects such as soil temperature, soil solution chemical status, soil density and drainable porosity also affect root growth and plant growth. He indicates that it is thus at present not feasible to specify drainage requirements of crops with the precision and generality that the engineer might prefer.

Zwerman and Corpuz (1965) indicate that nitrogen fertilization of imperfectly drained soils can raise the yields of some crops on those soils to levels approximately equal to those achievable with subdrains installed. This applies only to imperfectly drained soils and not to waterlogged soils.

Childs (1970) indicates that it can be difficult to establish the need to install drains in terms of yield increases which give benefits exceeding costs except in self evident cases where the land without drains is embarrassingly wet.

Trafford (1970) states that field drainage is not an easy subject on which to obtain satisfactory experimental data to compare crop yields from land without subdrains to land with different drainage intensities (depths and spacings of subdrains). Plot sizes must be relatively large. Large buffer areas are required between plots of differing drainage intensity. It is difficult to find satisfactory areas of uniform soil to run fully replicated experiments. Since drainage removes only excess soil water, responses to drainage should be more obvious in wet years than in dry years. To get crop yield data indicative of drainage intensity a field experiment must run several years. Experiments dealing with intensities of drainage are very expensive and relatively difficult to manage. It is not surprising that very few drainage experiments have been completely satisfactory from a statistical point of view.

Russell (1934) reports experiments which show drained plots to give increases in yield over undrained plots, but there was very little difference between plots drained with different depths and spacings of tiles.

Beer et al (1965) reports results from 15 years of yield measurements on replicated plots having drain spacings of 15 ft, 30 ft and 60 ft on an Iowa, U.S.A., planosol soil. There were plots of continuous maize and a maize-oats-hay rotation. Yields fluctuated considerably from year to year but the plots with the 15 ft drain spacing consistently yielded slightly higher than the plots with 60 ft drain spacings. The significantly different 15-year averages for the rotation corn for 15 ft and 60 ft spacings were 99 bu/ac and 93 bu/ac respectively. The statistically non-significant 8-year average yields for continuous maize were 106 bu/ac and 102 bu/ac from the 15ft and 60 ft spacings respectively.

From the management standpoint it was necessary to plant all of the maize plots on the same day. Any possible benefits which might have accrued from earlier planting of the plots with 15 ft drain spacings were lost. From the rotation experiments yield increases of 16 bu/ac of oats due to drainage were reported.

Monke et al (1967) working in Ohio, U.S.A., with replicated plots on a silt loam soil with drains 0.9m deep reported 5-year average maize yields of 123, 110 and 105 bu/acre respectively for subdrain spacings of 25, 50 and 100 ft. They did not consider the increased yield to justify the increased cost of drains spaced narrower than 100 ft on this soil.

Trafford (1970) reported results from Thorgensen in Denmark and Janota in Czechoslovakia. Thorgensen obtained increases of 287 lbs/ac of oats, 12,300 lbs/ac of turnips and 660 lbs/ac of barley due to subdrains, but no significant differences between six spacings and depths of subdrains. Janota had plots with subdrains of 5 depths from 0.8 to 1.4m and 5 spacings from 6 to 14m. Janota's yields of barley ranged from 2860 lb/ac to 3880 lb/ac for the drained plots compared to 3220 lb/ac for undrained plots in 1930, which was considered to be a normal year. He might have gotten greater differences in a wet year.

Barker (1963) gives results for 3 years of winter wheat crops showing yield increases of 50% for subdrained plots compared to undrained plots, but he got only small, statistically non-significant, increases in yields from plots with 5½ and 11 yard drain spacings when compared with plots with 30 yard drain spacings.

As a result of observations on field work described later in this thesis, it seems possible that some of the reasons for obtaining significant differences in crop yields from subdrained land compared to land without subdrains, but little or no significant difference between plots with different depths and spacings of subdrains may be: (1) the experiments have not included very wide spacings; (2) deep seepage allowed the narrow spacing or deeper depth plots to influence the water table on other plots more than expected; and (3) only in very wet years will water tables be brought close enough to surface in subdrained plots for large differences in yield of the crop in the field to occur due to intensity of drainage.

Agronomic requirements in terms of crop production management must include not only healthy plant growth but also the field management aspects allowing efficient movement of tillage, planting, and harvesting equipment over the land without causing long term damage to soil structure. With a short frost free season and a cool moist climate in the St. Lawrence lowlands, a few extra days with improved field vehicle mobility at planting and harvest times can make a big difference to overall farm performance even if the yield per acre of actual planted crop is not changed. Van Schilfgaarde (1970) indicates the need for consideration of soil trafficability in drainage design. No one seems to have yet developed a satisfactory way of measuring the effect of drainage on soil trafficability. Some investigators such as Kim (1969) have made beginnings in this direction.

The requirements for optimum drainage appear to vary with the crop to be grown. Since many different crops are likely to be grown during the life of the drainage system it appears necessary to be somewhat conservative in system design and to try to provide adequate drainage for the more sensitive of the crops likely to be grown. Good system design could also provide for straight forward installation of additional subdrain laterals in the case of a shift from extensive field crop production to intensive high value garden crop production.

Of the valuable field crops to be grown in the St. Lawrence lowlands, maize, beans, alfalfa and cereal grains are known to suffer in poorly drained conditions. It is reasonable that one of these crops be chosen as an indicator crop for field experiments involving subdrainage effects.

Until more specific drainage requirement criteria are established for crops in this region it appears conservatively reasonable to try to provide drainage facilities which are capable of preventing the water table from rising closer than 150 mm (6 in) to the surface during a growing season storm of recurrance interval once-in-20 years or less. The system should also provide for lowering the water table from 152 mm (6 in) to 305 mm (12 in) in 12 hours after the end of the storm and to 457 mm (18 in) in 48 hours after the end of the storm. These requirements approximate those recommended by Neal (1934) for Minnesota and by Kidder and Lytle (1949) for Illinois. A system with these capacities should have adequate capacity for removal of surplus water following snowmelt.

Theories of Flow to Drains

Theories to describe the flow of water to drains have been developed by several authors using different approaches.

Since detailed mathematical developments in drainage theories are well covered by the originators, and by some authors making comparison between theories, the details of mathematical developments will be reproduced only in special instances. Aspects of some theories which have particular reference to some St. Lawrence lowland problems and to experiments described later in this thesis will be presented. Some pertinent assumptions and application restrictions will be included and comments made.

Steady Saturated Flow to Drains

(1) Drainage of ponded water. By use of potential flow theory Kirkham (1949) developed analytical and flow net solutions for cases of saturated homogeneous soil with water ponded above the surface. Some useful conclusions are obtained by considering one example in detail.

A flow net of a situation with an infinitesimal depth of ponded water over saturated soil containing parallel subdrains 0.6 ft in diameter, 40 ft apart and 4.5 ft deep, running just full is presented as Figure 1. There is an impervious layer 6 ft below the soil surface. In the left half of the figure, streamlines are labelled with the fraction of the total flow which occurs between the given streamline and the zero streamline. In the right hand half of the figure equipotentials are labelled in feet of water. This flow net shows that 60 per cent of the inflow from the ponding enters the soil within 4 ft on either side of the drain.

The flow net also shows that 40 per cent of the flow enters the drain from its underside. This suggests that if subdrains are laid on an impervious layer or if the hydraulic conductivity of the drain bedding is much reduced by remoulding by a drainage trencher much inflow capacity is lost.

The closeness of the equipotential lines near the drains indicates that nearly half of the total potential is used up within two diameters of the subdrain.

For the case shown in Figure 1 Kirkham (1949) gives the approximate drain flow to be

$$Q = \frac{2\pi K\ (t + a - 2r)}{\ln\left[(2a - 3r)/r\right]} \qquad (1)$$

where Q = volume of flow into a unit length of drain per unit time

K = hydraulic conductivity length per unit time,

t = depth of ponded water on the soil surface. Other dimensions are defined by Figure 2, for equation (1) and subsequent equations.

This equation is a close approximation for cases where the drain spacing is at least 5 times the drain depth and the impermeable layer is at least twice the drain depth.

This theory shows for a homogeneous soil that inflow is nearly proportional to drain depth until the drain approaches an impervious layer. Providing drain tubes have capacity to convey the water away, rates of inflow to subdrains should be much increased by enveloping them in more pervious materials. In situations where pondings will occur, surface grading to concentrate the water near the drains should greatly increase the drainage rate.

Results for several special ponded water cases have been published including; an analysis by Kirkham (1948) of flow to drains placed in an impervious layer; sand tank models of stream lines from ponded water by Harding and Wood (1942); and a potential theory analysis for flow to drains placed in a soil overlying an artesian acquifer by Kirkham (1954).

The problem of drain tube opening dimensions and their effect on flow from saturated soils has been discussed by several authors. Kirkham (1950) presented a complicated mathematical treatment. Ernst (1962) presents a simpler analysis. Field observations have failed to verify these theories. One explanation is that the theory assumes that the hydraulic conductivity remains constant near the drains, whereas the soil properties are often changed drastically during or after drain installation. MacKenzie (1962) reports impedence of drainage by iron deposits near and in the drains. Flodquist (1931) presents evidence of hydraulic conductivity increasing with time after subdrain installation in heavy soils.

(2) Drainage of Steady Precipitation. While in nature precipitation seldom occurs at a constant rate, the steady state case is of considerable importance because some field situations may approximate steady state sufficiently for practical purposes. Steady state theory also provides some of the background necessary to treat nonsteady cases.

Schwab (1966) gives a development of the ellipse equation. This equation is based on the Dupuit - Forchheimer assumptions (1) that the streamlines in a system of gravity flow towards a shallow sink are horizontal and (2) the velocity along these stream lines is proportional to the slope of the free water surface but independent of the depth of the saturated flow layer. For conditions were influent seepage from rainfall, snowmelt, or irrigation is constant for a sufficient time that the water table achieves a fixed position the drain discharge will also be constant. Since the water table is below the surface, water enters the soil uniformly across the surface and is not concentrated near the drains as in the ponded water case.

Assuming that a constant rate of rainfall is removed equally well at all distances from the drain $q_x = \left(\frac{L/2 - x}{L/2} \right) \frac{Q}{2}$ (2)

where q_x is the rate of flow across a vertical plane at any x,

Q is the total rate of flow into a drain from both sides.

Other dimensions are defined by Figure 2.

From the Dupuit - Forchheimer assumptions and Darcy's Law (Darcy 1856)

$$q_x = - y V_x = K y \left(\frac{dy}{dx}\right) \qquad (3)$$

where V_x is the velocity at x, and K is the hydraulic conductivity.

By equating equations (2) and (3) the differential equation is

$$y\, dy = \left(\frac{Q}{L K}\right) \left(\frac{L}{2} - x\right) dx \qquad (4)$$

Integrating from $x = 0$ and $y = d$ to $x = x$ and $y = y$

$$y^2 - d^2 = \frac{Q}{L\,K}\,(L\,x - x^2) \tag{5}$$

Equation (5) is an equation of an ellipse, hence this steady state equation is often referred to as the "ellipse equation".

Substituting $x = L/2$ and $y = b$ for the mid-point of the water table line yields

$$L = \frac{4K\,(b^2 - d^2)}{Q} \tag{6}$$

but $Q = L\,R$ where R is the drainage rate in volume per unit area drained per unit time (m/day) so (6) may be written as $L^2 = \frac{4K}{R}\,(b^2 - d^2)$ (7)

Essentially this same solution was first developed by Colding in 1872, though equivalent forms have been developed later and apparently independently by several other workers, including Hooghoudt (1940). Hooghoudt (1940) presented the case for flow to parallel ditches as well as tube drains.

The principal limitation of the ellipse equation when used for tube drains is that convergence of the stream lines near the drains is ignored.

Hooghoudt (1940) judiciously combined solutions for radial flow and horizontal flow to drains to develop an equivalent depth d_e as given in Figure 3 to be used to adapt the ellipse equation for use to any reasonable depth to an impervious layer.

If the depth d in equation (7) is replaced by d_e and the distance b by $d_e + h$, where h is the rise of the water table above the drain axis, the ellipse equation becomes $L^2 = \frac{4K}{R}\left[(d_e + h)^2 - d_e^{\,2}\right]$

$$= \frac{4K}{R}\,(2d_e + h)\,h = \frac{8\,K\,d_e\,h}{R} + \frac{4\,K\,h^2}{R} \tag{8}$$

When the impervious layer is right at the base of the drains, d_e becomes zero and

$$L^2 = \frac{4 K h^2}{R} \tag{9}$$

The term $\frac{4 K h^2}{R}$ is taken by Luthin (1966) to represent flow to the drains primarily through the saturated soil above the drains and the term $\frac{8 K d_e h}{R}$ to represent flow through saturated soil below drain depth. If the hydraulic conductivity K_b of the layer of soil below drain depth is different than the hydraulic conductivity K_a of the soil above drain depth, equation (8) may be modified to

$$L^2 = \frac{8 K_b d_e h}{R} + \frac{4 K_a h^2}{R} \tag{10}$$

to give a solution for a two layered soil problem.

It can be seen from equation (8) that for homogeneous soil cases where it is suitable to apply the modified ellipse equation the spacing can be increased approximately linearly with increased depth of drains. The term h essentially represents drain depth minus an allowance for a shallow root zone always protected from saturation. In many practical cases d_e will be approximately the same magnitude as h. Even in a layered soil, as long as K_2 is not zero, some increase in spacing L is possible when depth is increased.

Nonsteady Saturated Flow from Falling Water Tables to Drains

While much understanding of flow through porous media to subdrains is obtained from the steady state cases, it is realized that most drainage flow in nature is nonsteady. Several approaches have been undertaken to establish equations relating the important parameters in nonsteady flow to drains.

Potential Theory for Falling Water Tables. Kirkham (1964) assumed that the region above the plane through the drain axes had infinite vertical conductivity and zero horizontal conductivity. Thus he took the initial condition as the equilibrium condition under steady precipitation,

$$z(x) = (R\ L/K)\ F(x)$$

F(x) was evaluated at $x = L/2$ from his steady state potential theory. He then "froze" the shape of the stream lines and considered the discharge through each stream tube as the precipitation was stopped. Replacing the medium of infinite conductivity with soil raises the water table to a value $B(x) > z(x)$. He then wrote expressions for the discharge through the stream tubes of top width Δx to derive the differential equation which he integrated and obtained

$$B/Bo = \exp\left[(B_o - B - K\ t/f)/L\ F\right] \tag{11}$$

Equation (11) reduces to $z/z_o = \exp(-K\ t/f\ L\ F)$ (12)

when the head loss through the layer above the drains may be ignored so that $z = B$.

The shape of the water table was then determined by evaluating F(x).

Guyon (1965) and Dagan (1964) also used potential theory for the study of falling or fluctuating water tables. They used slightly different boundary condition assumptions than Kirkham and obtained solutions essentially the same as the solution obtained by Van Schilfgaarde using the Dupuit-Forchheimer assumptions, and described below.

Dupuit - Forchheimer Assumptions Applied to Falling Water Table Cases. Boussinesq (1903) showed that the differential equation for steady state flow to parallel subdrains in a homogeneous soil obtained by the Dupuit - Forchheimer assumptions could be adjusted to the case of nonsteady flow by adding a rate of change of drainable soil water in storage term $f\ \partial y/\partial t$, where f is the drainable porosity. This establishes the nonsteady flow differential equation

$$K \frac{\partial}{\partial x}(y\ \partial y/\partial x) + R = f\ \partial y/\partial t \tag{13}$$

Bousinesq obtained a solution to this equation for an initial condition of the termination of previously constant rainfall, i.e. R = 0, and with the drains penetrating to the impervious layer of a shallow aquifer, i.e. d = o. Assuming the variables were separable he obtained the solution

$$L^2 = (9 K t/2 f) h_o h/(h_o - h) \quad (14)$$

Dumm (1954) reports the work of Glover who independently obtained essentially the same solution.

When the drains do not penetrate to the impervious layer the boundary conditions can no longer be satisfied by the Boussinesq type of solution. To overcome this difficulty Glover (Dumm 1954), Kraijenhoff van de Leur (1958) and Maasland (1959) have linearized the differential equation (13) to

$$K \bar{y} \partial^2 y/\partial x^2 + R = f \partial y/\partial t \quad (15)$$

where the variation in y is considered small compared to the variation in $\partial y/\partial x$, and y is considered constant.

Starting from an initially flat water table with the boundary conditions written as

$$y = y_o = d + h_o \text{ for } o < x < L \text{ at } t = o$$
$$y = d \text{ for } x = o, L \text{ at } t \geq o$$
$$dy / dx = o \text{ for } x = L/2 \text{ at } t \geq o$$

a solution is obtained with a Fourier series as

$$y - d = (4 h_o/\pi) \sum_{n = 1, 3, 5 \ldots}^{\infty} (1/n) \text{ Sin } (n \pi x/L) \exp (-n^2 \pi^2 K D t/f L^2) \quad (16)$$

Glover takes the average depth $\bar{y}$ equal to $D = d + h_o/2$ or the average initial depth of the water bearing stratum. Except for the earliest time period during which the water table changes from flat to elliptical all terms in the Fourier series except the first term may be neglected. This simplifies (16) to

$$L^2 = \pi^2 K D t/f \quad \ln(4h_o/\pi h) \qquad (17)$$

Since the Dupuit - Forchheimer assumptions represent the physical case in the field less well as the depth to the impermeable layer increases, the applicability of equation (17) can be improved by using Houghoudt's equivalent depth d_e. Also if the difference $(h_o - h)$ is large the use of D based on h_o becomes less suitable. To overcome this problem, equation (17) should be used in successive steps for small values of $(h_o - h)$, or small values of time t. Taking these things into account equation (17) achieves the more useful form

$$L^2 = \frac{\pi^2 K t (d_e + h_o/2)}{f \ln(4h_o/\pi h)} \qquad (18)$$

Maasland (1959) using the same linearization of the Boussinesq equation as Glover (1954) derived solutions for some recharge patterns.

Werner (1957) used another linearization of the Bousinesq equation and developed a solution using Laplace transforms. He showed how his solutions could be applied to intermittent recharge or variable precipitation problems.

Van Schilfgaarde (1963, 1964) made use of an incomplete beta function to solve the nonsteady flow differential equation (13). He rounded off his solution to a simpler form as

$$L^2 = \frac{9 K t d_e}{f \ln\left[\frac{h_o(2d_e + h)}{h(2d_e + h_o)}\right]} \qquad (19)$$

which is valid for small time increments t.

For practical calculations of drain spacing there is very little to choose between equations 18 and 19. The variations in K, f and d_e to be found for natural soils will lead to much greater variation than will the falling water table equation chosen to calculate L.

A semi-graphical approach. Bouwer and Van Schilfgaarde (1963) have taken a semi-graphical approach to adapt the steady-state solution to a falling water table case. They have then developed graphs relating R/K and h/d for various L/d ratios to be used for determining drain spacings to give prescribed drawdown rates.

Intermittent Recharge. Surplus of rainfall or irrigation beyond root zone moisture storage requirements provides intermittent recharge to ground water. Several authors have investigated the theoretical response of subdrain systems to intermittent recharge which raises water tables above subdrain levels.

Werner (1957) and Maasland (1959) have presented analyses of intermittent recharge based on a superposition of solutions from a linearized form of the nonsteady differential equation (13).

Kraijenhoff van de Leur (1958) proposed a drainage-soil system parameter defined as $j = f\, L^2/\pi^2 K\, (d_e + h_o/2)$ which he called the reservoir coefficient. This reservoir coefficient is convenient to characterize different soil-drainage systems.

Van Schilfgaarde (1970) uses an approach which combines in a factor B with units of time, the geometric restraints of the system as fixed by L and Kirkham's function F and the soil properties f and K. By this approach Van Schilfgaarde establishes the nonsteady differential equation

$$dh / dt + h/B = 0 \qquad (20)$$

Making use of impulse forcing functions, converting rainfall to a histogram pattern, and assuming no surface runoff or deep seepage, he produces a solution function with which he can predict water table height at the end of arbitrarily long sequences of time increments. With this approach he proposes that frequency distributions of water table heights associated with design parameters such as drain depth and spacing, soil type and root depth can be established to indicate the risk of water tables being at a prescribed height in the root zone for a certain time period in any year. Van Schilfgaarde's system factor B achieves essentially the same purpose as Kraijenhoff van de Leur's storage constant.

According to Van Schilfgaarde (1970) the restraint that keeps the theories of flow to drains from being applied more widely in actual field design is not the lack of validity of the theories but the inability to find the input necessary to apply the theory.

The Soil Medium and its Effects on Flow to Drains

The nature of soil constituents and laws pertaining to soil water movement are described by Childs (1957), Yong and Warkentin (1966), Baver (1963) and other authors. Since, from the foregoing section it is seen that the two soil properties required for many of the depth and spacing equations are the saturated hydraulic conductivity K and the drainable porosity f, this review will deal primarily with these two properties.

Saturated hydraulic conductivity

Measurements of saturated hydraulic conductivity may be divided into laboratory measurements on cores removed from the field, auger hole measurements in the field and calculations from subdrain outflow and water table measurements.

Laboratory Methods. The basic principles of the well established constant head, and falling head methods of measuring hydraulic conductivity of soil cores are given in several basic texts such as Yong and Warkentin (1966), Luthin (1966), Taylor (1963) and Terazaghi and Peck (1962). Greater detail with respect to obtaining "undisturbed" cores from the field, transporting them to the laboratory, preparing them for test and conducting the tests is given by Reeve et al (1957), and the U.S. Salinity Laboratory Staff (1954).

Cases have been reported (Mason, Lutz and Peterson 1957) indicating the disappointments with the results of laboratory measurements of hydraulic conductivity where these results are to be used for drainage design purposes. Flow to drains in the field is through a large volume of undisturbed soil. Core samples are small and are affected by small scale inhomogeneities, such as root channels, cracks etc. Though samples are designated "undisturbed" they often suffer compaction during sampling and vibration during transport. Special techniques such as those developed by Smith et al (1944) or Campbell (1968), are required to prevent flow between the sample and permeameter wall from influencing the measured conductivities. Samples may indicate soil layers of significantly different texture and hydraulic conductivity but the continuity of the layers through the field is often uncertain. Mason, Lutz and Petersen (1957) indicate the limited precision possible in obtaining field values of hydraulic conductivity from laboratory measurements on "undisturbed" samples. Their analyses show that with laboratory determinations on five samples from one site an investigator could classify the hydraulic conductivity of the site into one of three broad classes (high, medium or low) with a 95% probability of being right; into four classes with an 80% probability of being right; but one would only have a 30% probability of being right in classifying the site into one of seven possible classes.

Auger Hole Methods. For field conditions where a relatively steady water table is found to a level higher than that for which K is required, the flow into, or out of, an auger hole or system of auger holes may be used for the determination of K. These methods sample a much larger soil volume than do laboratory methods and thus have more meaning for drainage design.

Single Hole Methods. The single hole methods are the auger hole, tube and piezometer methods. Several authors, including Kirkham (1955), Luthin (1966), Maasland and Haskew (1957), and Boersma (1965) have reported on single auger hole methods.

The auger hole method uses an uncased cylindrical hole about 10 cm in diameter augered to some depth below the water table. The tube method uses a hole cased so that water can enter only through the bottom end. The piezometer method uses a cased hole, commonly of 5 cm diameter with a cavity about 10 cm long augered out below the end of the casing. For all three methods water is bailed or pumped out of the hole and the rate of rise of water in the hole after baling is observed. The flow of water into the hole can be expressed as

$$dV/dt = -\pi r^2 \, dh/dt = K \, h \, S \tag{21}$$

where dV/dt is the rate of filling of the hole volume, h is the difference in elevation between the water table and the water level in the hole, S is a shape factor, and r is the radius of the hole.

Integration of (21) between levels h_1 and h_2 which occur at times t_1 and t_2 yields

$$K = \frac{\pi r^2}{S} \left[\frac{\ln (h_1/h_2)}{t_2 - t_1} \right] \tag{22}$$

Measuring the water level at known times enables the calculation of a series of estimates of K.

The shape factor S describes the influence of the flow system geometry on the resistance to flow. S values have been obtained by electric analogue studies such as those reported by Kirkham (1955). The auger hole method measures primarily horizontal hydraulic conductivity; the tube method measures primarily vertical hydraulic conductivity, and the piezometer method some combination of horizontal and vertical conductivity.

Multiple Well Methods. Childs (1952) proposed a two-well method for determining horizontal hydraulic conductivity in the field. Water is pumped from one well to another. By measuring the pumping rate and the head difference established, and using appropriate geometrical factors, the hydraulic conductivity can be calculated.

Kirkham (1955) proposed the use of a four-well method to avoid effects of surface sealing of the wells which may occur in the use of the two-well method.

Precision of Results from Auger Hole Tests. Boersma (1965) recommends pumping the hole several times before making the measurements to be used in calculating K so that inflow can remove any smearing effects due to augering the hole. Then K values obtained from subsequent pumpings of a single auger hole may be quite close. However, Boersma states that one hundred fold variations in K may be obtained from auger holes a few metres apart. He recommends that 4 or 5 auger holes be used to obtain K values for any particular soil area.

Van Schilfgaarde (1970) recognizes that hydraulic conductivities determined by auger hole methods have considerable variability but still says that "more extensive application of currently available field methods (auger hole methods) can result in significant improvement in present design methodology."

Even though auger hole methods sample a much larger soil volume than do laboratory measurements on soil cores, Ede (1960) states that auger hole methods suffer from the defect that for drainage purposes the sample of soil affected by the auger holes is very small compared to the field size. He states that several auger hole tests in the same field often reveals a scatter in results in which the arithmetic mean has no physical validity and considerable interpretive experience is required to obtain a 'result'. The scatter is stated to be much less in silts than in soils such as clay and peat where large scale structural features determine their ability to transmit water. Ede gives data which show standard deviations as large as the mean of hydraulic conductivities for some measurements in peat soils. He also states that fields subjected to drainage do not show the marked variations in water table shape that the wide variations in hydraulic conductivity measured by the auger hole or laboratory methods would suggest should occur.

Thus it seems that more realistic values for field scale hydraulic conductivity for use in design of drainage systems should be obtained by measurement of water table positions at successive times on some fields in which drainage systems are established.

Calculation of Hydraulic Conductivity from Drain Spacing Equations. Hoffman and Schwab (1964) calculated hydraulic conductivities using a falling water table drain spacing equation and observed water table heights for lacustrine anisotropic silty clay soil in north central Ohio. They concluded that drain spacing can be determined for a stratified anisotropic soil with much less scatter using a drain spacing equation and measurements of drain discharge rate and water table positions, than can be obtained by auger hole or laboratory methods.

Hydraulic conductivity can be calculated using the steady state equation (8) if measurements of instantaneous subdrain discharge and water table height are obtained. Since it is difficult and expensive to make adequate measurements of discharge, falling water table equations such as (17), (18) or (19) may be used but a value of drainable porosity is needed.

Field Measurement of Hydraulic Conductivity in the Absence of a Water Table. Because of problems of timing, field investigations may need to be carried out in a dry part of the year when the water table is below the level of the main body of soil through which drainage water will flow. Similar problems exist with arid lands being considered for irrigation schemes. Two methods to measure hydraulic conductivity in the field under such conditions are the double-tube as used by Bouwer (1967) and the air-entry permeameter as described by Bouwer (1966).

Determination of Drainable Porosity.

Simply defined, the drainable porosity f is the volume fraction of the soil which is emptied between the conditions of "saturation" and "field capacity". Field capacity is the water content the soil retains after draining by gravity. In coarse sandy soils the saturation and field capacity water contents are well defined, (Yong and Warkentin 1966). In clay soils field capacity and saturation are not constant values (Yong and Warkentin 1966) (Childs 1970).

If ample free water is available, as may occur during periods of ponding or in moist mild winter conditions when additional rain or snowmelt occurs and evapotranspiration is small, swelling of clay soils can continue for some time, increasing both the saturation and field capacity water contents.

As a water table is lowered by subsurface drainage the water content of the soil above the water table reduces rapidly at first then more slowly as the hydraulic conductivity of the unsaturated soil decreases. From the standpoint of f values for use in drainage spacing equations, the volume of soil which is drained in the first 24 hours is the volume of prime importance. The amount of water continuing to flow down from the unsaturated zone over longer times is relatively small (Ede 1960).

The continuity in the water system above the water table can be important in supplying water to root zones by capillary movement up from the water table (Wesseling et al 1957).

It appears that estimates of the effective drainable porosity in a soil may be obtained by: 1) measuring the water content of the soil in the field when the soil is saturated, then again one or two days later when the water table has fallen, 2) by measuring the volume of outflow from a subdrain system for a measured water table drop (Hoffman and Schwab 1964) or, 3) by measuring the moisture retention characteristics of "undisturbed" soil samples with a pressure plate apparatus and taking the volume of water removed between saturation and 0.1 bar of suction to represent the drainable pore space (Richards 1965). Some authors recommend use of the water content at 0.33 bar suction to represent field capacity. Childs (1970) indicates that while field capacity may not be repeatedly measured as a particular precise amount, it is quite a high water content if not the highest desirable water content. He states "from the point of view of drainage alone there can be no such thing as over-drainage and no such thing as an excessively intense design of drainage system. One can therefore, in the absence of precise information about the agronomic consequences, adopt a reasonable factor of safety without fear of causing losses by excessive zeal".

Partially Saturated Flow

The equations presented earlier for flow to drains have been based on saturated flow. Physically, during a drainage event, water may be flowing from unsaturated soil above the water table as well as through saturated soil. Authors such as Gardner (1958), Bouwer (1959), and Sewell and Van Schilfgaarde (1963) have tried to produce solutions for flow systems including unsaturated flow. The simplest concept that has been proposed to try to account for unsaturated flow in a meaningful way in relation to drainage design makes use of the capillary fringe (Van Schilfgaarde et al (1966) Luthin (1957). The capillary fringe concept (or as Pierpoint and Farrar (1966) would call it, the equipotential zone concept) presumes transitions sharp enough for practical purposes at a height below which the soil is essentially saturated but at a pressure less than atmospheric, and above which the soil water content is sufficiently less to severely restrict flow. Childs (1972) indicates that for the majority of soils where a capillary fringe can be identified in the field it is usually found to be 10 to 20 cm in depth regardless whether the soil is a sand, silt or clay. This suggests that the depth of a capillary fringe is related more to soil structure than to soil texture. A capillary fringe of height w enlarges the flow region without increasing the head to be dissipated. Use of this concept would change the steady state drainage flow equation from (7) to

$$L^2 = (4K/R) \left[(b + w)^2 - (d + w)^2\right] \qquad (23)$$

Gardner (1962) proposed the use of a mean diffusivity for the solution of the falling water table problem. By this approach Gardner uses the water content of the soil but avoids using a water table height.

Flow to Subdrains in Layered Soils

In the cases described earlier the subdrains have been considered to be at or above the impervious layer. Many soils in the St. Lawrence lowlands have greater hydraulic conductivity in the top two feet than at greater depth. The lower soil may still have a significant hydraulic conductivity. Kirkham (1949) investigated two-layered soils for the ponded water case, where the subdrains were placed in the lower layer but the trench was backfilled with the more pervious upper layer soil. He showed that under such conditions if K_1 is constant and K_2 is reduced such that the ratio K_1/K_2 is 1, 5, 10 and 100, the relative inflow is 100, 46, 42 and 41 respectively. This shows that even with very slowly permeable subsoils almost 50% of the homogeneous case inflow can be obtained if the trench is backfilled with the material from the more pervious upper stratum.

For the case of falling water tables Schwab (1966) indicates that there is still merit in placing drains in the less permeable stratum. While water tables fall more slowly in the lower stratum the ultimate fall will be to a lower depth if drains are placed deep. This creates additional storage capacity in the soil and increases the amount of rain necessary to bring water tables near the surface. The deeper ultimate water tables also encourage deeper root growth. Bornstein et al (1967) show for a sloping fragipan soil with hydraulic conductivity decreasing with depth that subdrains at a depth of 3 ft intercepted downslope flow from the upper 5 to 7 ft of soil.

Anisotropic Soils

It is not unusual for the horizontal hydraulic conductivity K_h to be greater than the vertical K_v. For such soils the drain spacings can be wider than for a homogeneous soil of hydraulic conductivity equal to the vertical hydraulic conductivity. Simply using a transformed total hydraulic conductivity $K = (K_h K_v)^{\frac{1}{2}}$, as Maasland (1957) proposes, gives an under-estimate of the feasible drain spacing because it neglects the possible improved vertical hydraulic conductivity in the backfilled trench over the subdrains.

Mole Drains

According to Miers (1970) and Trafford (1970), the operation of mole plows in a direction across subdrain laterals has been successful in improving the drainage of clay soils and allowing wider spacing of subdrain laterals in England. It has been established in England that mole channels soon collapse in conditions where free water remains in them for a short time or where permanent water tables are very near the mole level.

According to Schwab (1966), mole drainage has not been generally effective in the United States except in parts of Louisiana and Florida. While mole drainage may yet have some application in Quebec, it is considered to be beyond the scope of this thesis.

Economic Evaluation of Subdrain Systems

The agronomic benefits of subdrains have been referred to earlier. Few specific references to the money costs and benefits have been found. Dillon, Parish and Purvis (1961) show financial benefits exceeding costs for subdrained fields growing cereal grains in eastern Ontario. They point out that drained land is a different asset than undrained land. Their study indicated; that a higher percentage of subdrained land should be devoted to grain production to get the advantages of increased profits from grain over hay; and that the higher yield potential of drained land can only be obtained with adequate fertilizing practices.

In the absence of definite agronomic requirements for a drainage system, the designer may compare the costs of alternative designs which would provide equally good removal of excess water.

Current Subdrain Design Practice

An outline of current subdrain design practice seems necessary to provide a background perspective for results presented later. This outline is due to information from literature noted and to verbal discussions with subdrain system designers.

The current practice for design of subsurface drainage systems for those flat land areas of Ontario and Quebec requiring complete gridiron systems involves the following; (Hore et al 1968, Jutras and Irwin 1970, Baillargeon 1965, 1970) 1) carry out a topographic survey and prepare a plan for the area to be drained, note possible outlet locations and controlling elevations: 2) From discussions with the farmer, and knowledge of the area, determine types of crops likely to be grown in the next 20 years. 3) From information from soil survey maps, a small number of soil samplings, and experience with drainage installations in the region, a spacing between lateral drains is selected. 4) A drainage plan is prepared, spacing drains to the area, maintaining a minimum depth of 2.5 ft and greater depths as required to maintain subdrain grades of 0.1 percent or more. 5) The flatness of the land or shallowness of the available outlets often forces the use of shallow depths and minimum grades on collectors and laterals. Hundreds of miles of deeper outlet ditches are being dug each year to help improve outlet conditions. Drainage pumps are used on a few installations where an adequately deep gravity outlet is not available. 6) Subdrain diameters are selected on the basis of having sufficient capacity on the installed grade to discharge a given drainage rate (sometimes called the drainage coefficient) from the area feeding the subdrain. Drainage rates commonly used are $\frac{3}{8}$ in/day (9.5 mm/day) or $\frac{1}{2}$ in/day (12.7 mm/day) for field crops and intensive pastures on mineral soils. Slightly higher rates $\frac{3}{4}$ in/day (19 mm/day) or 1 in/day (25.4 mm/day) are used for vegetable crops on sandy loams and organic soils. Except for a few measurements such as those reported by Hore and Gray (1957) no serious attempt is currently made to use hydraulic conductivity measurements and drainage equations to calculate drainage spacings in Ontario and Quebec. The majority of subdrains are being installed at spacings less than 66 ft between laterals in both provinces.

Ede (1971) states that when drainage designers adjust spacings from a regional norm to account for some apparent difference on a particular farm they seldom make adjustments to the extent the physical soil conditions permit or require. In a region where the norm is a 60 ft (18 m) spacing there are some systems installed with drains at 80 ft (24 m) spacings when 200 ft (60 m) spacings would suffice, and other systems with spacings of 50 ft (15 m) when the spacing should be 25 ft (7.5 m) because of very low soil hydraulic conductivity.

Van Beers (1965) and Van Schilfgaarde (1970) indicate that in the Netherlands auger hole methods are used to obtain K values and locate layers of different hydraulic conductivities. Then drainage equations such as those given earlier are used to select drain spacings for the feasible depths. Some adjustment is then made for field shapes and other local conditions. From analyses of many years of weather and water table height records, the design drainage rates recommended are 7 mm/day (.275 in/day) for field crops. Higher drainage rates may be used for high value vegetable crops.

In England very few hydraulic conductivity determinations are made. Depths and spacings are selected by designer experience (Miers 1970). Drainage rates are adjusted somewhat to account for greater rainfall excesses in the regions of the country having higher rainfalls. Much drainage work is done on gently undulating land with systems with short laterals. Much use is now being made of mole drains and subsoiling as secondary drainage treatments across subdrained land.

Practices in the United States of America vary widely with climatic regions. The procedure for flat lands in Ohio, Michigan, Illinois and Indiana is essentially the same as described above for Ontario and Quebec.

CHAPTER III

THE EXPERIMENTAL FIELDS

To assess the performance of subsurface drains and the usefulness of some of the theories of flow to drains in designing subsurface drainage systems for this region it was decided to conduct field experiments on two soil types. The soils selected were; Ste. Rosalie clay and Soulanges fine sandy loam. These two soils represent respectively poorly drained clay and imperfectly drained sandy loam soils in the St. Lawrence lowlands. A situation for intermediate drainage cases might be inferred by judgement from observations on these soils.

Location

Arrangements were made to rent land from two farmers located near St. Clet in Soulanges County, Quebec, about 20 miles west of the Macdonald Campus. The co-operating farmers were Mr. Paul Emile Vincent with a Soulanges fine sandy loam soil and Mr. Jean Paul Martineau with a Ste. Rosalie clay soil. The location of their farms is shown on the regional map, Figure 4.

Description of the Soils

Both Ste. Rosalie clay and Soulanges fine sandy loam cover a large area in Soulanges County. Lajoie and Stobbe (1950) showed 11,546 acres or 13.4% of the County to be occupied by Soulanges fine sandy loam and 26,674 acres or 32.6% of the County by Ste. Rosalie clay. There are very large acreages of Ste. Rosalie clay soil in other counties in south-western Quebec. Ste. Rosalie clay has much in common with Rideau clay and other clay soils prevalent in the Ottawa and St. Lawrence lowlands. The Soulanges fine sandy loam is similar to some other sandy loams which are shallow over clay in this region.

The general descriptions of the Ste. Rosalie clay and Soulanges fine sandy loam as given by Lajoie and Stobbe (1950) are reproduced in Appendix Tables B1 and B2.

Particle Size Analyses

The particle size distributions presented in Figures 5 and 6 were obtained by standard hydrometer particle size analyses from typical samples taken at the depths stated on the graphs. The textural classification and the proportions of the samples falling in the clay, silt and sand size fractions are given in Appendix Tables B3 and B4.

From observations along 5,000 ft of trench on the Vincent farm, the Soulanges fine sandy loam was found to have a depth of 20 to 28 inches above a relatively structureless clay. There is more coarse sand in the 15 to 24 inch deep stratum than in the top soil. The top soil is a fine sandy loam with enough clay and silt size material to be greasy when moist and to restrict infiltration rates.

Bulk Densities

In Table 1 are presented bulk densities measured in the fields by taking three samples at each depth, in a 10 cm diameter "undisturbed" sampler, from the sides of pits dug at each of the two farms.

The values in Table 1 show that the bulk density increases with depth from the topsoil into B horizon. There is then a marked decrease in bulk density in the C horizon below 25.5 inches (65 cm). The clay generally becomes softer and wetter below that level.

TABLE 1

Bulk Densities of Soils on Martineau and Vincent Farms. g of dry soil/cc of field volume

Depth inches	Vincent Farm Soulanges fine sandy loam	Martineau Farm Ste. Rosalie clay
1.0 - 4.0	1.30	1.12
4.5 - 7.5	1.33	1.29
7.5 - 10.5	1.50	1.51
10.5 - 13.5	1.53	1.36
16.5 - 19.5	1.48	1.32
22.5 - 25.5	1.43	1.36
28.5 - 31.5	1.13	1.31
34.5 - 37.5	1.12	1.33

Climate

Some impression of the general climate of the region may be gathered from the following data from the weather observations at the Montreal International Airport for the 27 years, 1942 - 1968, (Powe 1969).

Mean Annuam Maximum Temperature 51.8°F

Mean Annual Minimum Temperature 35.7°F

Mean Annual Temperature	43.8°F
Maximum observed Temperature	96.3°F, Aug. 1944
Minimum observed Temperature	-35.6°F, Jan. 1957
Mean Annual Rainfall	28.28 in
Mean Annual Snowfall	99.1 in
Mean Annual Total Precipitation	38.19 in
Greatest Annual Total Precipitation	47.65 in (1954)
Least Annual Total Precipitation	30.80 in (1964)
Greatest Monthly Precipitation	8.49 in (June, 1943)
Least Monthly Precipitation	0.02 in (Aug. 1957)
Greatest Monthly Snow	52.4 in (Feb. 1960)
Greatest 24 hr Rainfall	2.85 in (5th July 1958)
Average number of days per month with .01 in or more precipitation	13 days
Average number of days per month with .25 in or more precipitation	4 days
Average growing season	Apr. 15 - Nov. 3.
Frost Free period	May 4 - Oct. 6, 155 days
Growing degree days above 42°F	3463
Mean May to Sept. precipitation	18 in
Mean Total Annual Potential Evapotranspiration	23 in
Mean Annual Surplus of Precipitation over Potential Evapotranspiration	15 in

Summaries of the monthly air temperatures and precipitation for the 30 years of records available at Montreal International Airport and of the records taken at the Vincent and Martineau Farms during the past 6 years are given as Tables B5 to B11. These tables show that 9 out of the last 13 years have had total annual precipitations less than the 30 -year mean annual value. The summaries of data for the Vincent and Martineau stations indicate mean monthly and mean annual precipitations roughly equivalent to those at Montreal International Airport. The records from the Montreal International Airport will give a good indication of the annual totals which have occurred in the past 30 years and which may be expected to recur in Soulanges County. In August 1965 before the records commenced at Martineau and Vincent stations more than 9 inches of rain fell at Valleyfield and Ormstown to the south of St. Clet. This large rainfall caused much difficulty and losses in the 1965 harvest operations. The mean monthly temperatures are slightly lower at Vincent and Martineau stations than at Montreal.

Surface Geology

Except for the top of Rigaud Mountain, most of the area of Soulanges and Vaudreuil Counties has been under the water of the Champlain Sea. In the locale of Martineau and Vincent farms sediments deposited in the marine Champlain Sea have filled former valleys and left a flat terrain grading gently towards the St. Lawrence river. From maps provided by Tremblay (1961) it is deduced that the depth of sediment over bedrock is about 120 ft (36 m) at the Martineau Farm and about 70 ft (21 m) at the Vincent farm. The level of the land is not greatly above the level of Lake St. Francis and the St. Lawrence River. These features combined with an annual precipitation excess over evapotranspiration from 8 to 25 in (203 to 635 mm) gives a situation with water tables at, or near, the soil surface in the spring of the year, and never many feet below the surface. Seepage from the higher land to the north may tend to maintain ground water levels in the region of these farms and may even create artesian conditions in some lands in this area.

The Drainage Installations

Plans of the experimental fields are given as Figures 7 and 8. The main areas involved in the work described in this thesis are the subsurface drain depth and spacing experiment and the subdrained and surface drained water balance plots. Concurrent field experiments were carried out by persons from the Department of Soil Science involving soil fertility and cultural practices studies.

In addition an area to the north of that shown on Figure 7 on the Martineau farm was used to observe falling water tables in a field with widely spaced parallel subdrains.

Martineau's Farm

The section of the Martineau Farm with the main drainage installations, as shown in Figure 7, is relatively flat with the general gradient in a southerly direction of about 2 ft per 1,000 ft. The soil is a Ste. Rosalie clay developed from the clay parent material. It is rare that the water table is deeper than about 4 ft (1.2 m) below the general land surface. A perennial stream, a tributary of the Rouge river, flows along the east side of Highway 3A. The summer level in this stream is about 3.6 ft (1.1 m) below the general land level. A tributary of this stream flows along the northern boundary of the Martineau Farm, as shown on Figure 24 . The summer level in this stream is also about 3.6 ft (1.1 m) below the general land level. The lowest level to which water would drain by gravity from the experimental field is thus about 3.6 ft (1.1 m) below the general land level. Since the soil is a clay and there is very little lateral gradient toward the stream, the water table recedes only slowly to the stream level in periods following snowmelt or rain. In order to provide adequate outlet for the subdrains installed on this farm, a pump had to be installed at the location shown on Figure 7. During periods when the snowmelt or rainfall rate exceeds the infiltration rate surface runoff flows southerly over the surface of the whole field. Prior to the establishment of the field as an experimental field, this surplus runoff would gradually concentrate towards the dead furrows of the former ploughing. At intervals of about 300 ft along the length of the field, shallow cross furrows (rigoles) directed some of the surface runoff to line ditches on either side of the field.

As shown on Figure A1 the natural water table in mid summer only reached levels of about 3.6 ft (1.1 m) deep except in the areas where the tiles were 4.5 ft (1.4 m) deep or deeper. Some water flowed through tiles to the pump every day of the year. The main collector tile line reached a depth of 5.5 ft (1.7 m) near the pump.

The tiles were installed in the Martineau Farm in early December 1965, under very difficult conditions. The first collector was installed in good condition but that night 10 inches of soft wet snow fell. During the subsequent 10 days while the installation was being made there was intermittent rain and snow with freezing at nights. The soil was saturated very nearly to the surface. Water flowed out of the tiles continuously during the installation process. No filter material was used. The tiles were blinded with 6 in (15 cm) or more of top soil containing dense sod roots. Then the wet soil was pushed from the spoil bank left by the trencher into the trench with a front end loader. Backfilling was done the same day as the trenching to prevent freezing of the spoil bank. Under the very wet digging conditions it was feared that the action of the digging wheel would smear the clay soil badly and perhaps reduce the flow rate toward the drains. As will be seen from observations reported later the subdrains performed very well in spite of these bad installation conditions. Fortunately the field was in sod at the time of the installations.

No crops were planted during 1966. The fields were cultivated several times for weed control and a land smoother was used to remove most of the micro-relief remaining from former land use.

Martineau Subdrain Depth and Spacing Experiment Layout. In order to provide efficient use of experimental land and reduce the problems due to variation in environment, the subdrain systems were designed with diagonal tile lines between parallel tile lines giving a spacing which varies continuously from 120 ft to 20 ft (36.6 m to 6.1 m). To investigate the same range of spacing using parallel drain systems at discreet spacing intervals of 20 ft (6.1 m) would have required approximately ten times as much land, even with only a modest amount of buffering for boundary effects.

Each depth treatment had an essentially constant depth of tile for 250 ft (76.2 m). Then there was a 50 ft (15.2 m) stretch where the tile grade was changed to permit the next depth treatment to have constant grade at the new depth. New shallow rigoles were ploughed in at the mid-point of this 50 ft (15.2 m) grade change buffer zone. It was hoped that these cross furrows would intercept surface runoff occurring from each depth treatment main plot and thus prevent surface runoff from one plot affecting the water to be handled by the drains on the next plot. By this arrangement it was expected that the water to be transmitted through the soil and carried by the drains would be merely that surplus rainfall or snowmelt occurring on the specific area of each individual depth treatment main plot. For the duration of the experiment there was no indication of surface runoff from one main plot to the next during the growing season. During the short snowmelt interval some overland flow did occur when line ditches and rigoles were still filled with snow and ice dams.

The range of spacings was selected for the following reasons:

1. On the clay soil, 20 ft spacings could be considered a practical minimum for almost any soil and cropping situation even though calculations using hydraulic conductivity values given by Warkentin (1965) for some Ste. Rosalie clay soils would indicate that spacings even less than 20 ft might be needed.
2. In practice in Soulanges County some systems have been installed for alfalfa and maize crops on Ste. Rosalie clay with spacings of 40 to 45 ft.
3. Some textbooks and technical bulletins recommend spacings of 30 to 60 ft for clay soils (Schwab 1966, Hore 1968).
4. Both the steady state and the falling water table theories for flow to drains in homogeneous soils indicate that for a given water table depth at mid-spacing the drains may be spaced wider if they are installed deeper.
5. Much of the subsurface drainage tile is installed in Canada as shallow as $2\frac{1}{2}$ ft, or less, due to tradition carried over from when tile trenches were dug by hand. Contractors are not keen to alter this practice as shallow digging is easier than deep digging. Trenching machines are now available which can easily dig $5\frac{1}{2}$ ft deep in stone-free soils. While future research might indicate economic benefits from even deeper drains, these experiments were restricted to the depths of $2\frac{1}{2}$ ft, $3\frac{1}{2}$ ft, and $4\frac{1}{2}$ ft. The depth of $2\frac{1}{2}$ ft was a practical minimum and $4\frac{1}{2}$ ft a practical maximum as a depth increase

from $4\frac{1}{2}$ ft to $5\frac{1}{2}$ ft was required to provide the gradient to convey the drain water from the experimental area to the pump.

6. In view of 40 ft spacings currently recommended for subsurface drainage systems in clay soils, a spacing of 120 ft was expected to provide very little improvement from an area having no subsurface drains.

The diagonal tile line between the two parallel lines provided two replicates at each depth. In the south-east corner of the field at the farthest possible distance from the subsurface drains and within the same field, plots of maize were grown to compare the yields with those obtained from the plots on the subsurface drained land.

Martineau Water Balance Plots. To provide excellent subdrainage for the Soil Science cultural practices and fertility experiments, and for the subdrained water balance plot, parallel drains at a spacing of 40 ft (12.2 m) were installed at a depth of approximately 3 ft (.9 m). A collector drain was installed at a depth of 5 ft (1.52 m) to provide the necessary drop for the 30° V notch weirs installed to measure the flow from the two tile lines in the subdrained water balance plot. A plastic sheet cut off 0.006 in (.15 mm) thick was installed to a depth of 4 ft (1.2 m) in a trench dug by the subdrainage trenching machine. From work reported by Hoffman and Schwab (1964) and others it was indicated that the main leakage affecting a subsurface drainage plot was likely to occur through the more porous top soil. The cut off was then placed at the mid-spacing between drain laterals so that there would be a minimum hydraulic gradient in the ground water between the sides of the plastic cut off. Above the plastic sheet a dike approximately 1 ft (.3 m) above land level was created by grading adjacent soil. The dike and plastic cut off sheet defined the drainage area of the water balance plot.

The dike prevented surface flow entering the plot from outside and the plastic cut off limited the area supplying flow through the soil to the subsurface drains.

The plot is called a water balance plot because of the facilities included to measure subsurface and surface runoff as well as soil moisture changes.

A plot of the same size but with surface drainage only was diked off as shown in the south-west corner of the field.

Vincent's Farm

Vincent's Farm is very flat land with about 2 ft of sandy loam deposited over clay which extends to great depth. It is rare that the water table is deeper than six feet below the ground surface. As shown on Figure 8, surplus surface water is removed from the fields by rigoles to a line ditch running down the south side of the experimental field to the main watercourse. The watercourse has a very mild gradient of about 1 ft in 2500 ft in a south-easterly direction. The bottom of this watercourse is about 5 ft (1.5 m) below the general land level. The summer water table is about the same level as the bottom of this watercourse. Another watercourse to a slightly greater depth exists 3,000 ft (900 m) to the west and one of about the same depth exists on the east side of St. Emmanuel Road. These watercourses establish the lowest level to which water drains by gravity. The clay substratum continues for considerable depth (perhaps the 70 ft to bedrock) and the distance to significantly lower land is several miles so that deep seepage is of little consequence in lowering the water table. In very dry seasons evapotranspiration and removal of water from wells may lower the water table slightly below the bed of these watercourses. During the snowmelt period in late March and early April of most years, the whole of the land is flooded to a depth of a few inches until the watercourses are able to carry off the surplus water. As a result of the high springtime level in the watercourses, it was necessary to instal pumps to provide free outflow from the subsurface drains. Subsurface drains were then installed as shown on Figure 8. To provide excellent subdrainage for the soil science cultural practices and fertility experiments and for the subdrained water balance plot parallel drains at a spacing of 50 ft were installed at a depth of approximately 3 ft (.9 m). Some subdrainage systems with a spacing of 60 ft (18.2 m) have been installed on farms in the region having a similar soil. A collector drain was installed to a depth of 5 ft (1.5 m) to provide the necessary fall for the 30° 'V' notch weirs installed to measure the flow from the subdrained water balance plot.

The subdrains were installed with good digging conditions in late November, 1965. November was dry after an exceptionally wet August and September. A small amount of water proceeded to flow from the clay subsoil into the drains immediately upon digging the drainage trenches. Fibreglass filter material was laid over the tiles immediately following the trenching machine and the tiles were blinded with 6 inches or more of top soil containing sod roots before the spoil bank left by the trencher was graded in.

<u>The Subdrain Depth and Spacing Experiment Layout</u> on the Vincent Farm is shown in Figure 10. The layout is similar to that on the Martineau Farm except that the drain spacings were increased up to 200 ft. The 200 ft spacing represents a spacing about three times as great as currently practiced and was expected to reach a situation of providing inadequate drainage. Because of the need to dig for grade, the deepest replicate has drains at approximately

4 ft (1.2 m). The shallowest replicate was installed with subdrains at approximately 2 ft (.6 m), the depth of the sand/clay interface.

Water Balance Plots were set up on the Vincent Farm similar to those on the Martineau Farm. The plot locations and drain installations are indicated on Figure 8.

CHAPTER IV

WATER TABLE OBSERVATIONS ON THE SUBDRAIN DEPTH AND SPACING PLOTS

Water table levels within the subdrain depth and spacing experimental areas on both Vincent and Martineau farms were observed in 1967 and 1968. In order to observe the performance of the system for water tables falling from the soil surface, without the delay and expense of waiting for a wet season, the fields were irrigated to bring the water table up to the surface.

Much of the work of obtaining the water table observations presented in this chapter was carried out by Mr. Christopher Tu. Details of procedures and problems are described in his M.Sc. Thesis (Tu 1968). Some of the results from his work are reproduced here because they are relevant to later work carried out by the author and reported later in this thesis. Acknowledgement is made on those figures reproducing information given by Tu (1968). The discussion in this chapter is the author's own.

Methods and Equipment

In the autumn of 1966 water table pipes were installed at the locations indicated in Figures 9 and 10. In each replicate, three spacings were chosen for the water table measurements. For each spacing three water table pipes were installed, one at the mid-spacing and one 1/6 spacing from each tile line. Schwab and other researchers have indicated the need to keep water table pipes and piezometers of the smallest practical diameter in order to minimize response lags. Since the whole volume in the pipe must be filled with water which flows into, or out of, the drainable pore space of the soil, the water level in the pipe could be expected to rise and fall slightly slower than was actually occurring in the soil.

The smallest practical pipe was found to be $\frac{1}{2}$ in standard steel pipe. The bottom of the pipes were sealed with corks. The water table pipes were perforated with four rows of 3/16 inch diameter holes at 6 in intervals along their length. Alternate rows were displaced by 3 inches. To avoid sealing of holes with silt, the tubes were covered with cloth.

An auger just slightly larger than the pipe was found to smear the clay soil excessively, giving a danger of reduced hydraulic conductivity near the pipes, and hence response delays. To minimize this problem a 2 in (5 cm) diameter hole was augered six inches deeper than the bottom of the pipe and the cavity below and around the pipe was filled with sand. The larger auger increased the flow area and the sand reduced the volume of water needed for response.

In 1967 the mid-spacing water table pipes were six feet long and the other water table pipes were one foot longer than the depth of tile in that plot. In 1968, 6 ft (1.8 m) long pipes were used to trace the water table below the tile depth at most pipe locations.

Water table levels were determined by a blow tube. A centimeter scale was glued to a $\frac{1}{4}$ in (6.25 mm) O.D. copper tube. A few feet of $\frac{1}{4}$ inch I.D. plastic tube was used to connect the copper tube to a mouthpiece. In measuring the water table, the copper tube was inserted in the water table pipe and lowered slowly while blowing through the plastic tube. The location of the water table was sensed by the sound of air bubbling through the water and the change in pressure upon entering the water. The depth through soil to the water table was measured by reading the scale on the copper tube opposite the top of the water table pipe. This technique of measuring of the water table is accurate to $\pm$ 0.25 cm (0.14 in). The elevations of the tops of water table pipes were determined with an engineer's level and the heights of the pipe tops above ground were also measured. By appropriate arithmetic the elevations of the water table and its depths below the ground surface were determined.

Water table pipes were flushed out with a knapsack sprayer with a plastic tube attached in place of the sprayer nozzle. When the pipes were filled with water, drawdown to depths of 3 ft or more occurred in 3 minutes or less, showing that the flow of water out of the pipes to the soil was rapid.

For the application of sprinkler irrigation, the fields were divided into three sections according to the depth of subdrains. The arrangement of the sprinklers and some of their specifications for the two fields are shown in Figures A9 and A10. The level of the water table was measured at four-hour intervals for the first two days, then at twelve-hour intervals for the next two days, and daily for the next few days until the water table fell below the subdrains.

Results and Discussion

Water Table Changes Through the 1967 Growing Season

The water table depths at mid-spacing through the period April to August 1967 for a subdrain spacing of 60 ft and depths of 2.5, 3.5 and 4.5 ft for the Ste. Rosalie clay are given in Figure A1. The mid-spacing water table depths for subdrain spacings of 20, 60 and 120 ft are given in Figures A2, A3 and A4 for subdrain depths of 2.5, 3.5 and 4.5 ft respectively. Observed water table depths on the Soulanges fine sandy loam through the 1967 growing season for subdrain spacings of 20, 100 and 200 ft and subdrain depths of 2.0, 3.0 and 4.0 ft are given in Figures A5 through A8. From Figures A2 to A4 and A6 to A8 it is seen that there is very little difference in water table depth through the season for the 3 spacings of subdrains at any one subdrain depth. From Figure A1 water table depths on the Ste. Rosalie clay are seen to be consistently deeper for the plots with the deeper drains. The water table stays near the level of the subdrains for much of the season except immediately following a rainy spell such as June 16 to 25, or during a long dry spell such as July 25 to August 20 when the water table drops below the drains. From Figure A5 a similar but not as sharply defined effect is seen for the Soulanges fine sandy loam.

From Figures A17 through A22 it is seen that the water table drops more rapidly for narrowly spaced subdrains than for the wider spaced subdrains in the first 48 hours after an irrigation or rainstorm.

From the data given in Figures A1 through A22 it appears that the effect of subdrain spacing on water tables is of short duration, while the longer term effects are controlled by the depths of the subdrains on these soils.

Through the growing season the depth of drains did not have as much effect on water table depth in the fine sandy loam as in the clay soil. The water tables stayed at about $4\frac{1}{2}$ ft (1.4 m) deep for much of the season throughout the fine sandy loam field. This suggests that there may be slow deep seepage to the main drainage ditches, which set a limit on water table lowering by gravity flow. Since the 1967 summer was not particularly wet, evapotranspiration may be responsible for lowering the water table to a level below the drains and nearly uniform through the field from June through to August.

Water Table Levels After Irrigation

From August 28 - 30, 1967, 6 in (15 cm) of water was applied by sprinkler irrigation to one depth treatment area at a time in Martineau's field. Water tables were raised to the ground surface. The water table depths were measured and the averages of the two replicates of observations were calculated. These water table drawdowns for three spacings for each depth are shown in Figures A11, A12 and A13.

From June 10 to 13, 1968, 5 in (12.5 cm) of water was applied to the Vincent field to bring the water table up to the surface. The results of water table drawdown across three drain spacings for each drain depth are shown in Figures A14, A15 and A16. Water table levels at mid-spacings are plotted against time after stopping irrigation for each subdrain depth in the two soils in Figures A17 to A22. The hours required for 6 in (12.5 cm) increments of water table drawdown at the mid-spacing after the end of the irrigations are given in Table 2. Since some rain occurred in the days after the end of irrigation the simple falling water table effect is partly obscurred. An indication of the probable time required for a particular drawdown if no rain had occurred during the recession period is given in brackets in Table 2. These bracketed times were estimated by subtracting from the actual time the amount of time which elapsed in the period of water table rise and fall during and after rain until a level equal to the pre-rain level was reached.

TABLE 2. HOURS REQUIRED FOR VARIOUS DEPTHS OF FALL OF THE WATER TABLE AT MID-SPACING AFTER END OF SOIL SATURATING IRRIGATION.

	Clay			Fine Sandy Loam		
Draw-down ft	Drain Depth ft	Drain Spacing ft	Time hrs	Drain Depth ft	Drain Spacing ft	Time hrs
0.5	2.5	20	3	2	20	2.5
	2.5	60	3.5	2	100	11
	2.5	120	7.5	2	200	14
	3.5	20	2	3	20	2.8
	3.5	60	4	3	100	8
	3.5	120	5.5	3	200	14
	4.5	20	1.5	4	20	2
	4.5	60	3	4	100	2.8
	4.5	120	6	4	200	3.5
1.0	2.5	20	7	2	20	5
	2.5	60	9	2	100	32
	2.5	120	16	2	200	37
	3.5	20	4.5	3	20	5.5
	3.5	60	10	3	100	16.5
	3.5	120	13	3	200	21
	4.5	20	3	4	20	4
	4.5	60	7.5	4	100	(6) 23*
	4.5	120	11	4	200	(9) 30*
1.5	2.5	20	15	2	20	9
	2.5	60	17	2	100	45
	2.5	120	33	2	200	(57) 85*
	3.5	20	12	3	20	9
	3.5	60	15	3	100	22
	3.5	120	20	3	200	(32) 72*
	4.5	20	4.5	4	20	(10) 28*
	4.5	60	10.5	4	100	(18) 35*
	4.5	120	16	4	200	(19) 40*
2	2.5	20	38	2	20	15
	2.5	60	50	2	100	(59) 96*
	2.5	120	(63) 95*	2	200	(70) 98*
	3.5	20	20	3	20	12
	3.5	60	21.5	3	100	(32) 68*
	3.5	120	48	3	200	(42) 82*
	4.5	20	8	4	20	(21) 39*
	4.5	60	15	4	100	(37) 54*
	4.5	120	21	4	200	(50) 71*
2.5	2.5	20	(155)204*	2	20	36
	2.5	60	(126)168*	2	100	(78)115*
	2.5	120	(202)236*	2	200	(95)123*
	3.5	20	36	3	20	27
	3.5	60	48	3	100	(48) 84*
	3.5	120	(85)117*	3	200	-
	4.5	20	12	4	20	(40) 58*
	4.5	60	21	4	100	(71) 88*
	4.5	120	(30) 52*	4	200	(74) 95*

* Indicates time for water table to fall was increased by rain which fell after the end of irrigation. Numbers in brackets indicate estimated times for the given water table fall when the effect of rain is subtracted. See graphs.

It is noted that in all replicates, even at the wider spacings, the water table fell very rapidly. The maximum time to fall 6 in (15 cm) was 7.5 hours on the clay and 14.5 hours on the fine sandy loam. The mid-spacing water table fell 12 in (30 cm) in 16 hours or less on the clay and 37 hours or less on the fine sandy loam. The longest times were for the very wide spacings and shallow depths. Since some authors have suggested that a drawdown of 12 inches in 24 hours gives adequate drainage, it would appear from these observations that adequate drainage could be provided by spacings as wide as 120 ft (36.4 m) on the clay and about 200 ft (61 m) on the fine sandy loam where the tile depth is 3 ft (.9 m) or more. The drawdown was most rapid in the sections with the deepest drains. On the Ste. Rosalie clay the rate of fall of the water table after the end of irrigation was much faster than would have been expected from calculations using K values reported for some Ste. Rosalie clays by Warkentin (1965) and the apparently reasonable, though slightly conservative, assumptions that f = 0.05 and that the soil could be considered to have much lower hydraulic conductivity at depths below 6 ft (1.8 m) than in the 0 - 6 ft (0 - 1.8 m) depth zone.

The relatively rapid fall of the water table could be due to some of the following reasons:

1. The effective field hydraulic conductivity could be much larger than that reported by Warkentin (1965) for laboratory permeameter and field auger hole measurements on some other Ste. Rosalie clays.

2. There may be significant flow at depths greater than 6 ft (1.8 m).

3. The drainable porosity might be less than the assumed 0.05 especially at depths below the topsoil.

4. With the experimental drain layout used, different rates of water table

drawdown between narrow spacings and wide spacings created a compound hydraulic gradient which would cause slight flow from the wide spacing areas toward the narrow spacing areas.

5. Hydraulic conductivity changes through the seasons, due to shrinking and swelling of the clay, formation and melting of ice lenses and plant root growth.

6. The soil may not have been completely saturated during irrigation. Air may have been trapped in the soil profile below the water table and escaped gradually after the end of irrigation.

7. A portion of the water removal may be due, not to tile drainage, but to evapotranspiration, deep percolation, and lateral flow. Van Schilfgaarde et al (1954), Schwab et al (1957) and Laliberte (1962) indicated that these factors had some effect on their field experiments. The effect of evapotranspiration would apply primarily in the second day and later, as water on the maize leaves and from the very wet topsoil would meet most of the evapotranspiration demand in the first 24 hours. Calculations indicate that evaporation could account for 25% of the water table fall observed between the second and fifth days after irrigation. Deep percolation should have been negligible because the permanent water table was only 5 ft (1.5 m) below the soil surface before irrigation was started.

On the Soulanges fine sandy loam the water table also fell more rapidly than would have been expected. Reasons for this could include the same effects suggested above for the Ste. Rosalie clay case.

While an effective field value of K can be estimated from these falling water table data, values for f and d_e would still need to be assumed. Accordingly, further treatment of this matter is left until measurements of f are presented and discussed.

These water table observations do indicate that the water table performs in a reasonable manner, with less variation in readings than could have been expected. The water table takes an elliptical shape with presumably a steep gradient near the drain. The drains had ample capacity to allow free outflow but soil flow restrictions near the drains could have caused the water table over the drains to be higher than drain level. There were no water table pipes beside the drains to provide observations on this point.

CHAPTER V

DRAINABLE POROSITY DETERMINATIONS

The drainable porosity is an essential factor for the use of falling water table equations to estimate required drain spacings. The concept of a percentage of a soil volume being filled with air as the soil is drained from saturation to field capacity is appealing in simplicity. Unfortunately, in a soil profile in the field the drainable porosity percentage may vary with depth. Also, the soil moisture content does not change from saturation to field capacity abruptly at the water table level. It changes gradually as the pore water tension increases above the water table. The depth of this transition may also be different when the profile is draining than when it is recharging, as indicated by the hypothetical moisture profiles for a soil with uniform moisture retention characteristics given as Figure 11.

It has been suggested by Ede (1960) that if one merely observes the amount of water table rise following a rain which occurs at a time when the soil is at field capacity, the drainable porosity can be determined as

$$f = \frac{\text{rain depth}}{\text{water table rise}}$$

Alternately, if one measures the amount of water drained out for a given water table drop the drainable porosity of a portion of the profile can be determined as

$$f = \frac{\text{drain outflow depth equivalent}}{\text{water table drop}}$$

These approaches may be close enough for practical drainage purposes, but one can reason that they are inaccurate if the shape of the moisture profile depends on whether the soil is draining or recharging.

Referring to Figure 11 which represents a soil whose moisture holding characteristics did not change with depth it would appear that due to the parallelism of the water content curves shown for different times t the drainable porosity could be estimated reasonably as

$$f = \frac{\text{drainage outflow depth equivalent for } \Delta t}{\text{water table drop in } \Delta t}$$

$$\text{or} \quad f = \frac{\text{rain depth in } \Delta t}{\text{water table rise in } \Delta t}$$

providing the first interval of Δt were not used. In both cases the adjustment of the slope of the moisture profile which takes place in the first time interval gives rise to a proportionately greater change in water table level for a given volume of water added, or drained away, than in the later time increments.

Since the soils in their field position might not fit the simple model described above, estimates of drainable porosity were made by : 1, laboratory measurements of the water content of soil samples for different moisture tensions; 2, measuring the water in the profile with a neutron moisture meter at various times as the water table dropped; 3, measuring the drain outflow and water table changes with time; 4, using observed rises of the water table following rains.

Drainable Porosity from Laboratory Moisture Retention Measurements

Materials and Methods

Four "undisturbed" samples were taken at depths of 3, 12, 18, 24 and 30 in (7.5, 30.5, 45.7 and 61 cm) from the periphery of pits dug on each of the two farms. The samples were taken by carefully pressing thin walled aluminium rings into undisturbed soil after the soil above it had been carefully removed to the sample depth. The rings containing samples were then dug out, trimmed and placed in plastic bags to retain moisture. The rings were approximately 2 in (5 cm) in diameter and 0.52 in (1.3 cm) high for the clay samples and approximately 1.2 in (3.0 cm) diameter and 1.6 in (4.0 cm) high for the fine sandy loam samples.

The samples were carefully transported to the laboratory. Equilibrium moisture contents were determined with a pressure vessel apparatus for pressures of 0.10, 0.33 and 15 bars. The normal procedure for water retention tests of "undisturbed" field samples as described by Richards (1965) was followed. Two samples from each depth at each farm were subjected to 0.10 and 0.33 bars pressure at successive times. The other two samples from each depth at each farm were subjected to 0.10 and 15 bars pressure at successive times.

Results and Discussion

The mean values of the moisture contents measured for the standard equilibrium pressures are given in Table 3. In that table are also presented the saturation water contents obtained by calculating the volume of voids in each sample from the sample dimensions and the weight of dry soil. The moisture contained by the samples at the time they reached the laboratory is presented as the "initial" moisture content. This moisture content should be relatively close to field capacity as it would exist in the field. The samples were taken on October 25, 1970. There had been approximately 1.08 inches of rain from October 21 to 23. The rain earlier in October would be approximately equal to the evapotranspiration. There was a surplus of about 2 inches of rain above the evapotranspiration demands in September which would replenish

TABLE 3. SOIL MOISTURE CONTENTS PER CENT BY VOLUME OBTAINED WITH PRESSURE ~~PLATE~~ APPARATUS.

Soil and Location	Sample Depth ins.	m	Moisture Per cent by Volume for Pressure Conditions Indicated: Saturation (1)	Initial (2)	0.10 Bar (3)	0.33 Bar (4)	15 Bar (4)	Sat - 0.10 Bar: means	σ	Sat - Initial: means	σ	"Available" Water: 0.10 Bar-15 Bar	Initial-15 Bar
Ste. Rosalie	3	.075	53.9	41.1	39.2	37.1	36.2	14.7	2.9	12.8	1.7	3.0	4.9
Clay Martineau	12	.30	46.0	35.8	36.9	36.1	32.2	9.1	3.6	9.2	2.9	4.7	3.6
Farm	18	.45	46.1	38.0	39.2	37.8	35.4	6.9	4.1	8.1	3.4	3.8	2.6
	24	.61	46.9	37.9	38.9	37.6	35.8	8.0	3.7	9.0	2.1	3.1	2.1
	30	.76	43.7	42.7	42.8	41.4	40.5	0.9	0.8	1.9	0.2	2.3	2.2
	mean							7.9		8.2			
Soulanges Fine	3	.075	40.2	36.0	32.6	26.2	24.4	7.6	7.2	4.2	2.6	18.2	11.6
Sandy Loam	12	.30	39.5	31.9	22.0	10.0	8.0	17.5	9.9	7.6	0.8	14.0	23.9
Vincent Farm	18	.45	41.6	35.8	20.8	13.8	8.8	20.8	7.8	5.8	3.0	14.0	27.0
	24	.61	52.2	42.8	42.9	40.8	38.4	9.3	2.8	9.3	0.4	4.5	4.0
	30	.76	56.1	47.9	48.0	45.4	43.4	8.1	2.2	8.2	0.6	4.6	1.3
	mean							12.7		7.0			

Notes (1) mean of 4 samples for each depth calculated from dimensions of samples.

(2) Initial water content is the water contained by the samples when they were taken on October 25, 1970.

(3) Mean of 4 samples for each depth. (4) Mean of 2 samples for each depth.

much of the moisture holding capacity emptied in the drier weather of July and August. It is possible that there had not been enough rain to bring the whole profile right up to field capacity before the soil samples were taken.

The moisture contents from the means of the samples for each depth are presented graphically in Figure 12. It is particularly noticeable that the initial moisture content, which is approximately field capacity is much higher than the 0.10 bar moisture content for the Soulanges fine sandy loam. This indicates that the drainable porosity would be seriously overestimated and the "available" water seriously underestimated if the field capacity were estimated from moisture contents measured in the laboratory at 0.10 bar suction. This bears out, in magnitudes important in the Ste. Lawrence lowlands, Richards' (1965) statement that measurements made on samples in the laboratory should be applied with caution to field situations, especially at the wet end of the moisture range.

The difference between the initial moisture content and the 0.10 bar moisture content is much less for the Ste. Rosalie Clay than for the Soulanges fine sandy loam, as might be expected from the general shape of moisture retention curves for clays and sands. The saturation minus the 0.10 bar moisture contents and the saturation minus initial moisture contents is given in Table 3. Some indication of the variability of these moisture contents is given by the standard deviations for the 4 sample differences which were used to obtain the mean differences presented in the table. The saturation minus initial moisture content is considered to be the best indication of drainable porosity as felt by the soil in the field. Even these values may be slightly high as the soil may not have been up to field capacity at the time of sampling. These observations show that if one is going to use soil samples to indicate drainable porosity the samples should be taken at approximately 2 days following appropriately large volumes of rain, or artificially applied water, for the soil to be at field capacity.

The saturation minus initial moisture content is treated as drainable porosity and plotted in Figure 13 along with drainable porosities estimated by other methods.

It is noted that the difference between the saturation and initial water contents at the 30 inch depth in the Ste. Rosalie clay is very small. It is not likely that this is due to the soil being wetter than field capacity at the time of sampling since the initial water content is practically identical with the 0.10 bar water content. The water content of the samples from this depth decreased very little when 0.33 bar and 15 bar pressures were applied. The small range of water contents obtained in samples at the 30 inch depth might be due to compaction of the soil into the sample rings. This possibility is supported by the observation that the soil is soft at this depth and observations with the neutron meter show saturation moisture contents at this depth almost always increasing with depth rather than decreasing as determined from these samples.

Drainable Porosity Determined by Soil Moisture Measurements in the Field

Methods and Equipment

Soil moisture contents were measured in situ with the Troxler neutron moisture meter at successive times following soil saturating irrigation. On the Martineau Farm one plot was located with a sod cover and one with a tall maize cover. On each plot 2 neutron meter access tubes and 2 water table pipes were installed. Tensiometers were also installed with the porous tip centers at depths of 6, 12 and 18 in (15, 30 and 46 cm). Holes, 4 inches in diameter, were augered out for hydraulic conductivity measurements. The plots were irrigated intermittently for 3 days prior to July 25, 1970. A single sprinkler watering a diameter of 140 ft (42.6 m) was used. Irrigation was stopped when the water table was at the surface. Neutron meter readings were taken every few hours to determine the soil moisture content for successively lower levels of the water table.

The same procedure was attempted at the Vincent farm on the Soulanges fine sandy loam but only enough water was available to irrigate the maize plot in October 1970. Some neutron meter readings were taken following the irrigation of the sod covered subdrained water balance plot on the Vincent Farm in June 1971.

Results and Discussion

Moisture contents determined from the neutron meter readings for the Ste. Rosalie clay on the Martineau Farm are given in Figure 14. These data are the average of the moisture contents obtained from the two access tubes in each plot except for the 0 and 10 hour amounts in the Martineau Maize plot. One access tube in this plot had to be replaced as the probe occasionally stuck.

From Figure 14 it can be seen that the saturation moisture content is not constant with depth. Perhaps little attention should be given to the water contents at the 6 in (0.15 m) depth as there is the known likelihood of neutrons escaping to the atmosphere with probe depths less than about 12 in (.3 m). The moisture content below the 48 in (1.2 m) depth should have been the same at all observation times since the soil was saturated below this depth throughout the observation period of 145 hours. However there is a variation of up to 5% moisture content at and below the 42 in (1.2 m) depth.

Comparison of the neutron meter observations in Figures 14 and 16 with the moisture retention sample data in Figure 12 shows saturation water contents as determined by the neutron meter about the same as those obtained by the "undisturbed" samples at the 30 in (0.77m) level for clay beneath the Soulanges fine sandy loam. However on the Ste. Rosalie clay site the neutron meter gives much higher water contents from the 18 to 30 in (0.46 to 0.77 m) depths than do the "undisturbed" samples. This difference could be due to some compaction of the "undisturbed" samples during sampling, and to an erroneous neutron meter calibration. The accuracy of the calibration of the neutron meter for absolute moisture contents above 40% is expected to be somewhat less than the claimed accuracy of $\pm$ 1% below 40% water content (Troxler 1968). However, since the same calibration curve was used for all measurements, the accuracy for differences between moisture contents should be quite good even if there is error in the total moisture content values.

Since the water table was at the surface at the time the moisture content readings commenced, the 0 hour readings would be expected to represent a saturated soil condition. However, since the water contents at the 12 and 18 in (0.30 and 0.46 m) levels are much lower on the sod plot than on the maize plot for the 0 hour readings one might suspect some trapped air at those depths in the sod plot.

There is also an indication of trapped air or restriction of downward flow of water between the 30 and 48 in (0.8 to 1.2m) depths on the maize plot since the moisture content at 10 hours was measured to be as much as 6% greater than at 0 hours for these depths. Some of this variation might be due to the lack of a second access tube for the 0 and 10 hour observations on the maize plot. Another apparent anomaly on the sod plot is the measured moisture content at 24 hours for the 24 and 30 in (0.6 and 0.75 m) depths being much less than the 0 and 12 hour observations. The water table was measured to be at 26 in (0.66 m) at 24 hours. One possible explanation would be that the water table might not have been falling as rapidly in the water table pipes as in the surrounding soil due to smearing etc. This seems an insufficient explanation for the large changes in moisture content measured with the neutron meter.

TABLE 4

Drainable Porosities Estimated from Neutron Meter Measurements

Soil Depth		Drainable Porosity Percent of Soil Volume					
		Ste. Rosalie Clay Plots After Irrigation 1970			Soulanges Fine Sandy Loam After Irrigation		
in	m	Sod plot	Maize plot	Mean	Maize 1970	Sod 1971	Mean
6	.15	15.0	18.0	16.5	5.0	4.0	4.5
12	.30	8.0	20.0	14.0	7.6	4.0	5.8
18	.46	8.5	16.5	12.5	9.0	4.0	6.5
24	.61	13.0	12.0	12.5	10.0	8.0	9.0
30	.76	12.0	11.0	11.5	3.0	6.0	4.5
36	.91	10.0	10.0	10.0	4.0	4.0	4.0

Note: Estimates were made from water contents plotted for successive times after the end of irrigations. Estimates of the difference between the saturation water content and the water content 24 hours after the water table had receded below the indicated soil depth were scaled from the graphs.

The water table level responded relatively rapidly in these pipes when this plot was re-irrigated a few days later to measure hydraulic conductivity by the auger hole method.

Since large volume rain storms could occur over shorter time periods than the irrigation used, air could be trapped in the root zone during a rain event just as well as during an irrigation event. Thus, the difference between the water content at the time the water table is observed at a particular depth and the water content 24 hours later could be considered to be a reasonable estimate of the volume of water to be removed by a subsurface drainage system. Subdrain outflow observations presented later show that essentially all of the drainage from a horizon in the Ste. Rosalie clay and Soulanges fine sandy loam soils occurs within 24 hours of the water table receding to a depth of about 8 inches (.20 m) below that horizon.

Accordingly, subtraction of the 24 hour later value from the value at the time of assumed cessation of saturation for that level has been carried out to give drainable porosities of the Ste. Rosalie clay and the Soulanges fine sandy loam. These drainable porosity values are given in Table 4 and Figure 13.

These values show a great deal of variation with depth even when averaged for the sod and maize plots in the same field. It is believed that much of this variability must be attributed to the neutron meter rather than the soil. Gravimetric sampling could be expected to give equally large variations.

The water table and tensiometer observations in the days following the soil-saturating irrigation of the sod plot are shown in Figure 15. The water table receded to a depth of about 0.8 m (31.5 in) in the first 48 hours then stayed between 0.8 and 1.0 m (31.5 and 39.3 in) for about 11 days before gradually receding further. The tensiometers were of the bourdon gauge type and could only be read with an accuracy of about 0.2 m suction, so the tension changes are probably more abrupt in Figure 15 than they were in the field in the early days of low tensions. The tensions at 6, 12 and 18 in (15, 30 and 46 cm) follow the water table depth reasonably closely for 6 days. This indicates a continuity in the capillary suction from the water table level to within 6 in (15 cm) of the surface while the water table recedes from the combined effects of drainage and evapotranspiration. From the 6th day onward the tension at the 6 in (.15 m) depth increases rapidly indicating evapotranspiration rates exceeding the rate of capillary flow from the water table. From the 10th day onward the tension at the 12 and 18 in (.30 and .45 m) depths also increase more rapidly than the water table drops. These observations suggest that the water contents as observed by the neutron meter should be very similar for times from 2 days to 6 days except for depths less than 12 in (.30 m). It might be inferred from these tension observations that deep subdrains which lowered the water table rapidly to depths of 4 ft (1.2 m) or more, and under most conditions prevented the water table from reaching closer than 2 ft (.6 m) to the surface, could provide the situation of a small soil water suction which would reduce the tendency for soil swelling and structural deterioration in the root zone and also provide some intergranular compression to increase topsoil strength and trafficability.

Soil moisture profiles obtained with the neutron moisture meter at the Vincent Farm are presented in Figure 16. The main difference from the measurements on the Martineau farm are in the top 2 ft of the profile, as would be expected because of the sandy loam in that layer. Unfortunately, the neutron meter was not functional at the time when the irrigation was stopped in June 1971. The first measurement available is at 7 hours after that irrigation stopped, by which time the water table was 11 in (0.28 m) below the surface.

Estimates of drainable porosity have been made by scaling from Figures 14 and 16 the difference between the saturation water content and the water content 24 hours after the water table had receded below the indicated depth. These estimates are given in Table 4 and plotted on Figure 13.

Determinations of Drainable Porosity from Drain Outflow Observations

Methods and Equipment

A natural drainage event following a rainfall or snowmelt might have been used for this determination. Since it was desirable not to wait many months for an appropriate drainage event, irrigation was used.

Sprinkler irrigation systems were set up on the subdrained water balance plots as shown in Figure 17 for the Ste. Rosalie clay soil and Figure 18 for the Soulanges fine sandy loam soil. Water table pipes were installed along 3 lines perpendicular to the subdrains. Discharge was determined from recordings of water levels behind 30° V notch weirs placed at the outlet of each of the two subdrains in each plot.

The irrigation sprinklers were set up with a staggered spacing to give better uniformity of distribution under the prevailing wind conditions.

Catch cans were spaced out over a section of the irrigated area to sample the uniformity of distribution. Sprinkler spacings were adjusted to give as good uniformity as possible. Rainbird 30 BW sprinklers with 9/64 in (3.57 mm) I.D. nozzles operating at a lateral pressure of 50 psi were found to provide the lowest application rate which could give reasonable uniformity of distribution. Irrigation was carried on for more than 60% of the time over a period of 5 days to give ample time for saturation of the lower parts of the soil profile. During the last 24 hours, irrigation was continuous except for short stops to refuel the pumping engine. An attempt was made to reach a steady state with the outflow rate equalling the application rate and with the water table at an equilibrium position near the soil surface at the mid-spacing between drains. This condition was essentially achieved on the Ste. Rosalie clay plot when it was irrigated July 27 to August 2, 1970. The steady state condition was not so well approximated when the Soulanges fine sandy loam was irrigated June 7 to 11, 1971.

Results and Discussion

Ste. Rosalie Clay Plot, Martineau Farm. The water table positions at successive times following the end of irrigation of the water balance plot on the Martineau Farm are shown in Figure 19. The hydrographs of outflow from the subdrains as well as the observed water table levels at the mid-spacing between the drains is given in Figure 20.

The water table pattern between the drains is reproduced only for Section B. The pattern was very similar for Sections A and C, though some pipes were showing response problems, probably due to smearing of the soil at the time of pipe placement. The pattern of drawdown between the central two drains appears realistic. The water table was about 4 cms (1.6 in) below the soil surface beneath the dead furrow at the center of the plot at the time irrigation ceased.

The water table position dropped continuously over the subsequent hours. The drop of the water table in the first 3 hours of slightly more than 9 cms

(3.6 in) at mid-spacing was quite remarkable. The rate of drop decreased with time. Flow from the tiles had ceased after 18 hours had elapsed. The water table position at that time is given reasonably closely by the line showing the 19-hour position. The water table was still above the level of the subdrains at that time at most of the water table pipes. It thus appears that some of the drainage is by deep seepage to levels below the drains either to replace air in pore spaces not previously saturated or to flow out longitudinally to drains which exist at a lower elevation many tens of feet to the south, or by deep seepage laterally under the plastic sheet barrier to the drain line on the east which serves as an outlet for the north field. Evapotranspiration could not account for more than 20% of the drop of the water table in the first 3 days following the cessation of flow from the tiles.

The response of the water table at pipes B15, B14, B13, and B1, B2 & B3 does not seem as consistent as that of the pipes B4, 5, 6, 7, 8, 9, 10 and 11. For the pipes named as inconsistent the water levels at the end of irrigation do not appear to be at a suitable elevation. Pipes 1 and 2 are in a zone which was still in rough ploughing. It is quite possible that in placing the pipes, some smearing of the soil occurred and reduced the hydraulic conductivity adjacent to the pipes. Pipe B1 must have been placed very close to the edge of the trench in which the 6 in (15 cm) collector tile carrying the drainage from the field to the north was placed. The section of that collector tile passing adjacent to this plot was placed in December when the soil was in a saturated condition. The soil in the trench was severely puddled and remoulded by the trenching and backfilling operation. Similarly, pipes B14 and B15 are in a turning strip which received a good deal of traffic when the surface soil was in a moist condition causing compaction and remoulding of the surface soil. Also, topsoil was scraped off this area to form the dikes. It is likely that the sod which exists within the drained plot itself and which has not had extraordinary traffic is partly responsible for the more uniform performance of the water levels observed in the water table pipes within the plot. It is noted that the water table does drop from all pipes at successive time intervals. Some of the non-uniformity in starting condition of water level in the pipes may be due to non-uniformity in the irrigation application. The irrigation application was monitored with catch cans and coefficients of uniformity of 70 - 80% were obtained for the area within the plot. These are as good as can be expected in a light windy condition from sprinkler irrigation. The irrigation application tapered off with distance beyond the plot boundaries.

As a steady state of outflow was approached it was remarkable how fast the outflow responded to the change in application rate when the irrigation was stopped. This suggests that the storage of drainable water in the soil was not as large as might have been anticipated.

The flow rates at the end of irrigation were 39.4 and 47.3 mm/day (1.55 and 1.86 in/day) respectively for the east and west tile lines. The total outflow from the two drains following the end of irrigation was only equivalent to 8.07 mm (0.318 in) from the plot area. Using the successive positions of the falling water table at Section B to represent the mean water table condition in the plot, the mean depths of water table drop across the drain spacing in the observed time increments were calculated. The mean of the observed outflow depths was then divided by the mean water table drop to get first approximation values of the pore space drained in each depth increment.

It was noticed that these calculated first approximation values for drainable porosity were quite low. It was also noted that the water table continued to drop at a significant rate after the outflow had ceased. This continuing drop might have been partly due to gradual release of air trapped deep in the profile and partly due to evapotranspiration as well as deep longitudinal or lateral seepage. Since the plot had been irrigated for 5 days the release of trapped air should not have been a big factor. Evapotranspiration in the first 2 or 3 days after irrigation would be met primarily from readily available soil water in the upper root zone. Thus, it might be suspected that deep seepage was the main reason for the further drop of the water table after drain flow ceased.

The rate of drop of the mean water table $\Delta h_B / \Delta t$ was calculated and plotted against the incremental mean position of the water table at mid-spacing. This graph, given as Figure 21 shows the water table drop to fall into two distinct rate zones, with the break in fall rate occurring at about the water table height at which outflow ceased. If deep lateral seepage was occurring after drain flow ceased it must have been occurring before. The seepage rate seemed to be a linear function of water table height. A linear relationship would be reasonable for a large scale seepage where Darcy's law applied. Projection of the deep seepage rate line shows a zero rate likely to occur when the water table reached a depth slightly less than the depth of the tile line to the east of the plastic barrier. It is thus not unreasonable to suspect that the hydraulic conductivity of this Ste. Rosalie clay is still significant to depths much greater than the barrier depth of 4 feet.

It was reasoned that the mean water table drop $\Delta \bar{h}$ is equal to a drop $\Delta \bar{h}_d$ due to flow to drains + a drop $\Delta \bar{h}_s$ due to deep seepage. The deep seepage rate line $\Delta \bar{h}_s / \Delta t$ was projected to higher water table levels to obtain values for the amounts of water table drop which might be due to deep seepage when the water table was in the upper profile. Since the water table elevation provides the potential energy to cause both the deep seepage and the flow to the drains, it seemed reasonable to consider the total pore space drained for any increment of water table drop to be made up of an increment supplying deep seepage flows and an increment supplying flow to the metered subdrains. Calculated values of $\Delta \bar{h}_s/\Delta t$, and the deep seepage component of drainable porosity are included in Table 5 as well as the second approximation of drainable porosities obtained for the profile increments.

Soulanges Fine Sandy Loam, Vincent Farm. Water table pipes and irrigation sprinklers were installed as shown on Figure 18. Irrigation was carried out intermittently over a period of 4 days to thoroughly wet the soil and then during the last 24 hours irrigation was carried on almost continuously until a near steady state condition was reached with the water table near the surface of the soil and outflow from the drains approximating the irrigation onfall. It was impossible to obtain an entirely steady state condition. At night time the irrigation rate from a 60 ft by 60 ft sprinkler spacing caused onfall at a faster rate than water would flow through the soil and out the drains, ponding occurred in the dead furrows and surface runoff began. Larger spacings of sprinklers 70 x 70 and 60 x 80 ft were tried but the coverage of irrigation on the plot was not sufficiently uniform. During the daytime the wind increased, as did the supply of solar energy. Much irrigation water was blown off the plot and irrigation with sprinkler spacings wider than 60 x 60 ft would not bring the water table near the surface or give adequate coverage on the plot. As night approached the evapotranspiration reduced and also the wind speed reduced so that the water table again reached the surface at the dead furrow at the centre of the plot at 11.00 p.m. Since it did not appear to be

TABLE 5 MEAN DRAIN OUTFLOWS, MEAN WATER TABLE DROPS AND ESTIMATES OF DRAINABLE POROSITY FOLLOWING IRRIGATION OF STE. ROSALIE CLAY WATER BALANCE PLOT, AUGUST 1970.

time t After End of Irrig. hours	Δt hours	Mean Drain Outflow in Interval mm (1)	Mean Water Table Drop $\Delta \bar{h}$ mm (2)	Drainable Porosity f First Estimate	Rate of Mean Water Table Drop $\Delta \bar{h}/\Delta t$ mm/hr	Water Table Height at mid-Spacing Line B h_B m	Average mid-spacing water table height for Δt m	Estimate Rate of Water Table Drop due to Deep Seepage $\Delta \bar{h}_s/\Delta t$ mm/hr	Rate of Water Table Drop due to Drain Outflow $\Delta \bar{h}_d/\Delta t$ mm/hr	Effective Water Table Drop due to Drains $\Delta \bar{h}_d$ mm	Modified Mean Drain Outflow mm (3)	Drainable Porosity f Second Estimate
0						.607						
3	3	4.47	121	.037	40.4	.415	.511	13.2	27.2	81.6	5.14	.063
7	4	2.54	102	.025	25.7	.313	.364	10.6	15.1	60.4	2.92	.048
11	4	.81	64	.013	15.9	.241	.277	9.0	6.9	27.6	.93	.035
15	4	.22	37	.006	9.3	.207	.224	8.1	1.2	4.8	.25	.053
19	4	.03	25	.001	6.3	.173	.190					
23	4		29		7.2	.142	.158					
27	4		22		5.4	.116	.129					
39	12		68		5.6	.034	.075					
47	8		38		4.8	-.007	.014					
69	22		73		3.3	-.093	-.050					
90	21					-.173	-.133					
117	27					-.235	-.204					
									TOTALS	174.4	9.24	

Estimate f for profile .207 to .607m above drains = 9.24/174.4 = .053.

Notes (1) Mean drain outflow in interval is the average of the discharges from the 2 tiles in the plot integrated over the interval Δt.

(2) Mean water table drop is the mean drop of the water table in the time interval as observed in the pipes across section B between the 2 drains.

(3) Outflow attributed to the area between the two metered subdrains increased by 15% over the mean drain flow to account for non uniformity of irrigation.

possible to obtain an application rate precisely equal to the outflow rate due to the complications of variable evapotranspiration and blow-off, the irrigation was shut off at 11.15 p.m., and water table pipe readings were commenced. The data on the descent of the water table after the end of irrigation are given for the observations from water table pipes on Section B in Figure 22. The response of the water table pipes on Sections A and C was very similar for the part within the actual water balance plot. There were no water table pipes on Sections A and C beyond the dikes.

The water table descent as shown on Figure 22 appears quite orderly within the plot. The response of the water table at pipes 1, 2, 14 and 15 beyond the plot boundaries is much less orderly. Something appears definitely wrong with the observations at pipe 1 since the readings for all times from 2 hours onward are the same and below the level of the tile line at that pipe. It is known that the sprinkler coverage beyond the dikes was less uniform and that irrigation tapered off rapidly beyond the dikes. The sprinkler arrangement was laid out to provide irrigation as uniform as possible within the plot and only such coverage beyond the dikes as would provide for coverage within the plot in case of a change in wind direction.

Since the water table descended very rapidly and since the outflow from the measured drains does not indicate a very large total drainable pore space, one wonders whether there might not have been some flow beyond the plot to the 5 ft (1.5 m) deep collector drain to the east of the plot or to the 4 ft (1.2 m) deep collector drain to the west of the plot, or to the lateral drains to the north and south of the plot due to the pressure differential causing seepage under the plastic barrier. The prospects of seepage were originally discounted because of the clay layer which existed uniformly in the field at a depth of about 2 ft (0.61 m) below the surface. This clay layer appeared relatively unstructured when examined at many places along the length of the trenches when the subdrains were installed. However, the drawdown rate does appear to be sufficiently rapid to indicate a significant hydraulic conductivity in the clay beneath the fine sandy loam.

The quick response of this soil to rainfall or irrigation is indicated by Figure 23 which shows the mid-spacing water table positions and drain flow hydrographs following irrigation. It is noted that the discharge rate begins to fall off as soon as irrigation is stopped and begins to increase very shortly after irrigation has started. The discharge then increases as the water table height increases until both approach a maximum. It is noted that the discharge from the north tile starts to decrease immediately on the cessation of irrigation whereas the discharge from the south tile continues at a near constant rate for approximately 1 hour after irrigation and then proceeds to drop rapidly. This 1-hour period is approximately the same as the time during which tiny pondings of water ceased to be in existence on the plot surface. In the periods from about 2 hours after the end of irrigation onwards the water table showed the essentially elliptical shape between the two subdrains in the plot. During the time from 0115 hr June 12th until 1015 hr June 12 the evapotranspiration should not have taken any water from the soil because until that time there was ample free water on the vegetation remaining from the irrigation and from dew. For times after 1015 hr on June 12, it is possible that the evapotranspiration moved a little water from the drainable porosity of the soil.

Drainable porosities estimated from drain outflows for the Soulanges fine sandy loam are given in Table 6 together with time, subdrain flow, and

TABLE 6. MEAN DRAIN OUTFLOWS, MEAN WATER TABLE DROPS AND ESTIMATES OF DRAINABLE POROSITY FOLLOWING IRRIGATION OF SOULANGES FINE SANDY LOAM PLOT, JUNE 1971.

Time Hours after End of Irrig. hours	Δt hours	Mean Drain Outflow in Interval mm (1)	Mean Water Table Drop $\Delta \bar{h}$ mm (3)	Drainable Porosity f First Estimate	Rate of Mean Water Table Drop $\Delta \bar{h}/\Delta t$ mm/hr	Water Table Height at mid-Spacing Line B h_B m	Average Mid-spacing Water Table Height for Δt m	Drainable Porosity f Second Estimate (4)
0						.593		
2.0	2.0	2.90	84	.035	42.0	.556	.574	.05
6.2	4.2	3.52	180	.020	42.8	.326	.441	.03
10.1	3.9	1.40	149	.010	38.2	.205	.265	.015
12.0	1.9	.34	46	.008	24.2	.145	.175	
14.0	2.0	.20	41	.005	20.5	.078	.111	
18.0	4.0	.18	58	.003	14.5	.030	.054	
24.0	6.0	.06	23	.003	3.9	-.008	.011	
36.0	12.0	.03	68		5.6	-.070	-.039	
59.0	23.0					-.200	-.135	
		(2)						

Notes (1) The Mean Drain Outflow in the interval is the average of the discharges from the 2 tile lines in the plot integrated over the interval Δt.

(2) Drain outflow stopped at 30 hours.

(3) The mean water table drop is the mean drop of the water table in the time interval as observed in the pipes across section B between the 2 drains.

(4) Drainable porosity increased by 15% since more than the average flow comes from between the drains due to non uniformity in irrigation. Also increased by 15% to allow for deep seepage and evapotranspiration implied from water table graph.

water table data. Second estimates of drainable porosities which make allowances for non-uniformity of irrigation and some seepage losses are also included in Table 6.

Drainable Porosity Estimated from Water Table Rises Following Rains

Methods and Equipment

Water tables were observed by Tu every few days through the 1967 Spring and Summer and irrigation of the subdrain depth and spacing plots. The rises in water tables following rains seen in the data presented by Tu (1968) and reproduced as Figures A1, A5, A19, A20, A21 and A22, provide an opportunity to estimate drainable porosity. The rises in the water table in the Ste. Rosalie clay following the rainfalls of 16 - 17 June and 30 August 1967, and in the Soulanges fine sandy loam following the rainfalls of 8 May 1967 and 13 June 1968 have been used to estimate the drainable porosity as

$$f_e = \frac{\text{rain}}{\text{water table rise}}$$

Results and Discussion

The results of these calculations have been superposed on the basic graphs from Tu (1968) and presented as Figures A1, A5, A19, A20, A21 and A22, to show clearly the rainfalls, water table rises, soil depths and drainage cases involved. From this simple approach values for f for the Ste. Rosalie clay ranging from 0.074 to 0.117 and for the Soulanges fine sandy loam from 0.029 to 0.061 have been obtained. It is realized that these values may be high because the water tables were not necessarily observed at their lowest levels prior to the effects of rain or their highest levels after the rain. Also, there would be some outflow to drains occurring during the interval

TABLE 7. DRAINABLE POROSITIES ESTIMATED FROM WATER TABLE RISES AFTER RAINFALLS.

Location and soil	Date of Rain	Depth of Rain inches	Water Table Before Rain depth inches	Levels After Rain depth inches	Rise of Water Table inches	Drainable Porosity Estimate	Mean Depth of Water Table inches
MARTINEAU Ste. Rosalie clay	16-17.6.67	.90	36.5	25.0	11.5	.078	32
			46.5	37.0	9.5	.094	42
			58.5	48.5	10.0	.09	54
	30.8.67	.70	29.0	23.0	6.0	.117	26
			36.5	28.0	8.5	.083	32
			40.5	31.0	9.5	.074	36
VINCENT Soulanges fine sandy loam	8.5.67	.59	46.0	30.5	15.5	.038	38
			49.5	36.5	13.0	.045	43
	13.6.68	.40	15.0	7.5	7.5	.053	11
			20.5	8.5	12.0	.033	14
			16.0	8.0	8.0	.050	12
			23.0	9.0	14.0	.029	16
			31.0	23.5	7.5	.053	27
			8.5	1.5	7.0	.057	5
			10.0	3.5	6.5	.061	7
			13.5	7.0	6.5	.061	10

Note: These estimates of drainable porosity are based on water table rises seen in Figures A1, A5, A19, A20, A21 & A22 from Tu (1968), and observed rainfall at the sites. Estimates are based on events where the soil could be at field capacity prior to the rainfall event. In the case of the 16-17.6.67 event on the Ste. Rosalie Clay the water table position was estimated from a projection of the one day later observation.

between observations which would decrease the rise in water table from that which would result without drainage. A compensating factor is the tendency for f to be underestimated because the rain would not need to replenish the full drainable pore space under a situation where the soil profile was actively draining down, as indicated in the theory presented at the outset of this chapter. Further refinements of these estimates are not justified since there are no intermediate water table observations during the time of water table rise.

Very good estimates of f over the soil profile would appear to be easily obtained by this method if one had a recording rain gauge and a water table recorder installed in a soil without drains. Unfortunately at the time of the field observations described in this thesis no water table recorder was available. Basic water level recorders which might have been purchased from instrument companies required a float and counterweight installation which would have required an auger hole of 5 inches (125 mm) in diameter. The problems due to lag in water table response in large auger holes have already been described. The pressure actuated bellows and recording mechanism that has been developed by the Field Drainage Experimental Unit, Cambridge, England, provides a recording of water table level (or pressure) with only a very small volume of soil water displacement. Such recorders are not available commercially. However there appears real scope for the fabrication and use of several such recorders in Quebec for determination of water table changes and hence drainable porosities and hydraulic conductivities on other soils.

Summary of Drainable Porosity Estimates

From the observations presented and discussed in this chapter, and presented in graphical summary form in Figure 13, it appears that the most satisfactory and convenient way of obtaining reasonable estimates from the drainable porosity of a particular soil is to take samples of that soil at a time when the profile can reasonably be considered to be at field capacity. Samples could be taken directly from an "undisturbed" location at appropriate depths in a pit. Rather than using "undisturbed" sample rings, the volume of a removed sample could be determined in the field with a volumeter or by the dry sand volume method. For swelling clays, samples should be taken both in springtime and autumn. The drainable porosity may be less in the springtime than in the autumn.

The second best method of determining the drainable porosity appears to be to observe the amount of rise of water table following a rain which comes at a time when the soil has previously been near field capacity. Four or more water table pipes in an area should be observed. In the case where other drainage investigations are underway an automatic water table recorder of small water volume displacement would be merited.

CHAPTER VI

HYDRAULIC CONDUCTIVITY DETERMINATIONS

Hydraulic conductivities were determined by (1) using steady state and falling water table drain spacing equations; and (2) using the single auger hole method.

Methods and Equipment

Water table levels were observed at successive times during and following soil saturating irrigation on several drained locations to provide the data for using a falling water table equation. Drain discharges were also measured during and following irrigations to provide the outflow data needed to use a steady state equation.

Single auger hole tests were made on several locations following methods outlined by Boersma (1965), and Luthin (1966).

Results and Discussion

Ste. Rosalie Clay

Steady State Drainage Case. The drain flow measurements and water table levels observed during the irrigation of the Martineau water balance plot and presented as Figures 19 and 20 were used along with equation (8) to calculate K. From equation (8)

$$K = \frac{R\,L^2}{4\left[(d_e + h)^2 - d_e^2\right]} \qquad (23)$$

The steady state mean outflow prior to the end of irrigation was 43.4 mm/day from the plot areas, h was 0.555 m for the mean of the 3 mid-spacing water table pipes, and L was 12.2 m (40 ft). Since the receding water table observations indicated capacity for considerable flow through the soil below drain level an equivalent depth d_e of 1.2 m (4.0 ft) was selected. As can be seen from Figure 3, this is the maximum equivalent depth for a drain spacing of 12.2 m (40 ft) regardless of the depth of the water conducting layer. Using this highest value of d_e also gives a conservative estimate of K.

Thus, $$K = \frac{43.4\ (12.2)^2}{4\left[(1.2 + .555)^2 - (1.2)^2\right]} = 0.985\ \frac{m}{day}$$

This is undoubtedly a somewhat low value for the aggregate field hydraulic conductivity. If there were no seepage to drains beyond the plot there would be a higher R for the same h. As indicated in the previous chapter, observations of slightly less irrigation onfall near the east and west borders of the plot suggest that the flow from between the two drains should be more than the mean of the total drain flow. These two features could effectively increase R and hence K by about 40%. If d_e were less than 1.2 m, K would also be higher.

Falling Water Table Cases. Since there are only minor differences in the equations for the falling water table case, Glover's equation, equation (18), was used to calculate K. Equation (18) may be rewritten as:

$$K = \frac{L^2\ f\ \ln(1.27\ h_o/h_t)}{\pi^2 t\ (d_e + h_o/2)} \qquad (24)$$

Observations on the Martineau Water Balance Plot together with K values calculated for this case are given in Table 8. Again the equivalent depth d_e has been taken as 1.2 m. Since f in the falling water table equation is the variable related to volume of water flowing to the drains for the soil volume between water table positions h_o and h_t, values of f have been chosen from Figure 13 as reasonable values for the particular water table positions h

TABLE 8. HYDRAULIC CONDUCTIVITIES CALCULATED FROM FALLING WATER TABLE OBSERVATIONS AFTER IRRIGATION OF MARTINEAU WATER BALANCE PLOT, STE. ROSALIE CLAY.

Time from End of irrig.	Time interval t	h mean of sections A, B & C	f drainable porosity	K for f given for depth zone	K for f = 0.06 through Profile
hours	days	m		m/day	m/day
0		.552			
1.7	.071	.505	.070	3.31	2.83
3	.054	.425	.065	5.14	4.75
7	.166	.337	.055	1.67	1.82
11	.166	.278	.050	1.43	1.72
15	.166	.236	.040	1.09	1.64
19	.166	.200	.040	1.12	1.67
23	.166	.164	.040	1.22	1.83

Note : Glover's equation, equation 18, was used to calculate K values. For this plot the drain spacing L = 12.2 m (40 ft), the depth from the soil surface to the drain center is 0.76 m (2.5 ft), and d_e was selected as 1.2 m (4.0 ft).

for the field drainage case. The values of K obtained in this way are an aggregate value of K for the total soil-drainage system. Large differences in K for different layers in a profile would show up only as small differences in K values calculated with falling water table equations. A large actual K in the upper layers of the profile should cause more lateral flow in the upper layers than assumed in the theory. The more rapid fall of the water table through the upper layers due to this modified flow pattern should show a slightly higher aggregate field K when the water table is falling through the upper layers.

The data in Table 8 show K decreasing with depth, except for the second depth increment. The rise in K from the first to the second increment might not be all due to an increase in hydraulic conductivity at that level. The value of f selected might be higher than actual for this zone. Also, some non-uniformity in water table pipe performance could affect this value.

Because of these aspects and the fact that the water table drops quite rapidly through these upper layers it is doubtful if there is any point in using other than a single value for f for the upper 0.5 m (20 inches) of the soil profile, when using a falling water table equation to calculate drain spacings. In Table 8 values obtained from the observed water table data but using a value of f = 0.06 for the profile are also given.

Determinations from widely spaced Drains. Because of the rapid drop of the water table at the Martineau subdrained water balance plot and the possible influence of deeper drains to the east and south of the plot, it was desirable to observe falling water tables on some widely spaced drains in a system with long parallel laterals which were unlikely to have their drainage effect improved by other drains. Fortunately, a drainage system suitable for such observations was available in the Martineau pasture north of the main experimental field. Parallel subdrains 900 ft (274 m) long with a spacing of 120 ft (36.6 m) and a depth of 4 to 4.5 ft (1.22 to 1.37 m) were installed in the pasture field in July 1969. As large a section at the center of this drainage system as could be covered with the water available was irrigated in August 1970. The layout of the drainage system, irrigation system and water table observation pipes is shown in Figure 24. This section of the field was irrigated 3 times. During the first irrigation the system was adjusted to give better uniformity of coverage. The water table response was not reasonable in some pipes during and following the first irrigation. Poor hydraulic conductivity around some water table pipes due to smearing on installation was suspected. New holes were augered nearby and pipes reinstalled. Some further adjustments to irrigation system and water table pipes were made during and after the second irrigation. Irrigation was continued a third time until the water table was almost at the surface at mid-spacings.

The layout of the irrigation system and water table pipes permitted observation of the water table at 3 sections across the 3 parallel drains. A large number of 1 quart oil cans were placed in the field to measure the uniformity of the irrigation and coefficients of uniformity calculated to 80 - 90%. These coefficients compare well with any sprinkler irrigation operation and indeed are not far different from the uniformities that may be achieved in natural rainfall.

The general shape of the water table at successive times after irrigation was very similar across the three sections, as can be seen from the similarity of Figures 25 and 26. Figure 25 gives the observations from Section E. The means of the observations from Sections D, E and F, are given in Figure 26.

Some non-uniformities of irrigation and infiltration can be suspected from the shapes of the water table at time t = 0 and t = 6 hours. The shallow pondings in some of the low spots disappeared in the first 3 hours after the end of irrigation and the water table had taken up the characteristic elliptical shape by t = 6 hours.

The water table between the 2 easterly drains along section F did not rise as high as along sections D and E. This accounts for the mean water table position between the easterly drains being lower than the water table at section E at t = 0.

The distance between water table observation sections was only 40 ft (12.2 m) while the spacing between subdrains was 120 ft (36.6 m). The response of the water table in the first few hours shows that some lateral flow occurred to equalize the potential energy in the soil water at equal distances from the subdrains. The levels observed for the 3 sections between each pair of drains were averaged to give mean values for the water table positions at successive times. It appears that a sufficiently long section of field was irrigated that the hydraulic gradient toward the drains would be a more dominant effect than the longitudinal gradient to drier ground. The three successive irrigations should have provided conditions for the soil to be essentially saturated below the water table after the third irrigation.

A rather strange feature about the water table position curve shown in Figures 25 and 26 is the fact that the water table over the drains is not right down to the mid-drain height but remains about 20 - 30 cms above the mid-drain height. It is known that the drains had adequate capacity to carry the water away without requiring this 30 cms surcharge head to give the energy gradient for the flow of water in the drains. This 30 cms head could indicate energy loss adjacent to the drains due to convergence of the stream lines near the drains and perhaps due to a somewhat lowered hydraulic conductivity near the drains due to remoulding of the soil by the trenching machine. Streamline convergence required by the fact that water can only enter tiles at 30 cm (1.0 ft) intervals may also be part of the cause of this water table surcharge adjacent to the tiles. The use of corrugated plastic drain tubes with perforations every 2 cm (.06 ft) along their lengths should reduce this restriction to flow into drains.

The six mid-spacing water table heights at successive times are given in Figure 27. This graph shows a less rapid recession of the water table in the first six hours after irrigation than in the subsequent 24 hours at observation pipes D3, E3 and F3. This lower rate of recession in the first 6 hours may be due to the fact that there was some slight ponding in the low spots and dead furrows at the time irrigation ceased. This ponded water moved into the soil during the first few hours and would have replaced water that was draining down. This would reduce the rate of fall when compared with the fall due to water moving out of drainable pore space only. In addition a small amount of rain occurred just after stopping irrigation which would reduce the apparent drawdown in the first few hours.

The reduced rate of drawdown extends over the first 12 hours in the case of the observations from pipes D7, E7 and F7. This may be due to the fact that the initial water table height was higher for these pipes than for the pipes D3, E3 and F3 and there was somewhat more ponding of water in dead furrows and small surface depressions in the section of the field between the two drains affecting pipes D7, E7 and F7.

It is noted that the recession continues more or less uniformly for the period from 12 hours to 48 hours for pipes D7, E7 and F7 whereas the recession proceeds less rapidly after about 24 hours for the pipes D3, E3 and F3. The rate of recession decreases for almost all pipes once the water table is more than about 70 cms below the surface. This reduced rate of recession when the water table is at greater depth could be expected to be due to both a decreased hydraulic conductivity in the soil at the lower depths and a reduction in the hydraulic gradient causing flow to the drains. It is obvious from this graph that there is a good deal of similarity in the slope of the recession curves for these different water table pipes. Indeed, in comparison to some other soils the relative uniformity of the slopes and water table positions is remarkable.

Calculated hydraulic conductivities are given in Table 9 along with pertinent measured times and water table heights. Considering the indications of deep seepage at the water balance plot on this Ste. Rosalie clay soil, and the relatively rapid fall of the water table for a spacing as wide as 120 ft (36.6 m), it was evident that there might be significant flow through the subsoil to a depth considerably below the drains.

Using a drainable porosity f of 0.06, K values were calculated for d_e values of 0.5, 1.52 and 2.95 m. A value of 2.95 m is the maximum d_e for a spacing of 36.6 m (120 ft) regardless of the depth of soil through which flow is occurring. From the results of these calculations, presented in Table 9, it appears that the soil must have a significant hydraulic conductivity for several metres below the drains. When the d_e value of 0.50 m is used K increases to higher values as the water table drops. When the higher values of d_e are used more realistic values of K, and values decreasing for the lower positions of the water table are obtained. The values of K obtained with a d_e

TABLE 9. HYDRAULIC CONDUCTIVITIES CALCULATED FROM FALLING WATER TABLE OBSERVATIONS AFTER THE THIRD IRRIGATION OF THE MARTINEAU PASTURE, STE. ROSALIE CLAY, AUGUST 1970.

Time from End of Irrig. (hours)	Time interval t (days)	h mean of pipes D3, E3, F3 Between drains 10 & 11 (m)	h mean of pipes D7, E7, F7 Between drains 11 & 12 (m)	K between drains 10 & 11 if d_e were 0.5m (m/day)	K between drains 11 & 12 if d_e were 0.5m (m/day)	K between drains 10 & 11 if d_e were 1.52m (m/day)	K between drains 11 & 12 if d_e were 1.52m (m/day)	K between drains 10 & 11 if d_e were 2.95m (m/day)	K between drains 11 & 12 if d_e were 2.95m (m/day)
0		1.141	1.186						
6	.25	1.041	1.108	10.2	9.3	5.2	4.8	3.1	2.8
12	.25	.789	1.035	16.6	9.6	8.3	3.9	4.9	2.9
18	.25	.612	.882	18.1	11.9	8.5	6.4	4.9	3.8
24	.25	.513	.785	16.9	12.4	7.5	6.0	4.2	3.4
36	.50	.379	.550	11.8	11.0	5.0	5.1	2.8	2.9
48	.50	.319	.392	9.8	12.2	4.0	5.3	2.2	2.9
60	.50	.276	.281	9.6	13.5	3.8	5.5	2.0	3.0
72	.50	.225	.224	11.4	12.0	4.4	4.6	2.4	2.5
Mean				13.1	11.5	5.8	5.3	3.3	3.0
σ				3.57	1.44	1.95	.62	1.19	.40

Note: Glover's Equation was used to calculate K.
The spacing between parallel subdrains was 36.8m (120 ft).
The average depth to subdrain centers was 1.22m (4.03 ft).
A drainable porosity of 0.06 was used for the profile.
The maximum value of d_e for a drain spacing of 36.8m is 2.95m.

of 2.95 m are still quite high for a clay soil and remarkably uniform for the successively lower positions of the water table.

Sylvestre (1972) indicated that hydraulic conductivities of the order of 2 m/day were obtained for depths from 2.2 to 4 m in some fields of Ste. Rosalie and similar clays late in the 1971 summer. He extended auger holes to a depth of 4 m in late summer when the water table was at a depth of about 2.2 m. Values of 2m/day seem high when compared to hydraulic conductivities reported in the literature for other clay soils.

These high K values may be due to the Champlain sea sediments in the St. Lawrence lowlands being geologically recent and unconsolidated deposits. Some geologists consider that these young sediments have been weathered to depths of 3 to 5 m. During some dry years in recent centuries the water table may have dropped below 5 m and some irreversible shrinkage of the clay occurred to create the structure that permits relatively high K values under current saturated conditions. At other places in Canada where clay soils have been consolidated by the heavy loads of glaciers or other overburden, lower hydraulic conductivities would be expected. The genesis of the Champlain Sea sediments thus supports the use of d_e values as high as 2.95 m. Before using such maximum d_e values as a general rule, a few deep auger hole tests should be made for localities in which large acreages are to be subdrained.

Even if the actual f were less than 0.06 for the lower position of the profile these results show that this clay soil has good internal drainage capacity and can be adequately drained with subdrains much wider spaced than would have hitherto been recommended.

The Falling Water Table Case for the Plots with the Subdrain Spacings Increasing Linearly. Now that a good indication has been obtained for the probable range of field hydraulic conductivity of the Ste. Rosalie clay at the Martineau Farm it is appropriate to re-examine the falling water table data obtained by Tu (1968), and presented as Figures A11 through A22. Values of K calculated from Tu's observations and the use of Glover's equation, equation 18, are given in Table 10. The K values in Table 10 show the hydraulic conductivity to be much underestimated from the falling water table observations for the 20 ft spacing. The data for the 60 ft spacing give K values similar to what would be expected for this soil from data obtained from the parallel subdrain cases. The 120 ft subdrain spacing data give K values somewhat higher than the 60 ft spacing data. The K values are calculated on the assumption of lateral flow only to parallel subdrains. The different K values obtained for the depth and spacing plots indicate that the more rapid fall of the water table in the region of the narrow spacings has established a longitudinal hydraulic gradient sufficient to cause flow from the wide spacing end toward the narrow spacing end of the plot. The differences are much more marked for the narrowest spacings than for the wider spacings. This feature of some longitudinal flow casts doubt on the suitability of plots with linearly increasing subdrain spacing to show adequately the effects of subdrain spacing on crop yield and soil conditions.

TABLE 10. HYDRAULIC CONDUCTIVITIES CALCULATED FROM FALLING WATER TABLE OBSERVATIONS FOLLOWING THE 1967 IRRIGATION OF MARTINEAU SUBDRAIN DEPTH AND SPACING PLOTS

Nominal Subdrain Depth ft	Time hours	20 ft Subdrain spacing h m	20 ft Subdrain spacing K m/day	60 ft Subdrain spacing h m	60 ft Subdrain spacing K m/day	120 ft Subdrain spacing h m	120 ft Subdrain spacing K m/day
4.5	0	1.270		1.270		1.295	
	4	.876	.64	1.074	2.36	1.168	4.69
	8	.666	.63	.958	2.15	1.100	4.17
	12	.528	.64	.737	3.14	.930	5.73
	16	.401	.75	.646	2.46	.808	5.48
	20	.351	.58	.539	2.86	.681	6.02
	mean		.65		2.59		5.22
3.5	0	.978		.991		.991	
	4	.716	.65	.826	2.62	.907	4.72
	12	.513	.38	.574	1.95	.734	3.26
	20	.381	.39	.396	2.12	.533	4.15
	36	.252	.26	.274	1.11	.653	2.10
	mean		.42		1.95		3.74
2.5	0	.686		.699		.699	
	4	.472	.82	.503	3.81	.615	5.54
	8	.351	.80	.412	3.09	.533	5.78
	12	.267	.82	.305	3.92	.483	5.17
	20	.201	.44	.165	3.20	.292	5.72
	36	.089	.46	.102	1.41	.216	2.15
	mean		.67		3.09		4.87

Note: These calculations are based on Glover's equation, equation 18. Values of d_e of 0.67, 1.50 and 3.00 m have been selected for subdrain spacings of 20 ft, 60 ft and 120 ft respectively.

Soulanges Fine Sandy Loam

Steady State Drainage Case. The Vincent subdrained water balance plot was irrigated in June 1971 in an attempt to create a steady state drainage case. The basic observations from that irrigation are given in the previous chapter. While an outflow rate constant for several hours was not achieved, Figure 23 shows that the outflow and mid-spacing water table heights were approaching maxima when irrigation was stopped. The maximum average discharge rate R from the two tiles was 37.4 mm/day from the plot area and the average height of the water table at the three mid-spacing observation points was 0.60 m above the drain centers.

This soil is obviously two layered. If it were assumed that essentially all the drain flow were through the fine sandy loam then the effective head h would be 0.46 m, the height of the water table above the sand/clay interface. Applying equation (9) for this case and neglecting flow through the clay layer yields for the hydraulic conductivity of the fine sandy loam

$$K = \frac{L^2 R}{4\ h^2} = \frac{(15.2)^2\ \ .0374}{4\ (.46)^2} = 7.2 \text{ m/day}$$

It is obvious from the rate of fall of the water table in the clay layer, both in the water balance plot and in the depth and spacing experiment area, that the hydraulic conductivity of the underlying clay is not zero. Thus K for the fine sandy loam will be less than 7.2 m/day.

A better estimate of the hydraulic conductivity of both the fine sandy loam and clay below it can be obtained by making use of equation (10),

$$L^2 = \frac{8\ K_b\ d_e\ h}{R} + \frac{4\ K_a\ h^2}{R}$$

where K_b and K_a are the hydraulic conductivities below and above the drains respectively.

Equation 10 may be rewritten as

$$\frac{R}{h} = \frac{8\, d_e\, K_b}{L^2} + \frac{4\, K_a\, h}{L^2} \qquad (25)$$

This is a linear equation of $\frac{R}{h}$ vs h.

The discharge measurements are presented in Figure 28 both as R vs h and R/h vs h. A straight line has been fitted to the R/h vs h data neglecting the 3 points at very low h. These points where R and h both approach zero can be expected to deviate from the relationship which exists for the higher h values. Taking the intercept on the R/h axis, 0.0225 days^{-1} to be $8\, d_e\, K_b/L^2$ and using the maximum possible value of d_e, 1.3 m (4.3 ft) for this drain spacing of 15.2 m (50 ft) yields the minimum hydraulic conductivity of the clay soil below the drains.

$$K_b = \frac{0.0225\ (15.2)^2}{8\ (1.3)} = 0.50 \text{ m/day}$$

From the R/h vs. h line, $4K_a / L^2 = 0.064$ days^{-1} metres^{-1}, the hydraulic conductivity of the soil above the drains may be estimated as

$$K_a = \frac{0.064\ L^2}{4} = \frac{0.064\ (15.2)^2}{4} = 3.7 \text{ m/day}$$

But the soil above the center of the drains is clay for a height of about 0.14 m with sand above that. The total hydraulic conductivity K_a can be considered to be

$$K_a = \frac{K_1\, l_1 + K_2\, l_2}{l_1 + l_2} \qquad (26)$$

where K_1 = the hydraulic conductivity of the sand layer

K_2 = hydraulic conductivity of the clay layer = K_b = 0.50 m/day

l_1 = average depth of saturation in the sand layer = 0.375 m

l_2 = average depth of clay layer above the drains = 0.14 m

Hence $$K_1 = \frac{3.7\ (0.375 + 0.14) - (0.50)\ .14}{0.375} = 4.9 \text{ m/day}$$

It would appear that the maximum value of hydraulic conductivity of the sand is 4.9 m/day and the minimum value of hydraulic conductivity of the clay beneath it 0.50 m/day.

Luthin (1966) states that if the hydraulic conductivity of the upper layer is 10 or more times the hydraulic conductivity of the lower layer, the flow pattern will be determined primarily by the upper layer. This is undoubtedly true when the water table is high up in the sand. But as the water table drops in the sand the hydraulic conductivity of the clay will have a progressively greater effect. An hydraulic conductivity of 0.50 m/day is still high enough to permit a good rate of flow to subdrains. Thus there appears to be merit in placing subdrains in the clay layer. The good performance of the 4 ft deep subdrains in the depth and spacing experiment area supports this statement.

Auger Hole Measurements of Hydraulic Conductivity

Hydraulic conductivities were measured by the single auger hole method on the Martineau farm in 1970 by Mr. G. Laflamme, for conditions of natural water tables and water tables raised by irrigation. Mr. Laflamme also measured the hydraulic conductivity of the clay beneath the Soulanges fine sandy loam for a natural water table condition in 1970. In June 1971 the author raised the water table into the Soulanges fine sandy loam by irrigation and made auger hole measurements to determine the hydraulic conductivity of both the Soulanges fine sandy loam and the clay beneath it. The results of the auger hole measurements are presented in Table 11. The hydraulic conductivities obtained by use of the auger hole and subdrainage system methods are summarized in Table 12. Included in Table 12 are some data from laboratory cores and

TABLE 11. SUMMARY OF RESULTS OF HYDRAULIC CONDUCTIVITY DETERMINATION BY THE AUGER HOLE METHOD.

Soil	Location	Measure. Made or Reported by	Dates of Measure.	Water Table Formation	No. of Holes	Depth to Water Table Metres Max	Min	Mean	K obtained m/day Max	Min	Mean	No. of Measure. Included
Ste. Rosalie Clay	Martineau St. Clet	Laflamme (1971)	May - Aug 1970	Natural	2	.81	.55	.63	.91	.05	.68	9
Ste. Rosalie Clay	Martineau St. Clet	Laflamme (1971)	July - Aug 1970	Irrigation	2	.76	.05	.38	1.27	.56	.98	18
Soulanges Fine Sandy Loam above Clay	Vincent St. Emmanuel	Broughton	June 1971	Irrigation	5	.33	.09	.15	4.46	1.05	2.20	6
Clay below Soulanges Fine Sandy Loam	Vincent St. Emmanuel	Broughton	June 1971	Irrigation	4	.95	.63	.78	3.15	1.02	1.98	5
Clay below Soulanges Fine Sandy Loam	Vincent St. Emmanuel	Laflamme (1971)	May - June 1970	Natural	2	.72	.69	.70	1.47	.13	.98	2
Ste. Rosalie Clay	Morgan Arboretum	Laflamme (1971)	May 1970	Natural	2	.64	.18	.33	1.10	.03	.69	3
Ste. Rosalie Clay *	Macdonald Farm	Warkentin (1965)	June 1961	Natural	2				.052	.011	.031	2

* These measurements were by the piezometer method. Auger holes used by Laflamme were 1.1 to 1.5 m deep.

TABLE 12. COMPARISON OF HYDRAULIC CONDUCTIVITIES OBTAINED BY VARIOUS METHODS, metres/day.

Soil	Location	Horizon	Range or mean	Auger Hole Method: Natural Water Table *	Auger Hole Method: Water Table by Irrig.	Drainage Steady State **	Equations Falling Water Table **	Laboratory undisturbed cores ***
Ste. Rosalie clay	Martineau Farm	Whole Profile	Range	.05 to .91	.56 to 1.27	.98 to 1.4	.98 to 5.4	
			Mean	.68	.98*	1.2	3.1	
	Morgan Arboretum	Whole Profile	Range	.025 to 1.10				
			Mean	.69				
	Macdonald Farm		Range	.011 to .052				.0004 to .293
			Mean	.031				.013
	Vaudreuil County	B Horizon K_v	Range					.034 to 3.2
			Mean					1.6
		K_h	Range					.043 to .34
			Mean					.19
		$K = \sqrt{K_v K_h}$	Mean					.56
		C Horizon K_v	Range					2.4 to 4.2
			Mean					3.28
		K_h	Range					.52 to 2.6
			Mean					1.26
		$K = \sqrt{K_v K_h}$	Mean					2.04
Soulanges Fine Sandy Loam	Vincent Farm	Top 60 cm	Range		1.05 to 4.46		4.7 to 16.8	
			Mean		2.20**	4.9	9.0	
Clay below Soulanges Fine Sandy Loam	Vincent Farm	Profile below 60 cm	Range	.13 to 1.47	1.02 to 3.15		.97 to 7.4	
			Mean	.98	1.98**	.50	2.3	

Notes: Measurements made or reported by; * Laflamme (1971); ** Broughton; and *** Warkentin (1965).

auger hole determinations reported by Warkentin (1965).

The data in Table 12 show overlapping of the ranges of hydraulic conductivity values obtained by use of auger hole and subdrainage system methods. The mean hydraulic conductivity obtained from falling water table equations was higher than that obtained by steady state equations, which in turn were higher than the means obtained by auger hole methods, except in the case of the clay beneath the Soulanges fine sandy loam where the value obtained by use of the steady state drainage equation was less than the values obtained by the other methods.

The range of values obtained by auger hole methods was greater than the range of values from drainage equations. The range from auger hole measurements was less than the 100fold indicated by Boersma (1965) to be possible. Some individual auger hole tests gave very low K values, but in all cases the maximum value was less than 2.1 times the mean value. The mean of K values obtained from auger holes after a summer irrigation was slightly higher than those obtained with a natural water table in spring. This could be due to a change in size of pores between soil peds. The drying and shrinking of the soil from May through July would cause cracking between soil peds. Since the watering and draining occurred over a shorter time when the soil was irrigated than when the water table rose due to snowmelt and spring rains, it is likely that cracks between peds would be slightly more open after the irrigations than after spring snowmelt and rains.

The K values obtained from drainage equations and subdrain system performance following irrigation were higher than values obtained by auger hole methods following irrigation. This suggests that much of the draining water has flowed through cracks between soil peds. Since the subdrain systems collect water from a large field area, a wider range of crack sizes contribute to the flow to the drains than to the auger holes.

Tables 11 and 12 include data for auger holes and laboratory core tests for Ste. Rosalie clays other than at the Martineau farm. The mean value obtained by Laflamme at the Morgan Arboretum is essentially the same as the mean value obtained at Martineau farm, but the mean of value reported by Warkentin for the Macdonald farm site is 20 times lower. The soil at Macdonald farm site reported by Warkentin appears to have a greater bulk density and less structure in the B and C horizons than the Morgan Arboretum, Vaudreuil County or Martineau farm sites. The Macdonald farm site may have had more reworking in its soil genesis than the other sites had.

The values reported by Warkentin from the laboratory core measurements for the Vaudreuil County site show vertical hydraulic conductivities higher than horizontal. The conductivities in the more dense B horizon were lower than in the C horizon. The values obtained from the laboratory cores for the Vaudreuil site were approximately the same magnitude as the values obtained at the Martineau farm by auger hole and drain system methods. These measurements show that hydraulic conductivity at drain level is still quite high and hence the assumption of homogeneous soil used for the drainage equation calculations is realistic. The drain flow is not primarily restricted to lateral flow through the upper root zone as suggested for some other clay soils by authors such as Hoffman and Schwab (1964) and Trafford (1970).

The values of K obtained by auger hole methods at the Martineau farm show that a good indication of probable K values to influence drainage design can be obtained by auger hole methods. At least 4 holes should be augered to sample different parts of a field. Values of K obtained from individual holes which are very much higher or lower than the average should be reconsidered before selecting a mean value to be used for drainage design purposes. Since the variation in values obtained from auger holes and by drain equations is such as to give a 50% of greater variation in drain spacings, the K values obtained should just be one of many factors considered by the designer in arriving at his decisions on drain depth and spacing for a particular field.

CHAPTER VII

PEAK DRAIN FLOW RATES

Results and Discussion

Some of the peak flow rates deduced from the water level records of the weirs placed on 2 subdrains on the subdrained water balance plots are given in Table 13. Unfortunately, a statistical treatment of the flows for the 3 years of observations is not possible because the records are incomplete. Problems such as power outages which stopped the drainage pumps, failures of recorder clocks or pens, and icing of equipment prevented reliable measurements of some subdrain flow events. Nonetheless, much is revealed by the records available from the years 1968-71.

From Table 13 it can be seen that flows as high as 76.2 mm/day (3.0 in/day) have occurred. Many flow peaks have been higher than 25.4 mm/day (1.0 in/day). Much of the flow was at rates well below 12.7 mm/day (.5 in/day). The observed peak flow rates also show clearly, contrary to the beliefs of some drainage designers, that it is seldom the hydraulic conductivity of the soil which restricts flow from subdrainage systems to 12.7 mm/day (0.5 in/day). Peak drainage rates for subdrains are often limited to a design rate near 12.7 mm/day (0.5 in/day) by the size of collector drain tubes used.

When the outflow rate is restricted by drain tube capacity to rates less than the soil could supply, the water table will not fall much faster near the drain tubes than at the mid-spacing.

Drainage rates of 12.7 mm/day (0.5 in/day) may lower the water table fast enough for practical purposes for most field crops in the St. Lawrence

TABLE 13. SOME PEAK FLOWS MEASURED FROM SUBDRAINS IN STE. ROSALIE CLAY AND SOULANGES FINE SANDY LOAM

Date	Ste. Rosalie Clay Martineau Farm				Soulanges Fine Sandy Loam Vincents Farm			
	drain 2	drain 3	drain 2	drain 3	drain 3	drain 4	drain 3	drain 4
d. m. y.	mm/day	mm/day	in/day	in/day	mm/day	mm/day	in/day	in/day
18.11.68	15.2		.60					
24.11.68	10.0		.39					
3.12.68					62.0	33.6	2.43	1.32
19. 3.69	45.2	64.4	1.78	2.53				
25. 3.69	5.8		.23					
7. 4.69	5.3	67.0	.21	2.64	9.9		.39	
8. 4.69	10.7	67.0	.41	2.64				
9. 4.69	14.5	45.2	.57	1.78				
10. 4.69	21.1	76.2	.83	3.00		10.5		.41
11. 4.69	13.2	46.7	.52	1.84				
12. 4.69	6.6	57.7	.26	2.27				
13. 4.69	6.6	42.0	.26	1.65	20.4		.82	
14. 4.69	1.3	32.8	.05	1.29				
16. 4.69		10.5		.41				
17. 4.69	11.8	35.0	.46	1.37				
18. 4.69	15.0	64.5	.59	2.54				
29. 4.69		15.0		.59				
12. 5.69					1.68	16.2	.07	.64
18. 5.69		11.3		.44				
19. 5.69		64.4		2.54				
20. 5.69		18.4		.72	3.57	25.2	.14	.99
11.12.69	5.3	14.8	.21	.58				
30. 3.70						5.3		.21
6. 4.70		10.5		.41	20.4	6.7	.80	.26
12. 4.70	10.5	10.5	.41	.41	21.0		.85	
13. 4.70	15.8	4.2	.62	.16	14.1	4.0	.55	.16
14. 4.70	15.8	23.7	.62	.93	3.6		.14	
15. 4.70	7.9	17.1	.31	.67	4.2		.16	
16. 4.70	11.0	11.3	.43	.44				
17. 4.70	9.2	9.2	.36	.36				
23. 4.70					9.5		.37	
25. 4.70					4.6	25.2	.18	.99
27. 4.70		13.7		.54				

Ste. Rosalie Clay Martineau Farm		
Date	drain 3	drain 3
d. m. y	mm/day	in/day
10.4.71	5.0	.20
11.4.71	10.8	.42
12.4.71	17.4	.69
13.4.71	22.4	.88
14.4.71	24.7	.97
15.4.71	10.8	.42
16.4.71	3.9	.15
17.4.71	17.6	.69
18.4.71	24.7	.97
19.4.71	27.6	1.08
20.4.71	31.6	1.24
21.4.71	27.6	.97
22.4.71	42.1	1.66
23.4.71	29.5	1.16
24.4.71	27.9	1.10
25.4.71	20.8	.82
26.4.71	13.7	.54
27.4.71	8.4	.33

lowlands area. However, most of the possible benefits of closely spaced subdrains in bringing the water table down rapidly after a rainfall or snowmelt event are lost if the outflow rate is constrained by the drain tube size. If drainage rate is to be limited by drain tube hydraulic capacity, laterals spaced 100 ft apart may give just as good drainage performance (water table drawdown) as laterals with 50 ft spacings in many of the St. Lawrence lowland soils. Observations presented from the depth and spacing experiment show that the rate of water table drop is increased by increasing the depth of the drains. These observations support the increasing of both depth and spacing of subdrains in systems being designed for Ste. Rosalie clay, Soulanges fine sandy loam and related soils. In soils with much greater variability in texture and hydraulic conductivity within a field the suggested wider spacing of drain tubes could leave unsatisfactory wet areas.

In Figure 29 a hydrograph of the runout from subdrain 3 in the Ste. Rosalie clay is given covering much of the 1971 snowmelt period. This figure shows that the subdrain flow rate responds very rapidly to snowmelt. Peak flows occur in the afternoons near the time of the daily maximum temperature. Flows decrease rapidly as the air cools down in the evening and reduces or stops the melt. Responses to rainfalls on top of snowmelt occurred on April 13 and 21. The duration of high flows was extended after those rains. The flow of snowmelt through the Ste. Rosalie clay soil reached a peak of 42.1 mm/day (1.66 in/day) on April 22. The total drain outflow of 244.1 mm (9.61 in) for the 3 week period was the major part of the water content of the snow pack on the plot. It might be expected that this drain performance was unusual because 1970-71 was a winter of very high snow fall with little penetration of frost in the soil. The winter was followed by a long slow snowmelt period.

Such records as are available show very similar drain flow patterns in March and April 1969 and 1970.

It was observed in 1967 and 1968 that snowmelt had proceeded considerably before subdrain flow began. Neutron meter observations showed an increase in water content in the upper 18 inches of both soils during the 66-67 and 67-68 winters. Occasional warm afternoons in these winter months followed by abruptly cold nights had apparently refrozen melt water before it could drain out of the profile. This reduced the capacity for March and April snowmelt to pass through the profile. However as the melt period progressed the tiles began to flow and a significant portion of the snowmelt passed out of the subdrains.

From Table 13 it is seen that drainage rates higher than those achieved during the plot irrigations occurred during some snowmelt periods. Since the irrigations brought the water table very near the soil surface, the higher rates which occurred during snowmelt might have been achieved by some surface ponding causing a ponded water case which allows greater flow into the soil directly over the drains. The thawing of ice lenses might also give a temporary increase in hydraulic conductivity.

From the standpoint of reducing nutrient losses by leaching, it would appear to be better if most of the snowmelt ran off the surface rather than through the subdrain systems. If there is no crop on the field that will suffer from a few hours or days of shallow flooding at that dormant time of the year, surface runoff of snowmelt can be promoted by restricting the discharge capacity of the drain laterals and collectors. Where pump outlets are used the pumps might only be started to drain the soil profile after the majority of the snowmelt had run off the surface.

A hydrograph of the May 17 - 20, 1969 drain flow event is reproduced as Figure 30. The cumulative rainfall shown in the figure is based on twice daily rainfall measurements and observations of time of stop and start of rain. It is likely that the rain came in a series of showers rather than as a steady uniform rain but no satisfactory recording gauge record is available. The rain on May 17 produced no runout, but it must have filled most of the profile moisture deficit. The subdrain runout rose rapidly during the May 18-19 rainfall. The recession was complete in about 32 hours after the cessation of rain. This hydrograph shows that when the drain tube capacity is not restricting subdrain flow rates can reach 64 mm/day (2.5 in/day) and the drainage of water temporarily stored in the soil profile is quite rapid. If the drain tubes had restricted the outflow to 12.7 mm/day (0.5 in/day) the recession would have lasted about 2 days longer.

The estimated relationship between drainage rate and mid-spacing water table height for the case of the 36.6 m (120 ft) spaced laterals on the Ste. Rosalie clay at Martineau pasture is given in Figure 31. The drainage rate has been estimated by determining the soil volume drained per unit time between the successive water table positions shown on Figure 26, and assuming a drainable porosity of 6%. The data shown in Figure 31 indicate that even with subdrain laterals 36.6 m (120 ft) apart this Ste. Rosalie clay has sufficient hydraulic conductivity to permit drainage rates in excess of 38 mm/day (1.5 in/day) if the subdrains are deep enough to permit h to reach 1.2 m (4.0 ft).

For the duration of this study it was only following the July 1968 rain storms that it appeared that there would be a benefit to maize from having a subdrain system with a capacity greater than 12.7 mm/day (0.5 in/day). However it is seen from the precipitation records in Appendix B that the years of this field work, 1966-1971, have contained 1968 and 1969 with precipitation slightly above the 30-year average. The other 4 years had 4 to 18% less than average precipitation. Years with as much as 30% more than average precipitation can be expected in the future. It is known that when more than 9 inches of rain fell in August of 1965, before the field work described in this thesis began, there were some vegetable and grain crops which would have benefited considerably from a subdrain rate in excess of 12.7 mm/day (0.5 in/day).

These features of the precipitation and the subdrain performance observed during the field work for this thesis indicate the desirability of developing a water balance model which takes into account precipitation, evapotranspiration, soil moisture, soil reservoir action, and drainage. Such a model should be used together with long term weather records for stations in the Ottawa and St. Lawrence lowlands to determine probabilities of recurrence of particular water table heights for different drainage rates. This could provide better guidance for the selection of drainage rates for the design of subsurface drainage systems for different soils, crops and locations in the region.

Additional points of considerable practical significance from the higher than expected outflow capacities of these soils are:

1. Low spots can be drained quite rapidly if drain tubes with sufficient capacity are placed right beneath those low points.
2. The drain spacings might be made quite wide, say 120 to 150 ft (36.6 to 45.8 m) on some of the clay soils if the land is graded slightly so that the low spots are right over the drains.
3. The flow capacity of some of these soils could fill the subdrain

laterals at their upper end giving drainage rates of 50 mm/day (2 in/day) for the upper part of a field and zero drainage rate in the lower part until after the upper end had drained down. Thus, in soils with slopes of 0.5% or more it may be desirable to use shorter laterals or place laterals diagonal to the slope to provide more uniform drainage.

CHAPTER VIII

MAIZE YIELD MEASUREMENTS

Materials and Methods

Maize was grown on the subdrain depth and spacing experiment areas on the Vincent and Martineau farms for the 4 years, 1967 - 1970, in an attempt to get an indication of the effect of drainage intensity on crop yield. Maize was also grown on nearby plots which had no subdrains, on the Martineau farm in 1969 and 1970 and on the Vincent farm in 1970. As indicated in Figures 9 and 10 the maize was planted in rows perpendicular to the diagonal center drain. To give an integrative effect, similar to that in a subdrained field where the water table would change in height with distance from the subdrains, plots were harvested for a length from the central subdrain to the mid-spacing. Since the subdrain spacings increased from 20 ft to 120 ft on the Ste. Rosalie clay and 20 ft to 200 ft on Soulanges fine sandy loam, plot lengths ranged from 10 ft to 100 ft. Eleven subplots were selected corresponding to subdrain spacings of 20, 30, 40, 50, 60, 70, 80, 90, 100, 110 and 120 ft on the Ste. Rosalie clay and 20, 30, 40, 60, 80, 100, 120, 140, 160, 180 and 200 ft on the Soulanges fine sandy loam. Based on recommendations from agronomy research workers, a minimum of 60 ft of maize row length was harvested for each subplot. This meant the harvesting of 6 rows centered on the 10-foot-half-spacing plot; 4 rows on the 15 ft-half-spacing plot... etc; with one row only harvested for those plots where the half spacing between drains was 60 ft to 100 ft.

This layout gave a split-plot design with main plots, of near constant subdrain depth, encompassing subplots with different subdrain spacings. The two main plots with the same subdrain depth, being located side by side, provided sampling replication nested within depth treatments. It was not possible to place additional replicates on either farm.

Good agronomic practice was followed in seedbed preparation, planting and weed control. The Vincent field was first plowed from sod in November 1965 and the Martineau field in May 1966. No crop was planted in 1966, but cultivations were carried out for weed control, and the land smoother was used to reduce micro-relief. Fertilization, at rates and analyses established from soil tests, was as uniform as possible over all plots. The fields were plowed in the fall of years 1966-1970.

The fields were planted in May, each year, starting at the end of the field which had the deepest subdrains and finishing at the end with the shallowest subdrains on the same or subsequent day. In 1967 wireworms caused much damage and Vincent's field was cultivated and planted a second time on June 16 and 17.

Atrazine and oil was sprayed for weed control. It was not sufficiently effective in 1967 and 1968. In those years further weed control was achieved by cultivation and hoeing. The atrzine and oil was uniformly effective in 1969 and 1970.

The subplots were harvested by hand following agronomic research practice and assisted by technicians from the Macdonald Campus Agronomy Department. Samples of maize ears, taken from the subplot yields, were weighed before and after drying. Yields were then converted to bushels per acre of shelled grain on a 15% moisture basis. The buffer areas beyond and between the subplots were harvested with a single row picker-husker towing a hopper wagon.

Results and Discussion

Yields From Subdrain Depth and Spacing Plots

The yields of maize obtained from the depth and spacing plots are given in Table 14 for the Ste. Rosalie clay field and Table 15 for the Soulanges fine sandy loam. Analyses of variance of these results for each of the four years at each of the two farms are given in Tables 16 through 24.

These analyses show significance at the 1% probability level due to spacings of subdrains on the Ste. Rosalie clay in 1967. For the Soulanges fine sandy loam, significance at the 0.5% level due to subdrain spacings was exhibited in 1968 and 1969; and spacings x depths interactions significant at the 5% level were exhibited in 1968. No significance due to subdrain depths was shown. This does not necessarily mean that subdrain depth was not important. The experimental design did not give randomized block replication of subdrain depth to provide a sensitive test for effects of subdrain depth on crop yields. The only test possible for the significance of subdrain depths was by using the mean square from the subsampling replication which was nested within depths. This does not provide as suitable a test for the significance of subdrain depth on crop yield as could be obtained by additional replications of the depth treatments in randomized complete blocks. The land and costs involved prevented such additional replication in these experiments.

It is very doubtful whether there was any truly significant effect of subdrain spacings on yields in 1967 on the Ste. Rosalie clay plots. The wireworm and weed infestation affected the crop severely that first year, and yields were so low that no conclusions about drainage effects should be drawn from the 1967 yield data.

TABLE 14. YIELDS OF MAIZE MARTINEAU PLOTS, STE. ROSALIE CLAY SOIL, 1967-1970. Data are bushels per acre of shelled grain 15% moisture basis.

Rep	Drain depth ft	Year	Drain spacing ft (subplots) 20	30	40	50	60	70	80	90	100	110	120	Main plot means	Mean for drain depth
1	4.5		77.2	69.3	42.4	38.9	59.7	66.5	48.5	69.5	57.2	41.1	49.2	56.3	56.2
2	4.5		47.1	55.1	47.4	34.0	53.3	51.2	68.6	72.1	74.3	59.4	53.2	56.0	
1	3.5	1967	56.6	37.8	47.3	39.3	56.4	40.7	61.7	67.9	53.2	50.6	35.6	49.7	56.9
2	3.5		45.7	48.7	63.3	44.4	87.9	67.8	71.3	76.1	74.2	64.6	60.8	64.1	
1	2.5		76.2	66.7	68.4	51.0	86.9	79.1	70.3	70.6	67.0	74.2	64.5	70.4	72.1
2	2.5		100.5	76.6	100.0	52.5	80.7	75.0	65.8	67.7	75.5	50.1	67.5	73.8	
mean			60.5	59.0	61.5	43.4	70.8	63.4	64.4	70.7	66.9	56.7	55.1	61.7	61.7
σ			15.3	14.5	21.4	7.3	16.0	14.7	8.5	13.1	9.6	11.8	11.8	9.3	
1	4.5		133.9	108.3	115.2	106.4	87.7	107.4	96.5	97.9	107.6	101.6	93.9	105.1	101.7
2	4.5		88.4	110.9	113.1	101.5	113.9	75.3	97.8	99.7	99.3	101.8	79.5	98.3	
1	3.5	1968	55.0	93.4	101.2	100.7	117.9	113.0	120.2	78.7	117.1	109.4	111.4	101.6	107.6
2	3.5		107.1	114.6	113.7	129.7	102.0	136.3	124.5	100.5	112.2	107.8	101.8	113.6	
1	2.5		99.4	125.5	117.8	101.4	120.5	127.5	99.3	96.2	116.5	112.4	104.6	110.7	112.9
2	2.5		87.7	127.7	102.4	110.2	123.0	68.5	91.6	201.9	113.3	119.7	119.2	115.0	
mean			95.3	113.4	110.6	108.3	110.8	104.7	105.0	112.5	111.0	108.8	101.2	107.4	107.4
σ			26.0	12.5	7.0	11.1	13.5	27.5	13.8	44.5	6.7	6.8	13.8	6.8	
1	4.5		178.5	157.0	148.4	125.6	128.4	125.6	138.8	144.6	92.5	119.8	130.4	135.4	139.2
2	4.5		114.3	136.1	162.4	161.4	157.3	147.6	138.6	134.5	138.5	145.1	136.6	142.9	
1	3.5	1969	214.6	146.0	123.8	123.8	120.0	116.4	139.2	183.1	117.1	133.6	132.9	141.0	135.9
2	3.5		135.2	139.7	143.8	144.2	133.7	103.4	142.2	121.8	162.3	101.8	109.5	130.7	
1	2.5		164.8	141.8	120.0	175.3	152.5	153.0	129.9	130.0	167.7	140.9	128.4	145.8	136.0
2	2.5		100.1	117.3	125.3	114.5	126.4	138.3	119.7	123.3	142.1	152.4	127.6	126.1	
mean			151.3	139.7	137.3	140.8	136.4	130.7	136.7	139.6	136.7	132.3	127.6	137.0	137.0
σ			42.8	13.1	16.9	23.9	15.1	19.1	8.7	22.9	28.2	18.6	9.4	7.6	
1	4.5		139.5	137.9	128.8	117.5	120.5	131.6	125.7	133.0	126.3	111.4	108.6	125.5	116.6
2	4.5		103.8	110.9	69.6	123.4	123.9	104.8	100.7	111.6	116.4	101.4	116.8	107.6	
1	3.5	1970	138.9	119.1	147.0	120.4	140.2	139.8	124.6	160.4	142.3	118.4	116.8	133.4	124.3
2	3.5		103.2	117.7	120.0	112.8	114.5	116.6	122.0	119.4	117.0	113.2	111.3	115.2	
1	2.5		131.3	123.2	142.9	121.6	133.8	114.3	121.3	137.3	119.8	126.7	153.9	129.6	128.3
2	2.5		140.0	132.4	129.1	124.5	122.7	126.1	120.9	141.7	123.6	124.3	111.8	127.0	
mean			126.1	123.5	122.9	120.0	125.9	122.2	119.2	133.9	124.2	115.9	119.9	123.1	123.1
σ			17.8	10.0	27.9	4.3	9.4	13.6	9.3	17.2	9.6	9.3	17.0	9.7	

TABLE 15. YIELDS OF MAIZE, VINCENT PLOTS, SOULANGES FINE SANDY LOAM SOIL 1967-1970.
Data are bushels per acre of shelled grain 15% moisture basis.

Rep	Drain depth ft	Year	Drain spacing ft (subplots) 20	30	40	60	80	100	120	140	160	180	200	Main plot means	Mean for drain depth
1	4		61.1	51.1	80.0	77.1	86.1	70.0	84.3	83.2	75.7	68.6	78.2	74.1	77.3
2	4		85.7	84.6	92.5	81.4	84.3	92.5	51.4	70.4	64.6	88.2	88.6	80.4	
1	3	1967	69.6	111.0	84.6	76.1	100.3	103.5	74.3	87.1	89.3	73.9	56.4	84.2	81.9
2	3		71.8	89.3	85.0	76.8	65.7	82.1	100.0	50.4	79.6	89.6	84.3	79.5	
1	2		68.6	85.0	67.5	65.0	77.8	97.1	98.2	84.3	75.4	68.9	62.1	77.3	81.9
2	2		81.1	114.2	114.6	80.7	72.5	78.6	117.8	50.7	60.4	68.2	113.2	86.5	
mean			73.0	89.2	87.4	76.2	81.1	87.3	87.7	71.0	74.2	76.2	80.5	80.3	80.3
σ			9.0	22.8	15.7	5.9	12.0	12.6	23.1	16.9	10.4	10.0	20.4	4.5	
1	4		134.0	130.2	131.7	122.7	115.8	123.9	129.0	130.7	126.5	119.7	126.9	126.5	124.0
2	4		124.2	135.6	120.4	131.0	112.6	126.2	133.9	135.5	71.2	118.7	127.6	121.5	
1	3	1968	169.4	171.4	149.2	150.4	136.7	107.2	130.0	139.0	104.3	102.8	110.9	133.8	132.1
2	3		133.4	143.3	146.3	146.6	131.4	114.2	152.4	127.3	114.3	113.7	111.5	130.4	
1	2		152.4	157.8	157.3	134.2	135.6	126.5	120.0	132.7	134.5	141.6	136.6	139.0	135.5
2	2		130.8	158.8	138.7	127.0	134.1	133.8	127.0	114.2	120.8	134.8	131.2	131.9	
mean			140.7	149.5	140.6	135.3	127.7	122.0	132.1	129.9	111.9	121.9	124.1	130.5	130.5
σ			16.9	15.7	13.2	11.0	10.7	9.6	11.0	8.7	22.5	14.2	10.6	6.0	
1	4		169.1	162.5	143.5	143.2	122.2	125.3	137.4	137.9	124.7	124.0	130.8	138.2	132.7
2	4		195.0	134.9	135.9	133.5	125.7	109.6	94.8	132.3	121.2	122.2	92.9	127.1	
1	3	1969	171.2	152.5	148.0	140.4	74.1	167.9	122.8	145.7	115.0	88.4	116.1	131.1	126.5
2	3		128.6	155.8	136.5	127.3	118.4	114.0	111.9	117.8	116.7	115.1	97.2	121.8	
1	2		189.0	147.3	146.3	116.0	119.3	128.8	116.4	110.5	127.6	119.2	113.0	130.3	126.7
2	2		148.0	128.5	148.8	140.1	110.5	116.0	110.5	107.2	119.3	108.0	117.3	123.1	
mean			166.8	146.9	143.2	133.4	111.7	126.9	115.6	125.2	120.8	112.8	111.2	128.6	128.6
σ			25.0	12.9	5.7	10.3	19.1	21.3	14.1	15.7	4.8	13.3	14.0	6.0	
1	4		71.5	94.5	89.0	85.4	100.1	77.5	92.5	100.7	76.7	81.7	85.9	86.9	96.0
2	4		90.2	99.0	100.0	100.0	110.9	111.6	104.1	128.2	102.1	105.0	103.7	105.0	
1	3	1970	118.2	108.2	114.2	96.4	108.5	93.4	98.7	109.1	108.5	104.4	114.2	106.7	105.6
2	3		83.6	101.6	91.1	116.8	110.7	106.6	108.0	100.9	107.5	131.1	91.1	104.5	
1	2		115.4	95.7	112.7	95.7	87.3	119.3	108.0	108.4	89.6	117.3	102.1	104.7	105.1
2	2		124.1	98.4	88.9	91.1	109.3	100.0	104.5	108.0	112.0	111.8	111.3	105.4	
mean			100.5	99.6	99.3	97.6	106.5	101.4	102.6	109.2	99.4	108.6	101.4	102.2	102.2
σ			21.6	4.9	11.7	10.7	9.6	14.8	6.0	10.0	13.6	16.4	11.1	7.5	

TABLE 16. ANALYSIS OF VARIANCE FOR YIELDS OF MAIZE GRAIN 1967, MARTINEAU SUBDRAIN DEPTH AND SPACING PLOTS, STE. ROSALIE CLAY.

Source of Variation	DF	SS	MS	F
Subdrain depths	2	3,576.66	1,788.33	4.496
Replicates in depths	3	1,193.30	397.77	
Spacings (b)	10	3,857.82	385.78	3.726 **
Spacings x depths	20	2,632.91	131.65	1.271
Error (b)	30	3,106.09	103.54	
Total	65	14,366.78		

** Significance at the 1% level
Coefficient of variability (b) = 16.5%

TABLE 17. ANALYSIS OF VARIANCE FOR YIELDS OF MAIZE GRAIN 1968, MARTINEAU SUBDRAIN DEPTH AND SPACING PLOTS, STE. ROSALIE CLAY.

Source of Variation	DF	SS	MS	F
Subdrain depths	2	1,374.97	687.49	1.791
Replicates in depths	3	1,151.60	383.87	
Spacings (b)	10	1,790.47	179.05	0.469
Spacings x depths	20	7,998.80	399.94	1.047
Error (b)	30	11,459.22	381.97	
Total	65	23,775.06		

Coefficient of variability (b) = 18.2%.

TABLE 18. ANALYSIS OF VARIANCE FOR YIELDS OF MAIZE GRAIN 1969, MARTINEAU SUBDRAIN DEPTH AND SPACING PLOTS, STE. ROSALIE CLAY.

Source of Variation	DF	SS	MS	F
Subdrain depths	2	158.64	79.32	0.078
Replicates in depths	3	3,037.34	1,012.45	
Spacings (b)	10	2,325.52	232.55	0.474
Spacings x depths	20	8,484.47	424.22	0.866
Error (b)	30	14,704.07	490.14	
Total	65	28,710.04		

Coefficient of Variability (b) = 16.2%.

TABLE 19. ANALYSIS OF VARIANCE OF YIELDS OF MAIZE GRAIN 1970, MARTINEAU SUBDRAIN DEPTH AND SPACING PLOTS, STE. ROSALIE CLAY.

Source of Variation	DF	SS	MS	F
Subdrain depths	2	1,579.07	789.54	0.652
Replicates in depths	3	3,633.06	1,211.02	
Spacings (b)	10	1,337.95	133.80	0.952
Spacings x depths	20	2,149.81	107.49	0.765
Error (b)	30	4,217.83	140.59	
Total	65	12,917.72		

Coefficient of Variability (b) = 9.6%.

TABLE 20. ANALYSIS OF VARIANCE FOR YIELDS OF MAIZE GRAIN 1967, VINCENT SUBDRAIN DEPTH AND SPACING PLOTS, SOULANGES FINE SANDY LOAM.

Source of Variation	DF	SS	MS	F
Subdrain depths	2	313.45	156.73	0.581
Replicates in depths	3	809.55	269.85	
Spacings (b)	10	2,663.47	266.35	0.992
Spacings x depths	20	3,952.44	197.62	0.736
Error (b)	30	8,053.06	268.44	
Total	65	15,791.97		

Coefficient of Variability (b) = 20.4%.

TABLE 21. ANALYSIS OF VARIANCE FOR YIELDS OF MAIZE GRAIN 1968, VINCENT SUBDRAIN DEPTH AND SPACING PLOTS, SOULANGES FINE SANDY LOAM.

Source of Variation	DF	SS	MS	F
Subdrain depths	2	1,518.13	759.07	4.868
Replicates in depths	3	467.83	155.94	
Spacings (b)	10	6,808.87	680.89	5.726 ***
Spacings x depths	20	4,675.27	233.76	1.966 *
Error (b)	30	3,567.64	118.92	
Total	65	17,037.74		

* Significant at the 5% level

** Significant at the 1% level

*** Significant at the 0.1% level.

Coefficient of Variability (b) = 8.4%.

TABLE 22. ANALYSIS OF VARIANCE FOR YIELDS OF MAIZE GRAIN 1969, VINCENT SUBDRAIN DEPTH AND SPACING PLOTS, SOULANGES FINE SANDY LOAM.

Source of Variation	DF	SS	MS	F
Subdrain depths	2	545.81	272.90	0.565
Replicates in depths	3	1,448.69	482.90	
Spacings (b)	10	18,673.04	1,867.30	7.817 ***
Spacings x depths	20	3,788.35	189.42	0.793
Error (b)	30	7,166.25	238.87	
Total	65	31,622.14		

*** Significant at the 0.1% level.
Coefficient of Variability (b) = 12.0%.

TABLE 23. ANALYSIS OF VARIANCE FOR YIELDS OF MAIZE GRAIN 1970, VINCENT SUBDRAIN DEPTH AND SPACING PLOTS, SOULANGES FINE SANDY LOAM.

Source of Variation	DF	SS	MS	F
Subdrain depths	2	1,296.03	648.02	1.059
Replicates in depths	3	1,836.27	612.09	
Spacings (b)	10	861.78	86.18	0.779
Spacings x depths	20	2,344.95	117.25	1.060
Error (b)	30	3,316.82	110.56	
Total	65	9,655.85		

Coefficient of Variability (b) = 10.3%.

TABLE 24. ANALYSIS OF VARIANCE FOR YIELDS OF MAIZE FOR THE YEARS 1968, 1969, 1970, MARTINEAU SUBDRAIN DEPTH AND SPACING PLOTS, STE. ROSALIE CLAY.

Source of Variation	DF	SS	MS	F
Years	2	28,914.4	14,457.2	16.636 *
Depths	2	1,429.5	714.7	.822
Years x depths	4	1,683.1	420.8	.482
Reps in years x depths	9	7,820.8	869.0	
Spacings	10	2,302.9	230.3	0.774
Linear	1	558.9	558.9	1.879
Quadratic	1	110.0	110.0	0.370
Cubic	1	308.0	308.0	1.035
Deviations (in residual)	7	1,326.0	189.4	0.637
Years x spacing	20	4,479.4	224.0	0.753
Years x lin. coef. for spac.	2	818.7	409.4	1.376
Years x quad. coef. for spac.	2	467.3	233.7	0.785
Deviations (in residual)	16	3,193.4	199.6	0.671
Depths x spacing	20	4,901.0	245.1	0.824
Depths x lin. coef. for spac.	2	1,386.8	693.4	2.331
Depths x quad. coef. for spac.	2	177.0	88.5	0.297
Deviations (in residual)	16	3,337.3	208.6	0.701
Years x depths x spacings	40	20,265.6	506.6	1.703
Yr. x depth x lin. coef. for spac.	4	1,560.0	390.0	1.311
Deviations (in residual)	36	18,705.6	519.6	1.747
Residual	165	49,082.7	297.5	
Grand Total	197	94,317.2		

* Indicates significance at the 2.5% level.

Coefficient of Variability (b) = 14.1%.

TABLE 25. ANALYSIS OF VARIANCE FOR YIELDS OF MAIZE FOR THE YEARS 1968, 1969, 1970. VINCENT SUBDRAIN DEPTH AND SPACING PLOTS, SOULANGES FINE SANDY LOAM.

Source of Variation	DF	SS	MS	F
Years	2	33,110.1	16,555.1	39.700 ***
Depths	2	866.5	433.3	1.039
Years x depths	4	2,493.4	623.4	1.495
Reps in Years x depths	9	3,752.8	417.0	
Spacings	10	12,450.2	1,245.0	7.468 ***
Linear	1	9,376.6	9,376.6	56.241 ****
Quadratic	1	1,332.6	1,332.6	7.993 **
Cubic	1	257.8	257.8	1.546
Deviations (in residual)	7	1,483.2	211.9	1.271
Years x Spacings	20	15,376.6	768.8	4.611 ***
Years x lin. coef. for spac.	2	8,614.2	4,307.1	25.834 ****
Years x quad. coef. for spac.	2	1,453.6	726.8	4,359 *
Deviations (in residual)	16	5,308.8	331.8	1.990
Depths x spacings	20	5,188.0	259.4	1.556
Depths x lin. coef. for spac.	2	542.0	271.0	1.626
Depths x quad. coef. for spac.	2	851.7	425.8	2.554
Deviations (in residual)	16	3,794.3	237.1	1.422
Years x depths x spacings	40	14,723.7	368.1	2.208
Yr. x dep. x lin.coef. for spac.	4	1,265.3	316.3	1.897
Deviations (in Residual)	36	13,458.3	373.8	2.242
Residual	165	27,509.0	166.7	
Grand Total	197	91,425.8		

* Indicates significance at the 5% level,
** indicates significance at the 1% level,
*** indicates significance at the 0.5% level and
**** indicates significance at the 0.1% level.

Coefficient of Variability (b) = 10.7%.

TABLE 26. DUNCAN'S MULTIPLE RANGE TEST FOR SIGNIFICANCE BETWEEN YIELDS DUE TO SPACINGS OF SUBDRAINS AT VINCENT FARM, SOULANGES FINE SANDY LOAM.

1968 Data, 5% level of significance.

Subdrain spacing ft	160	180	100	200	80	140	120	60	40	20	30
Mean Yield bu/ac	111.9	121.9	122.0	124.1	127.7	129.9	132.1	135.3	140.6	140.7	149.5

1968 Data, 1% level of significance.

Subdrain spacing ft	160	180	100	200	80	140	120	60	40	20	30
Mean Yield bu/ac	111.9	121.9	122.0	124.1	127.7	129.9	132.1	135.3	140.6	140.7	149.5

1969 Data, 5% level of significance.

Subdrain spacing ft	180	80	200	120	160	140	100	60	40	30	20
Mean Yield bu/ac	111.2	111.7	112.8	115.6	120.8	125.2	126.9	133.4	143.2	146.9	166.8

1969 Data, 1% level of significance.

Subdrain spacing ft	180	80	200	120	160	140	100	60	40	30	20
Mean Yield bu/ac	111.2	111.7	112.8	115.6	120.8	125.2	126.9	133.4	143.2	146.9	166.8

In order to check whether these were effects due to years, and hence climatic factors, the analyses of variance, given in Tables 24 and 25 were made for the data of the three years 1968, 1969 and 1970. The 1967 data were left out because of the effects of wireworms and weeds that year. Table 24 shows the effects of years to be highly significant, but no significant effects of depths or spacings of subdrains are indicated for the Ste. Rosalie clay plots.

The analysis given in Table 25, for the plots on the Soulanges fine sandy loam, indicates that a significant part of the variability is due to differences between years. Also, there is significance at the 0.5% level due to spacings and the years x spacings interaction. A yield versus spacing predictor has a linear term that is significant at the 0.5% level and a quadratic term significant at the 1% level. Spacings showed significant effects in the 1968 and 1969 yields.

The weather data given in Tables B8 and B9 show Martineau and Vincent farms to have received total precipitations in 1968 and 1969 slightly higher than the 4-year, 1967-70 average for their own stations and also slightly higher than the 30-year average at Montreal International Airport. At the Vincent farm in 1969 the March, April, May and June rainfalls were respectively 0.55, 2.11, 2.13 and 0.69 in above the 30-year mean rainfalls for these months. In 1968 the March, June and July rainfalls were respectively 1.48, 0.70 and 2.41 inches higher than the 30-year means for those months. The 5 in of irrigation applied by Tu in June 1968, to obtain falling water table observations, undoubtedly accentuated the effect of spacings on yield at the Vincent farm. That 5-inch irrigation raised the June water supply to 8.92 in (near the 30-year maximum) and the 1968 total to 43.58 in (about 8.5% less than the 30-year annual maximum).

Even a year of average rainfall has need of drainage removal of some surplus water. The yield data confirm that greater differences due to wide drain spacings can be expected in the wetter years. An experiment with more replication would need to run for several years (perhaps 15 years) to provide good prediction of the percentage differences in crop yields which could be expected due to particular spacings and depths of subdrains.

The hydraulic conductivity calculations based on the falling water table observations, after irrigation of the subdrain depth and spacing plots, indicate that there is some flow from the wide-spacing end to the narrow-spacing end of the main plots. This casts some doubt on the comparability of the crop yield performance obtained from linearly increasing spacing and constant spacing drain systems. The performance of a 120 ft spacing in these linearly increasing spacing areas may be equivalent to the performance of a narrower spaced (perhaps 100 ft) parallel subdrain system. None-the-less, the lack of significance of spacing in the analysis of variance of the maize yields indicates that subdrains of widely different spacings do not cause much yield difference on the Ste. Rosalie clay.

In Figures 34 and 35 graphs of the yields of maize grain obtained for each spacing in 1968, 1969 and 1970 on the Soulanges fine sandy loam are presented. These graphs support the analysis of variance. The change in yield with spacing is very small and randomly distributed in 1970. In 1968 and 1969, the wetter years, the yields decreased by about 25 bu/ac from spacings of 20 ft to 100 ft. There is a near constant yield for spacings from 100 ft to 200 ft.

The results of Duncan's multiple range test for 1968 and 1969 data are presented in Table 26. The mean yields for the 6 subplots with the same subdrain spacings are used for each year since there were no significant differences due to subdrain depths. As can be seen from Figures 34 and 35 and in Table 26, the yields do not decrease smoothly with increasing subdrain spacing.

In 1968 for a 0.01 probability significance level the yields for spacings up to 140 ft, except for the 80 and 100 ft spacings, were not significantly lower than the highest yielding spacing. From the data for 1968 and 1969 there appears to be a real yield advantage to having spacings of 80 ft or less on the Soulanges fine sandy loam.

There does not appear to be anything special about the subplots with subdrain spacings of 80 and 100 ft which would cause a yield lower than on subplots with subdrain spacings of 120 and 140 ft. In 1969 the mean yield from subplots with a subdrain spacing of 100 ft was higher than from those subplots with a subdrain spacing of 120 or 140 ft. Yields from the 6 individual subplots with subdrain spacings of 80 and 100 ft fluctuated considerably from year to year, as can be seen from Table 15. Thus, there does not appear to be a residual effect carrying over from year to year for those subplots. Also, the standard deviations for subplot yields from different subdrain spacings are of the same order of magnitude. It is noted that in 1969 the mean yields from subplots with subdrain spacings from 80 to 200 ft were not different at the 1% significance level.

Yields From Plots Without Subdrains

The yields of maize grain obtained on the plots without subdrains are given in Table 27. Analyses of variance comparing the treatments of subdrains and no subdrains are given as Tables 28, 29 and 30. These analyses show no significance due to drainage at either farm for the 1970 crop. The 1969 data show significance at the 2.5% level. As mentioned earlier, it was not possible to have randomized blocks for drained and undrained plots on one farm. Thus the error term used for calculating F in Tables 28, 29 and 30, has been based on the sampling within treatment experimental units

TABLE 27. YIELDS OF MAIZE FROM PLOTS WITH AND WITHOUT SUBDRAINS.

Farm and Soil	Year	Plot Number	Yield Without Subdrains bu/ac	Yield With Subdrains bu/ac.
Martineau	1969	1	136.6	135.4
Ste.		2	114.4	142.9
Rosalie		3	114.8	141.0
clay.		4	114.2	130.7
		5	93.5	145.8
		6	129.6	126.1
		mean	117.2	137.0
Martineau	1970	1	137.7	125.5
Ste.		2	107.0	107.6
Rosalie		3	136.8	133.4
clay		4	111.1	115.2
		5	128.9	129.6
		6	104.3	127.0
		mean	121.0	123.1
Vincent	1970	1	109.6	86.9
Soulanges		2	85.5	105.0
fine		3	77.3	106.7
sandy		4	85.5	104.5
loam		5	98.6	104.7
		6	104.8	105.4
		mean	93.6	102.2

Notes : (1) Yields are based on shelled grain at 15% moisture content.

(2) Plots without subdrains are 6 plots taken at random with 90 ft of row length from a single block of maize grown at a distance of 400 ft or more from the nearest subdrain.

(3) Yields from plots with subdrains are the mean yields from the 6 main plots of the subdrain depth and spacing experiment area on the named farm.

TABLE 28. ANALYSIS OF VARIANCE FOR YIELDS OF MAIZE GRAIN FROM PLOTS WITH AND WITHOUT SUBDRAINS, 1969, MARTINEAU FARM.

Source of Variation	DF	SS	MS	F
Subdrainage treatments	1	1,176.12	1,176.12	8.379 *
Error	10	1,403.72	140.37	
Total	11	2,579.84		

* Significant at the 2.5% level.
Coefficient of variability 9.3%

TABLE 29. ANALYSIS OF VARIANCE FOR YIELDS OF MAIZE GRAIN FROM PLOTS WITH AND WITHOUT SUBDRAINS, 1970, MARTINEAU FARM.

Source of Variation	DF	SS	MS	F
Subdrainage treatments	1	13.02	13.02	0.079 NS
Error	10	1,635.78	163.58	
Total	11	1,648.80		

Coefficient of Variability 10.5%

TABLE 30. ANALYSIS OF VARIANCE FOR YIELDS OF MAIZE GRAIN FROM PLOTS WITH AND WITHOUT SUBDRAINS, 1970, VINCENT FARM.

Source of Variation	DF	SS	MS	F
Subdrainage treatments	1	224.47	224.47	2.064 NS
Error	10	1,087.30	108.73	
Total	11	1,311.77		

Coefficient of Variability 10.6%

rather than replication. This testing procedure is satisfactory where there is no significance between treatments, as in 1970. Where significance is indicated between treatments in 1969 the lack of complete block replication precludes the determination of whether the significance is truly due to treatments or the experimental error. The relatively high F value suggests that plots with subdrains could give significantly higher yields than plots without subdrains.

There was a 19.8 bu/ac or 16.9% greater mean yield on the plots with subdrains than on the plots without subdrains on the Ste. Rosalie clay in 1969. As seen from Tables B5 and B8 the total annual precipitation in 1969 at Martineau farm was 3.93 in greater than the 4-year Martineau mean, or 1.98 in greater than the 30-year mean at the Montreal International Airport. The precipitation at Martineau farm in 1969 was slightly higher than the 30-year Montreal International Airport precipitation for the months of March, April, May and June. It seems probable that the yield increases due to subdrainage will be higher in those years with above average rainfall in the planting and growing seasons. Years with wetter conditions than 1969 have occurred in the past and may be expected to recur. Yield differences higher than 16.9% can be expected in wetter years. It is unfortunate that randomized complete block experiments could not be arranged in the 4 years of operation of the subdrain depth and spacing project to allow better measurements and conclusions about the extent of probable effects of drainage treatments on crop yield.

None-the-less, something has been learned about the performance of subdrain systems on these soils and the increases in yields of maize possible as a result of subdrain installations. Future experiments to determine more satisfactorily the effects of subdrain systems on crop yield should only be undertaken if it is possible to arrange randomized complete blocks to get an adequate measure of experimental error.

Possible Designs for Future Experiments

As a result of observations on these field experiments the following suggestions are made for future field experiments to measure effects of subdrain depth and spacing on yields of crops.

1. Because of the relatively long distance of influence of subdrains on water table, no attempt should be made to combine spacing subplots with depth main plots.

2. In order to get more information from the large amount of land and money required, a randomized complete block design with drainage treatments as main plots could have subplots with different crops, fertilizers or planting dates. To measure planting date benefits and still meet statistical analysis conditions subplots on each drainage treatment should be planted on the day when the plot with the poorest drainage is ready and other subplots planted on the earliest possible day for each drainage treatment.

3. Because of the large area required to make a complete block with 4, or more, drainage treatments it may be necessary to have the randomized replicate blocks on separate farms. Soil conditions should be as uniform as possible within replicate blocks. The 3 or more replicates, whether on separate farms or not, should be enclosed, if possible, within a 1 km radius to minimize climatic differences between blocks.

4. The experiments should run for 10 years or longer to pick up the effects of wet, dry, cool and hot years.

5. Because of the large variations among subplot yields for the same drainage treatment (see standard deviations in tables 14 and 15) 200 ft (60 m), or more, of maize rows should be harvested to get a representative yield for a subplot.

6. In order to get enough precision to indicate whether or not significant differences in crop yields occur due to drainage treatments it is desirable to have 3 or more degrees of freedom

for treatments and 10 or more degrees of freedom for error. Some possible experimental designs are compared in Table 31.

TABLE 31. COMPARISON OF POSSIBLE RANDOMIZED COMPLETE BLOCK EXPERIMENT DESIGNS FOR CROP YIELD VERSUS DRAINAGE TREATMENT EXPERIMENTS.

Experiment design	No of drain. treats.	No of rep. blocks	DF for treats.	DF for reps.	DF for error	F for 5% sign. treats.	F for 5% sign. reps.	Total no. of plots
(a)	4	4	3	3	9	3.86	3.86	16
(b)	4	5	3	4	12	3.49	3.26	20
(c)	5	4	4	3	12	3.26	3.49	20
(d)	6	3	5	2	10	3.33	4.10	18
(e)	6	4	5	3	15	2.90	3.29	24

Design (e) with 6 drainage treatments and 4 replicates would give the best chance of confirming or rejecting a hypothesis that crop yield differences due to drainage treatments occur, but this design might be considered too expensive in land and operations. A choice between designs (b), (c) and (d) would depend primarily on the physical layout possible within the fields available. If it were easier to get 3 sites than to get 4 sites, and each site had adequate space, design (d) would be chosen. Slightly less buffer land would be needed for an increase in the number of treatments than for an increase in the number of replicates.

CHAPTER IX

SOIL TRAFFICABILITY

Economic crop management requires good soil trafficability to allow efficient use of farm machines. Of two fields having equal yields in the standing crop, the more economical field will be the one which allows greater flexibility in timing of field operations.

Soil surface conditions on the Martineau and Vincent fields were observed to note soil trafficability differences, some of which were due to drainage. Differences were observed by noting dates when tillage, planting, and harvesting operations could proceed, and by observing differences in topsoil condition with distance from subdrains.

Measurements of the mobility performance of a Massey-Ferguson 135 tractor were undertaken on the Martineau and Vincent farms in 1969. The details of the methods employed and the results obtained in these mobility tests are presented in the M.Sc. Thesis of Kim (1969).

Observations by the author, in addition to those presented in Kim (1969), are given here with some related discussion.

1. In the 5 springs 1967-1971 the soil on the subdrained plots was dry enough to permit seedbed preparation 8 to 21 days earlier than nearby areas having surface drainage only.
2. The soil was firm enough to permit a tractor to develop its drawbar pull before the soil was dry enough to proceed with seedbed preparation.
3. On the Ste. Rosalie clay :
   (a) the springtime soil surface conditions were uniform over all of the area having subdrains at depths of 3.5 and 4.5 ft (1.1 and 1.4 m); where the subdrains were only 2.5 ft (0.76 m) deep the

surface was notably softer and wetter for subdrain spacings of 70 to 120 ft (21.3 to 36.6 m) than for spacings less than 70 ft (21.3m).

(b) It was noted at the time when the subdrained plots were dry enough to permit seedbed preparation to commence that the topsoil was progressively wetter and softer as the distance increased away from the last tile line. At a distance of about 200 ft (61 m) to the south of the 5 ft (1.5 m) deep collector tile (see Figure 7) ones boots would sink about 2 in (5 cm) into the muddy fall-plowed topsoil. The topsoil was uniformly soft and muddy at distances greater than 200 ft (61 m) south of the collector tile.

4. On the Soulanges fine sandy loam, in the area with subdrains 2 ft (0.6 m) deep the tractor slippage was greater and the soil too soft and sticky where the subdrain spacings were greater than about 100 ft (30 m) on the first 2 days that seedbed preparation could proceed on the areas with subdrains at depths of 3 and 4 ft (0.9 and 1.2 m). There were no marked differences in soil surface condition with increasing subdrain spacing throughout the areas with subdrains 3 and 4 ft (0.9 and 1.2 m) deep.

5. In the 5 years, 1967 - 1971, the subdrained Ste. Rosalie clay was dry enough for spring grain seedbed preparation to proceed 4 to 8 days earlier than the subdrained Soulanges fine sandy loam. A similar situation was noted on the Macdonald farm where clay and sandy loam soils existed on the same subdrained field. The difference appears to be due to differences in continuity of moisture conducting capillaries. High evaporation rates resulting from a few hours of bright sunshine and drying wind in mid-April appear to cause evaporation at rates faster than the clay capillaries can supply. It is suggested that this causes discontinuities in clay capillaries. It appears that the capillaries in the sandy loam are able to conduct water fast enough to meet the evaporation capabilities. Thus springtime evaporation needs to remove water from 2 ft (61 cm) or more of sandy soil profile but only perhaps 4 in (10 cm) of clay soil profile

before the surface becomes dry enough for seedbed preparation. This drying phenomenon creates a kind of "paving" sufficient to carry the tractor and permit tillage of the top 3 in (7.5 cm) of clay soil even though soil at greater depths is still at field capacity.

6. Rains of more than about 0.05 inches, whether large enough to cause subdrain flow or not, would cause the surface of both soils to become sticky and slippery. Delays, while waiting for surface drying to allow planting or harvesting operations to proceed, were slightly less for the Soulanges fine sandy loam than for the Ste. Rosalie clay.

7. Reviews of weather records and discussions with farmers indicate that in about 3-out-of-10 years worse weather conditions for harvest may be expected than occurred in any of the 4 years, 1967 - 1970. Excess rain, or conditions of high humidity and low evapotranspiration, in October and November affect farmers with large acreages more severely than farmers with small acreages to harvest. Some farmers cited situations where maize harvest was stopped due to immobility of tractors, harvest machines and wagons in soft muddy soil in a field without subdrains, but harvest operations proceeded at the same time in nearby subdrained fields of similar soil type.

8. No quantitative relationship has been established between degree of drainage and soil trafficability improvement. To get good estimates of the field machine work time available, and the probable capabilities of subdrainage to increase the time suitable for field machine work, a long term study involving observations of field conditions and weather parameters at several sites would be required.

CHAPTER X

SUMMARY AND CONCLUSIONS

From the observations and calculations during the course of the research described in this Thesis, the important findings and conclusions are summarized as follows :

1. Discharges measured at the outlets of four subdrains show that peak drainage rates can reach 3 in/day (76.2 mm/day) on Ste. Rosalie clay and 2.43 in/day (62.0 mm/day) on Soulanges fine sandy loam. The peak rates observed are much higher than would have been expected for these soils prior to the measurement of actual outflow rates and hydraulic conductivities.

2. The peak outflow rates were observed from drain tubes which had excess flow capacity. On normal farm subdrain installations the drain tube capacity will restrict the peak outflows to about 0.5 in/day) (12.7 mm/day). From observations presented, it is seen that it is the flow capacity of the drain tubes and not the hydraulic conductivity of the soil which limits peak outflow capacities of normal subdrain systems.

3. When the capacities of the drain tubes are not limiting and when the subdrains are shallower than 3 ft and spaced 50 ft or less between laterals, the hydrograph of outflow recedes rapidly (20 to 40 hrs) after the end of the snowmelt or rainfall event causing the flow.

4. Outflow measurements show that 75% or more of the water content of snow may flow through the soil to subdrains during the snowmelt period. If it is deemed desirable to reduce leaching due to such snowmelt seepage, subdrain capacities could be restricted or outlets controlled to cause most of the snowmelt to runoff over the land surface before the subdrains remove excess water from the soil profile.

5. Where outflow was not restricted by the drain tubes, water tables dropped more rapidly after the end of rainfall or irrigation than would previously have been expected for these soils. These observations indicatec

high hydraulic conductivities for depths of 4 meters (13 ft) or more.

6. The water table observations following irrigations showed classical, near elliptical, water table shapes between subdrains. These observations, together with hydraulic conductivities calculated from drain flow equations and by auger hole methods, indicate good applicability of known steady state and falling water table theories to water table performance on these St. Lawrence lowland soils when they are not frozen.

7. Mean hydraulic conductivities calculated from auger hole tests are approximately one half of the values calculated from observations of water table positions and subdrain flow rates. This difference is probably due to flow through the larger pores and cracks reaching the subdrains but not being adequately represented in the flow to the auger holes. Some of the difference may be due to the possible selection of too high a drainable porosity for the drain equation calculations.

8. The results of the four methods of determining drainable porosity show that the most suitable method is to take volumetric soil samples when the soil is at field capacity. The measured field capacity water content may then be subtracted from the saturation water content to get a value for drainable porosity. The second most satisfactory method is to record the water table rise following a rainfall which occurs when the soil is at field capacity on an area without subdrains. Since drainable porosity is a field feature it should be measured under field conditions rather than by use of the laboratory pressure plate apparatus.

9. The crop measurements indicate that maize grain yield in the field is relatively insensitive to spacing of subdrains. (a) On the Ste. Rosalie clay, no significant difference due to spacing of subdrains was found. (b) On the Soulanges fine sandy loam, for the 4 years in which yield data were obtained, yields were significantly higher for subdrain spacings less than 60 ft (18.3 m) than for subdrain spacings greater than 140 ft (42.7 m) in 1968 and 1969. The data indicate that yields of maize grain could average 20 bu/ac higher for subdrain spacings less than 60 ft (18.3 m) than for subdrain spacings from 120 to 200 ft (36.6 to 61 m) on the years with more than average rainfall in spring and early summer.

10. It was not feasible to get sufficient replication to properly test yield differences between areas with different depths of subdrains or between areas with and without subdrains. However, on the basis of the data obtained, it seems unlikely that yield increases greater than about 8% could be achieved for deep subdrains compared to shallow subdrains, or greater than about 20% for subdrained land compared to land without subdrains.

11. Subdrained land showed suitability for spring seedbed preparation 8 to 21 days earlier than land without subdrains in the 4 years of the field observations. Ste. Rosalie clay was also seen to have more convenient and less expensive harvesting conditions for maize grain when subdrained than when without subdrains.

12. The water table drawdown and soil surface condition observations show benefits for the installation of subdrains 3.5 ft (1.06 m) deep, or deeper, on the two soils studied. The performance of the drainage systems observed indicates that subdrains could be placed as much as 100 ft (30.5 m) apart, on many St. Lawrence lowlands farms without much reduction in drainage effect when compared to the more common spacings of 40 to 60 ft (12 to 18 m). Some additional benefits appear to be possible through use of land smoothing to present the low spots in the field within 10 ft (3 m) of the subdrain lateral positions.

13. Some longitudinal seepage appears to cause a drainage system with a linearly increasing spacing to give more rapid fall of the water table at wide spacings than would occur in a system of parallel subdrains.

14. A conservative approach to confirming the adequacy of drainage systems with wider spacings of subdrains would be to :

(a) Make auger hole tests to obtain comparative hydraulic conductivity values for some existing systems and some new systems to be installed in the region.

(b) Install some systems with subdrains spaced at 80 to 200 ft (24 to 61 m) but with the collectors conveniently placed to permit the future installation of intermediate laterals if more rapid drainage were found to be necessary.

(c) Place water table recorders at the mid-spacing of some additional systems having spacings between laterals of 40 to 200 ft (12.2 61 m) to get some years of records of the performance of natural water tables on subdrained fields in this region. From these records, field scale hydraulic conductivities could be estimated.

CHAPTER XI

RECOMMENDATIONS FOR FURTHER RESEARCH

As a result of the research for this thesis it is suggested that the following topics are potentially valuable for future research.

1. A water balance model taking into account precipitation, evapotranspiration, soil moisture, soil reservoir action, and drainage should be developed and used together with long term weather records for stations in the Ottawa and St. Lawrence lowlands to determine probabilities of recurrence of particular water table heights for different drainage rates. This could provide better guidance for the selection of drainage rates for the design of subsurface drainage systems for different soils, crops and locations in the region.

2. A characterization of soils which would relate the rate of fall of the water table to drain geometry, without having to measure and use widely varying values of hydraulic conductivity and drainable porosity, would provide a useful guide for subdrain design.

3. Drainage is one of the factors affecting conditions for the operation of field machines. Other factors involved are: weather, soil type, plant cover and machine characteristics. Research to establish limits of conditions suitable for the field operations of farm machines should assist the decision making of field machinery designers and farm managers. Operating conditions to be considered could include: seedbed preparation, forage and grain harvesting, field haulage of crop and manure and soil damage due to

machine traffic.

4. Flow measurements should be made on some subsurface drains with lengths of 600 ft. (180 m) or more to get further information on actual drainage rates occurring on soils in Quebec and Eastern Ontario.

5. Further controlled field measurements with adequate replication are needed to establish the financial benefits of improved production of various crops due to subsurface drainage.

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FIGURES

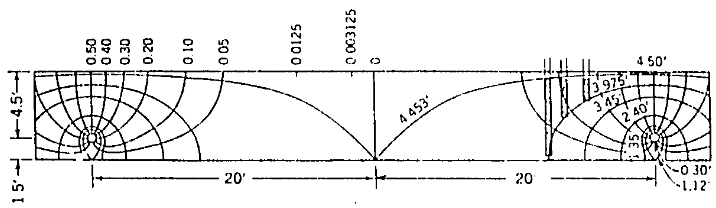


Figure 1. Flow Net for Parallel Drains in a Saturated Soil Overlying an Impervious Layer. (Redrawn from Kirkham, 1949).

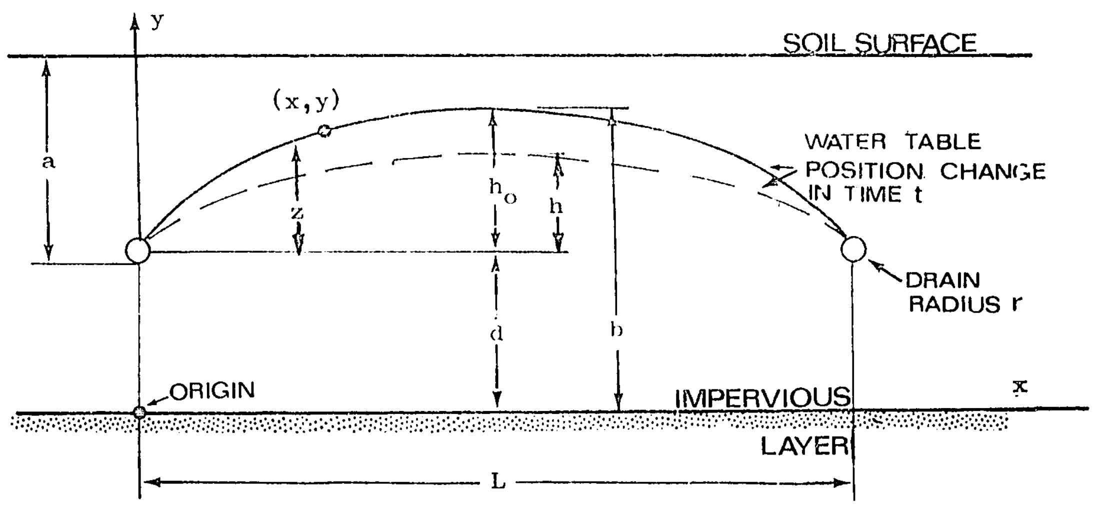


Figure 2. Symbols and Geometry for Subdrain Spacing Equations.

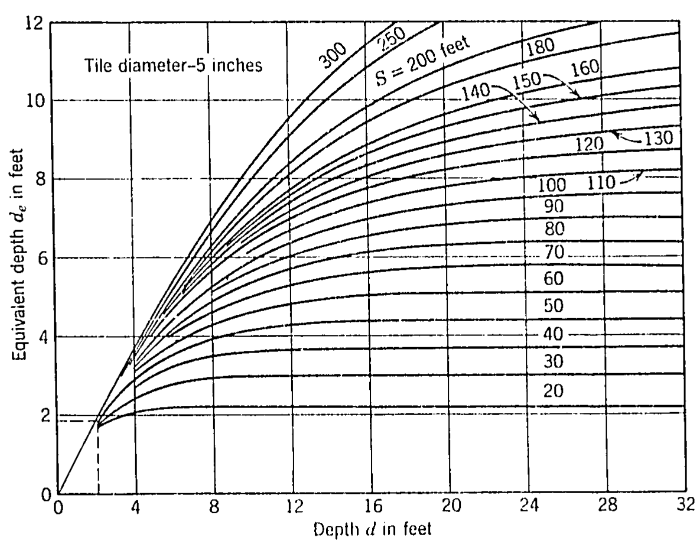


Figure 3. Equivalent Depth for the Water Conducting Layer Below the Drain. (Compiled by Van Schilfgaarde, 1963; Original Data from Hooghoudt.)

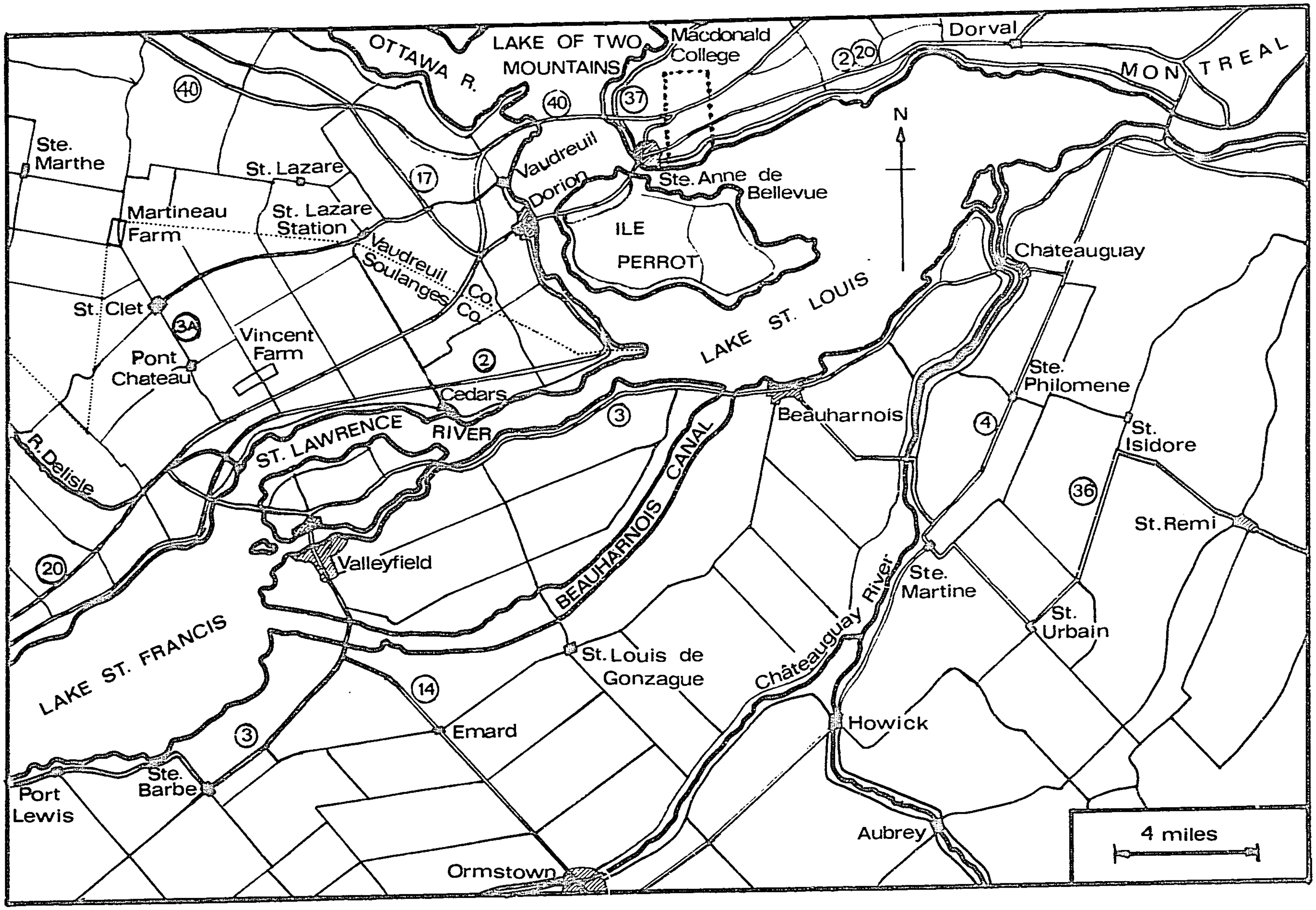
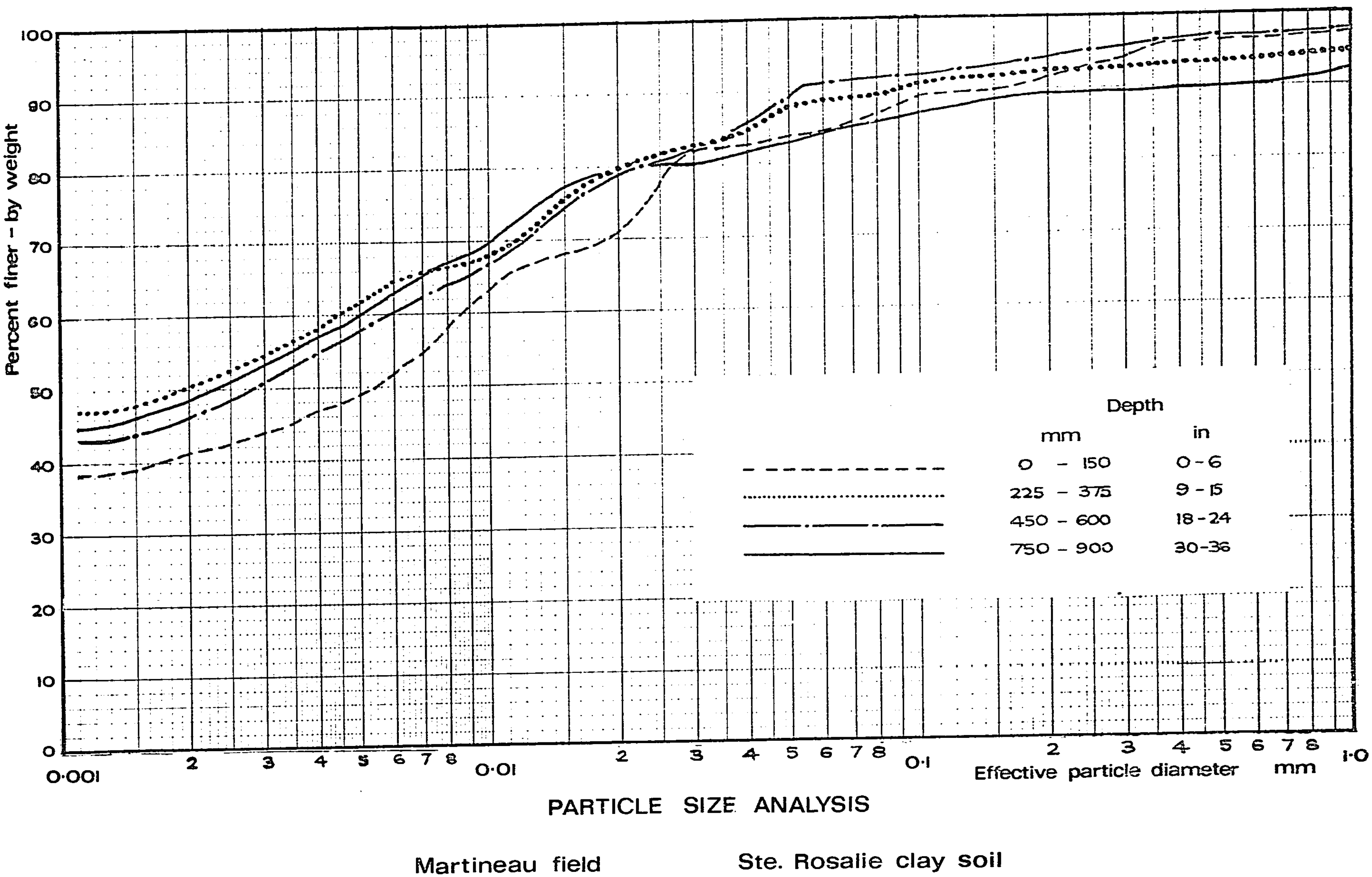
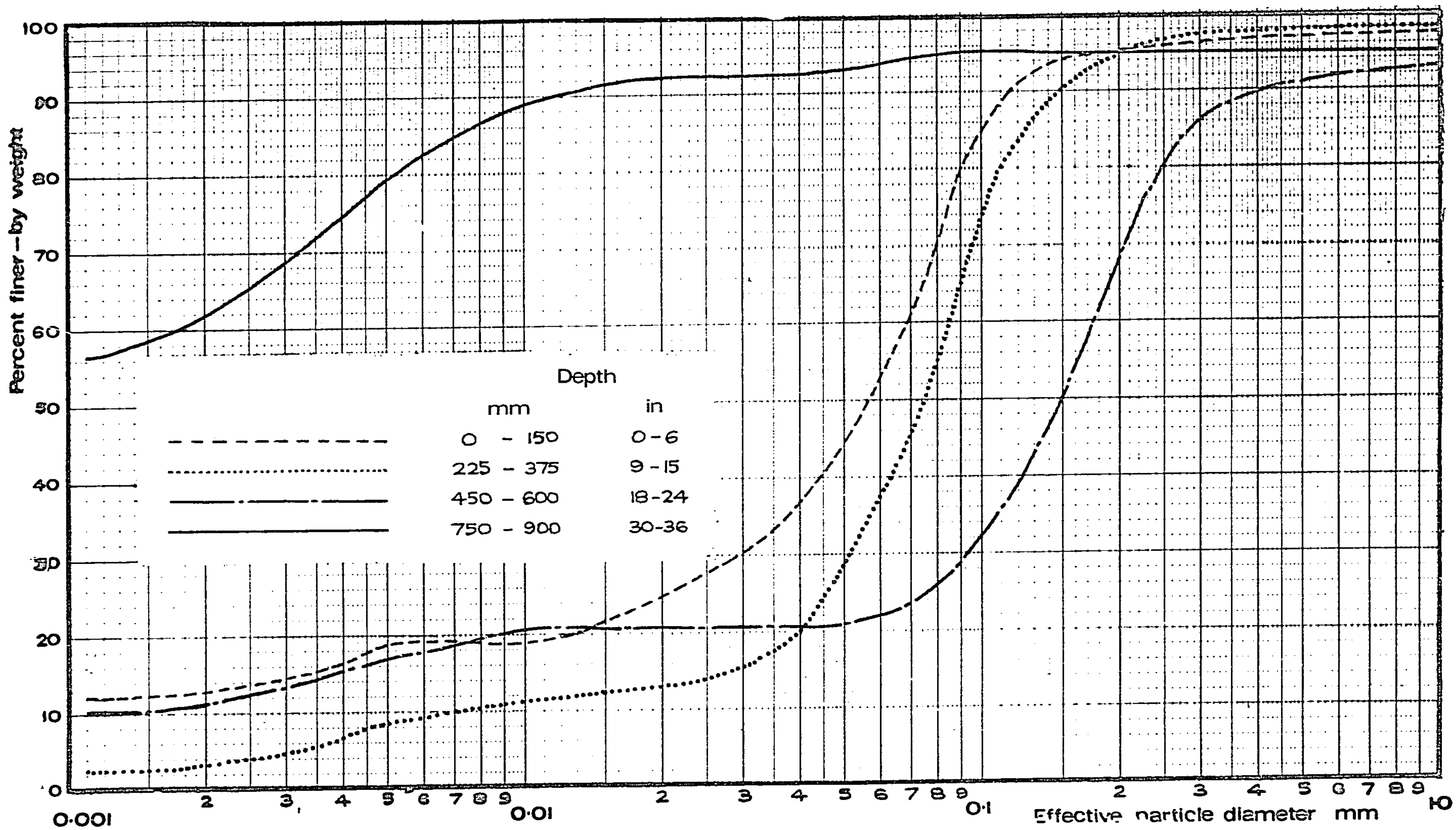


Figure 4. Map Showing Part of South-western Quebec and Location of Vincent and Martineau Farms.



Percent finer - by weight
100
90
80
70
60
50
40
30
20
10
0
0·001
2
3
4
5
6
7
8
0·01
2
3
4
5
6
7
8
0·1
2
3
4
5
6
7
8
1·0
Effective particle diameter mm
Depth
mm
in
0 - 150
0-6
225 - 375
9 - 15
450 - 600
18-24
750 - 900
30-36
PARTICLE SIZE ANALYSIS
Martineau field
Ste. Rosalie clay soil

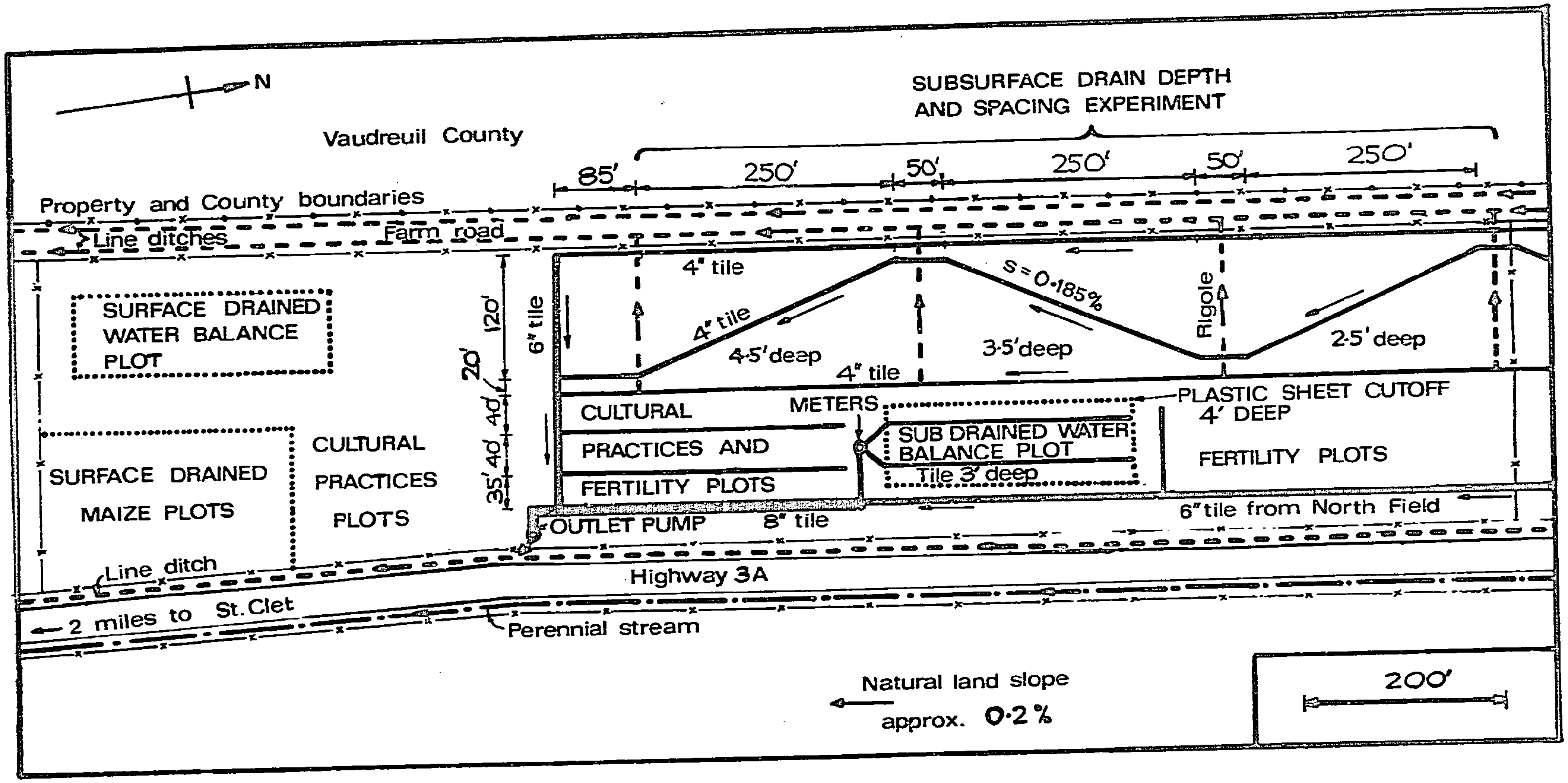
Figure 5.



PARTICLE SIZE ANALYSIS

Vincent field   Soulanges fine sandy loam soil

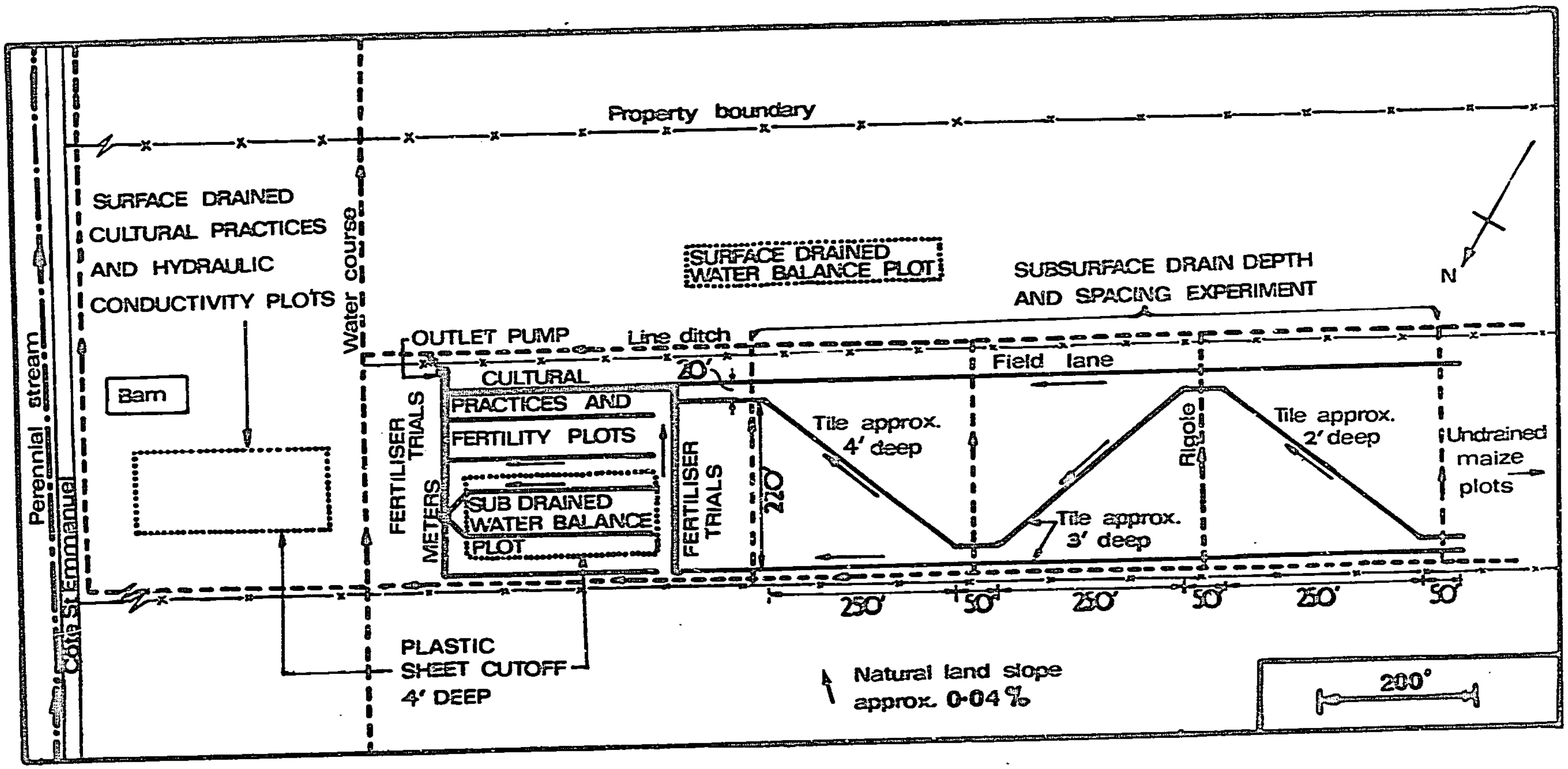
Figure 6.



PLAN OF EXPERIMENTAL FIELD – J. P. MARTINEAU FARM, SOULANGES COUNTY, P.Q.

STE. ROSALIE CLAY SOIL

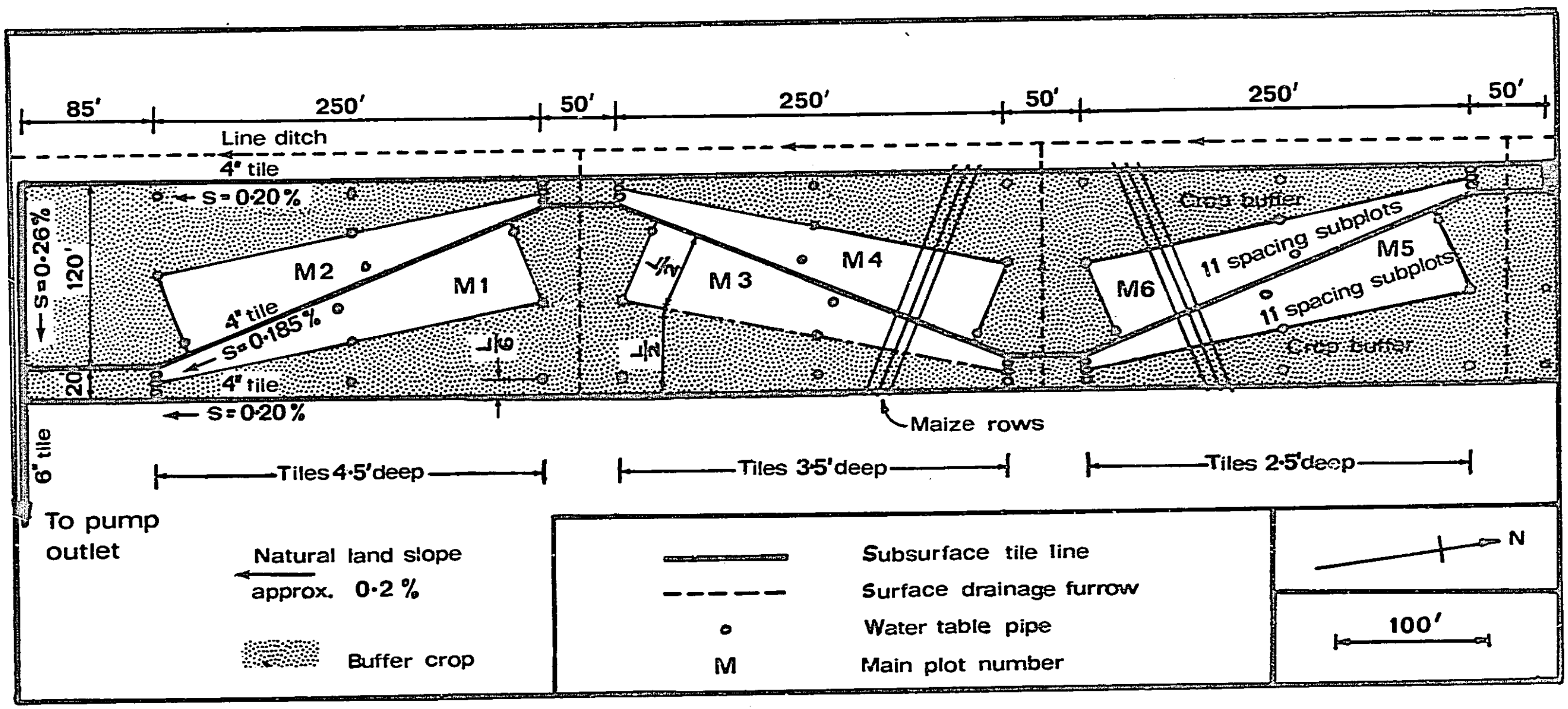
Figure 7.



PLAN OF EXPERIMENTAL FIELD – PAUL EMILE VINCENT FARM, SOULANGES COUNTY, P.Q.

SOULANGES FINE SANDY LOAM SOIL

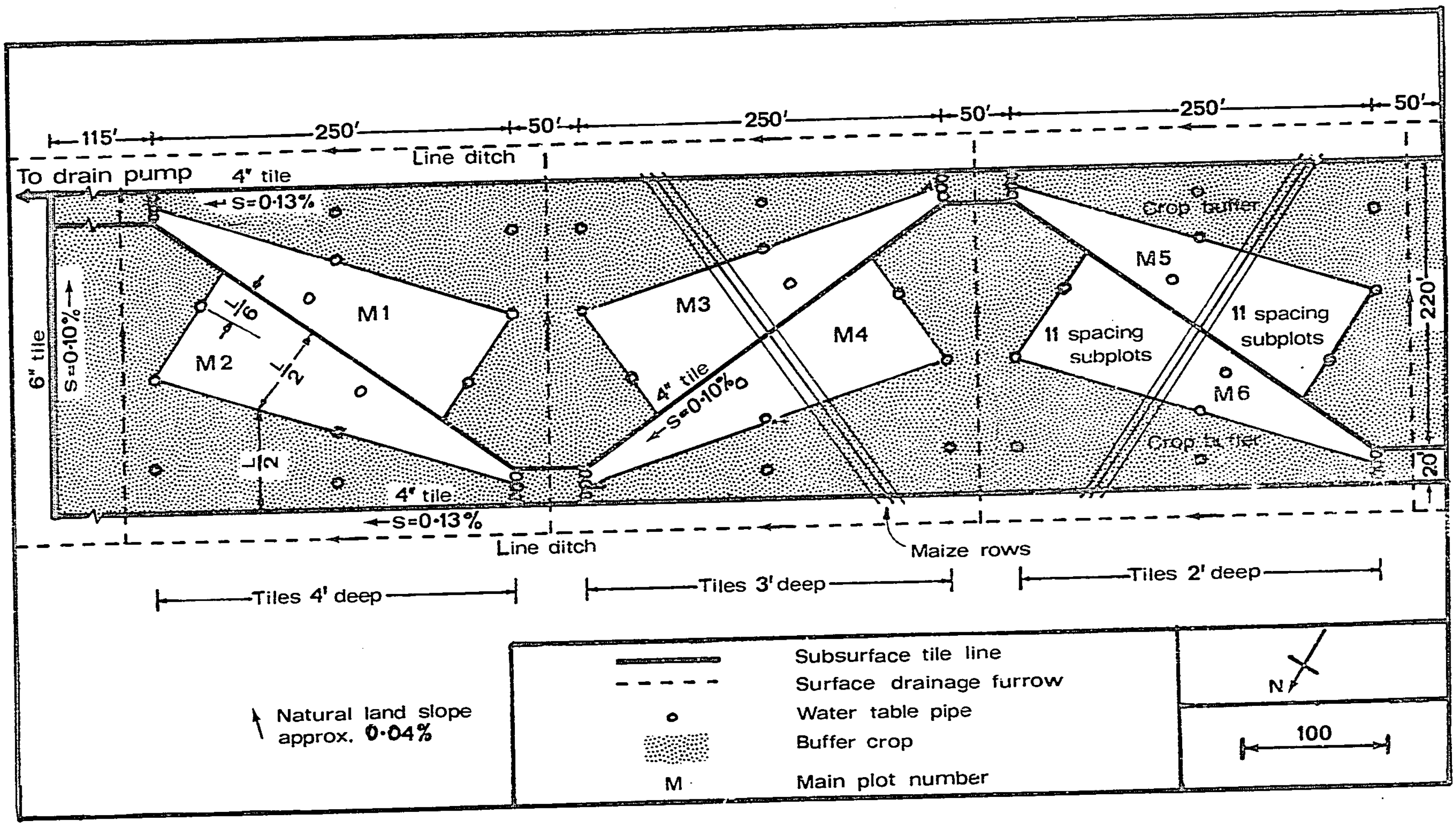
Figure 8.



LAYOUT OF SUBSURFACE DRAIN DEPTH AND SPACING EXPERIMENT

Martineau field Ste. Rosalie clay

Figure 9.



LAYOUT OF SUBSURFACE DRAIN DEPTH AND SPACING EXPERIMENT

Vincent field

Soulanges fine sandy loam

Figure 10.

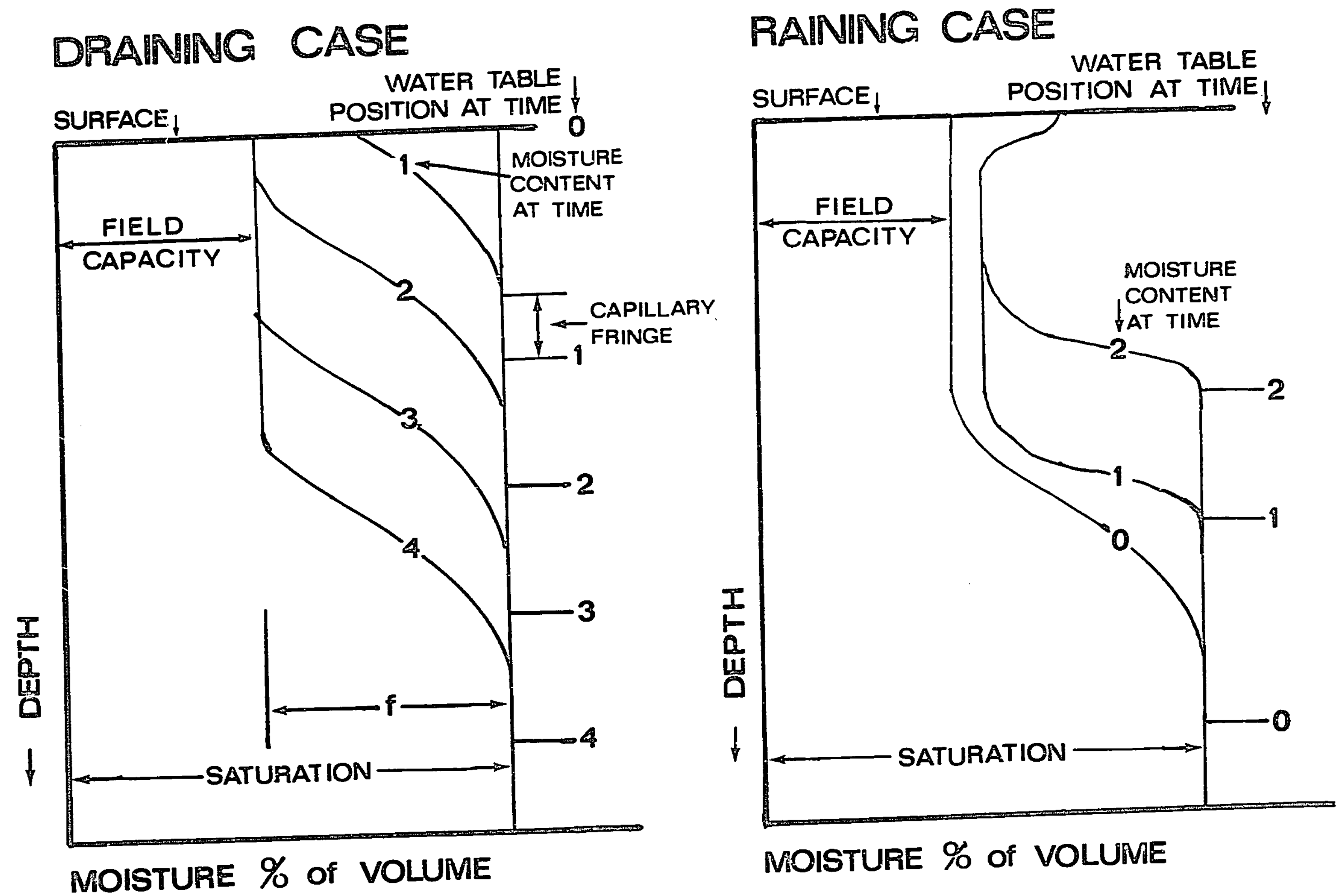


Figure 11. Hypothetical Soil Moisture Profiles at Successive Times During Periods of Falling and Rising Water Tables.

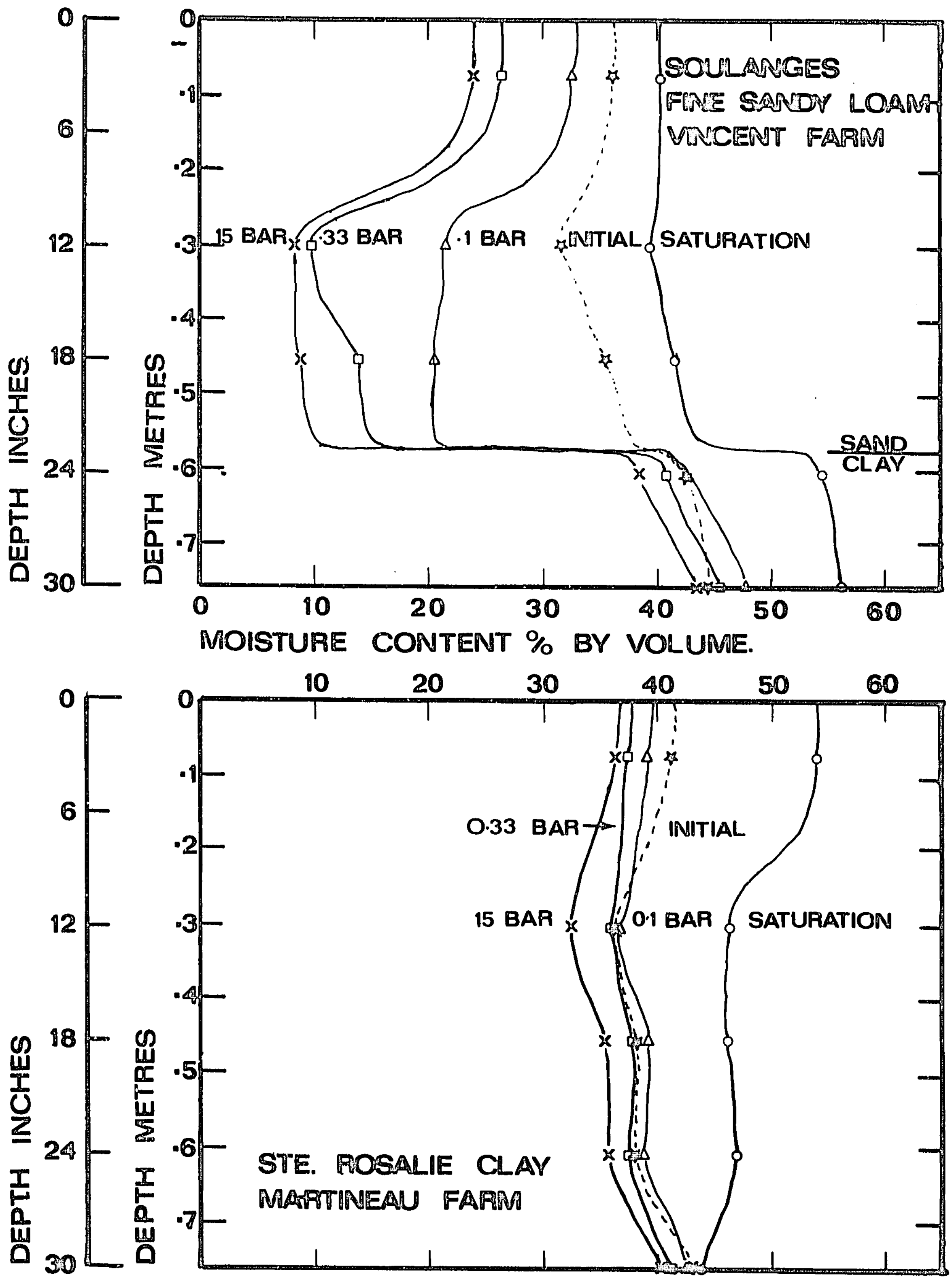


Figure 12. Soil Moisture Profiles for the Conditions of Saturation, Initial Moisture, and 0.10, 0.33 and 15.0 bar Pressure.

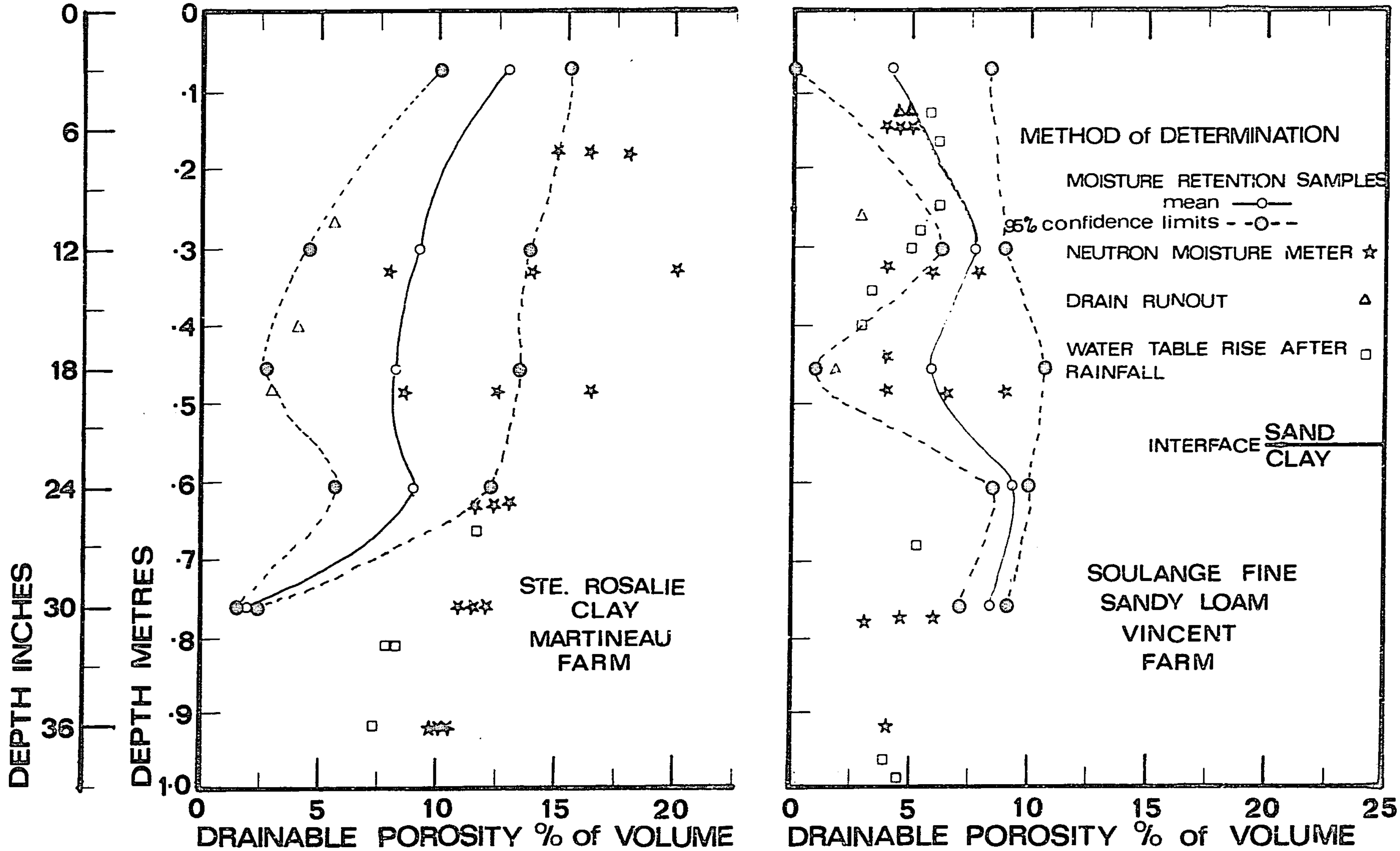


Figure 13. Drainable Porosities Estimated by Four Methods.

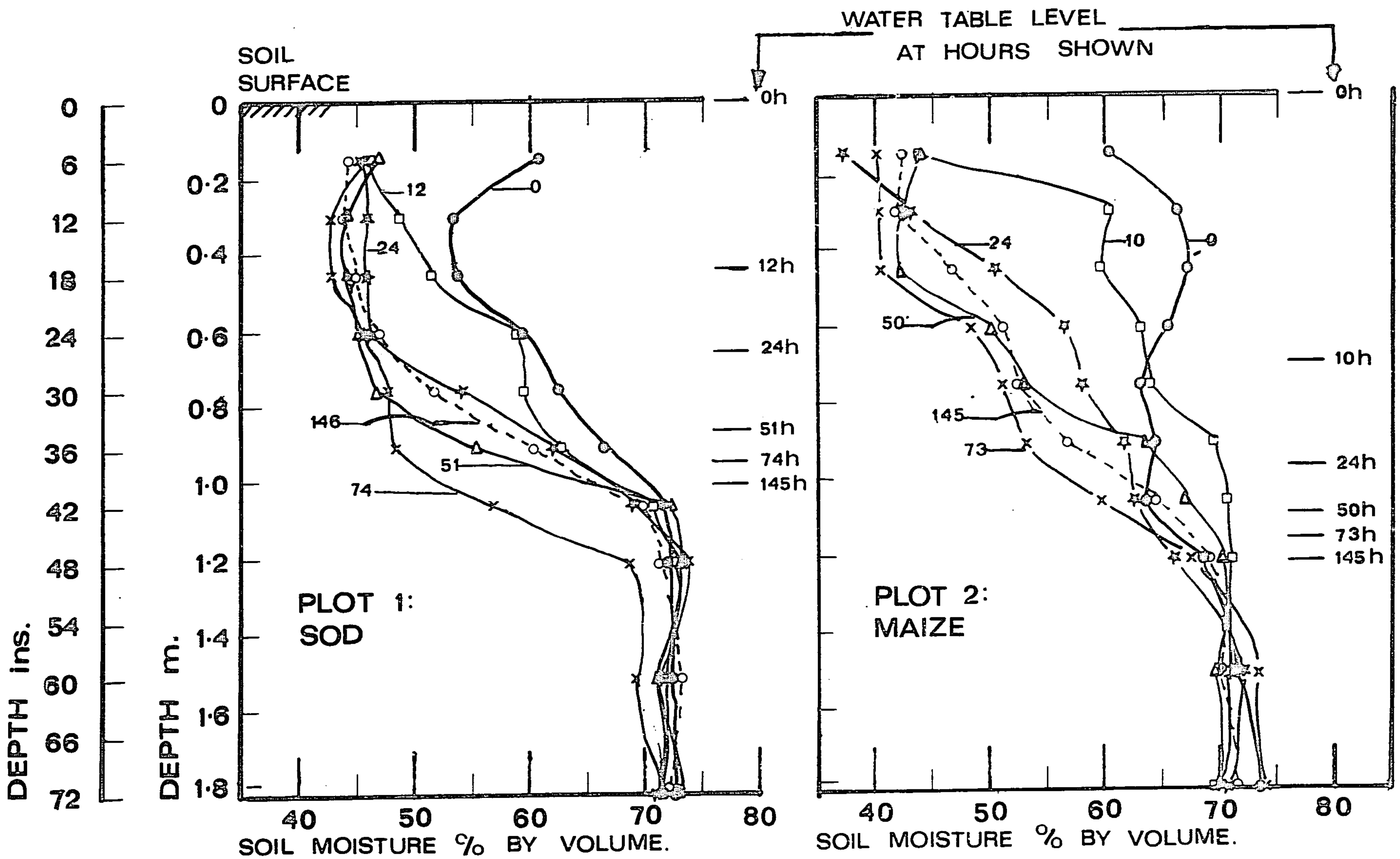


Figure 14. Soil Moisture Contents and Water Table Levels at Indicated Hours After Irrigation Ended July 25, 1970, Martineau Farm, Ste. Rosalie Clay. Moisture Contents Determined in Situ by a Troxler Neutron Moisture Meter.

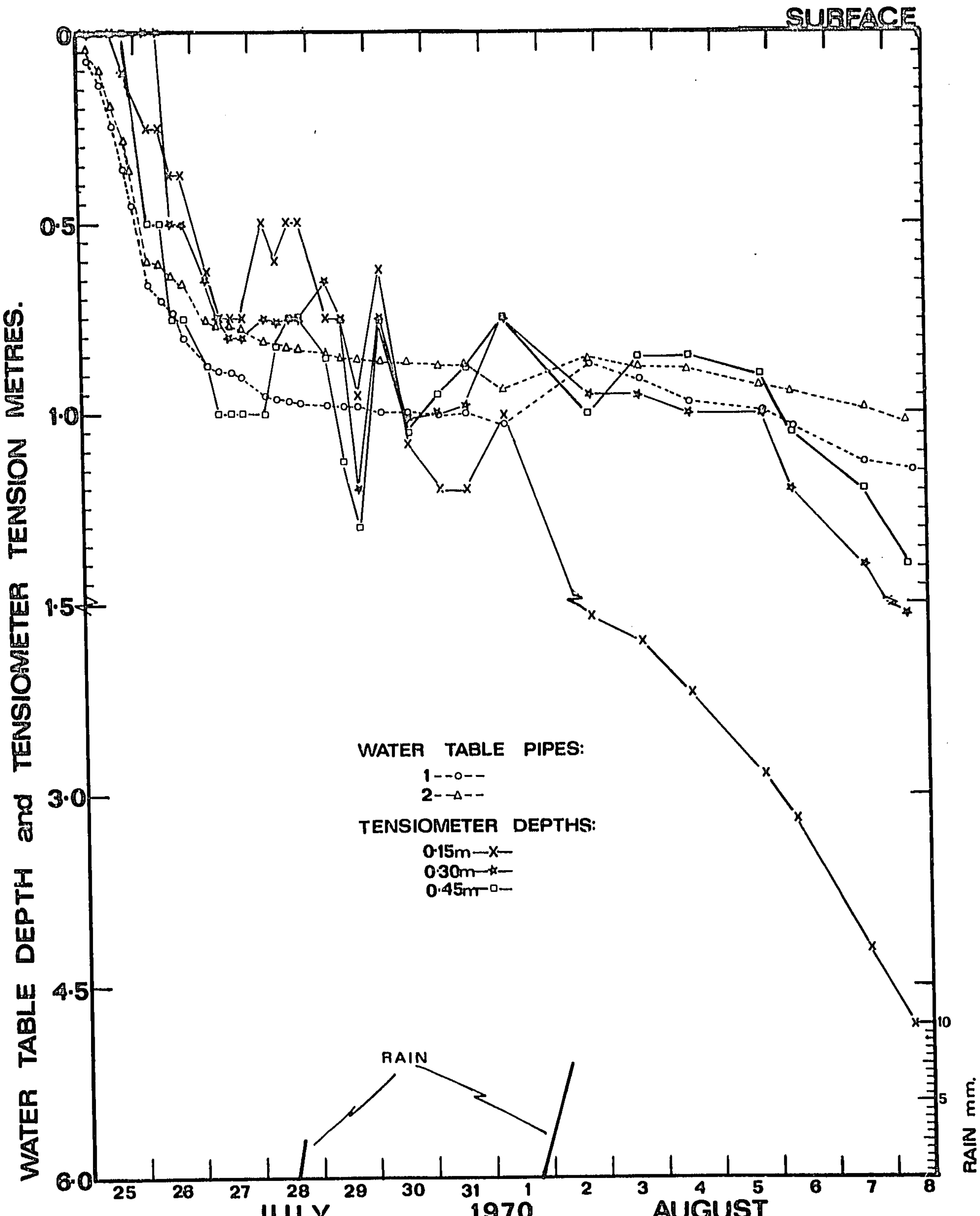


Figure 15. Water Table and Tensiometer Observations After End of Irrigation of Sod Covered Drainable Porosity Plot, Martineau Farm, Ste. Rosalie Clay, 1970.

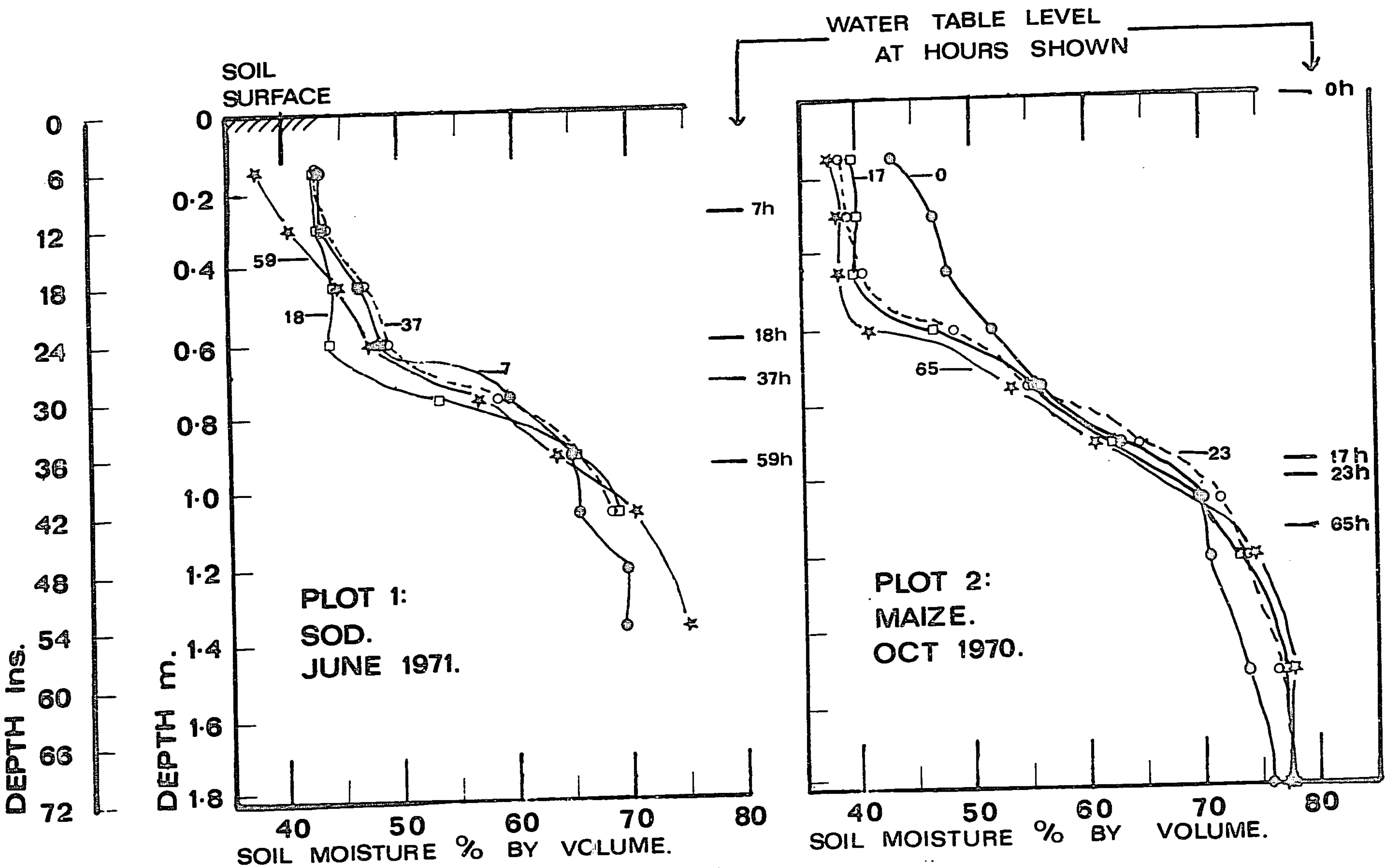


Figure 16. Soil Moisture Contents and Water Table Levels at Indicated Hours After Irrigation was Stopped for Two Soulanges Fine Sandy Loam Plots, Vincent Farm. Moisture Contents Determined in situ by a Troxler Neutron Moisture Meter.

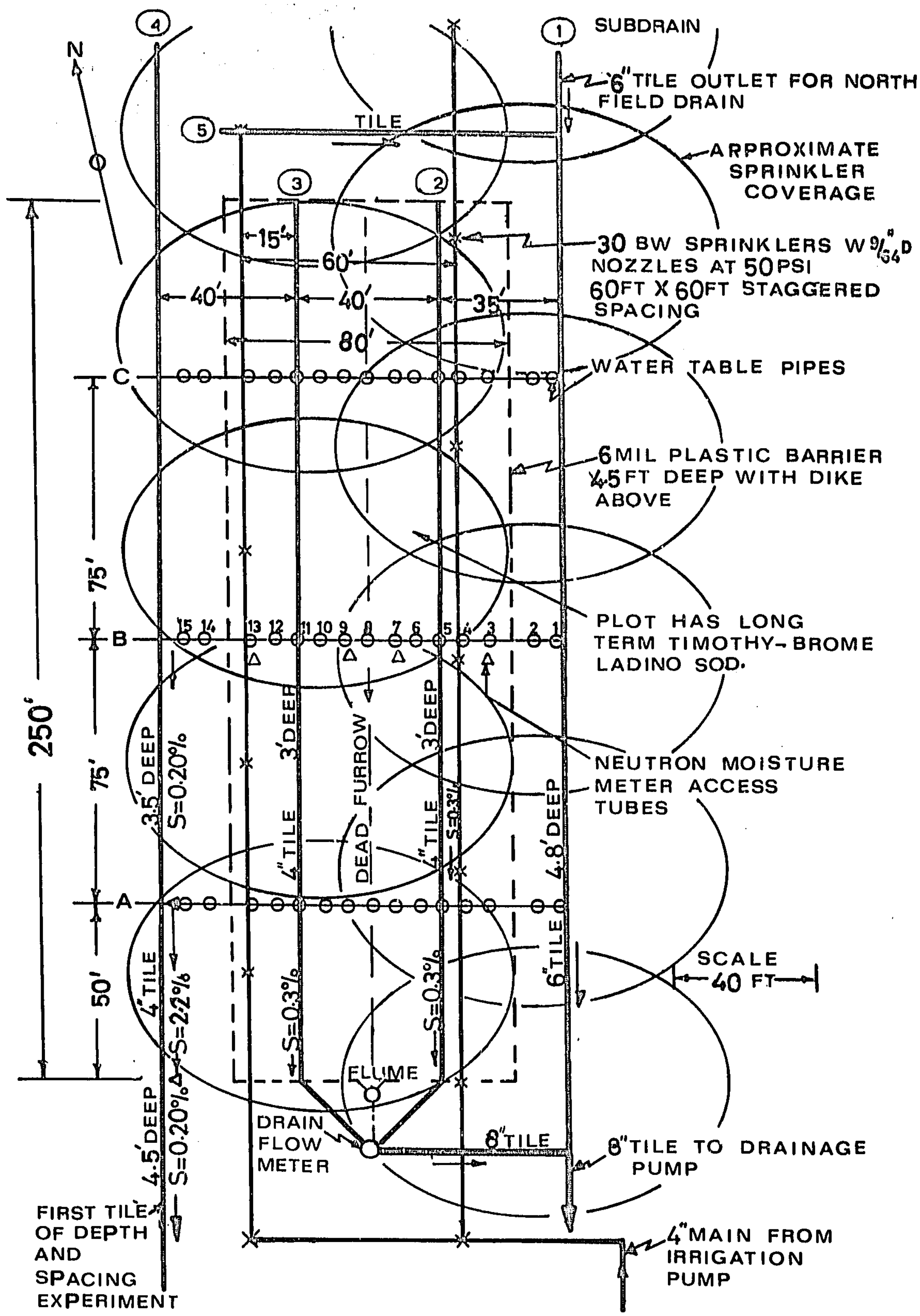


Figure 17. Locations of Irrigation Sprinklers, Water Table Pipes, and Neutron Meter Access Tubes on Subdrained Water Balance Plot, Martineau Farm, Ste. Rosalie Clay Soil, 1970.

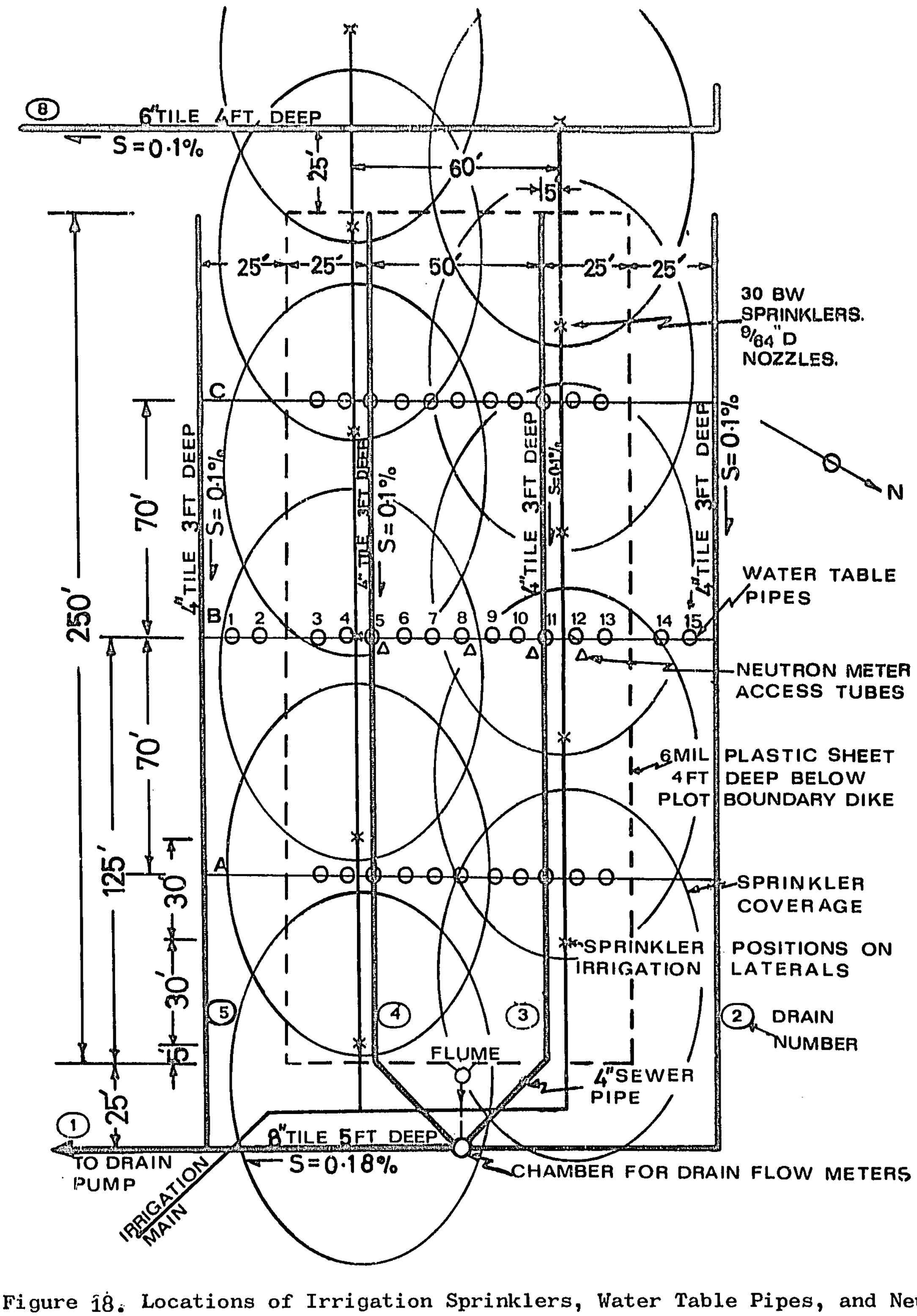


Figure 18. Locations of Irrigation Sprinklers, Water Table Pipes, and Neutron Meter Access Tubes on Subdrained Water Balance Plot, Vincent Farm, Soulanges Fine Sandy Loam, June 1971.

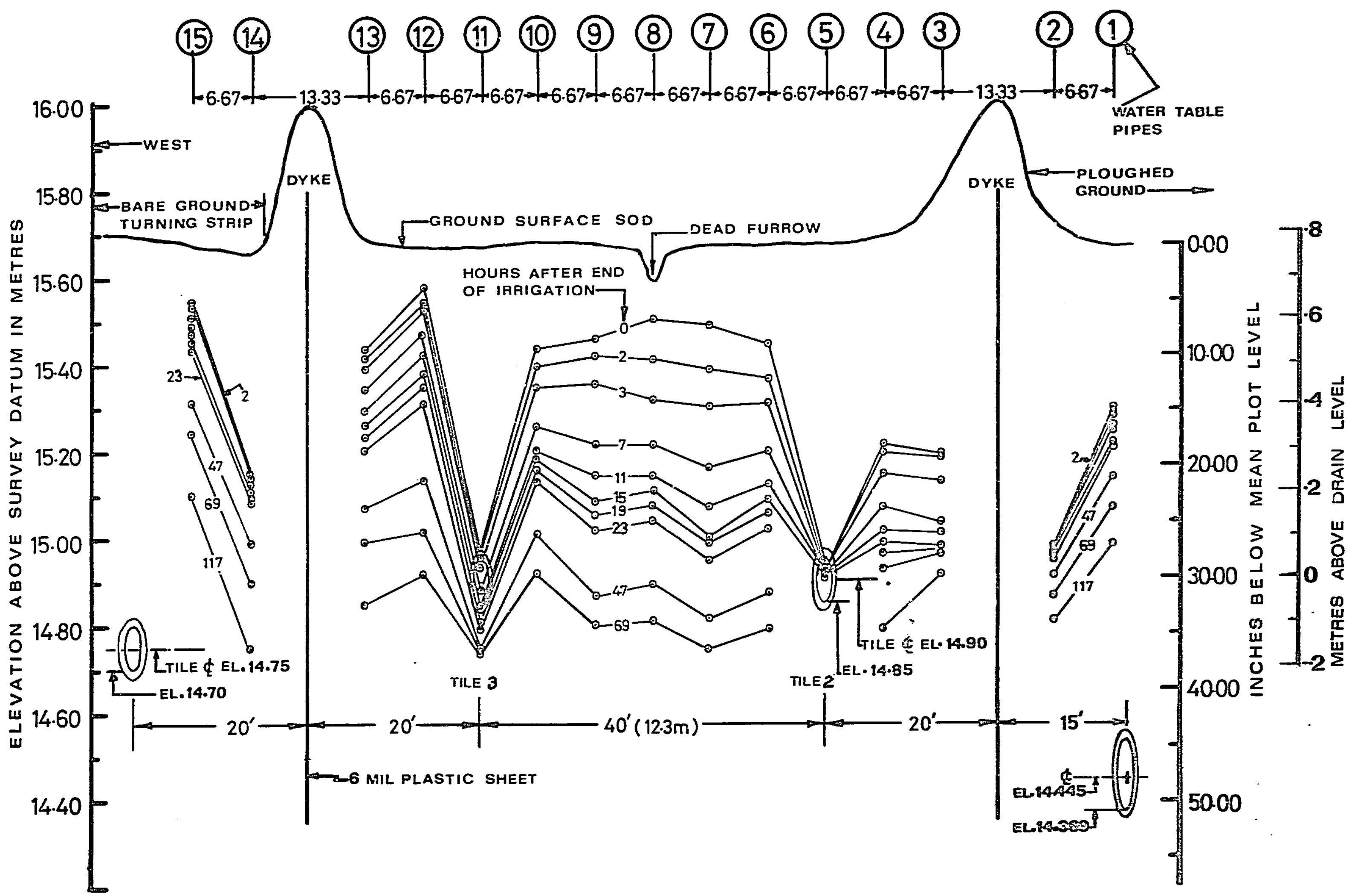


Figure 19. Water Table Positions at Section B at Successive Times After Stopping Irrigation, 1730 hrs August 2, 1970, Martineau Subdrained Water Balance Plot, Ste. Rosalie Clay.

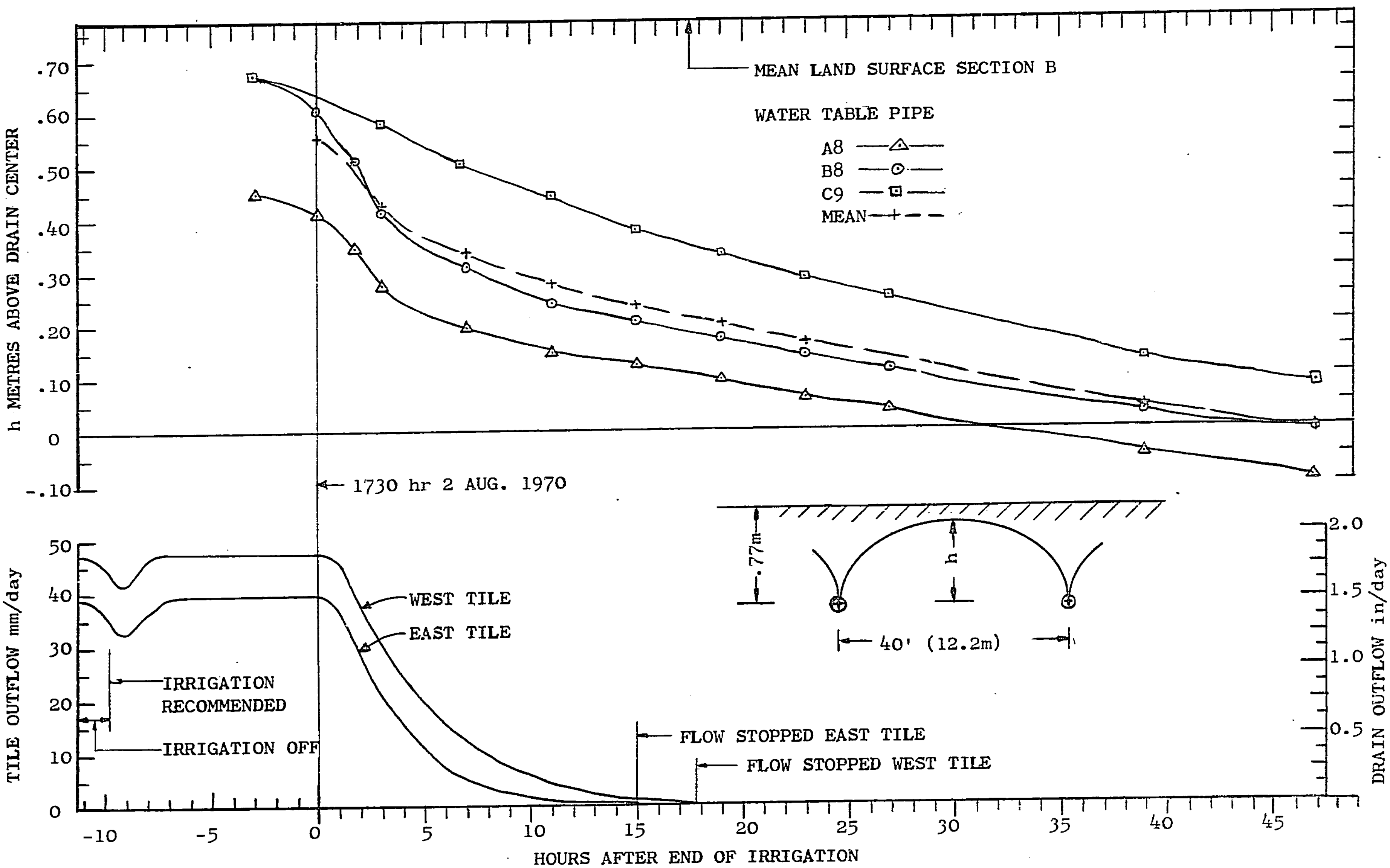


Figure 20. Mid-spacing Water Table Heights and Drain Outflow Hydrographs Following Irrigation, 2 August 1970, Martineau Subdrained Water Balance Plot, Ste. Rosalie Clay Soil.

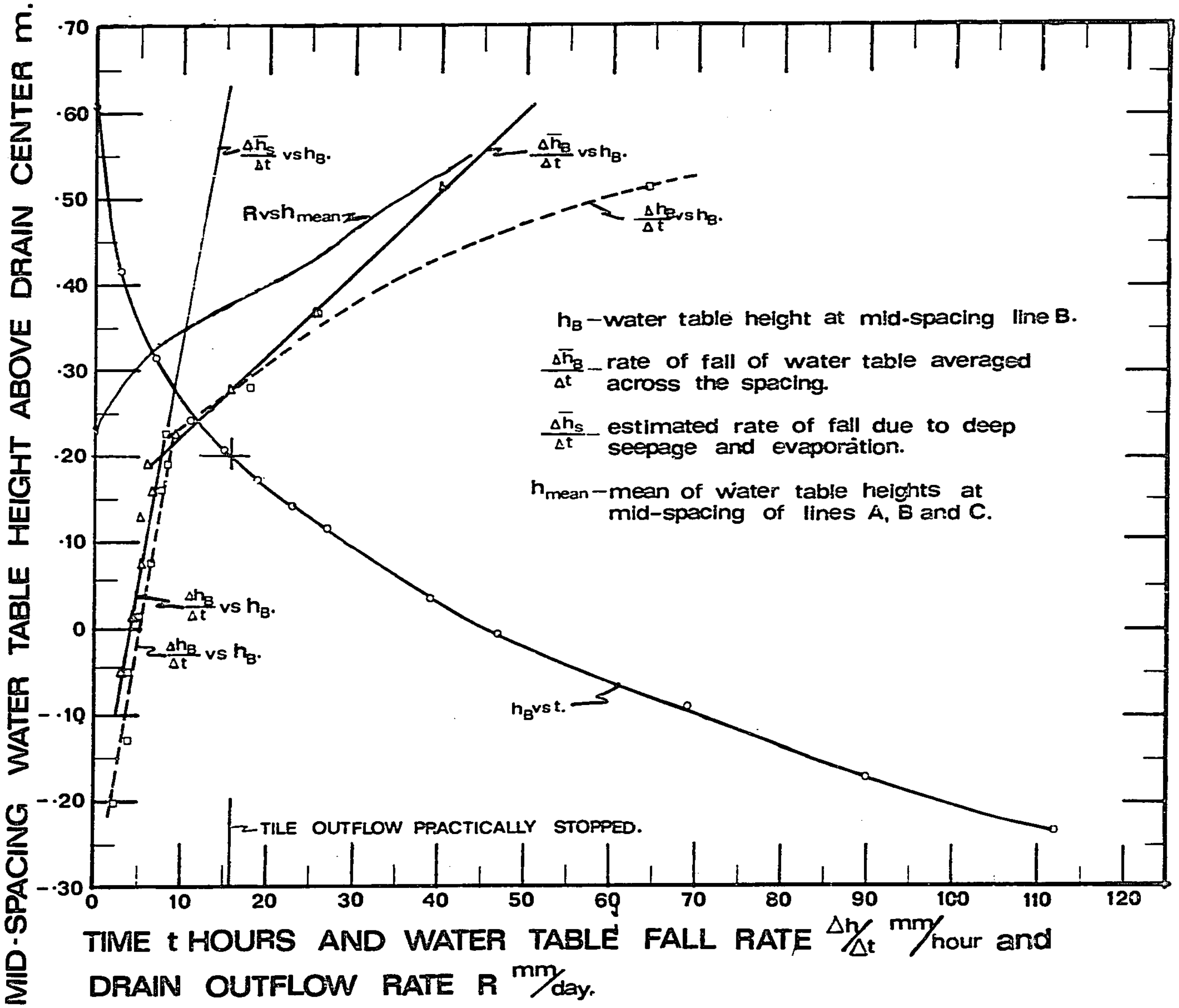


Figure 21. Rates of Water Table Fall, Subdrain Outflow and Deep Seepage After Stopping Irrigation, 1730 hrs August 2, 1970, Martineau Subdrained Water Balance Plot, Ste. Rosalie Clay Soil.

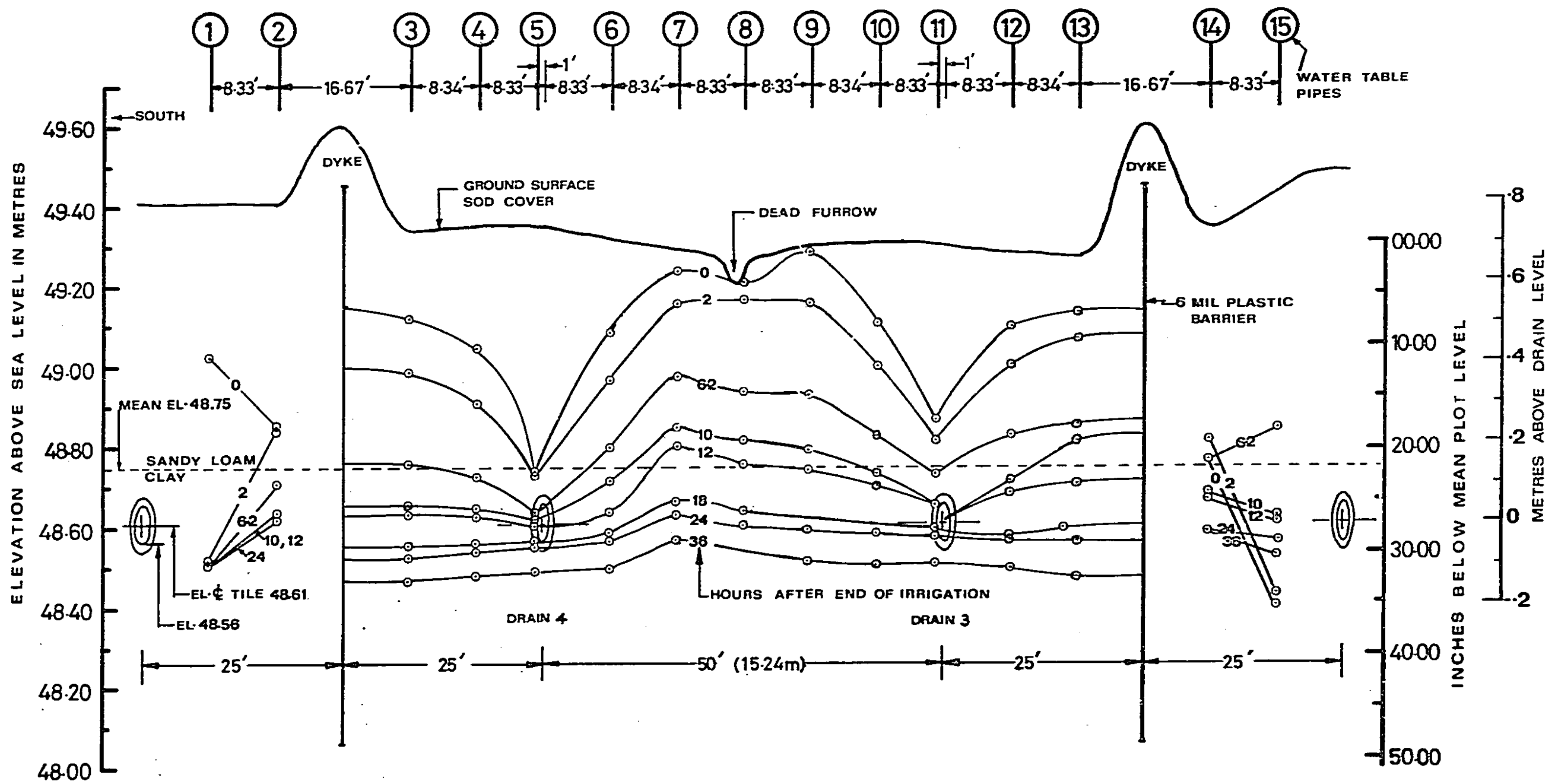


Figure 22. Water Table Positions at Section B at Successive Times After Stopping Irrigation, 2315 hr June 11, 1971, Vincent Subdrained Water Balance Plot, Soulanges Fine Sandy Loam.

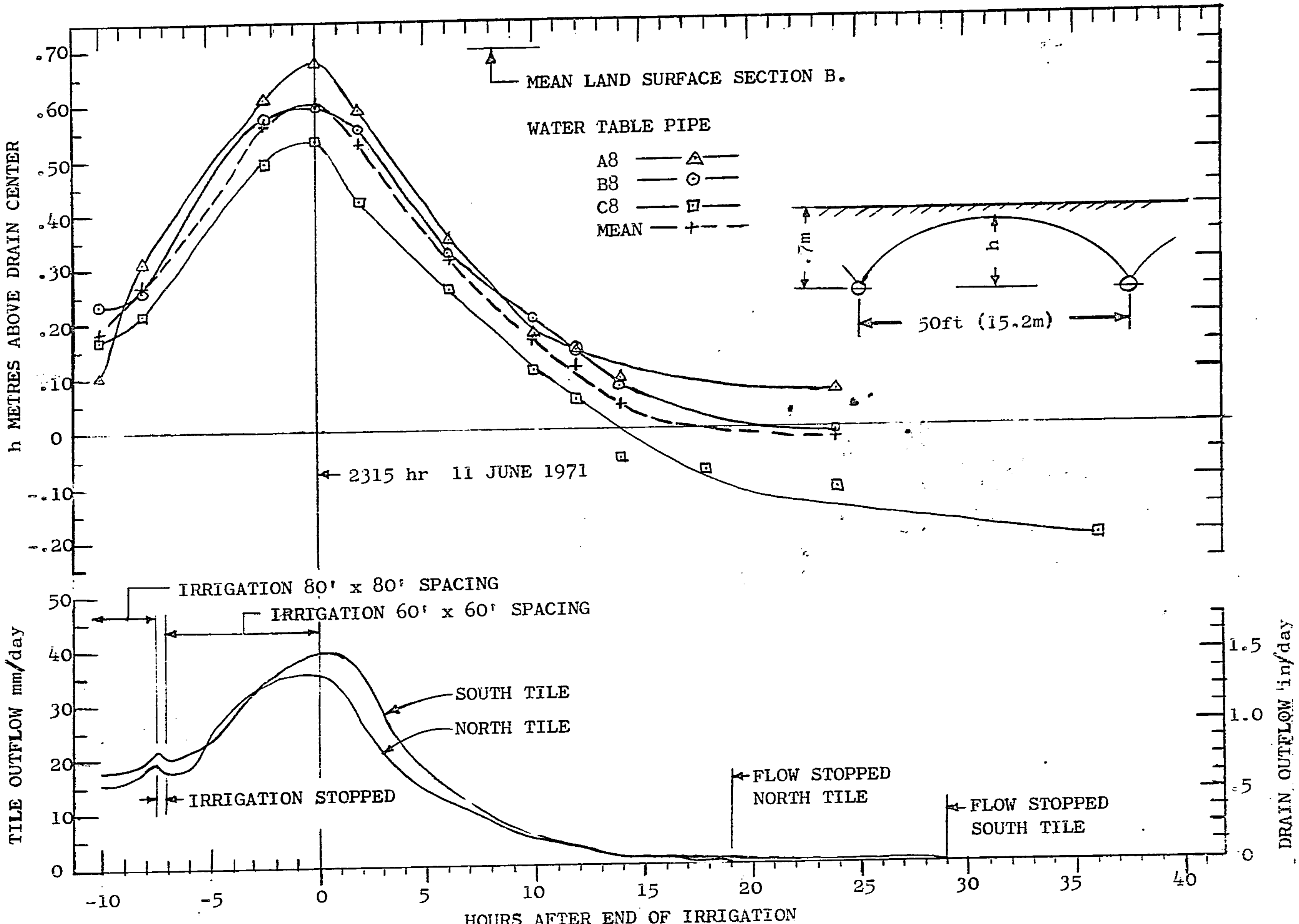


Figure 23. Mid-spacing Water Table Heights and Drain Flow Hydrographs Following Irrigation, 11 June 1971, Vincent Subdrained Water Balance Plot, Soulanges Fine Sandy Loam Soil.

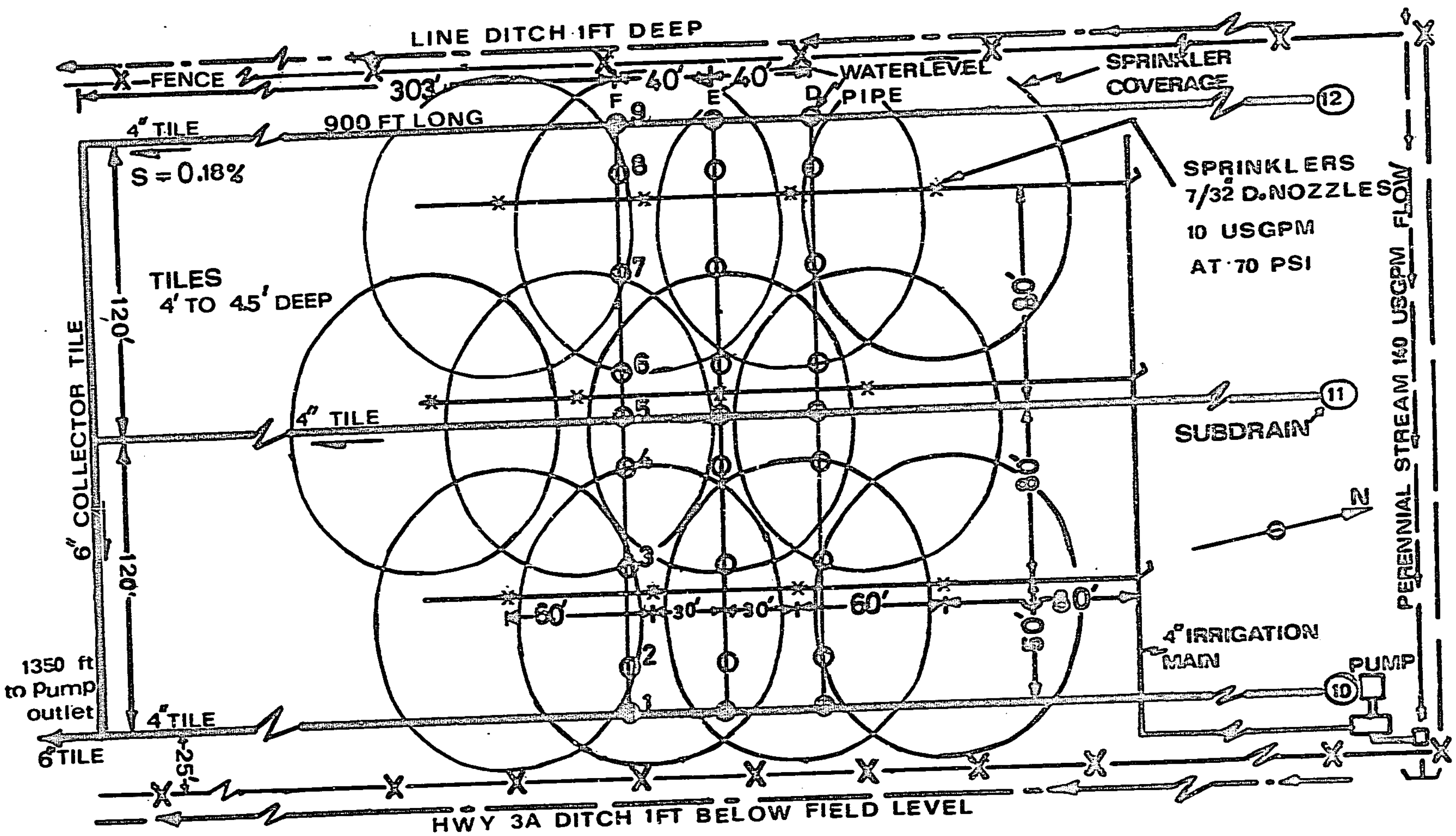
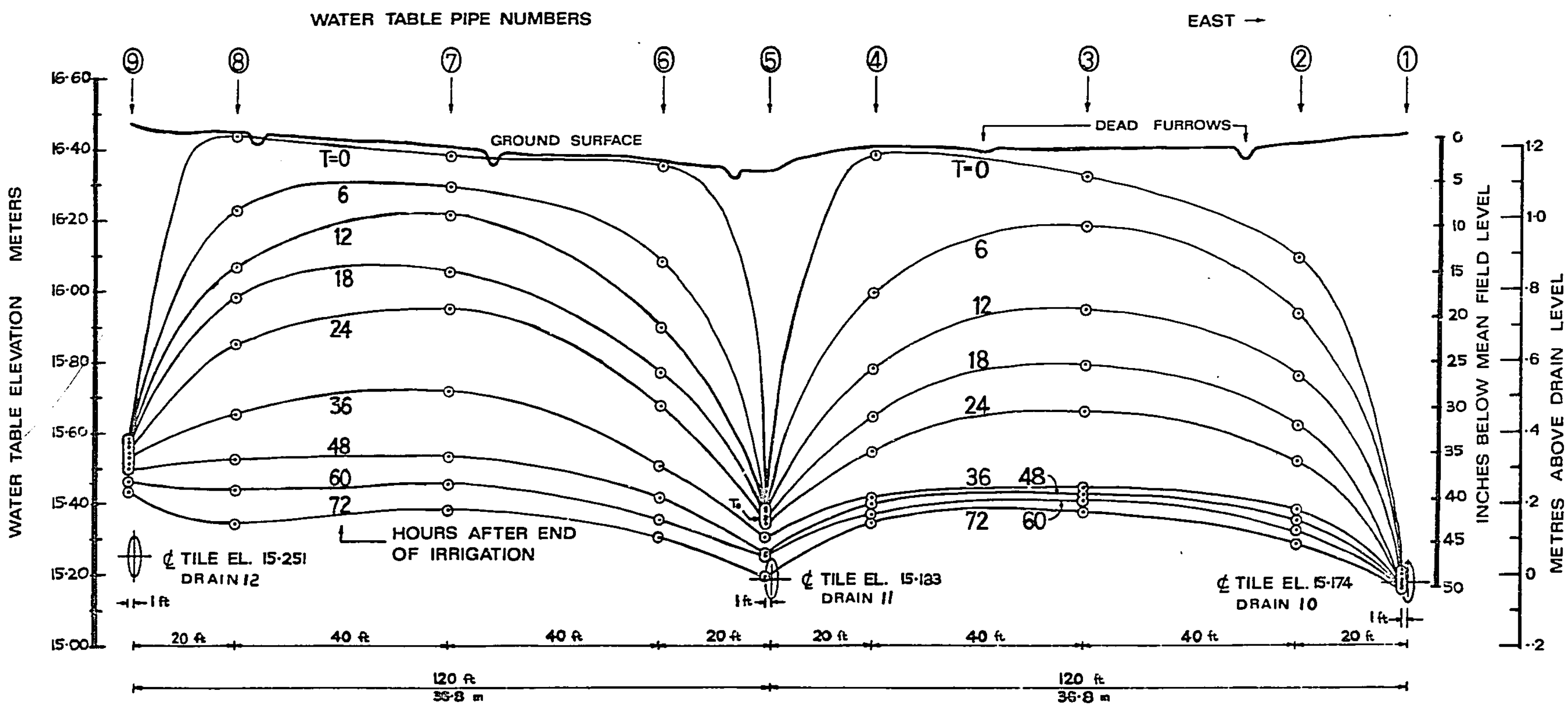


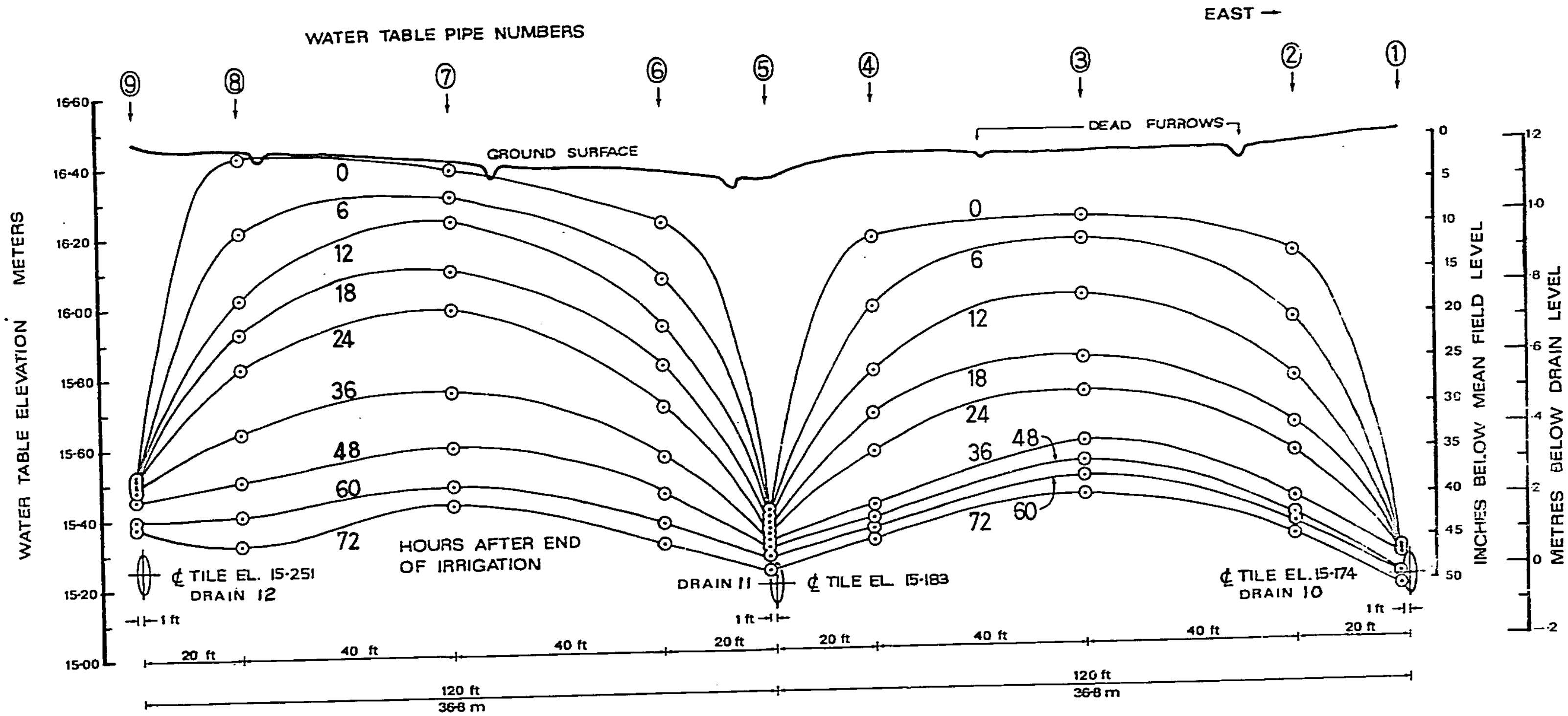
Figure 24. Locations of Irrigation Sprinklers and Water Table Pipes for Falling Water Table Tests August 1970 at Martineau North Pasture, Ste. Rosalie Clay Soil.



WATER TABLE POSITIONS AT SECTION E AT SUCCESSIVE TIMES AFTER STOPPING 3rd IRRIGATION AT 1830 hrs AUGUST 16 1970

MARTINEAU NORTH PASTURE STE. ROSALIE CLAY SOIL

Figure 25.



WATER TABLE POSITIONS, AVERAGE OF SECTIONS D,E, AND F, AT SUCCESSIVE TIMES AFTER STOPPING 3rd IRRIGATION AT 1830 hrs

AUGUST 16 1970 MARTINEAU NORTH PASTURE STE. ROSALIE CLAY SOIL

Figure 26.

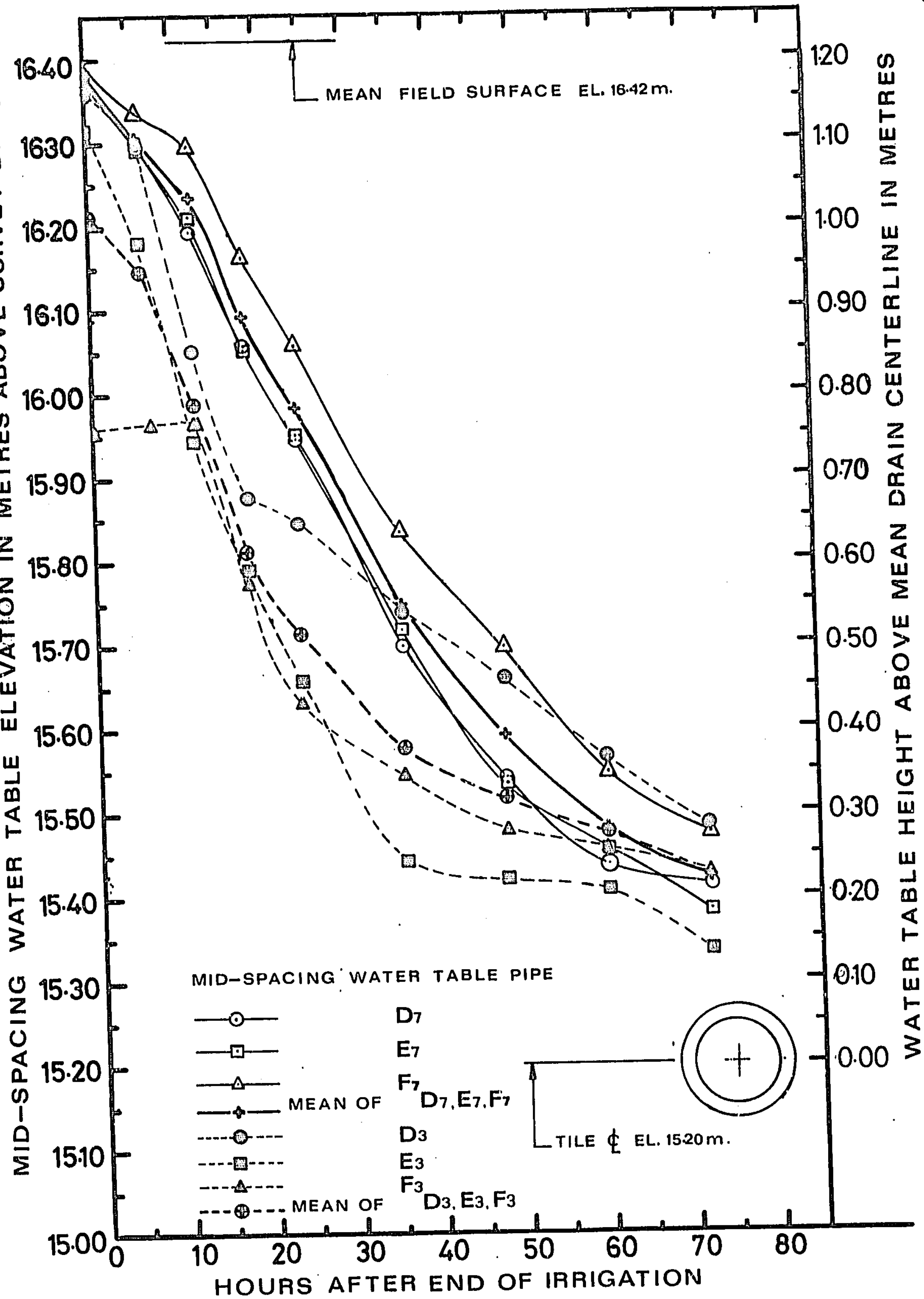


Figure 27. Mid-spacing Water Table Heights after Stopping 3rd Irrigation at 1830 hrs August 16, 1970, Martineau North Pasture Ste. Rosalie Clay, Subdrain Spacing 36.6 m (120 ft).

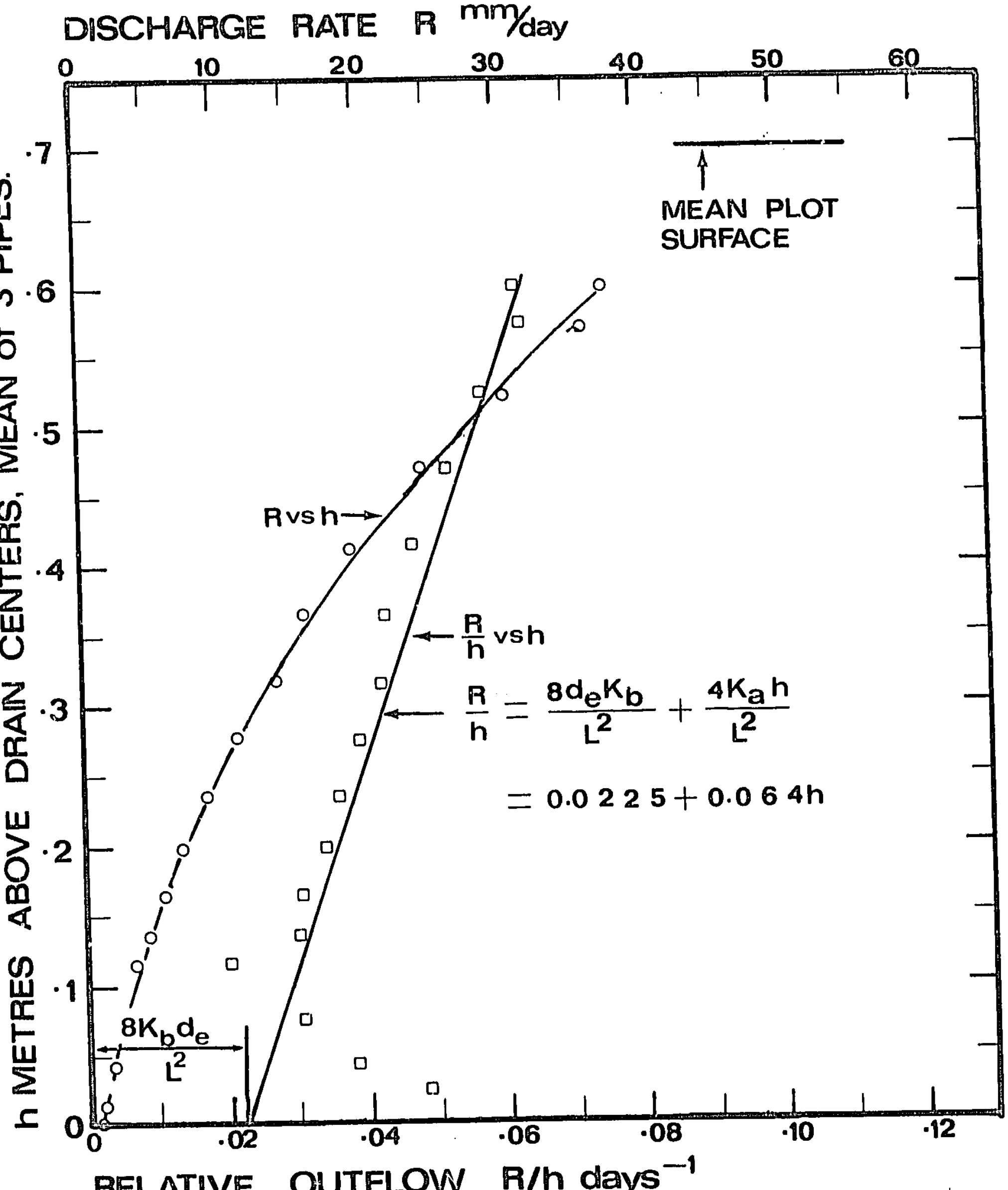
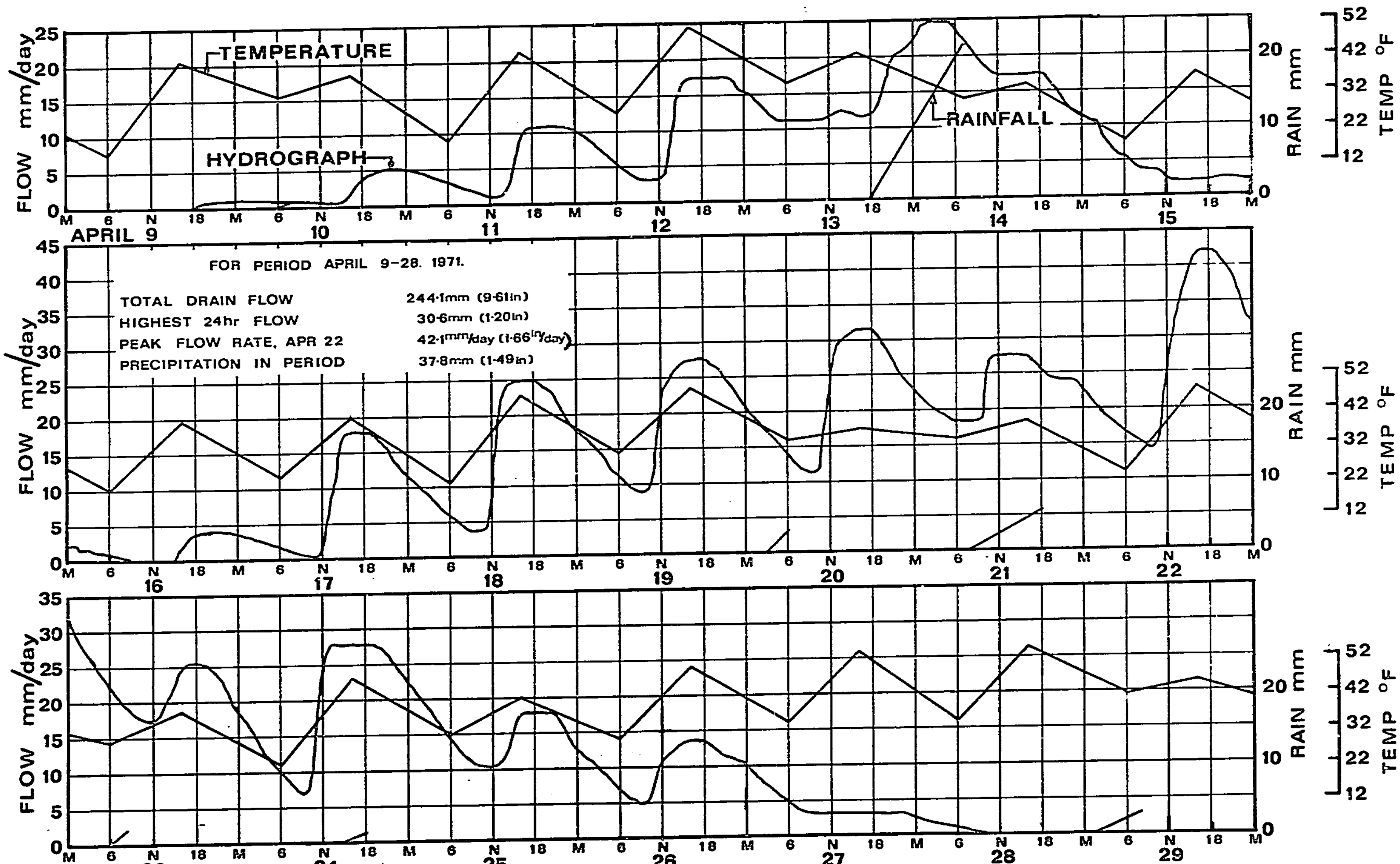
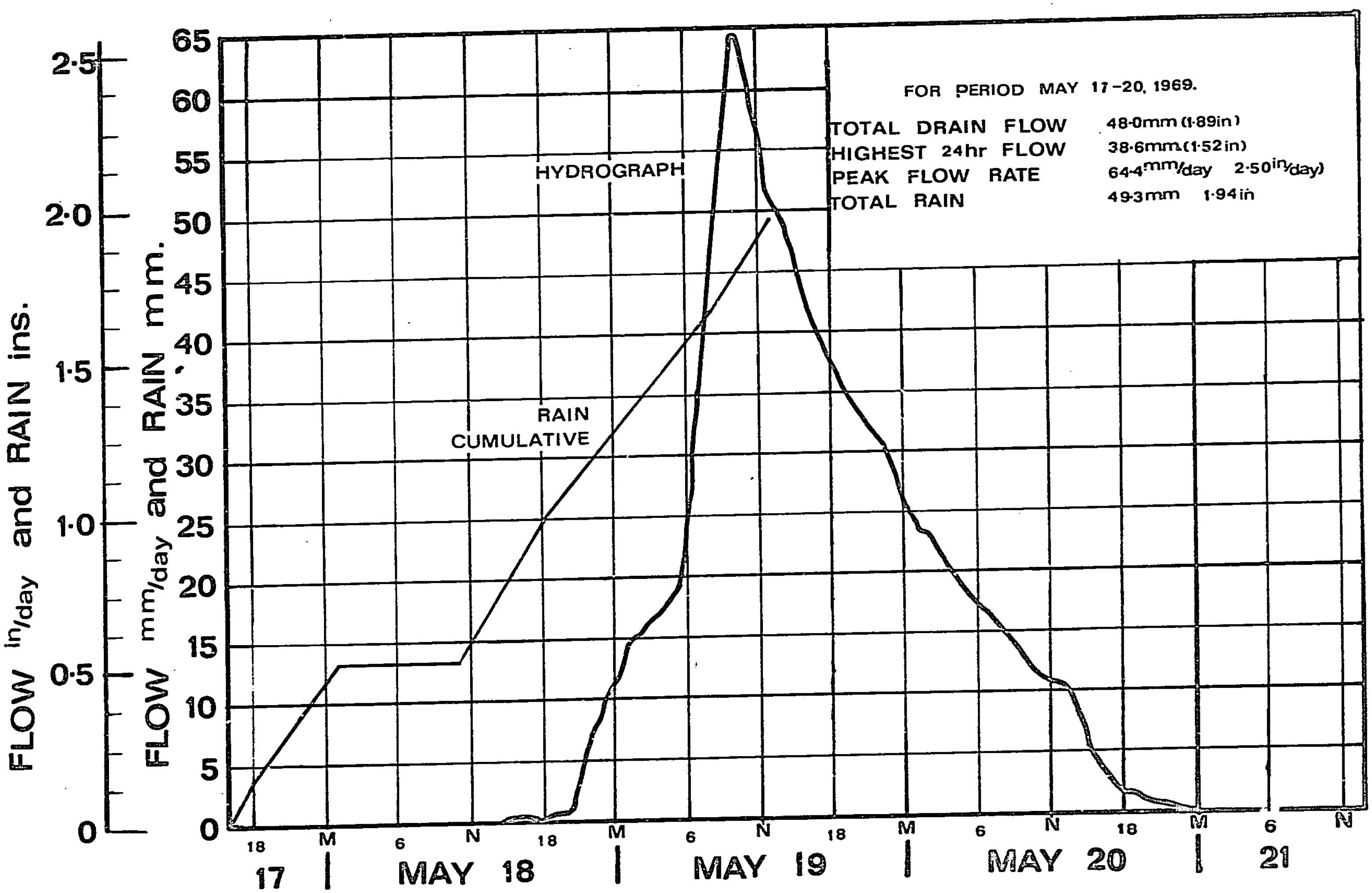


Figure 28. Measured Subdrain Outflow as a Function of Mid-spacing Water Table Height, Vincent Subdrained Water Balance Plot, Soulanges Fine Sandy Loam, June 11 - 12, 1970.



PRECIPITATION, AND HYDROGRAPHS FROM SUBDRAIN 3, MARTINEAU FARM SNOWMELT PERIOD APRIL 1971

Figure 29.



RAIN, AND HYDROGRAPH FROM MARTINEAU SUBDRAIN 3, MAY 1969.

Figure 30.

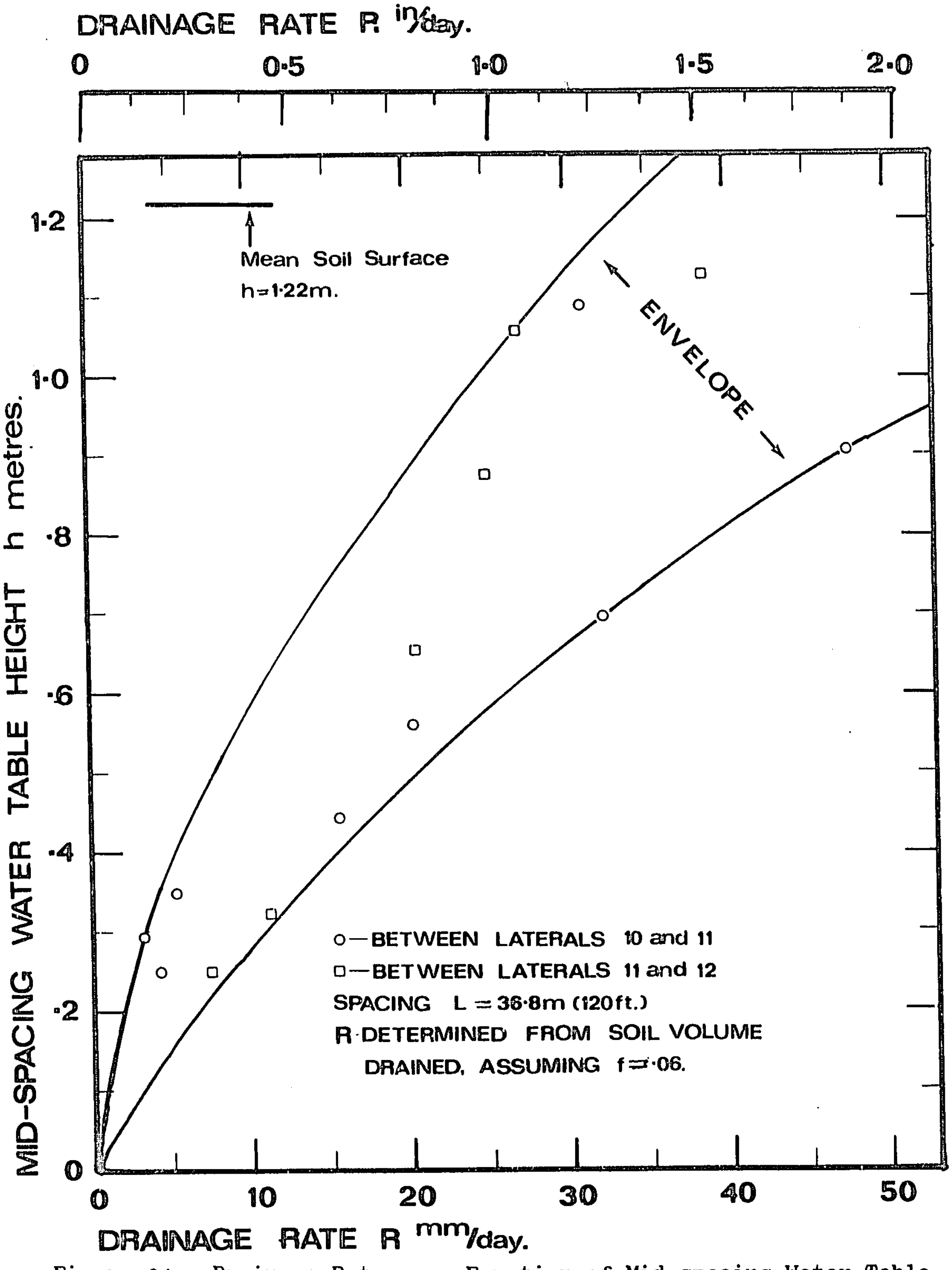


Figure 31. Drainage Rate as a Function of Mid-spacing Water Table Height for Ste. Rosalie Clay, Martineau Farm, Calculated from Falling Water Table Observations of August 1970.

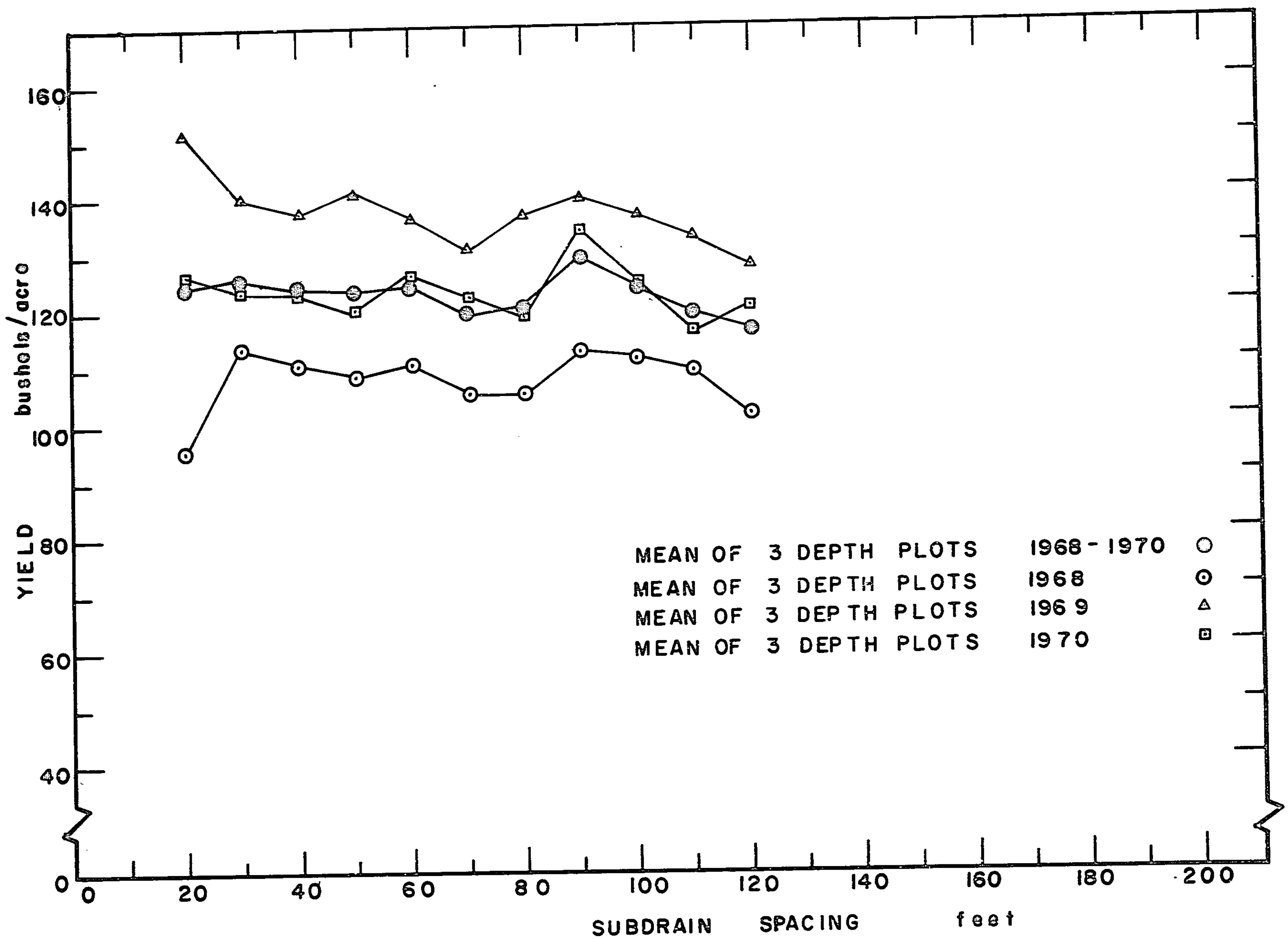


Figure 32. Yields of Maize Grain, 15% Moisture Basis, vs. Spacing Between Subdrains, 1968-1970, Martineau Farm, Ste. Rosalie Clay.

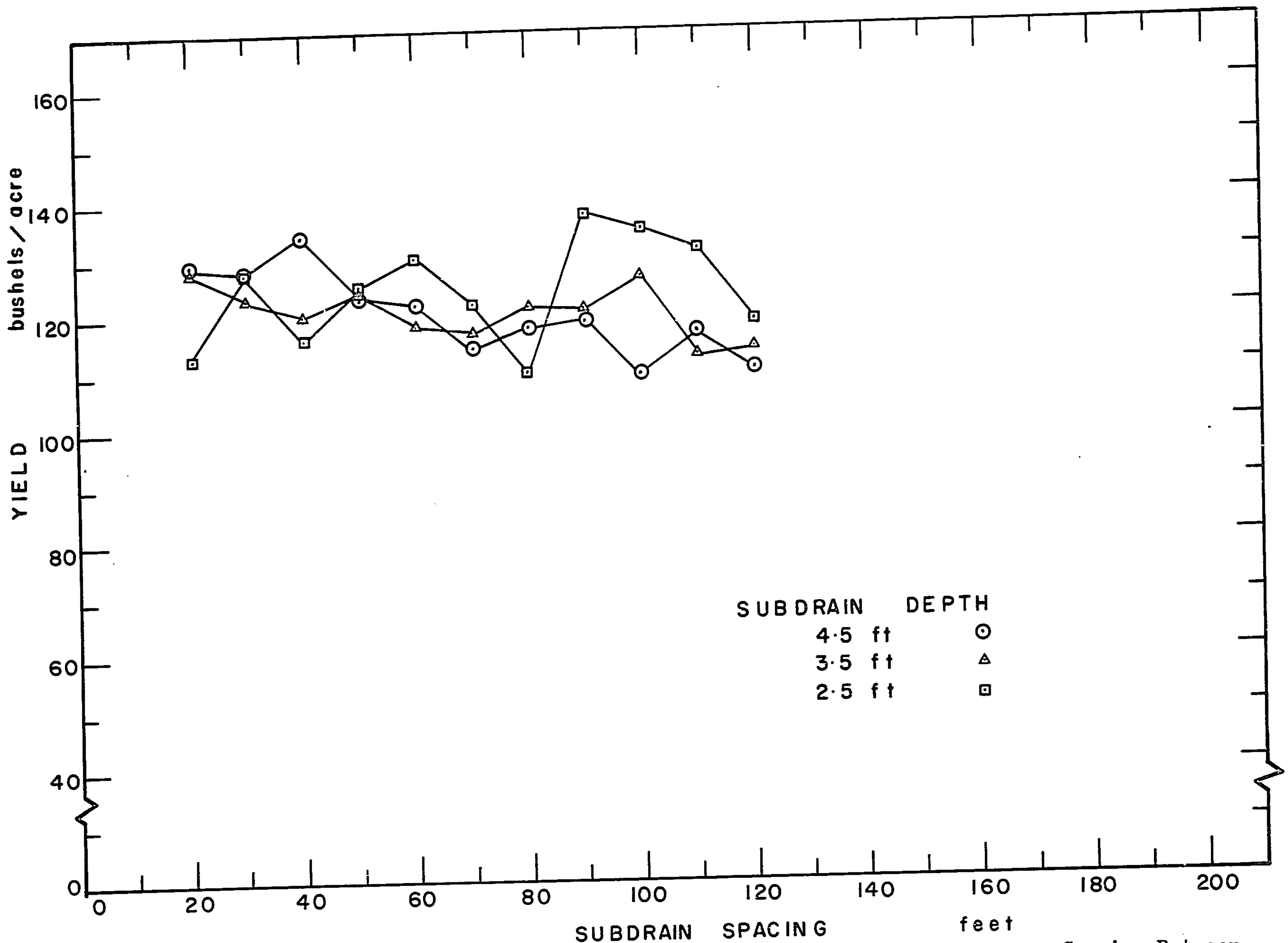


Figure 33. Mean of 1968 and 1969 Yields of Maize Grain, 15% Moisture Basis, vs. Spacing Between Subdrains for Three Subdrain Depths, Martineau Farm, Ste. Rosalie Clay.

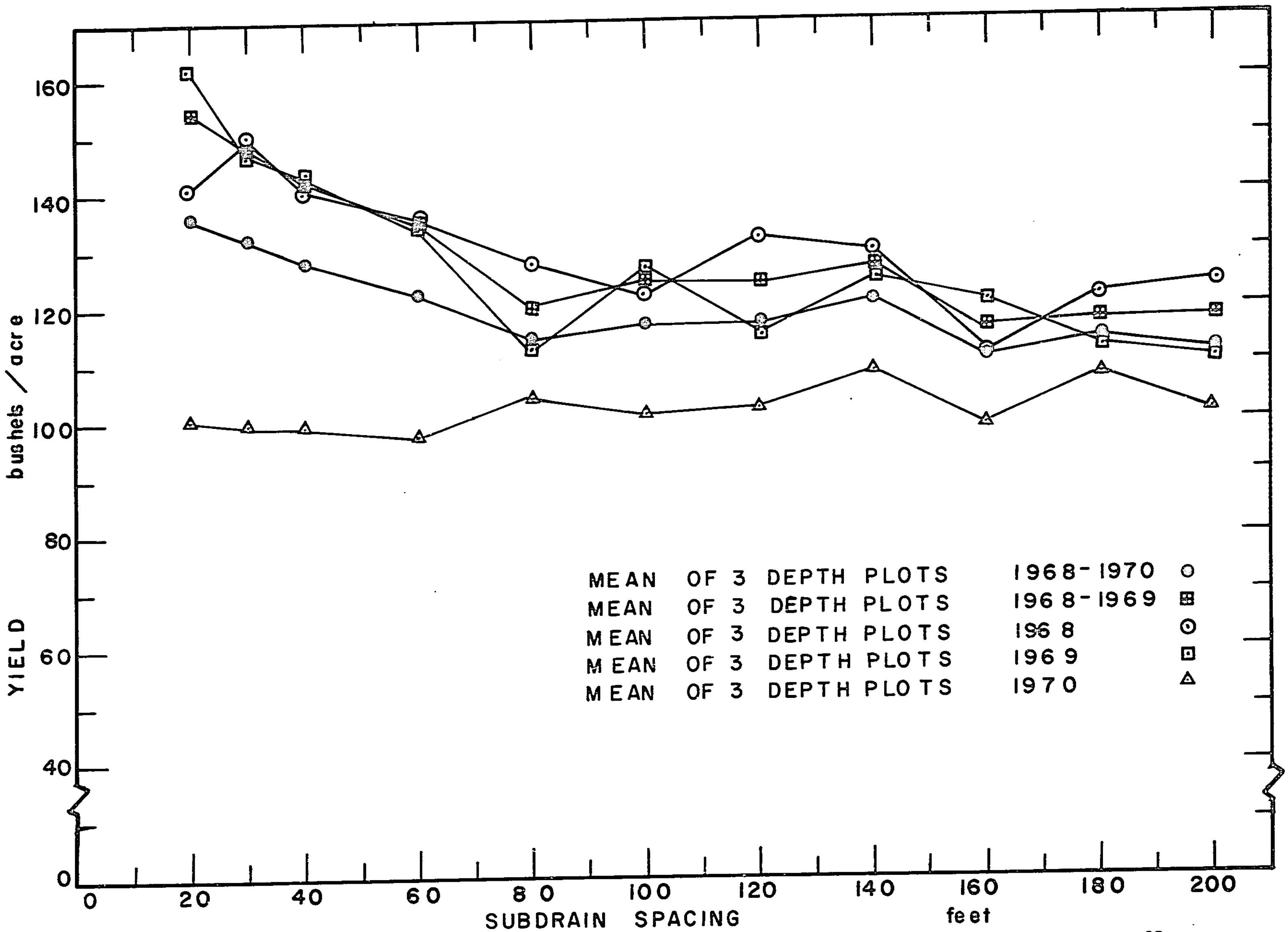


Figure 34. Yields of Maize Grain, 15% Moisture Basis, vs. Spacing Between Subdrains, 1968-1970, Vincent Farm, Soulanges Fine Sandy Loam.

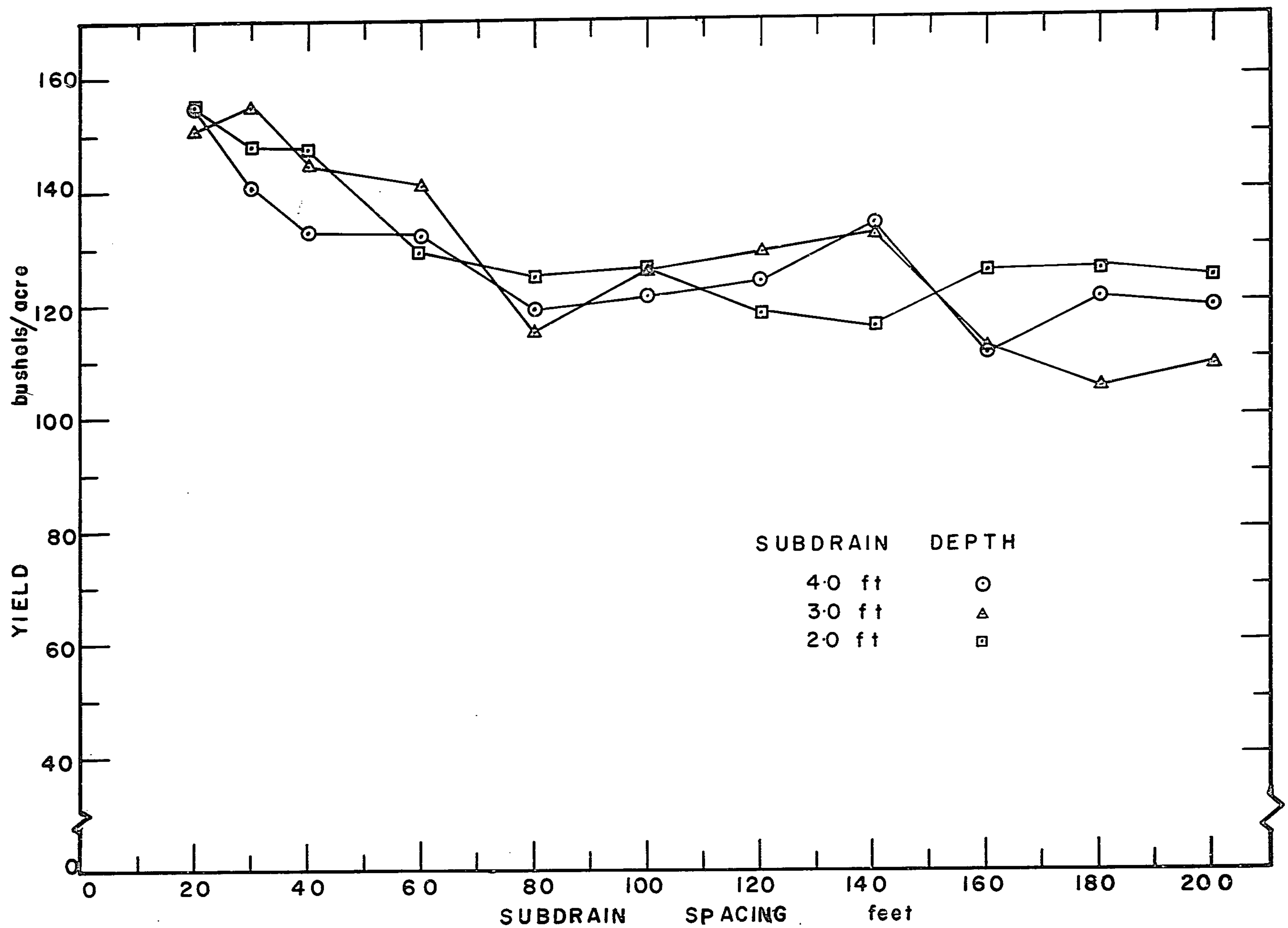


Figure 35. Mean of 1968 and 1969 Yields of Maize Grain, 15% Moisture Basis, vs. Spacing Between Subdrain, for Three Subdrain Depths, Vincent Farm, Soulanges Fine Sandy Loam.

APPENDIX A

This appendix contains figures reproduced from measurements made by Christopher K.W. Tu. Some figures include calculations by R.S. Broughton. These figures are included because they contain basic observations on the experimental fields which are used together with observations made by the author as the basis of calculations and discussions in this thesis.

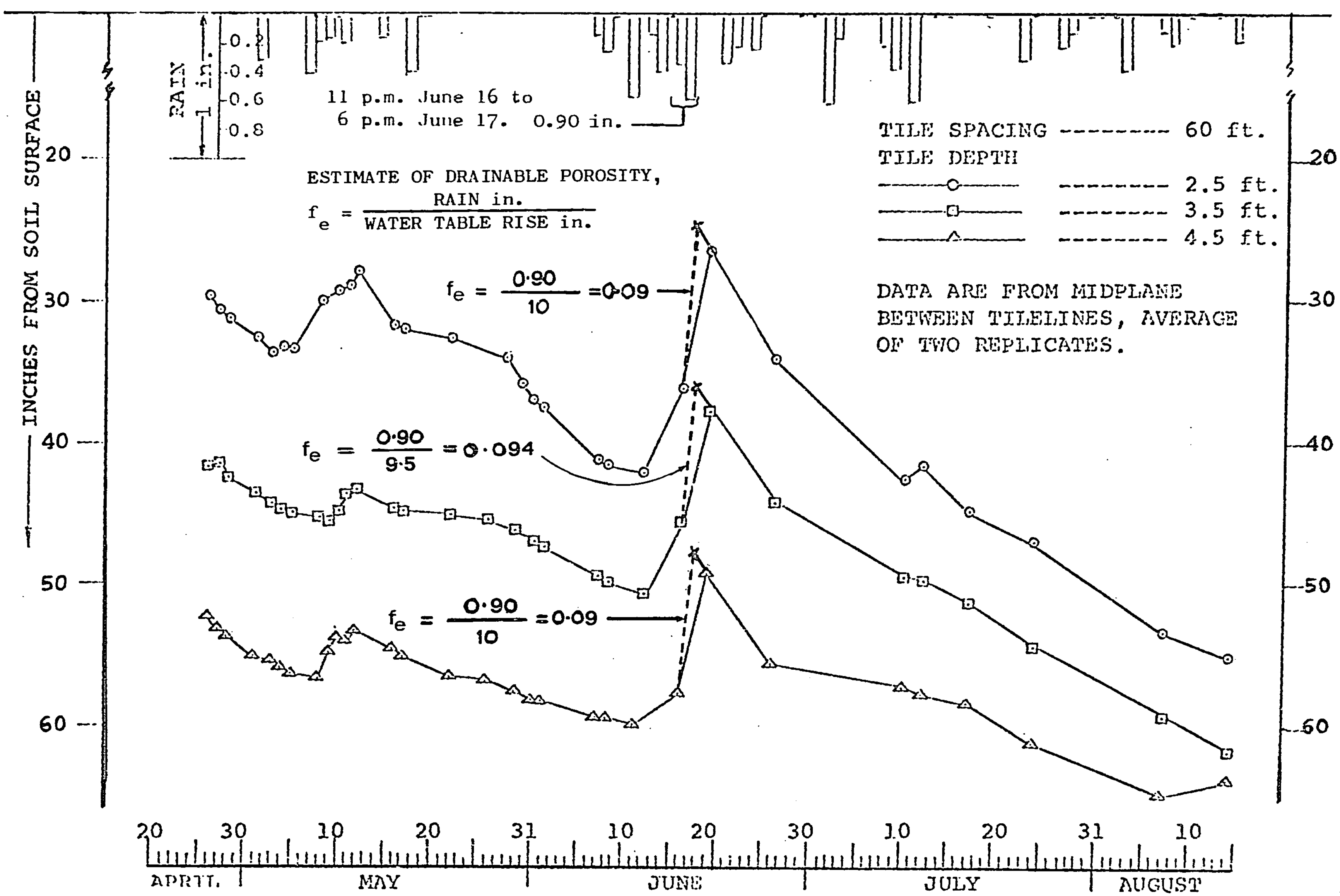


Figure A1. Water Table Depths Through the 1967 Growing Season, for Subdrains with a Spacing of 60 ft and Depths of 2.5, 3.5, and 4.5 ft, Martineau Farm, Ste. Rosalie Clay. (After Tu, 1968).

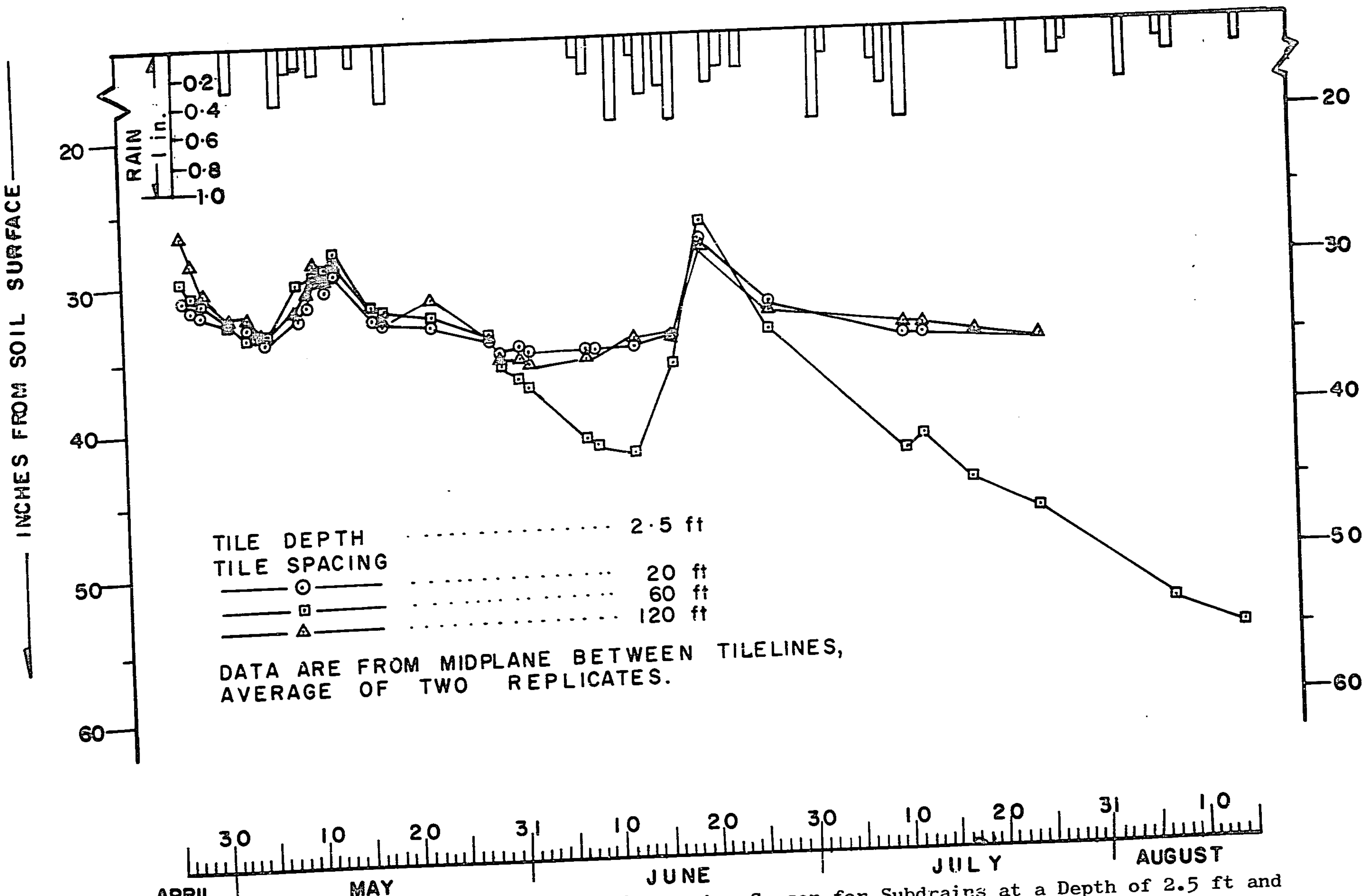


Figure A2. Water Table Depths Through the 1967 Growing Season for Subdrains at a Depth of 2.5 ft and Spacings of 20, 60 and 120 ft, Martineau Farm, Ste. Rosalie Clay.

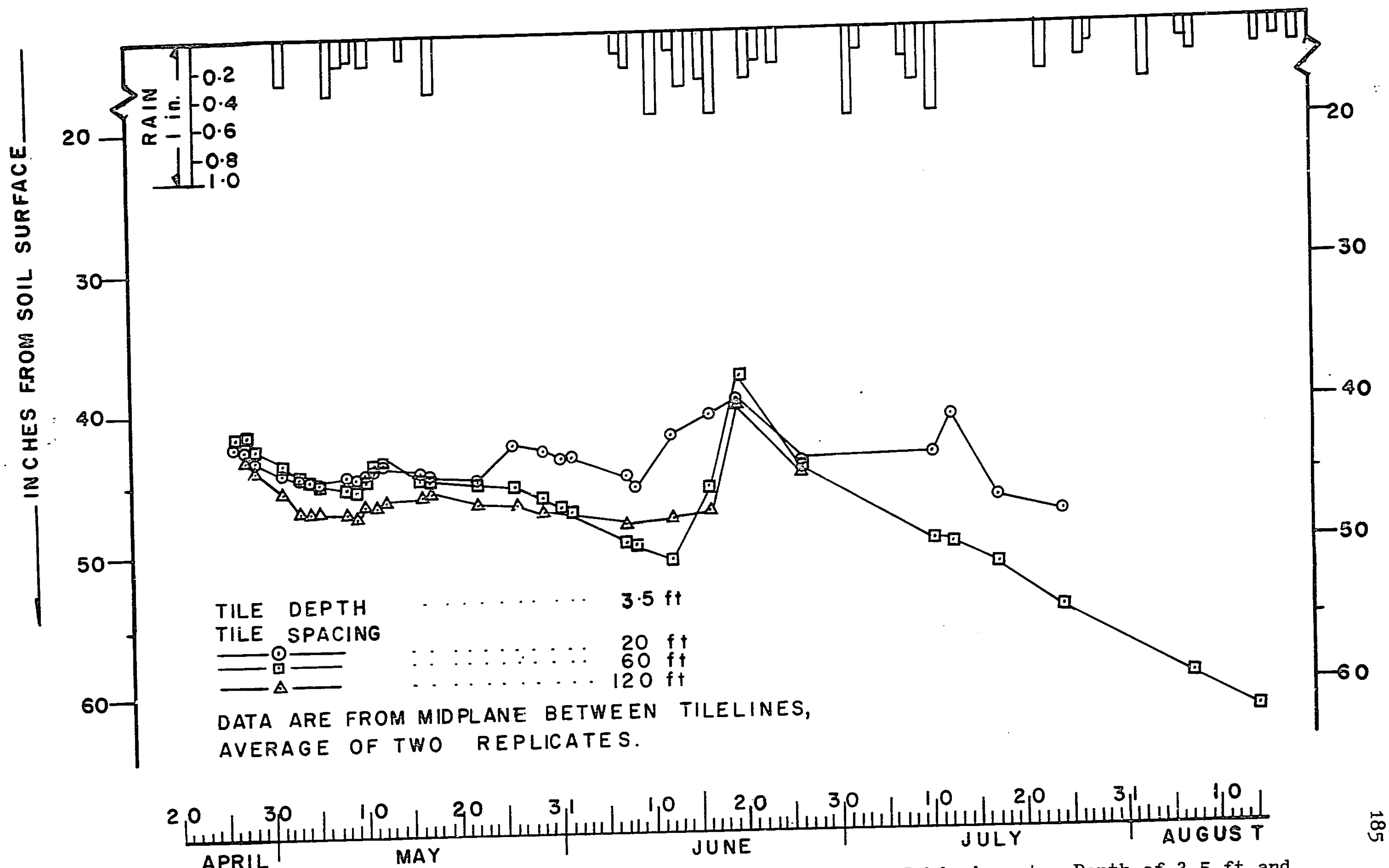


Figure A3. Water Table Depths Through the 1967 Growing Season for Subdrains at a Depth of 3.5 ft and Spacings of 20, 60 and 120 ft, Martineau Farm, Ste. Rosalie Clay.

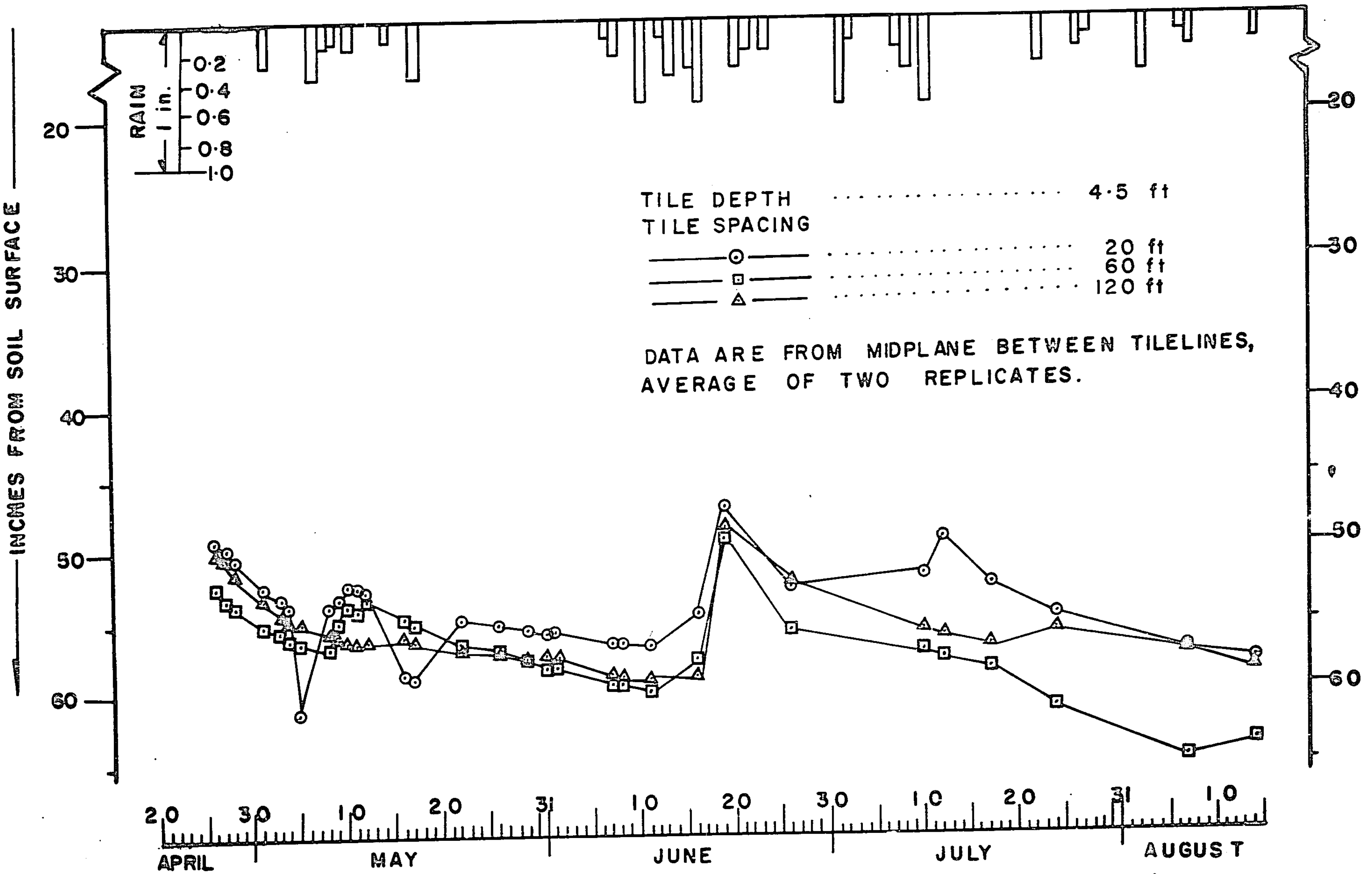


Figure A4. Water Table Depths Through the 1967 Growing Season for Subdrains at a Depth of 4.5 ft and Spacings of 20, 60 and 120 ft, Martineau Farm, Ste. Rosalie Clay.

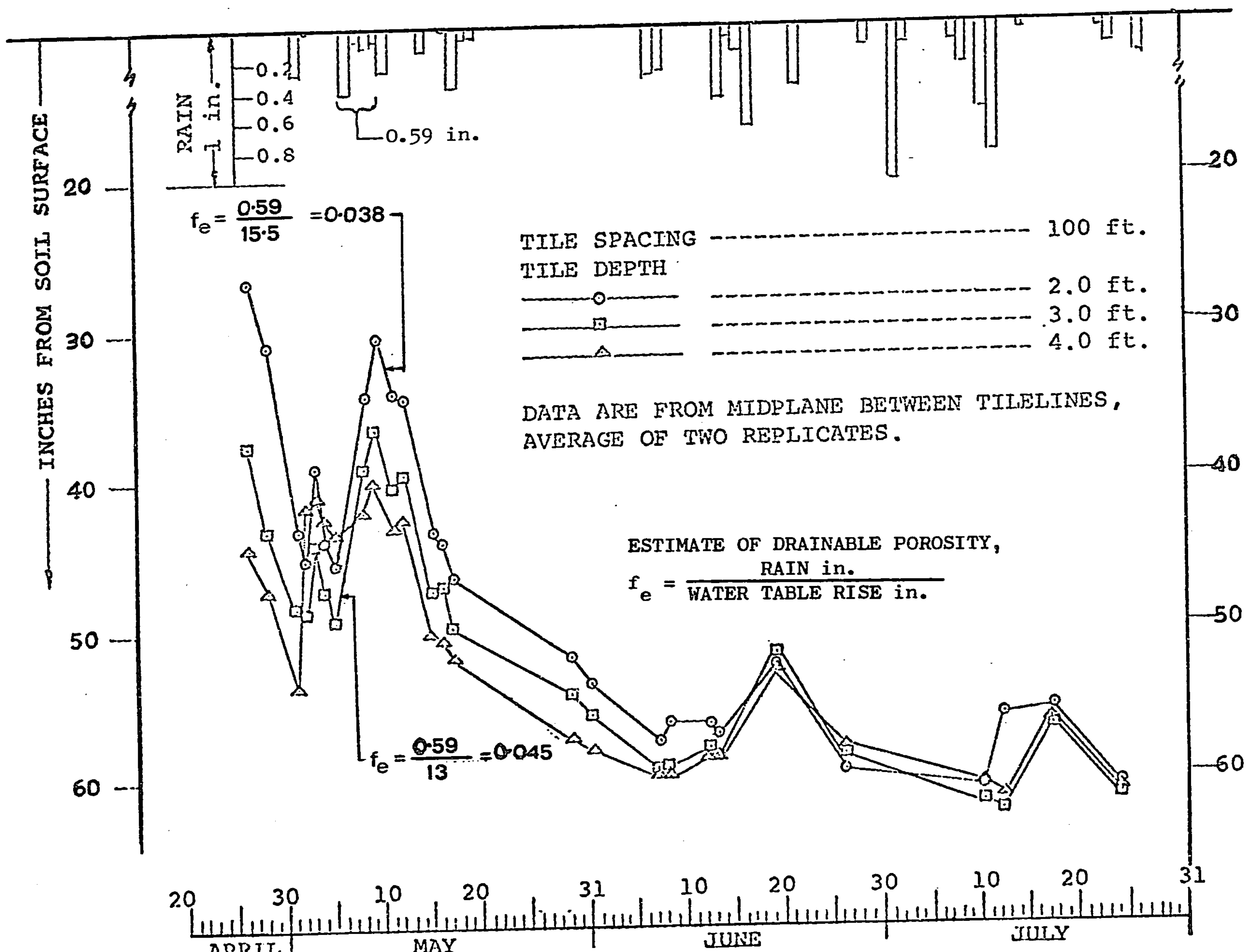


Figure A5. Water Table Depths Through the 1967 Growing Season for subdrains with a Spacing of 100 ft and Depths of 2.0, 3.0, and 4.0 ft, Vincent Farm, Soulanges Fine Sandy Loam. (After Tu, 1968).

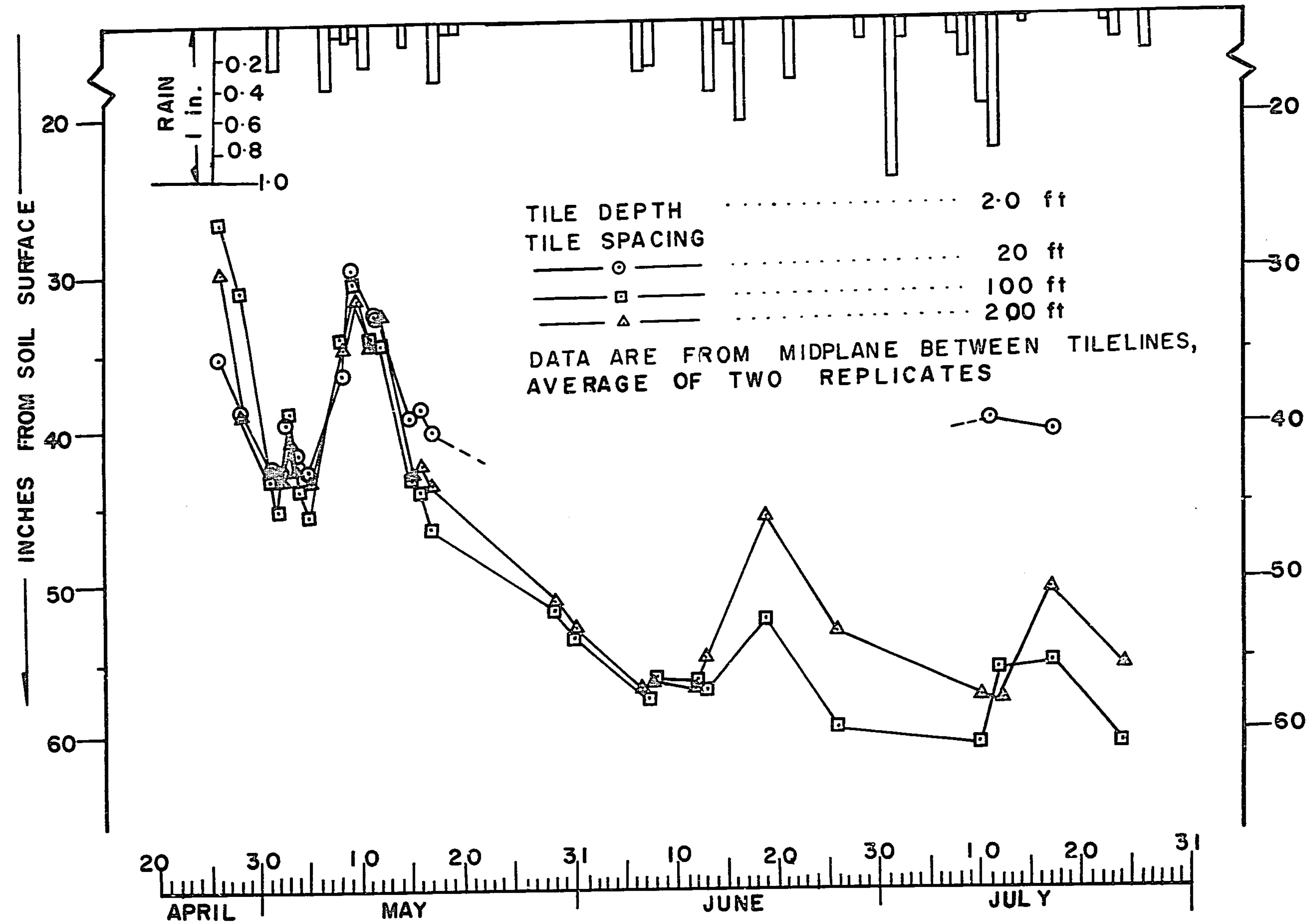


Figure A6. Water Table Depths Through the 1967 Growing Season for Subdrains at a Depth of 2.0 ft, and Spacings of 20, 100 and 200 ft, Vincent Farm, Soulanges Fine Sandy Loam.

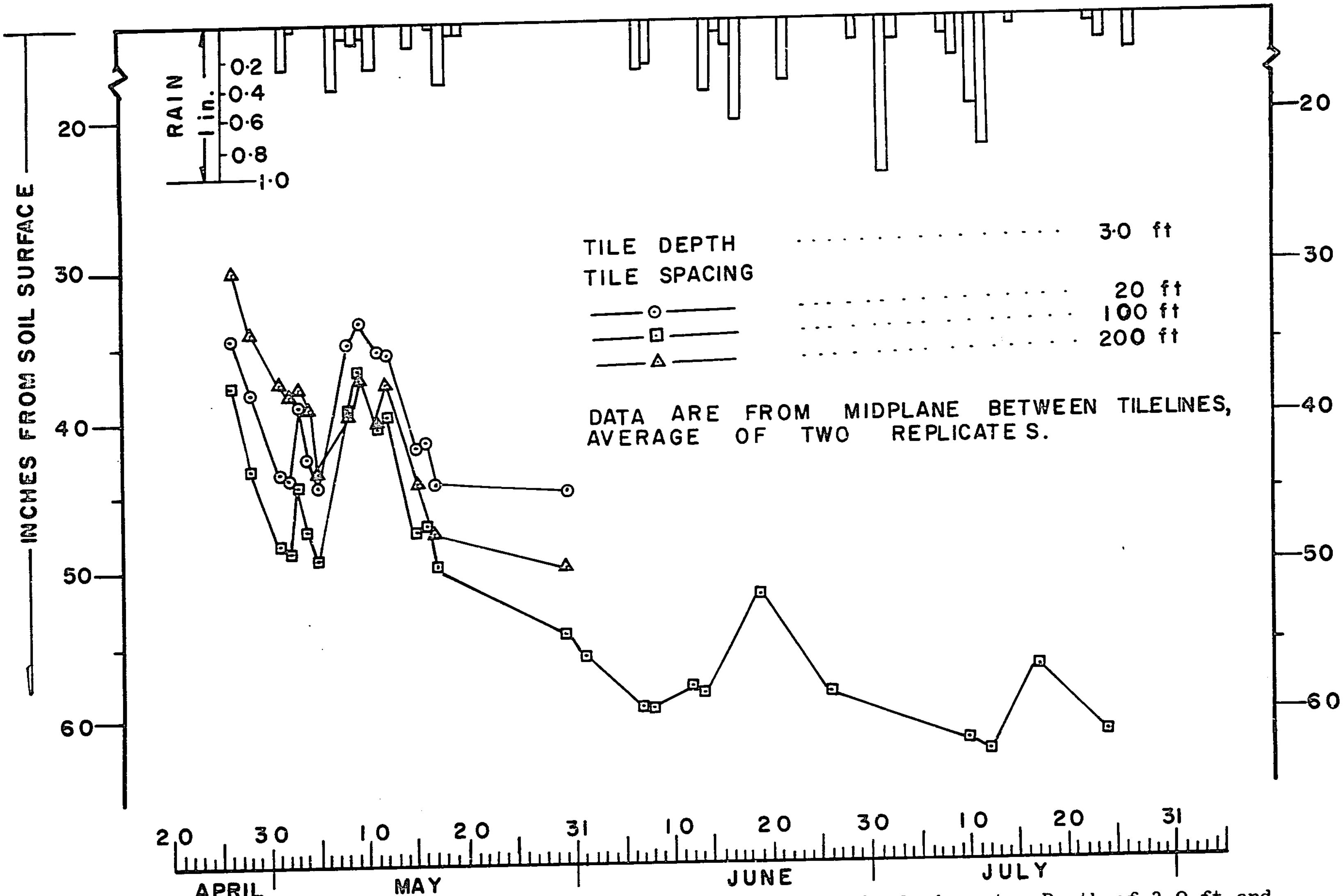


Figure A7. Water Table Depths Through the 1967 Growing Season for Subdrains at a Depth of 3.0 ft and Spacings of 20, 100 and 200 ft, Vincent Farm, Soulanges Fine Sandy Loam.

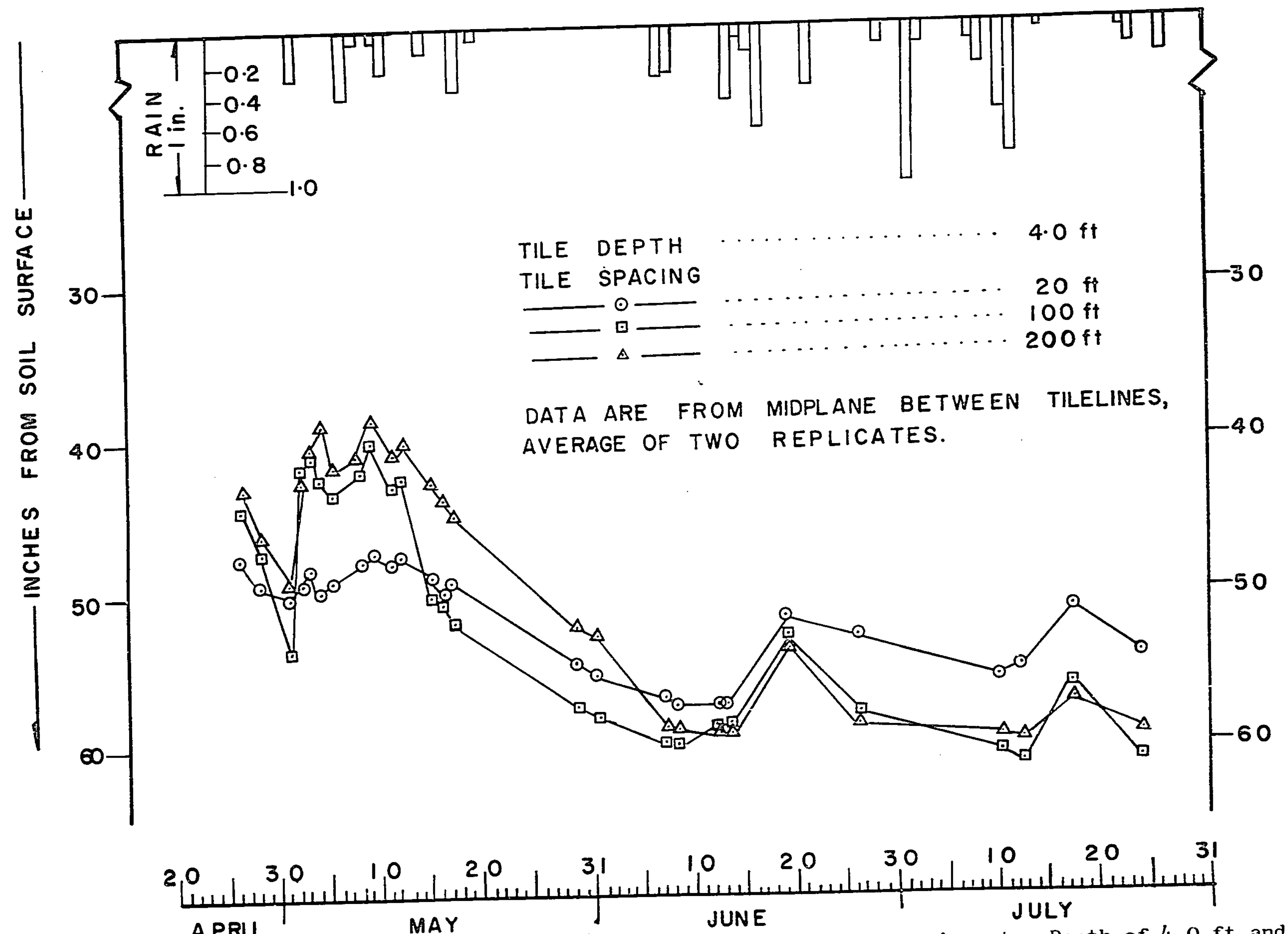
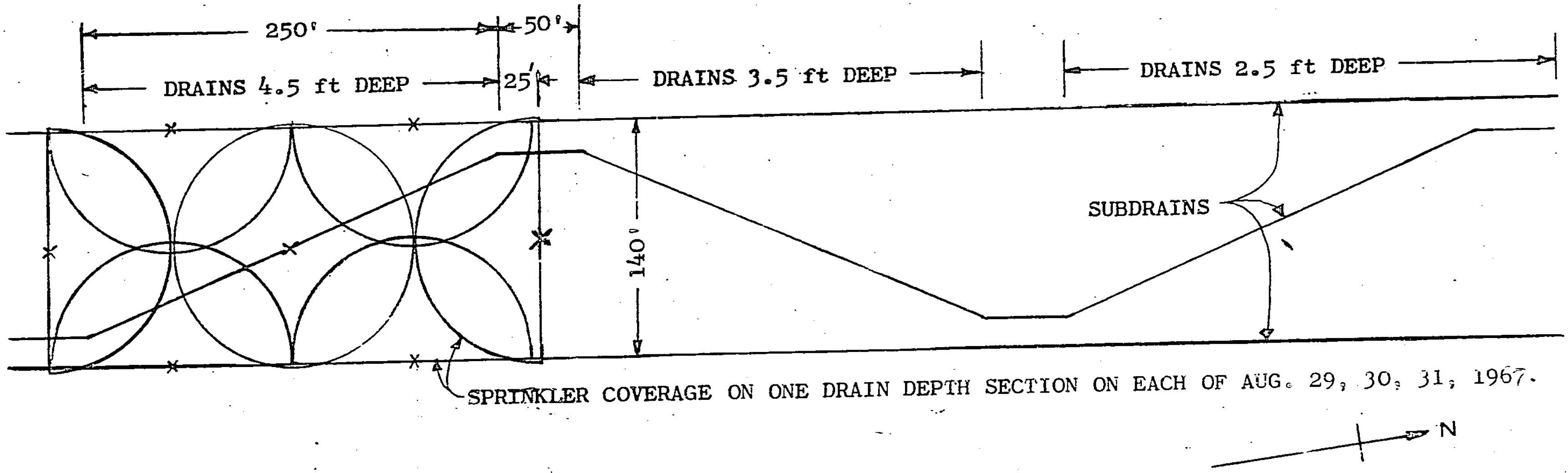


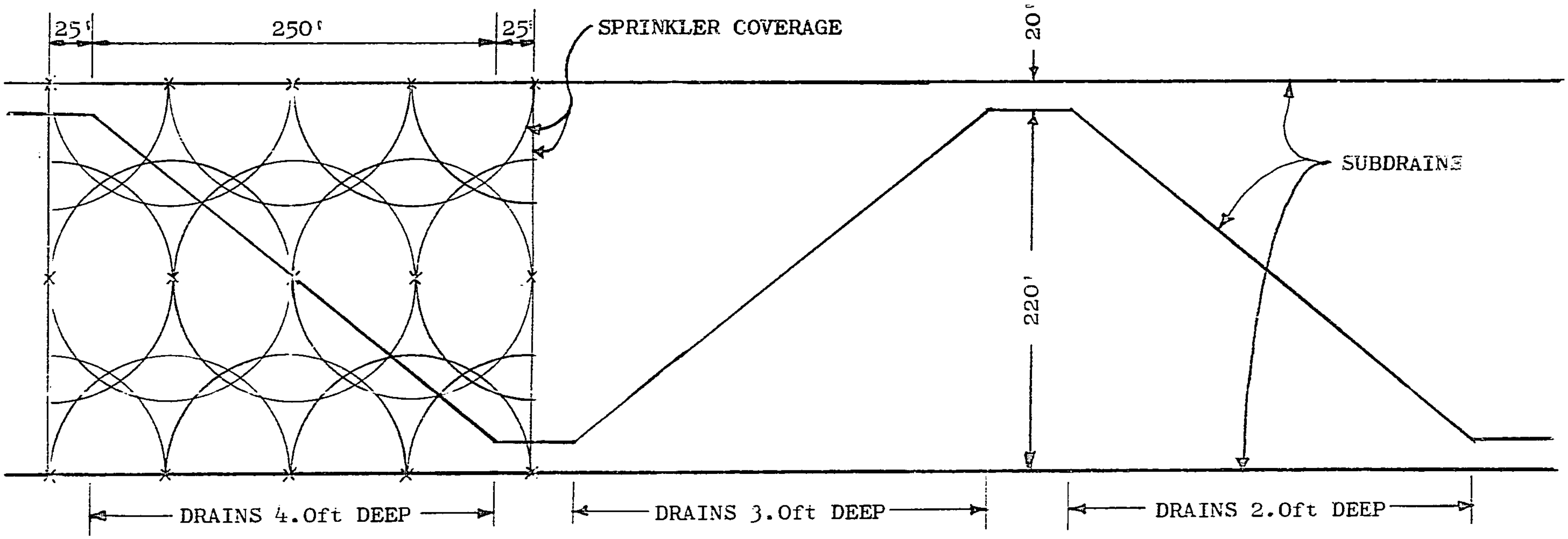
Figure A8. Water Table Depths Through the 1967 Growing Season for Subdrains at a Depth of 4.0 ft and Spacings of 20, 100 and 200 ft, Vincent Farm, Soulanges Fine Sandy Loam.

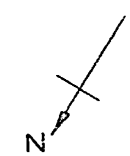


IRRIGATION SPECIFICATIONS

SPRINKLER LOCATIONS	X	DISCHARGE	33.2 USgpm
NOZZLE DIAMETER	0.375 in	RATE OF APPLICATION	0.53 in/hr
PRESSURE	70 psi	DURATION OF APPLICATION	11.3 hr
RADIUS OF APPLICATION	75 ft	AMOUNT OF APPLICATION	6.0 in
SPRINKLERS RAINBIRD	65D		

Figure A9. Layout of Irrigation Sprinklers for Water Table Drawdown Tests on Subdrain Depth and Spacing Plots, Martineau Farm, Ste. Rosalie Clay Soil. (after Tu)





IRRIGATION SPECIFICATIONS

SPRINKLER LOCATIONS	X	DISCHARGE	33.2 USgpm
SPRINKLERS	RAINBIRD 65D	RATE OF APPLICATION	0.67 in/hr
NOZZLE DIAMETER	0.375 in.	DURATION OF APPLICATION	7.5 hr
PRESSURE	70 psi	AMOUNT OF APPLICATION	5.0 in
RADIUS OF APPLICATION	75 ft	DATES OF APPLICATION	JUNE 10-13, 1968

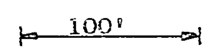


Figure A10. Layout of Irrigation Sprinklers for Water Table Drawdown Tests on Subdrain Depth and Spacing Plots, Vincent's Farm, Soulanges Fine Sandy Loam Soil. (after Tu)

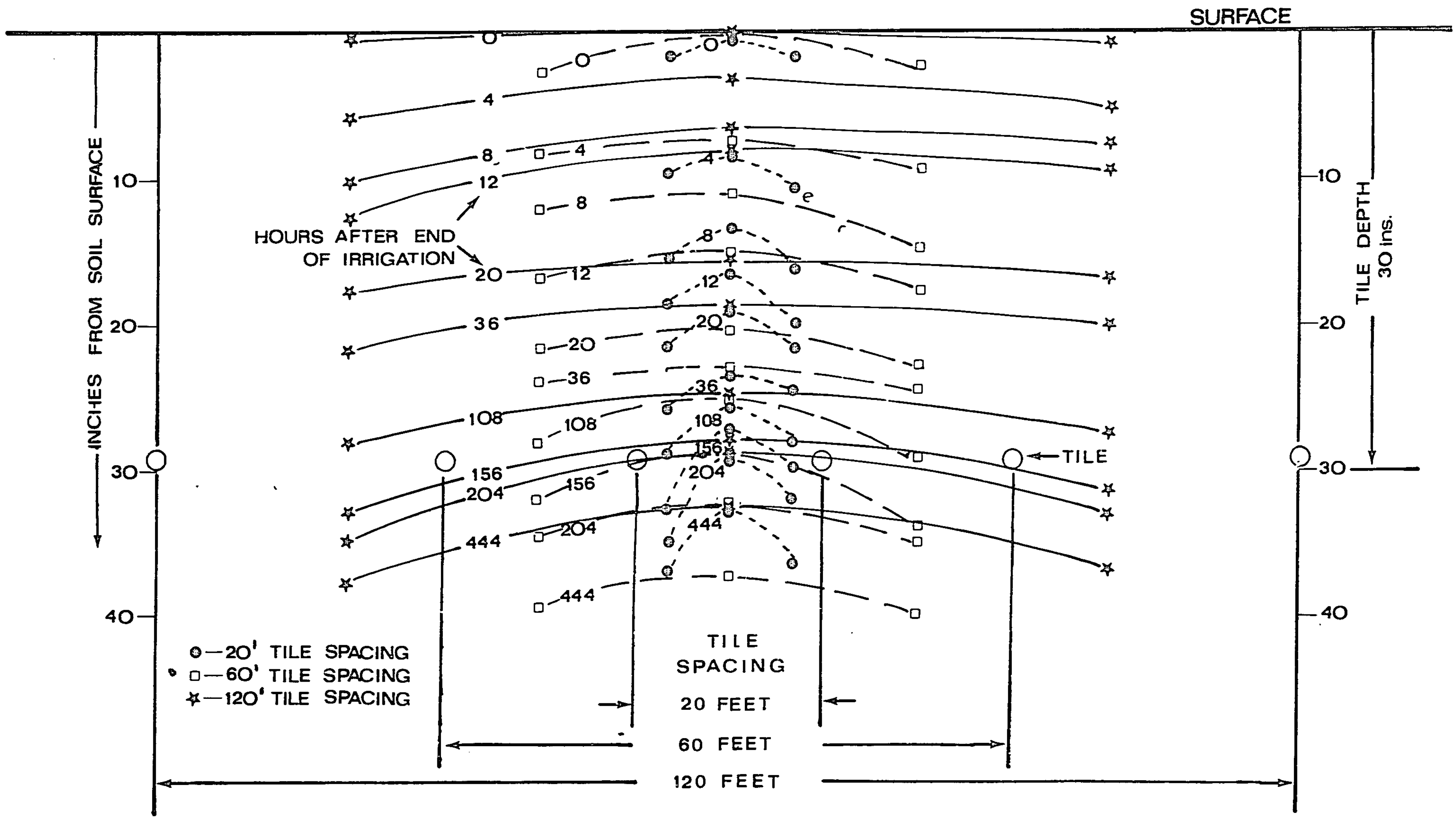


Figure A11. Water Table Positions at Successive Times after Stopping Irrigation, 8 p.m. August 31, 1967, Ste. Rosalie Clay, Subdrains 2.5 ft Deep. Data are the Average of Two Replicates. (After Tu, 1968).

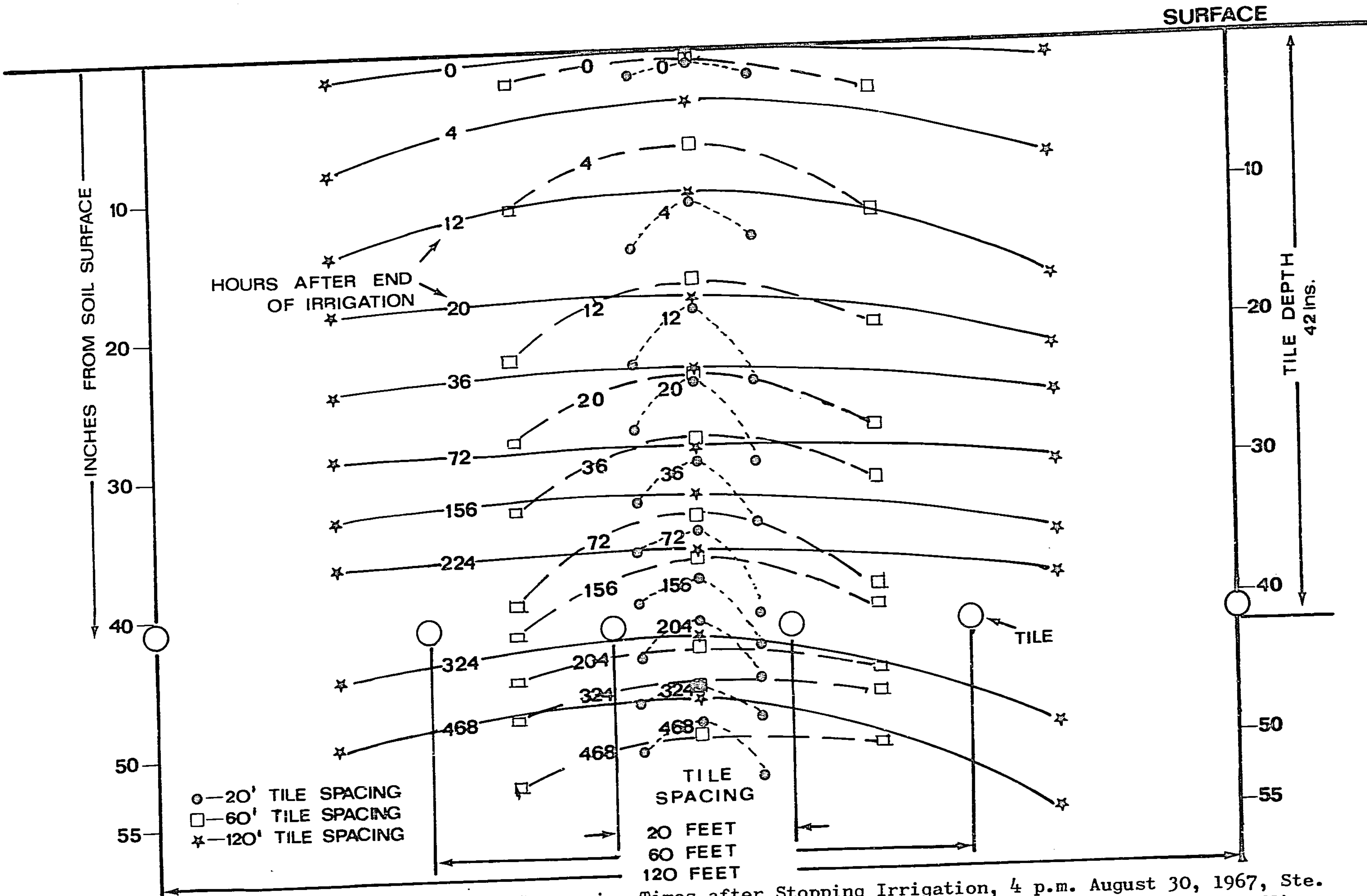


Figure A12. Water Table Positions at Successive Times after Stopping Irrigation, 4 p.m. August 30, 1967, Ste. Rosalie Clay, Subdrains 3.5 ft Deep. Data are the Average of Two Replicates. (After Tu, 1968).

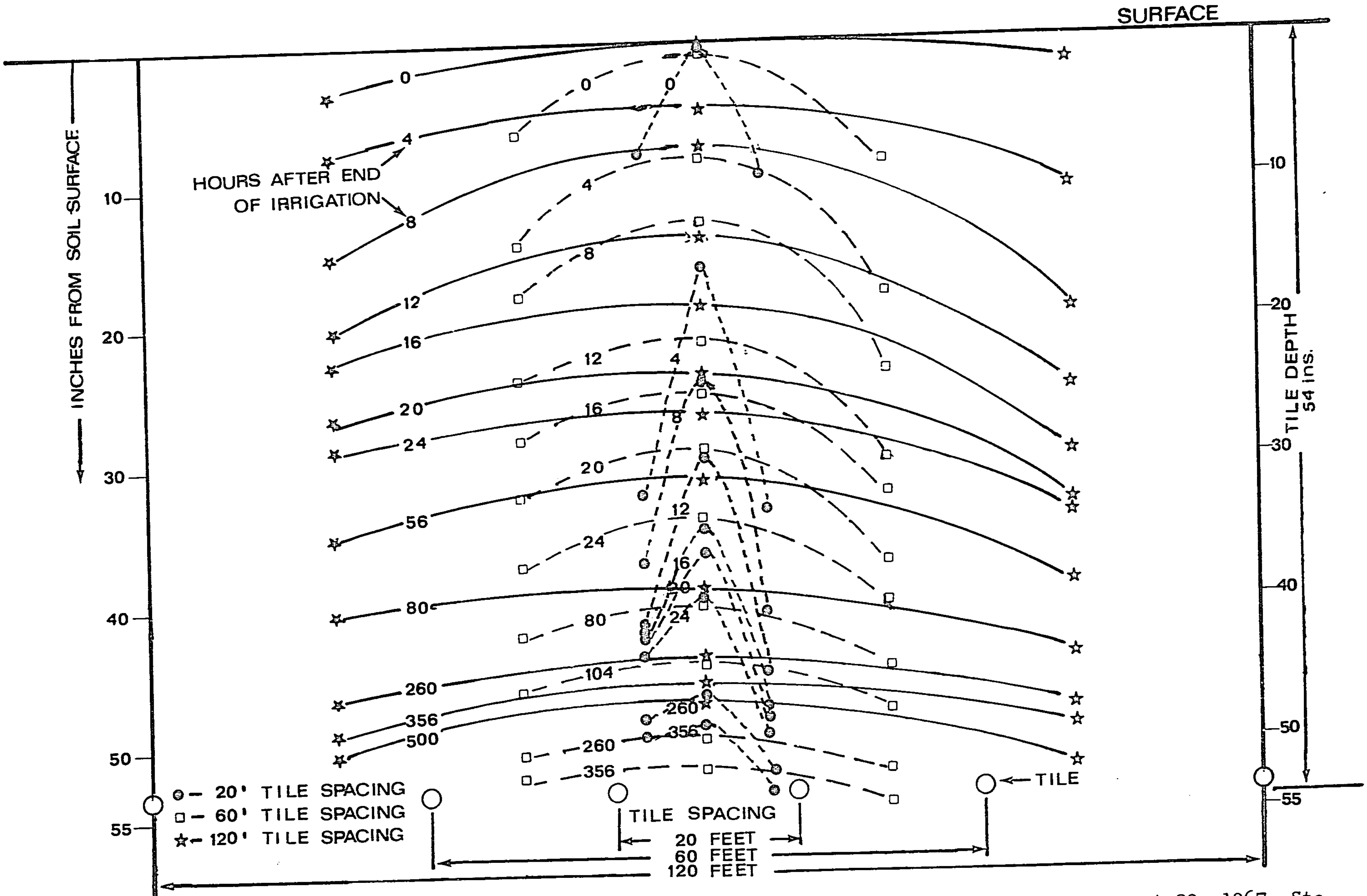


Figure A13. Water Table Positions at Successive Times after Stopping Irrigation, 11 a.m. August 29, 1967, Ste. Rosalie Clay, Subdrains 4.5 ft Deep. Data are the Average of Two Replicates. (After Tu, 1968).

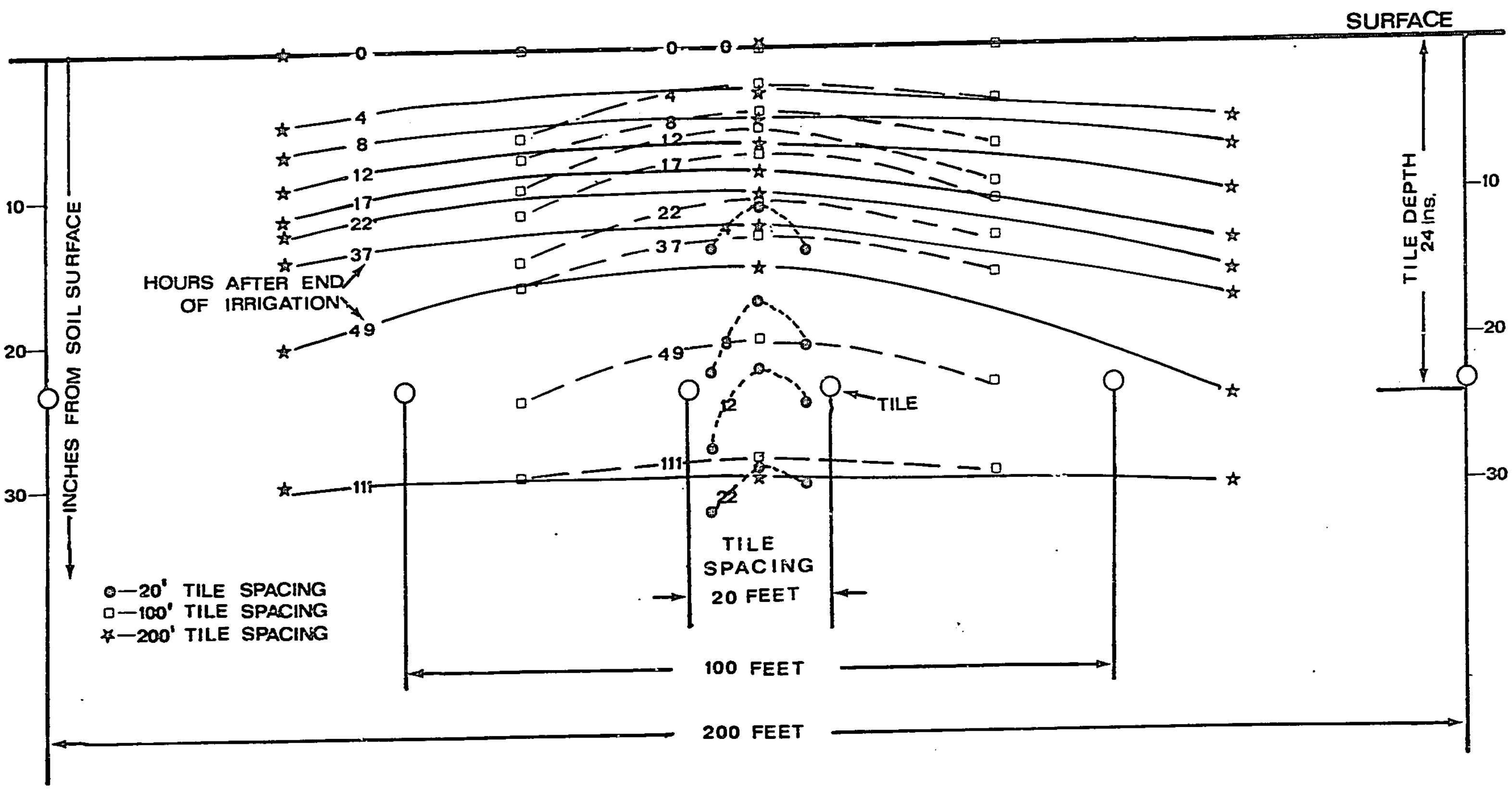


Figure A14. Water Table Positions at Successive Times after Stopping Irrigation, 7 p.m. June 10, 1968, Soulanges Fine Sandy Loam, Subdrains 2 ft Deep. Data are the Average of Two Replicates. (After Tu, 1968).

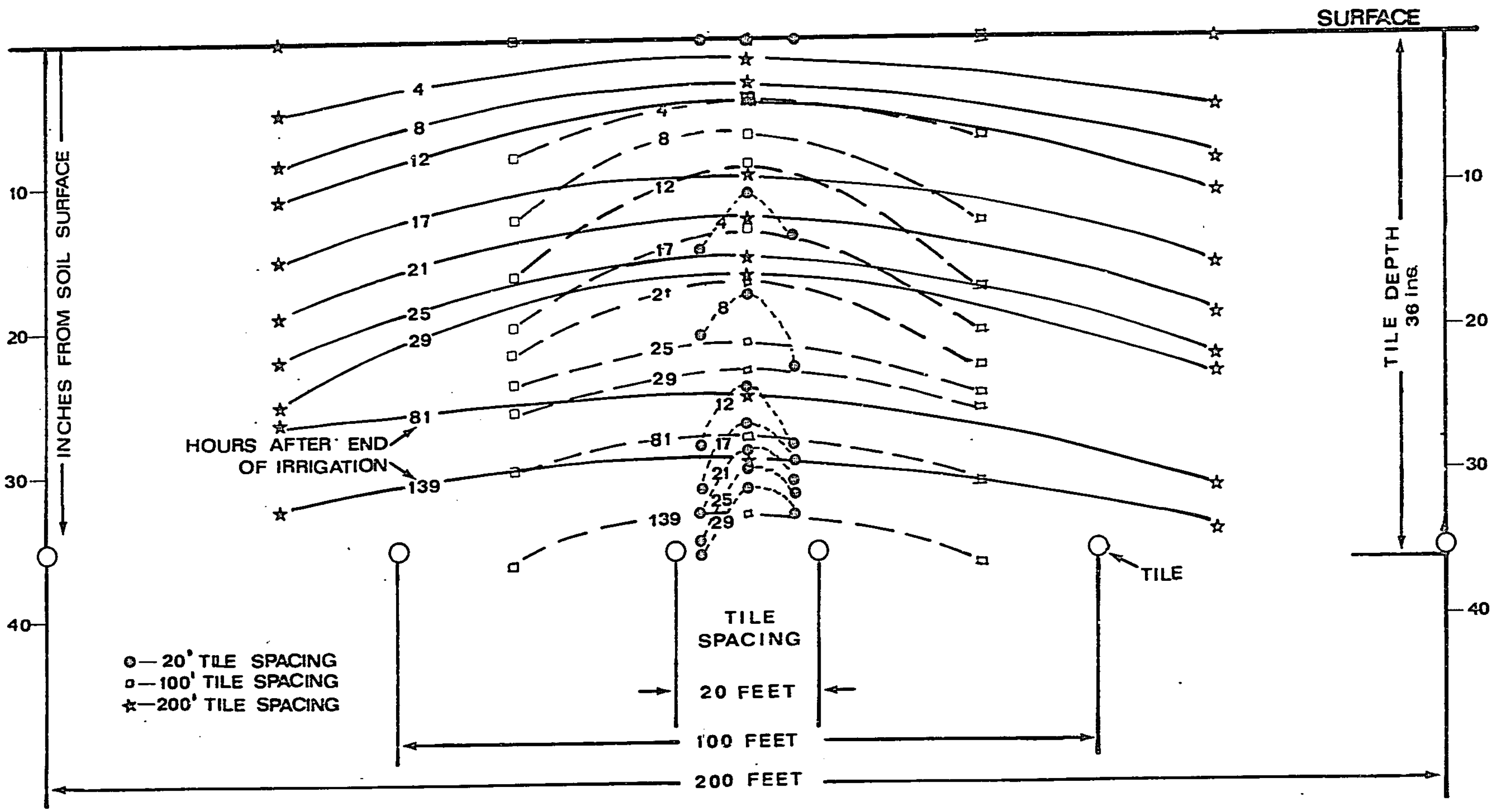


Figure A15. Water Table Positions at Successive Times after Stopping Irrigation, 7 p.m. June 11, 1968, Soulanges Fine Sandy Loam, Subdrains 3 ft Deep. Data are the Average of Two Replicates. (After Tu, 1968).

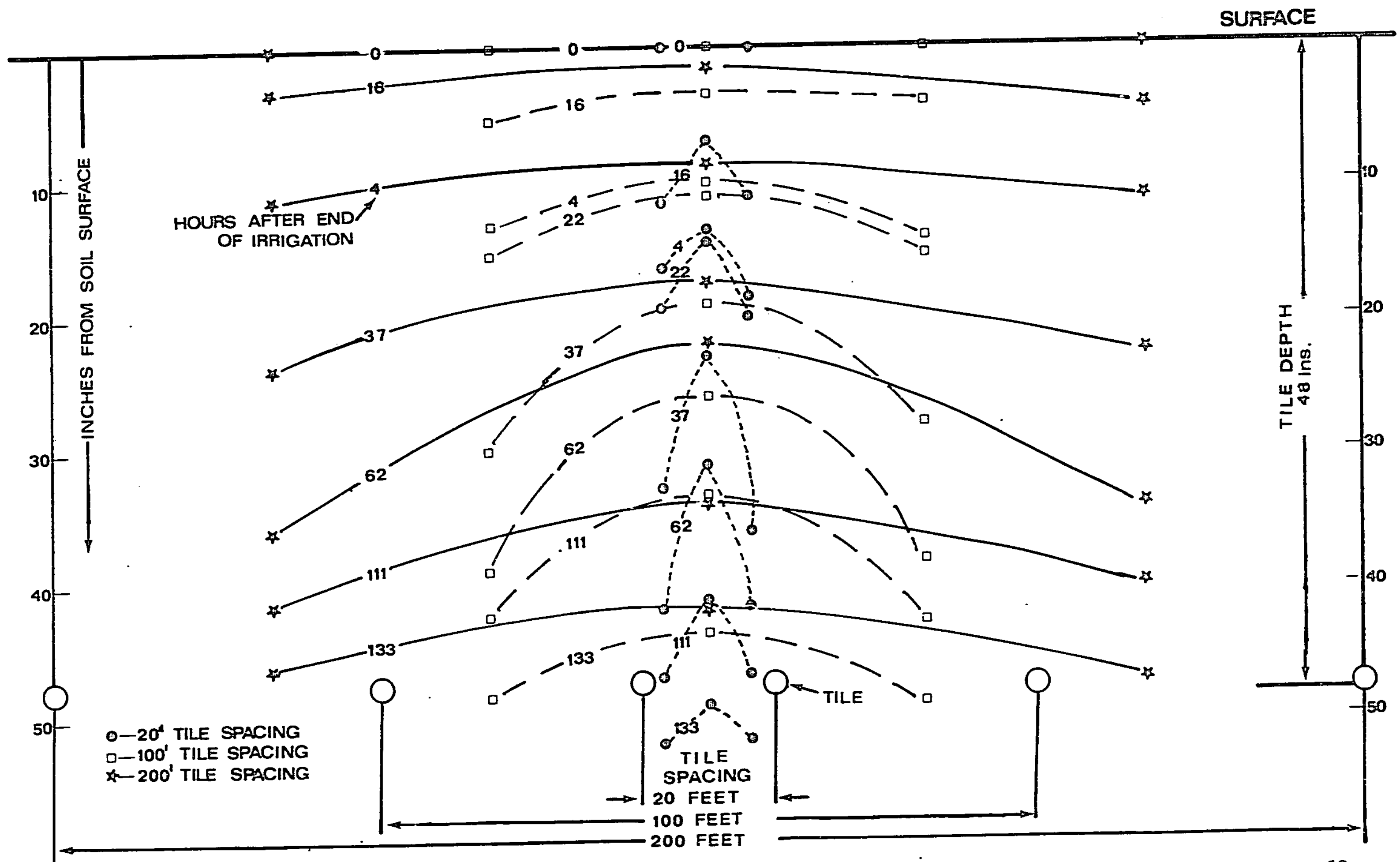


Figure A16. Water Table Positions at Successive Times after Stopping Irrigation, 8 p.m. June 12, 1968, Soulanges Fine Sandy Loam, Subdrains 4 ft Deep. Data are the Average of Two Replicates. (After Tu, 1968).

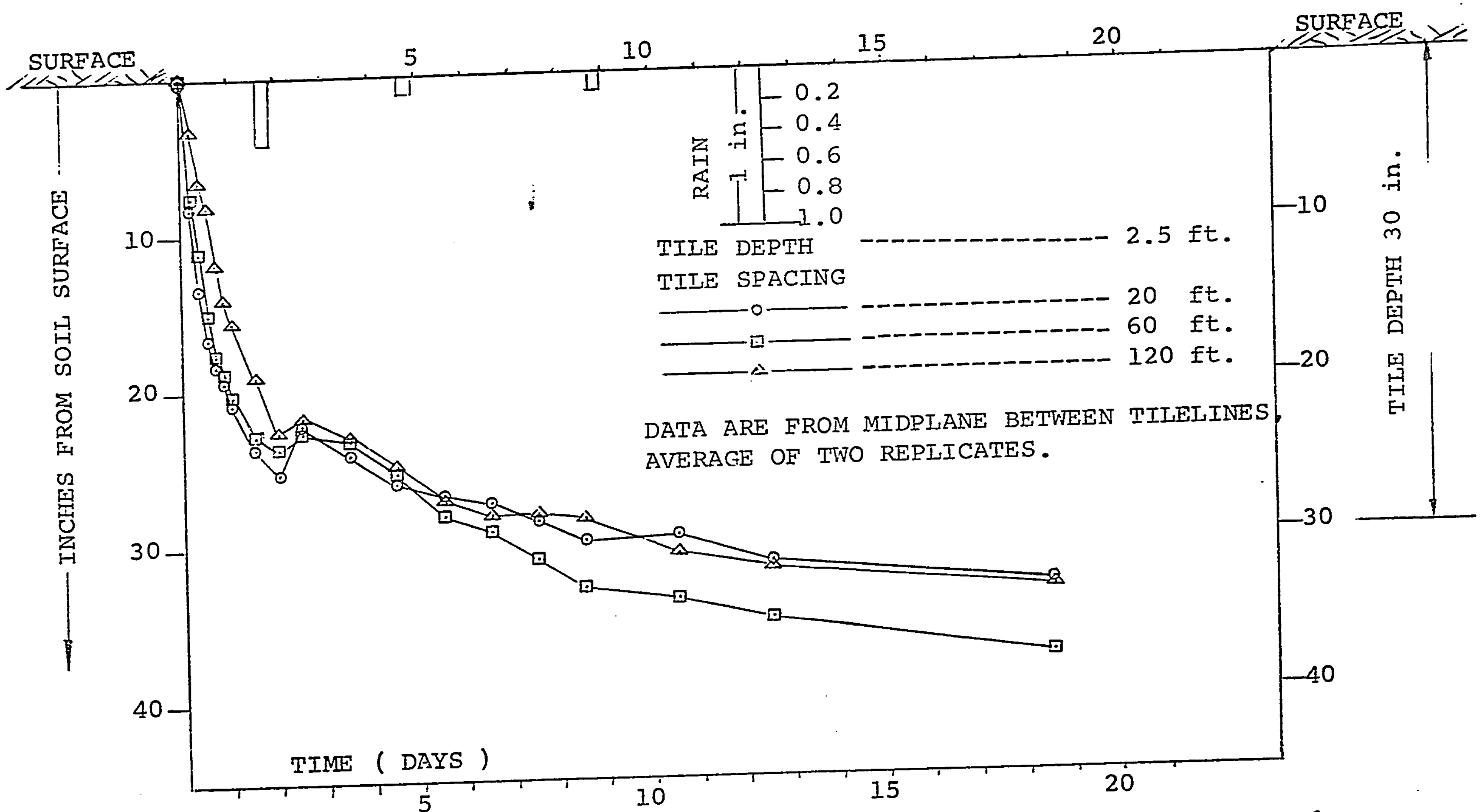


Figure A17. Water Table Changes at Midplane after Stopping Irrigation, 8 p.m. August 31, 1967, Martineau Field, Ste. Rosalie Clay, Subdrains 2.5 ft Deep. (After Tu, 1968).

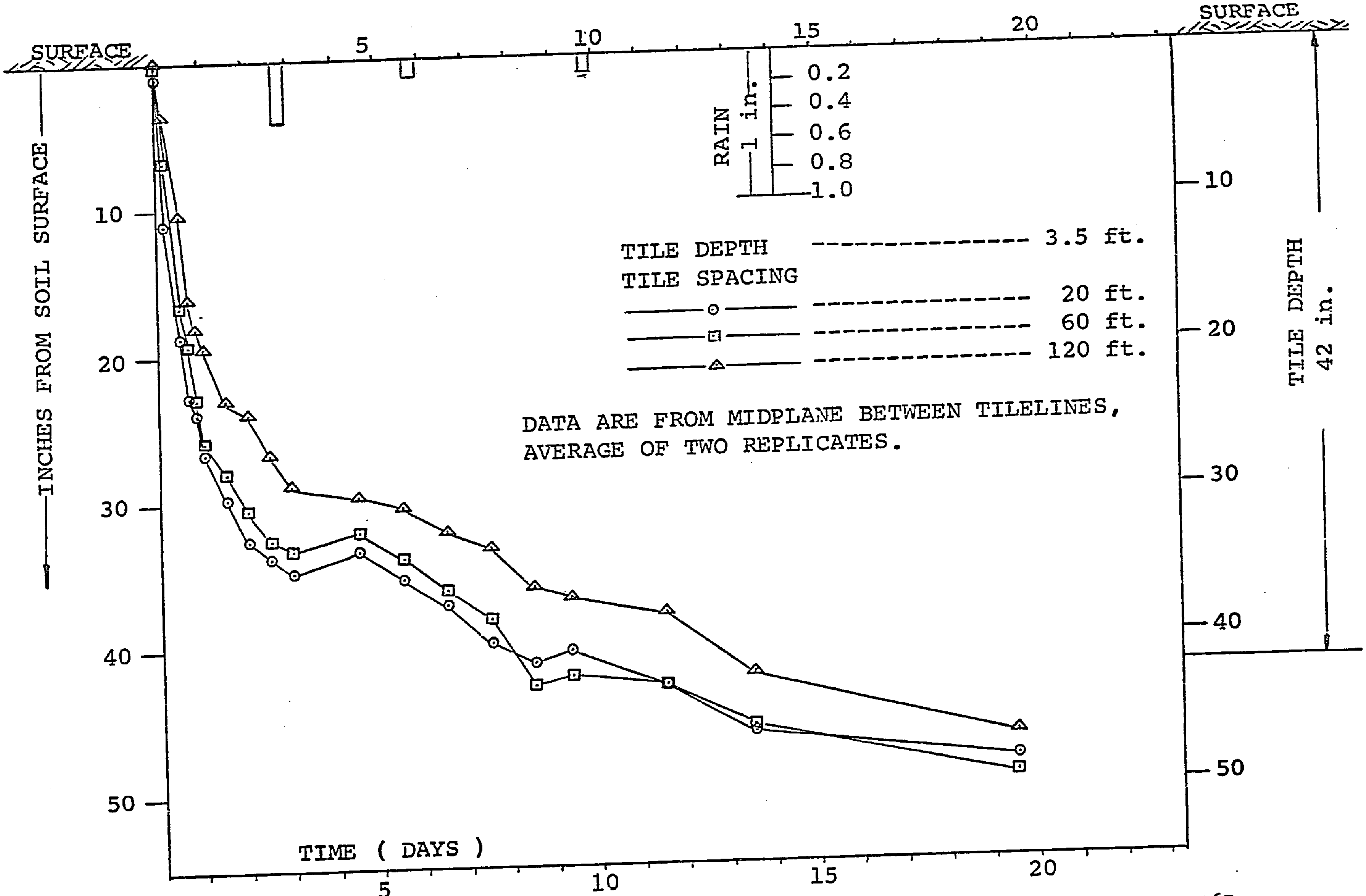


Figure A18. Water Table Changes at Midplane after Stopping Irrigation, 4 p.m. August 30, 1967, Martineau Field, Ste. Rosalie Clay, Subdrains 3.5 ft Deep. (After Tu, 1968).

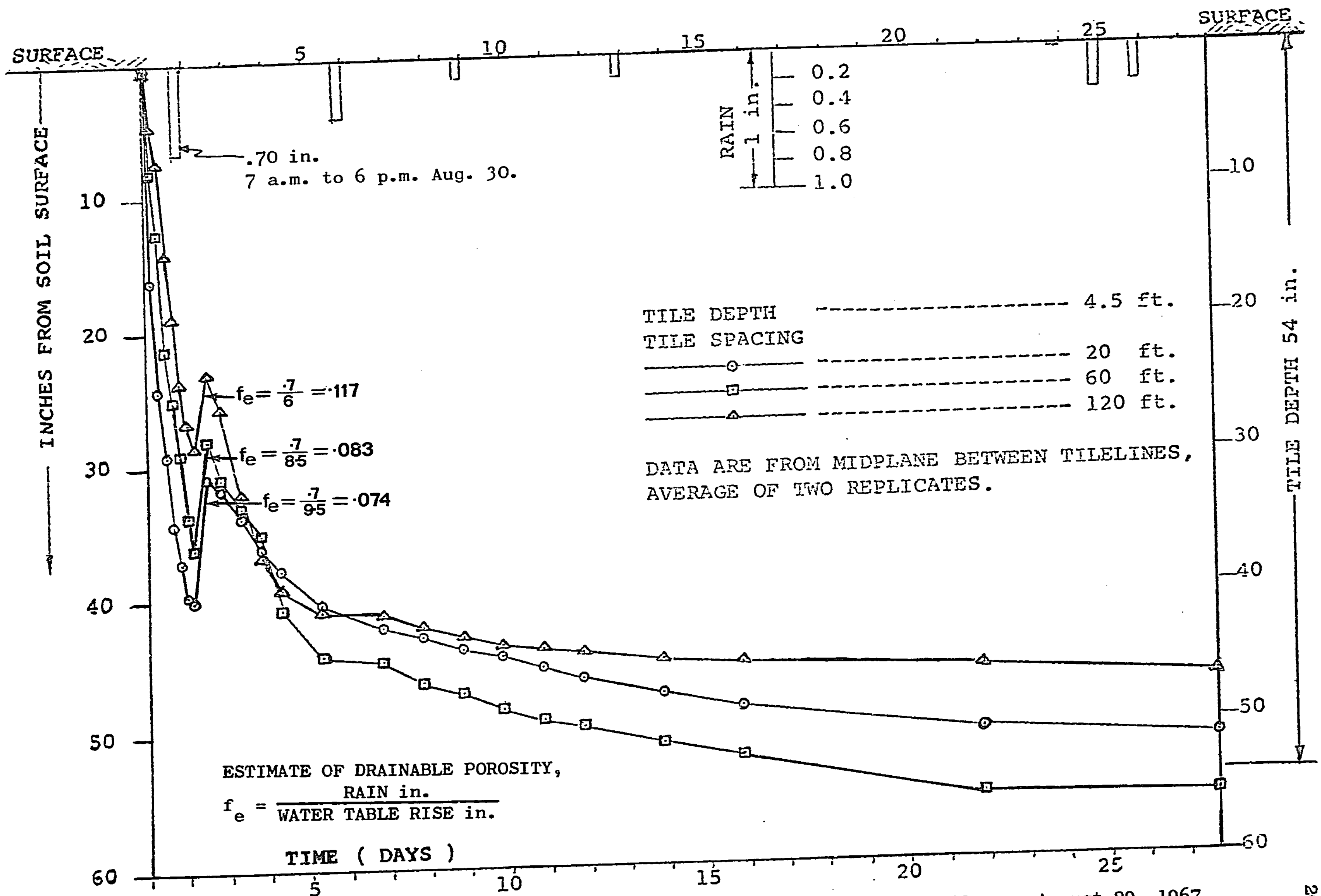


Figure A19 Water Table Changes at Midplane after Stopping Irrigation, 11 a.m. August 29, 1967, Martineau Field, Ste. Rosalie Clay, Subdrains 4.5 ft Deep. (After Tu, 1968).

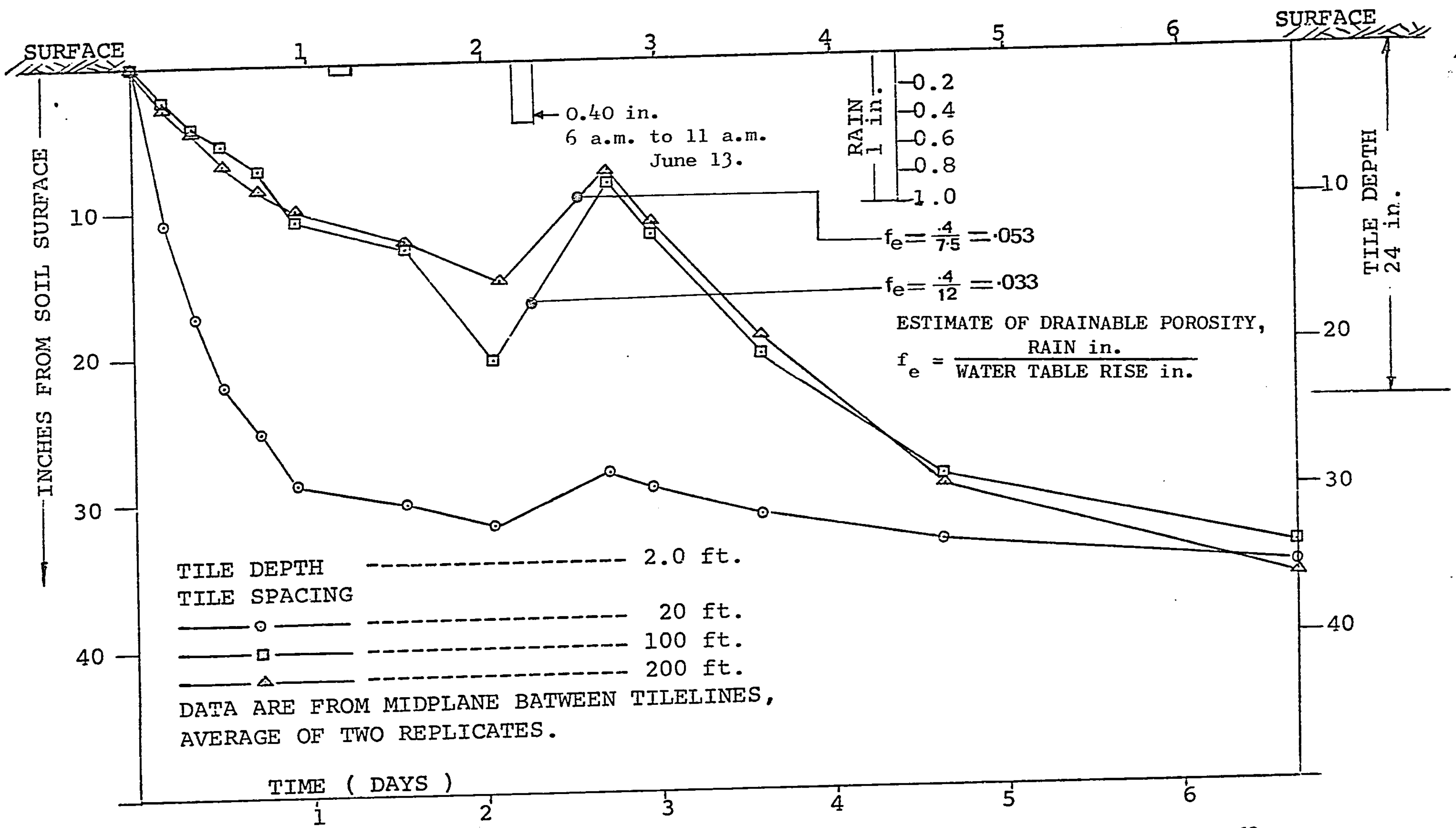


Figure A20. Water Table Changes at Midplane after Stopping Irrigation, 7 p.m. June 10, 1968, Vincent Field, Soulanges Fine Sandy Loam, Subdrains 2 ft Deep. (After Tu, 1968).

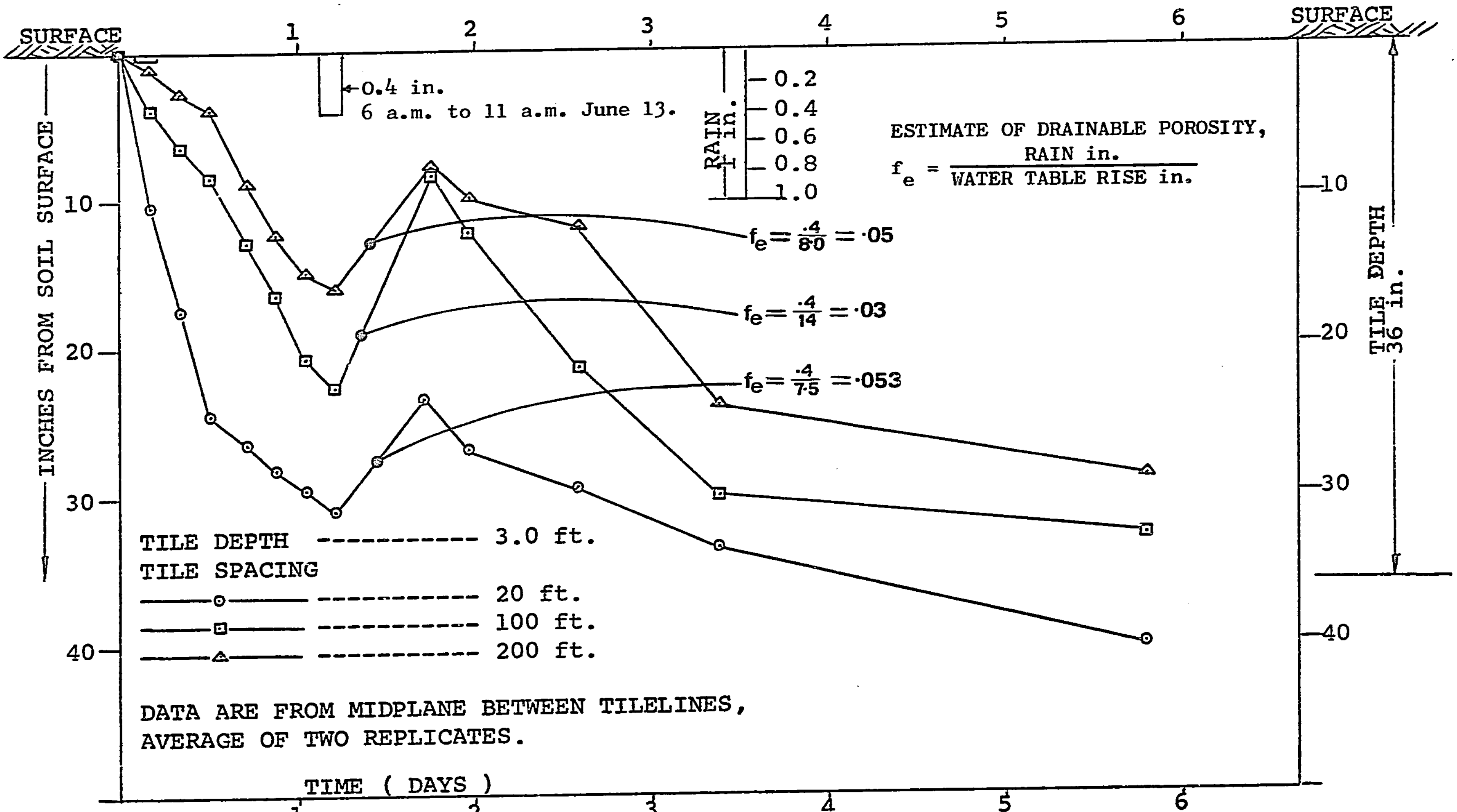


Figure A21. Water Table Changes at Midplane after Stopping Irrigation, 7 p.m. June 11, 1968, Vincent Field, Soulanges Fine Sandy Loam, Subdrains 3 ft Deep. (After Tu, 1968).

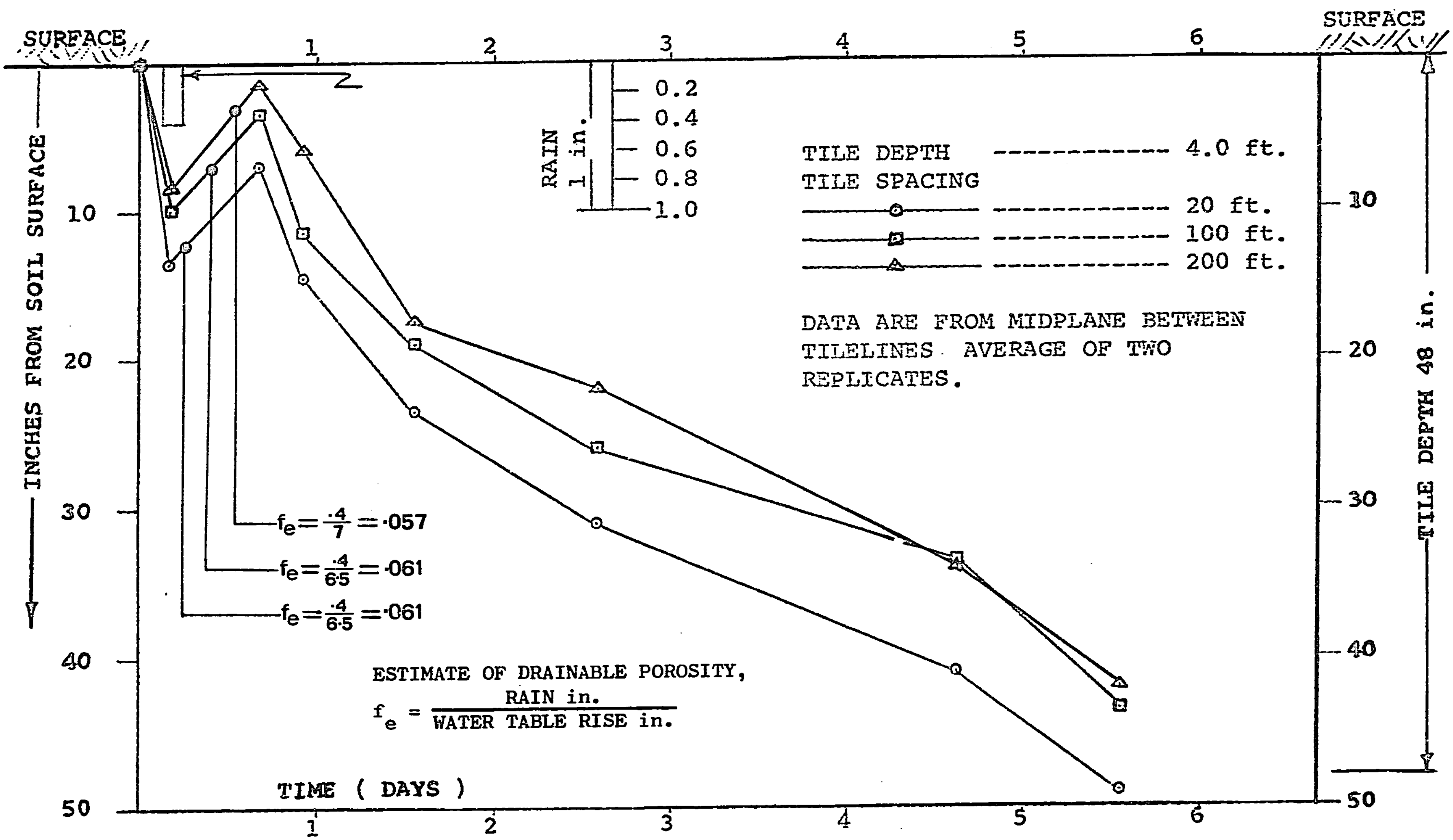


Figure A22 Water Table Changes at Midplane after Stopping Irrigation, 8 p.m. June 12, 1968, Vincent Field, Soulanges Fine Sandy Loam, Subdrains 4 ft Deep. (After Tu, 1968).

APPENDIX B

DATA TABLES

TABLE B1

A General Description of a Cultivated Ste. Rosalie Clay Profile (after Lajoie and Stobbe 1950)

Horizon	Variation in Depth	Description
Ac	5" - 8"	Very dark greyish brown to dark grey clay, granular structure, sticky when wet, friable when moist and hard when dry; pH 5.5 to 6.2.
A2	0" - 3"	Grey clay, somewhat mottled. Not generally present, but may occur in pockets of discontinuous layers 1 to 3 inches thick.
Bg1	4" - 8"	Brownish grey clay strongly mottled with rusty specks and streaks; fine blocky structure; very plastic and sticky when wet; firm when moist and hard when dry; , pH 5.8 to 6.5. (Locally this layer is referred to as "argile rouillee".)
Bg2	8" - 16"	Brownish grey clay, mottled with rusty brown; fine blocky structure. This layer differs from the one above in being less intensely mottled. pH 6.2 to 7.0.
C		Grey heavy clay; blocky to fragmental structure; very plastic and very slowly permeable; pH 6.8 to 7.4.

TABLE B2

A General Description of a Cultivated Soulanges
Fine Sandy Loam Profile
(After Lajoie and Stobbe 1950)

Horizon	Variation in Depth	Description
A1	5" - 7"	Very dark brown to dark greyish brown fine to very fine sandy loam, very soft crumb structure, pH 4.7 to 5.7.
A2	2" - 4"	Light grey to brownish grey leached fine sandy loam to loam.
B1	8" - 12"	Yellowish brown mottled with grey and rusty brown fine sandy loam, very friable, pH 5.0 to 6.0, some platy structure.
B2	10" - 18"	Light yellowish brown, mottled with grey and rusty, brown, fine to very fine light sandy loam, mica fragments, some thin platy structure, pH 5.5 to 6.5.
C	0" - 15"	Bluish grey sand, platy, friable, pH 6.2 to 7.0.
D		Clay or silty clay.

TABLE B3

Particle Size Distribution
Martineau's field, Ste. Rosalie Clay

Depth (in.)	Clay (%) 0.002 mm	Silt (%) 0.002-0.02 mm	Sand (%) 0.02-2.0 mm	Stratum Textural Class
0 - 6	40.5	30.5	29.0	Clay
9 - 15	50.5	29.5	20.0	Clay
18 - 24	46.0	33.0	21.0	Clay
30 - 36	48.0	31.5	20.5	Clay
36 - 48	63.0	24.0	13.0	Clay
48 - 60	67.5	18.5	14.0	Clay

TABLE B4

Particle Size Distribution
Vincent's field, Soulanges Fine Sandy Loam

Stratum Depth (in.)	Clay (%) <0.002 mm	Silt (%) 0.002-0.02 mm	Sand (%) 0.02-2.0 mm	Stratum Textural Class
0 - 6	13.0	12.0	75.0	Sandy Loam
9 - 15	3.5	9.5	87.0	Sandy Loam
18 - 24	11.5	9.0	79.5	Sandy Loam
30 - 36	62.0	30.0	8.0	Clay
36 - 48	80.5	11.0	8.5	Clay
48 - 60	73.5	16.5	10.0	Clay

TABLE B5. MONTHLY AND ANNUAL TOTAL PRECIPITATION OF RAIN AND SNOW, INCHES of WATER at MONTREAL INTERNATIONAL AIRPORT

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL TOTAL
1942	2.97	4.16	4.44	3.04	2.37	1.72	1.55	3.35	4.03	3.15	3.21	5.76	39.75
1943	2.38	3.15	3.53	3.31	2.75	8.49	3.65	4.04	0.90	4.50	2.71	2.09	41.50
1944	2.14	2.50	2.19	2.44	1.57	3.18	3.66	0.48	4.96	1.71	3.04	3.85	31.72
1945	3.27	1.90	2.09	4.11	6.90	2.17	5.89	2.95	5.61	4.65	3.65	2.13	45.32
1946	3.84	2.62	1.27	2.68	3.18	1.84	2.27	2.62	5.58	3.49	3.70	5.48	38.57
													39.34 *
1947	4.98	3.30	2.92	3.08	3.94	3.88	5.29	1.39	3.73	1.01	3.81	2.39	39.72
1948	2.09	2.12	4.58	2.43	2.28	2.77	2.99	2.88	0.44	2.45	5.00	3.57	33.60
1949	3.31	2.14	2.91	3.10	1.77	2.81	2.37	3.20	3.38	1.34	4.09	3.63	34.05
1950	4.03	4.07	3.26	2.51	2.94	1.82	3.96	3.44	2.21	2.59	5.10	3.53	39.46
1951	4.07	2.39	4.84	3.69	2.06	3.11	4.06	3.25	3.22	1.94	5.53	4.35	42.51
													37.87 *
1952	3.78	3.33	2.96	2.36	3.81	4.83	4.65	5.20	4.33	3.97	2.50	4.47	46.19
1953	3.67	1.57	3.79	3.25	3.28	3.37	2.79	1.83	2.83	1.63	1.66	3.87	33.54
1954	4.24	5.66	2.19	4.48	3.95	3.97	1.93	3.96	4.86	3.19	4.05	5.17	47.65
1955	1.35	2.35	6.50	1.18	1.89	2.28	1.63	4.19	2.42	2.95	1.68	1.15	29.57
1956	1.93	2.89	3.10	3.29	3.57	2.27	5.30	4.11	1.89	1.13	1.65	2.29	33.42
													38.07 *
1957	3.13	1.72	1.24	1.92	2.59	6.05	3.07	0.02	4.32	2.49	3.24	4.66	34.45
1958	3.40	4.97	1.97	2.00	2.41	2.86	6.38	3.93	4.19	3.71	2.12	2.97	40.91
1959	4.87	2.64	2.06	1.90	0.83	3.57	1.88	5.22	1.50	5.63	3.61	2.53	36.24
1960	2.48	6.87	2.39	3.47	2.00	2.45	3.45	1.19	2.27	4.77	3.03	2.69	37.06
1961	1.24	2.85	2.71	4.21	2.46	5.17	3.07	5.41	0.83	2.55	2.46	3.46	36.42
													37.02 *
1962	3.86	3.02	1.96	4.92	1.54	3.06	5.03	2.36	2.70	4.59	1.62	2.84	37.50
1963	1.64	2.32	3.36	3.34	3.47	3.61	2.47	5.88	4.64	0.55	5.87	1.14	38.29
1964	4.36	1.23	2.70	2.44	1.69	1.23	4.57	3.69	1.29	1.73	2.91	2.96	30.80
1965	2.17	2.94	0.72	2.50	1.81	0.73	3.38	6.29	4.06	5.11	5.15	1.94	36.80
1966	3.41	2.48	3.04	0.81	1.50	3.00	2.77	4.78	3.15	1.76	3.70	4.24	34.64
													35.61 *
1967	2.18	1.71	0.59	2.75	2.29	4.65	2.65	2.98	2.22	2.82	3.30	3.69	31.83
1968	1.85	1.50	3.33	2.39	1.99	3.39	1.86	2.63	2.45	2.65	3.83	4.09	31.96
1969	3.17	0.80	1.88	3.88	3.72	4.62	2.35	3.50	4.47	2.25	4.32	4.25	39.21
1970	0.74	1.79	2.07	2.48	2.05	1.91	2.16	4.06	4.62	3.28	2.99	3.61	31.76
1971	2.53	4.96	2.71	1.79	1.54	1.89	2.22	4.09	3.05	1.52	2.11	3.31	31.72
													33.30 *
MEAN 67-70	1.99	1.45	1.97	2.88	2.51	3.64	2.26	3.29	3.44	2.75	3.61	3.91	33.70
MEAN 42-71	2.97	2.86	2.78	2.86	2.60	3.22	3.31	3.43	3.20	2.84	3.39	3.40	36.87
σ 42-71	1.10	1.36	1.24	0.94	1.16	1.57	1.32	1.49	1.43	1.32	1.17	1.61	4.73
MEAN 42-68													38.19

* Mean annual total precipitation for previous 5 years.

TABLE B6. MONTHLY AND ANNUAL TOTAL INCHES OF RAINFALL at MONTREAL INTERNATIONAL AIRPORT. **

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL TOTAL
1942	0.95	1.23	2.22	2.08	2.37	1.72	1.55	3.35	4.03	3.08	2.33	1.66	26.57
1943	0.28	0.93	1.51	2.34	2.75	8.49	3.65	4.04	0.90	4.50	2.27	0.18	31.84
1944	0.23	0.19	1.29	1.83	1.57	3.18	3.66	0.48	4.96	1.71	0.88	0.75	20.73
1945	0.55	0.80	1.60	4.11	6.89	2.17	5.89	2.95	5.61	4.50	2.21	1.13	38.41
1946	0.74	0.56	1.14	2.30	3.18	1.84	2.27	2.62	5.34	3.39	2.46	1.97	27.81
													29.07 *
1947	2.20	TR	1.14	2.12	3.94	3.88	5.29	1.39	3.73	1.01	2.83	0.76	28.29
1948	0.01	0.54	3.66	2.43	2.28	2.77	2.99	2.88	0.44	2.45	4.77	2.06	27.28
1949	1.12	0.67	1.01	2.62	1.77	2.81	2.37	3.20	3.38	1.34	2.36	2.93	25.58
1950	1.71	TR	1.10	2.43	2.94	1.82	3.96	3.44	2.21	2.59	4.78	1.15	28.13
1951	1.58	0.75	3.28	3.49	2.06	3.11	4.06	3.25	3.22	1.94	3.88	0.67	31.29
													28.11 *
1952	1.50	0.66	1.48	2.32	3.81	4.83	4.65	5.20	4.33	3.95	2.36	2.20	37.29
1953	1.79	0.30	3.48	3.11	3.28	3.37	2.79	1.83	2.83	1.63	1.58	2.54	28.53
1954	0.54	0.98	0.75	4.03	3.95	3.97	1.93	3.96	4.86	3.19	2.99	1.37	32.52
1955	0.18	0.48	2.22	1.18	1.89	2.28	1.63	4.19	2.42	2.94	1.15	0.33	20.89
1956	0.29	0.15	0.17	3.29	3.57	2.27	5.30	4.11	1.89	1.13	0.75	0.70	23.62
													28.57 *
1957	1.20	1.04	0.29	1.85	2.59	6.05	3.07	0.02	4.32	2.49	3.24	3.20	29.36
1958	0.51	0.13	0.25	1.02	2.41	2.86	6.38	3.93	4.19	3.71	1.09	0.19	26.67
1959	1.44	0.24	1.06	1.90	0.76	3.57	1.88	5.22	1.50	5.48	2.03	0.74	25.82
1960	0.40	1.66	0.77	3.43	2.00	2.45	3.45	1.19	2.27	4.77	2.90	0.33	25.66
1961	0.07	2.17	0.79	2.94	2.46	5.17	3.07	5.41	0.83	2.55	1.39	1.76	28.61
													27.22 *
1962	1.55	0.26	0.10	3.59	1.54	3.06	5.03	2.36	2.70	3.80	0.93	0.27	25.19
1963	0.05	0.02	1.14	3.15	2.25	3.61	2.47	5.88	4.64	0.55	5.52	0.40	29.68
1964	3.25	TR	1.43	2.08	1.69	1.23	4.57	3.69	1.29	1.73	2.33	1.27	24.56
1965	0.59	1.46	0.01	2.50	1.81	0.73	3.38	6.29	4.06	4.80	2.86	0.98	29.47
1966	0.06	0.65	2.31	0.71	1.47	3.00	2.77	4.78	3.15	1.76	3.54	2.07	26.27
													27.03 *
1967	0.48	0.01	0.29	2.72	2.14	4.65	2.65	2.98	2.22	2.82	2.54	2.55	26.05
1968	0.46	0.50	2.52	2.39	1.99	3.39	1.86	2.63	2.45	2.65	2.38	0.13	23.35
1969	2.20	0	1.21	3.37	3.72	4.62	2.35	3.50	4.47	2.18	3.78	1.59	32.99
1970	0.13	0.49	1.00	1.85	1.75	1.91	2.16	4.06	4.62	3.28	2.64	0.06	23.95
1971	0.24	0.47	0.11	1.46	1.54	1.89	2.22	4.09	3.05	1.52	0.84	1.73	19.16
													25.10 *
MEAN RAIN 67-70	0.82	0.25	1.56	2.58	2.40	3.64	2.26	3.29	3.44	2.73	2.84	1.08	26.58
MEAN * SNOW 67-70	1.17	1.20	0.71	0.29	0.11	-	-	-	-	0.02	0.78	2.83	7.11
MEAN RAIN 42-71	0.88	0.58	1.31	2.49	2.55	3.22	3.31	3.43	3.20	2.78	2.52	1.26	27.52
MEAN ** SNOW 42-71	2.09	2.28	1.47	0.37	0.05	-	-	-	-	0.06	0.87	2.14	9.35
σ RAIN 42-71	0.81	0.54	1.00	0.85	1.17	1.57	1.32	1.49	1.42	1.26	1.21	0.90	4.36

* Mean annual total rainfall for previous 5 years.

** See Table B5 for total annual precipitation, rain and snow.

TABLE B7. MONTHLY AND ANNUAL MEAN TEMPERATURES, DEGREES FAHRENHEIT, at MONTREAL INTERNATIONAL AIRPORT

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL TOTAL
1942	15.0	14.7	33.2	45.1	59.7	66.5	69.9	67.3	60.1	49.2	34.9	14.1	44.1
1943	8.0	15.8	23.4	35.5	54.6	66.0	71.6	66.6	57.4	47.4	34.4	15.4	41.3
1944	17.8	14.4	23.4	38.6	60.9	65.2	71.1	71.9	60.7	47.0	35.8	13.8	43.4
1945	5.7	18.5	36.8	47.6	52.1	64.2	69.5	68.8	61.4	46.2	34.8	17.3	43.6
1946	14.3	10.8	38.4	42.3	53.6	65.2	69.8	65.4	62.4	50.7	37.6	21.8	44.4
1947	16.5	14.1	29.0	38.2	51.3	63.2	71.3	72.5	60.1	55.0	34.3	16.7	43.5
1948	10.9	12.4	26.9	43.5	54.1	63.9	71.1	70.7	63.2	47.8	42.5	26.8	44.5
1949	21.0	21.0	26.9	44.6	55.9	68.5	72.5	70.9	58.7	52.5	31.6	25.4	45.8
1950	22.6	12.6	20.4	39.4	55.7	65.4	69.6	65.9	56.0	49.0	38.0	21.8	43.0
1951	16.8	17.7	30.2	44.5	56.3	63.8	69.7	65.2	58.9	49.5	31.5	20.8	43.7
1952	16.4	20.7	28.7	45.3	53.3	66.2	72.6	68.6	60.6	45.5	38.2	25.6	45.1
1953	20.9	22.4	31.7	44.1	57.7	66.9	71.4	68.5	60.0	50.1	41.3	29.1	47.0
1954	9.0	22.8	27.6	42.6	54.0	65.1	67.6	65.6	57.2	50.7	37.6	21.8	43.5
1955	12.1	16.4	25.3	44.7	60.2	68.3	74.7	72.1	58.5	49.2	34.8	13.8	44.2
1956	18.6	18.8	21.7	39.7	49.7	64.2	66.5	67.0	55.5	49.6	35.6	22.2	42.4
1957	8.1	20.6	29.5	45.1	54.3	68.0	69.4	65.9	60.9	49.4	38.9	26.8	44.7
1958	19.6	12.2	32.5	45.0	52.3	60.1	69.4	67.7	59.9	47.5	37.6	10.4	42.9
1959	13.7	12.2	25.5	43.8	59.3	65.6	73.5	71.7	64.1	47.6	34.1	23.3	44.5
1960	14.4	21.9	23.2	42.4	61.5	66.1	68.7	68.9	60.7	47.6	40.6	19.2	44.6
1961	7.4	19.8	26.7	41.4	53.2	63.9	70.0	68.6	65.6	51.1	37.2	24.4	44.1
1962	13.8	11.8	30.4	41.7	58.6	67.1	66.7	68.2	57.4	47.1	33.1	19.2	42.9
1963	14.5	9.9	25.2	42.0	54.2	66.7	71.6	64.2	54.6	54.1	40.1	11.4	42.4
1964	21.1	17.3	29.5	43.1	58.7	65.8	70.9	64.0	57.7	46.3	34.5	21.9	44.2
1965	12.7	15.9	27.7	40.9	57.0	64.6	66.8	65.9	59.6	46.4	32.2	25.8	43.0
1966	14.5	17.9	30.9	42.1	52.7	66.9	70.1	66.6	55.9	47.1	39.2	21.7	43.8
1967	19.6	7.2	21.8	39.9	48.3	66.9	69.9	66.8	58.8	47.9	32.1	22.6	41.8
1968	6.9	11.6	30.1	47.4	53.4	61.5	68.8	63.6	62.3	50.6	31.6	16.5	42.0
1969	16.8	20.8	25.6	41.0	51.8	64.1	68.1	69.0	57.4	46.0	36.7	17.4	42.9
1970	3.8	14.6	25.5	42.5	54.4	64.2	70.8	68.6	63.1	50.8	37.9	12.8	42.4
1971	7.8	17.6	22.9	37.3	54.8	64.5	68.4	66.2	62.8	52.1	32.1	19.2	42.1
MEAN 67-70	11.7	13.6	25.8	42.7	52.0	64.2	69.4	67.0	60.4	48.8	34.6	17.3	42.3
MEAN 42-71	14.0	16.1	27.7	42.4	55.1	65.3	70.1	67.9	59.7	49.0	36.0	20.0	43.6
σ 42-71	5.1	4.1	4.3	2.9	3.3	1.9	1.9	2.5	2.7	2.4	3.1	5.0	1.2

TABLE B8. MONTHLY AND ANNUAL PRECIPITATION, RAIN AND SNOW INCHES OF WATER MARTINEAU, STATION 724, ST. CLET NORTH, QUEBEC. *

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL TOTAL
1965													
RAIN								**	3.70	3.79	2.59	.91	
SNOW									-	.40	1.75	.40	
TOTAL									3.70	4.19	4.34	1.31	
1966													
RAIN	.13	1.15	1.46	.58	1.69	3.13	2.89	2.78	2.48	1.13	3.72	2.50	23.64
SNOW	3.16	.94	.46	.08	-	-	-	-	-	.02	.22	2.98	7.86
TOTAL	3.29	2.09	1.92	.66	1.69	3.13	2.89	2.78	2.48	1.15	3.94	5.48	31.50
1967													
RAIN	.78	-	.76	3.02	1.91	3.38	2.80	2.77	2.26	2.70	2.16	2.14	24.68
SNOW	1.74	1.32	.24	-	-	-	-	-	-	-	1.06	1.16	5.52
TOTAL	2.52	1.32	1.00	3.02	1.91	3.38	2.80	2.77	2.26	2.70	3.22	3.30	30.20
1968													
RAIN	1.01	.44	2.89	1.85	2.38	3.36	5.97	2.44	2.46	2.76	3.24	.63	29.43
SNOW	1.46	1.24	.86	-	-	-	-	-	-	-	1.56	3.72	8.84
TOTAL	2.47	1.68	3.75	1.85	2.38	3.36	5.97	2.44	2.46	2.76	4.80	4.35	38.27
1969													
RAIN	1.89	-	2.53	4.36	3.95	3.87	2.71	2.72	1.70	2.29	3.20	1.99	31.21
SNOW	1.52	1.60	.68	.18	-	-	-	-	-	.24	.34	3.08	7.64
TOTAL	3.41	1.60	3.21	4.54	3.95	3.87	2.71	2.72	1.70	2.53	3.54	5.07	38.85
1970													
RAIN	.42	.67	1.47	2.53	2.54	2.05	2.54	1.41	4.26	2.05	3.44	.03	23.41
SNOW	.74	2.08	1.28	.70	.10	-	-	-	-	-	.16	3.74	8.80
TOTAL	1.16	2.75	2.75	3.23	2.64	2.05	2.54	1.41	4.26	2.05	3.60	3.77	32.21
1971													
RAIN	.32	.61	.08	1.79	2.94	1.48	2.83	3.18	4.41	1.71	.89	1.53	21.77
SNOW	2.54	4.56	3.30	.20	-	-	-	-	-	-	1.62	1.54	13.76
TOTAL	2.86	5.17	3.38	1.99	2.94	1.48	2.83	3.18	4.41	1.71	2.51	3.07	35.33
MEAN 67-70													
RAIN	1.03	.28	1.91	2.94	2.70	3.17	3.51	2.34	2.67	2.45	3.01	1.20	27.21
SNOW	1.37	1.56	.77	.22	.03	-	-	-	-	.06	.78	2.93	7.72
TOTAL	2.40	1.84	2.68	3.16	2.72	3.17	3.51	2.34	2.67	2.51	3.79	4.12	34.92
σ 67-70													
RAIN	.63	.33	.98	1.06	.88	.78	1.65	.63	1.11	.34	.58	1.03	3.75
SNOW	.43	.38	.43	.33	.05	-	-	-	-	.12	.65	1.22	1.56
TOTAL	.93	.63	1.19	1.10	.87	.78	1.65	.63	1.11	.32	.69	.76	4.33

** commencement of records for this station

* 10 inches of fresh snow fall is considered to be 1.0 inches of water

TABLE B9. MONTHLY AND ANNUAL PRECIPITATION, RAIN AND SNOW INCHES OF WATER VINCENT, STATION 723, ST. EMMANUEL, QUEBEC.*

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL TOTAL
1965													
RAIN								**	2.99	3.95	2.35	1.67	
SNOW									-	2.70	1.81	.67	
TOTAL									2.99	6.65	4.16	2.34	
1966													
RAIN	-	1.00	2.01	.86	1.79	3.52	1.82	2.91	2.31	1.36	3.95	2.57	24.10
SNOW	4.08	1.52	.85	.10	-	-	-	-	-	-	.35	2.69	9.59
TOTAL	4.08	2.52	2.86	.96	1.79	3.52	1.82	2.91	2.31	1.36	4.30	5.26	33.69
1967													
RAIN	4.18	-	.17	2.93	1.84	3.06	3.45	2.50	1.70	2.84	1.58	2.45	26.7
SNOW	1.58	3.03	.69	-	-	-	-	-	-	-	1.37	1.00	7.67
TOTAL	5.76	3.03	.86	2.93	1.84	3.06	3.45	2.50	1.70	2.84	2.95	3.45	34.37
1968													
RAIN	1.03	.45	2.79	1.93	1.79	3.92	5.72	2.63	2.38	2.48	2.91	.29	28.32
SNOW	1.78	1.59	1.29	-	-	-	-	-	-	-	1.99	3.61	10.26
TOTAL	2.81	2.04	4.08	1.93	1.79	3.92	5.72	2.63	2.38	2.48	4.90	3.90	38.58
1969													
RAIN	1.91	-	1.86	4.60	4.68	3.91	2.40	2.38	2.24	2.64	3.24	1.45	31.31
SNOW	.69	1.50	.65	.10	-	-	-	-	-	.20	.40	2.89	6.43
TOTAL	2.60	1.50	2.51	4.70	4.68	3.91	2.40	2.38	2.24	2.84	3.64	4.34	37.74
1970													
RAIN	.44	.26	1.59	2.12	2.54	1.72	1.73	1.85	4.90	1.66	3.27	.08	22.16
SNOW	.86	2.69	.86	.50	-	-	-	-	-	-	.72	3.54	9.17
TOTAL	1.30	2.95	2.45	2.62	2.54	1.72	1.73	1.85	4.90	1.66	3.99	3.62	31.33
1971													
RAIN	.04	.69	.39	1.03	1.56	1.78		4.36	3.35	1.27	0.77	2.61	
SNOW	2.00	4.25	2.99	.16	-	-		-	-	-	1.34	1.67	
TOTAL	2.04	4.94	3.38	1.19	1.56	1.78		4.36	3.35	1.27	2.11	4.28	
MEAN 67-70													
RAIN	1.89	.18	1.60	2.90	2.71	3.15	3.33	2.34	2.81	2.41	2.75	1.07	27.14
SNOW	1.23	2.20	.87	.15	-	-	-	-	-	.05	1.12	2.76	8.38
TOTAL	3.12	2.38	2.47	3.05	2.71	3.15	3.33	2.34	2.81	2.46	3.87	3.83	35.52
σ 67-70													
RAIN	1.64	.22	1.09	1.22	1.38	1.04	1.75	.34	1.43	.52	.80	1.10	3.82
SNOW	.53	.77	.39	.24	-	-	-	-	-	.10	.71	1.22	1.68
TOTAL	1.88	.74	1.32	1.18	1.38	1.04	1.75	.34	1.43	.56	.81	.39	3.33

** commencement of records for this station

* 10 inches of fresh snowfall is considered to be 1.0 inches of water

TABLE B10. MONTHLY AND ANNUAL MEAN AND MAXIMUM AND MINIMUM OBSERVED TEMPERATURES, DEGREES FAHRENHEIT, STATION 724, MARTINEAU FARM, ST. CLET NORTH, QUEBEC.

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL MEAN
1966													
MAX	**						***	84	81	73	66	46	
MIN	**							45	27	11	9	-15	
MEAN								64.6	54.2	45.5	38.0	13.8	
1967													
MAX	44	35	51	63	78	86	85	85	80	77	57	52	
MIN	-23	-33	-15	16	25	38	47	43	32	21	-2	-11	
MEAN	18.0	6.6	20.4	39.4	47.0	65.7	67.6	65.9	57.3	46.4	30.3	21.7	40.5
1968													
MAX	39	44	62	79	77	80	90	82	81	81	50	43	
MIN	-25	-16	-9	20	23	41	41	36	35	25	10	-23	
MEAN	4.9	9.3	31.6	46.3	51.8	60.0	65.6	62.6	60.7	49.3	30.4	14.2	40.6
1969													
MAX	40	37	46	72	80	90	87	88	82	75	57	40	
MIN	-11	-4	-15	4	27	34	37	38	32	19	6	-20	
MEAN	14.5	11.2	24.2	39.6	53.0	63.9	69.9	67.4	56.4	45.1	35.8	16.1	41.4
1970													
MAX	42	39	46	79	84	86	90	90	83	78	59	51	
MIN	-29	-27	2	15	27	39	38	37	37	23	11	-21	
MEAN	1.6	11.9	24.5	41.5	53.3	62.3	68.5	66.6	57.5	49.7	36.8	10.9	40.4
1971													
MAX	38	41	49	56	88	91	88	89	83	74	71	47	
MIN	-27	-31	-12	10	28	36	38	34	37	24	-2	-15	
MEAN	5.2	15.7	21.0	34.6	53.7	66.6	69.6	69.6	61.9	50.8	30.8	17.9	41.4
4 YEAR MEAN 67 -70	9.8	9.8	25.2	41.7	51.3	63.0	68.0	65.6	58.0	47.6	33.3	15.7	40.7

** MAX and MIN refer to the maximum and minimum temperatures recorded in the month

*** Records of Temperature commenced June 1966.

TABLE B11. MONTHLY AND ANNUAL MEAN AND MAXIMUM AND MINIMUM OBSERVED TEMPERATURES, DEGREES FAHRENHEIT, STATION 723, VINCENT FARM, ST. EMMANUEL, QUEBEC.

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL MEAN
1966													
MAX	**				***	89	90	87	80	73	66	44	
MIN	**					37	45	43	27	17	12	-6	
MEAN						64.5	66.1	65.3	54.8	45.9	37.8	19.4	
1967													
MAX	*	37	42	64	78	85	85	84	80	78	57	53	
MIN	-2.4	-33	-18	18	26	41	49	43	32	23	0	-12	
MEAN	-	6.0	18.0	39.8	48.2	66.9	67.3	67.7	58.2	47.1	31.7	22.1	39.4
1968													
MAX	40	42	65	80	76	81	88	83	81	82	50	44	
MIN	-25	-12	-4	21	27	44	43	41	43	27	11	-21	
MEAN	7.2	10.6	29.6	43.0	52.6	59.8	67.8	64.6	61.4	49.6	30.8	15.7	41.1
1969													
MAX	40	36	43	72	89	89	88	87	80	75	58	40	
MIN	-9	-1	-7	9	38	37	43	40	33	22	7	-19	
MEAN	16.2	19.2	20.7	40.3	65.8	62.2	68.6	68.5	57.0	45.5	36.4	17.5	43.2
1970													
MAX	44	46	45	78	83	84	90	90	83	78	58	52	
MIN	-24	-22	-5	18	30	41	43	40	37	24	12	-25	
MEAN	3.0	13.0	24.8	41.5	55.5	62.8	70.7	68.6	58.1	48.6	37.1	10.2	41.2
1971													
MAX	40	44	47	58	88			90	84	74	73	50	
MIN	-25	-31	-7	13	30			35	40	26	0	-7	
MEAN	6.4	16.3	21.1	35.8	54.3			65.8	62.5	50.7	30.5	18.8	
4 YEAR MEAN 67 -70	6.6	12.2	23.3	41.2	55.5	62.9	68.6	67.4	58.7	47.7	34.0	16.4	41.2

* Max thermometer broken

** Max and Min refer to the maximum and minimum temperatures recorded in the month

*** Records of temperature commenced June 1966.